OOPS MIDDLE MILE PLANNING CONSULTING REPORT

Middle Mile Logistics

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1.0 Executive Summary

The purpose of this consulting report is to present a fully optimal model for Oops (an E-commerce Company) that reduces the cost of the company while transporting packages between Oops shipping centers. With the rapidly growing digital world, E-commerce has emerged as a major option for everyone to buy and sell any product, right from all basic needs to specific need categories. With the growing demand for shopping through E-commerce, shipping companies have been facing issues in different sectors to fulfill customer requirements on time, and generating adequate margins for the company has become a critical thinking topic. The same problem is being faced by our client - “OOPS” and hence the company wants to reduce the overall cost of shipping by getting optimal solutions on package assignment to vehicles, the number, and types of vehicles assigned to shipping centers, and the number of operators to be relocated from one shipping center to another.

From the information provided, the ISEN consulting firm has built a Mixed Integer Linear Programming (MILP) to optimize the Oops Middle Mile Logistics problem and reduce the overall cost. Reducing the total cost involves reducing transportation costs (operating cost of vehicles), operator relocation costs (proportional to relocation distance), and package costs (if delayed). With the given parameters of package, vehicle, operator, trip/shipping, and shipping center, variables are defined and objective functions & constraints are developed to minimize the overall cost.

In Conclusion, the ISEN consulting firm is providing Oops with a Mixed Integer Linear Programming (MILP) model developed taking into account the various operating constraints of the company that is done in minimum possible total cost to fulfill the demand of customers. Thus, Oops can increase its profit by deploying this model to plan its Middle-Mile Logistics.

2.0 Introduction

This part of the report will give a background on the problem, a brief introduction to middle-mile logistics, the problem statement, and the assumptions made to develop the Mixed Integer Linear Programming model.

2.1 Background

The world has changed, so have the people and so has the technology. The whole market is moving towards digitization. The development in the sector of web tools has made people's life much easier than before, and also the covid pandemic has made a significant impact on the living style of people around the world. These days most people avoid going outside for the purpose of shopping, instead, they prefer to leverage the advancements made in E-commerce and use applications/websites on their smartphones or computers to shop for things they want from the comfort of their homes.

Fig 1: Growth of E-Commerce in the US

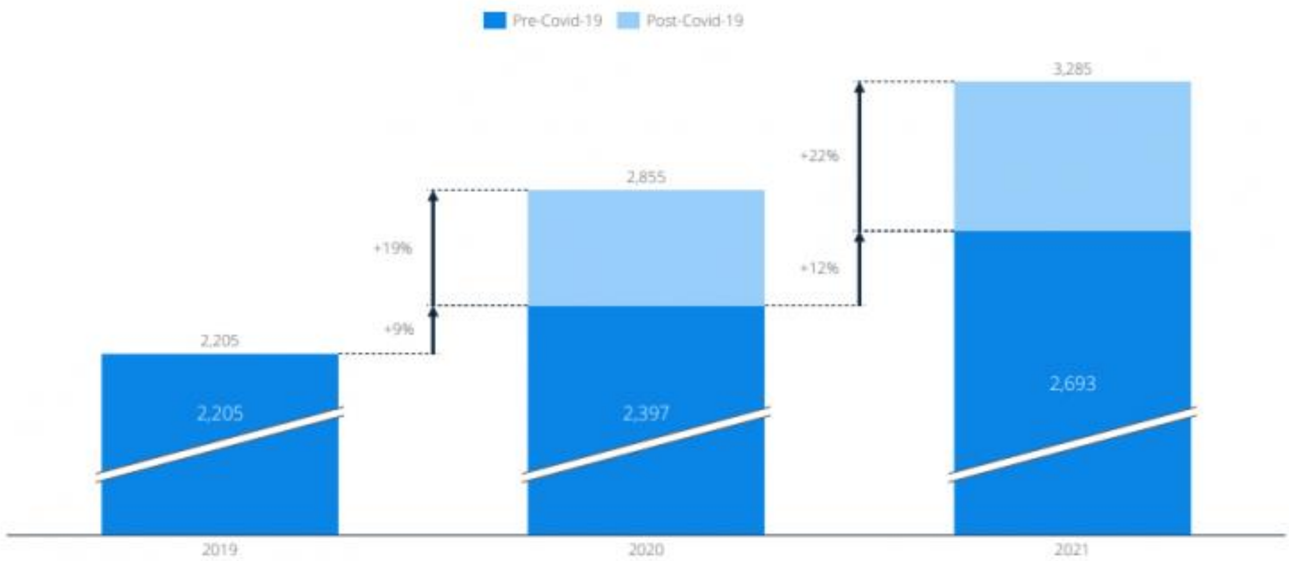

Fig 2: Impact of Covid on E-Commerce growth

With the emergence of E-commerce companies, customers now have a wide variety to choose from which in turn has increased the competition among E-commerce companies. E-commerce companies now must be highly efficient in every part of their operations to make better profits and survive in the market. Oops is one such company that has decided to optimize its middle-mile logistics and make it more cost-efficient.

2.2 Middle Mile Logistics

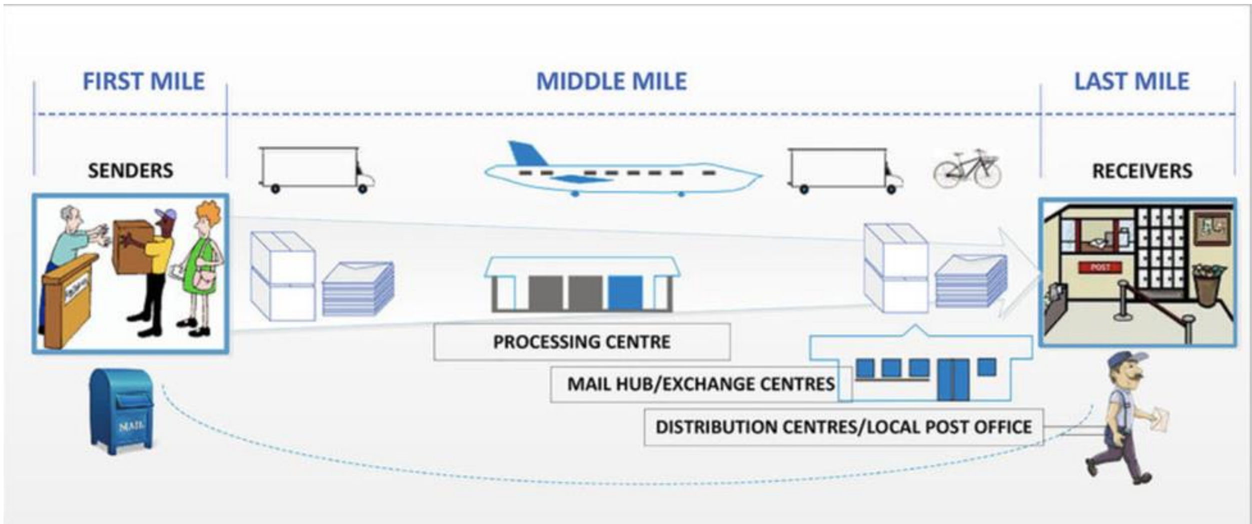

Fig 3: General overview of Middle Mile Logistics

The middle mile delivery stage of the supply chain is when products are moved between facilities before being picked up for delivery. A middle-mile delivery often takes a path from a holding or fulfillment center to a distribution hub.

The procedures required for middle-mile delivery are referred to as middle-mile logistics. It involves working with vehicles to transport goods between the two locations. Planning and scheduling for middle-mile deliveries must consider driver availability, order load, and other considerations.

2.3 Problem Statement

Oops targets the luxury market. While its prices are higher, it guarantees that products/packages will be delivered on or before a given deadline (measured in hours) or the product is free. Oops wants to optimize its Middle Mile Logistics by reducing the cost incurred in the Middle Mile. The total cost incurred in Middle Mile Logistics for Oops is made up of the operating cost of vehicles, relocation cost of operators, and the cost of the package if delivered late. There are certain parameters and operating constraints given by Oops to ISEN consulting firm which have to be taken into account while developing the Mixed Integer Linear Programming model. They are:

Package info:

For each package, Oops provides the ISEN consulting firm with its origin shipping center, destination shipping center, weight, the time limit to reach its destination shipping center, cost, and the shipping incompatibilities of the packages (if two packages are incompatible, the packages must not travel in the same vehicle even if they are going from the same origin center to same destination center).

Vehicle info:

ISEN consulting firm will be given the number of trucks, planes, and trains present in the central depot that can be used for Middle-Mile logistics. Oops also provides the maximum weight capacity and speed of each vehicle type.

Operator info:

Oops hires highly versatile operators so every operator can operate any vehicle. ISEN consulting firm will be given the number of operators living near each shipping center. In case an operator is to be relocated from his/her home shipping center to another shipping center due to operational demands, the operator must be paid a bonus, proportional to the relocation distance. The relocation cost per mile for the operator will also be given.

Trip/Shipping info:

Oops strictly adheres to the maximum weight capacity of the vehicle and no vehicle can be overloaded. It also strictly advises against loading incompatible packages in the same vehicle. Oops has fixed the operational cost per mile of each vehicle type and this value must be used to calculate the operating cost of vehicles.

Shipping center info:

ISEN consulting firm will be given the maximum number of vehicles (independent of vehicle types) that can be loaded or unloaded in a particular shipping center which is set by labor unions.

2.4 Assumptions

- The allocation of vehicles from the depot to shipping centers is instantaneous at the beginning of the day.
- The relocation of operators from their home shipping centers to other shipping centers is instantaneous at the beginning of the day.
- Each vehicle starts at one shipping center and goes directly to the destination shipping center. That is, vehicles will not make intermediate loading/unloading stops.
- The loading and unloading of vehicles happen instantaneously.
- The distance between shipping centers is the same irrespective of the vehicle type (as the distance between point A to point B may be different when traveling via road, rail or plane).

3.0 Mixed-Integer Linear Programming Model

This part of the report consists of the final proposed model which contains the parameters given by Oops to ISEN consulting firm, decision variables ISEN consulting firm has chosen to develop the model, objective function developed by ISEN consulting firm to reduce costs, and the constraints to meet the operating conditions of Oops along with a brief description of each of the following.

3.1 Decision Variables

These are the variables representing the various decisions that model will make to create the Middle Mile Logistics system for Oops.

$\mathbf{P_{sijkn}}$-

$\begin{cases} 1 \textit{ if part "s" going from center "i" to center "j" is assigned in vehicle "n" of type "k"} \\ 0 \textit{ otherwise} \end{cases}$

$\mathbf{Vec_{ik}}$ - *Number of vehicles to which packages are assigned from the center "i" to center "j" of vehicle type "k"*

$\mathbf{Z_{ij}}$ - *Number of workers relocating from the center "i" to center "j"*

$\mathbf{PZ_s}$ - $\begin{cases} 1 \textit{ if package } \text{"s"} \textit{ is delievred late} \\ 0 \textit{ otherwise} \end{cases}$

$\mathbf{Vec\_c_{ijk}}$ - *number of vehicles of type "k" going from the center "i" to "j"*

$\boldsymbol{y_s}$– $\begin{cases} 1 \textit{ if 1st constraint in } C13 \textit{ is relaxed} \\ 0 \textit{ otherwise} \end{cases}$

$\mathbf{Vec\_R_{ijkn}}$ – $\begin{cases} 1 \textit{ if nth vehicle of type k is going from center i to j} \\ 0 \textit{ otherwise} \end{cases}$

$\mathbf{y2_{ijkn}}$-

$\begin{cases} 1 \textit{ if atleast one package is assigned to vehicle } \text{"n"} \textit{ of type } \text{"k"} \textit{ going from center } \text{"}i\text{"} \textit{ to } \text{"}j\text{"} \\ 0 \textit{ otherwise} \end{cases}$

3.2 Parameters

The following Parameters have been considered based on the problem defined by OOPS:

S:	Total number of packages
N:	Total number of centers
W_s:	Weight of package "s"
PT_s:	Maximum delivery time of package "s"
C_s:	Penalty cost of package "s" if Package is delayed
K:	Total number of vehicle types
V_k:	Total number of vehicles of each type "k" available at the center depot
W_cap_k:	Maximum weight capacity of the vehicle of type "k"
SP_k:	Average Speed of vehicle of type "k"
NW_i:	Total number of operators living near the center "i"
RC:	Relocation cost per mile for an operator
CPM_k:	Operating cost per mile for a vehicle of type "k"
D_{ij}:	Distance between center "i" and center "j"
ML_i:	Maximum number of vehicles that can be loaded at the center "i"
MUL_j:	Maximum number of vehicles that can be unloaded at center "j"

Part_trav$_{sij}$: Origin center “i”, Destination center “j” for package “s”. From OOPS, we will get data regarding each package’s origin and destination shipping center. We will feed it to the model in this way.

M: Parameter to constraint part 1 of C13: Tracking of packages being delayed. Will have Max ($D_{i,j}$).

M2: Parameter to constraint part 2 of C13: Tracking of packages being delayed. Will have value of 1.

M3: Parameter to constrain part 1 of C2: Tracking Routes assigned to each vehicle. Will have value = S. This because it’s possible that all parts are going from particular center “i” to particular center “j” and all are allocated to vehicle number “n” of type “k”. Check constraint for more explanation.

M4: Parameter to constrain part 1 of C2: Tracking Routes assigned to each vehicle. Will have value = 1.

3.3 Objective Function

The objective is to ensure that all the packages are delivered to the correct locations while ensuring all the demands/restriction that Oops has defined at the minimum cost.

min cost: $\sum_{j=1}^{N}\sum_{i=1}^{N} Z_{ij} D_{ij} RC + \sum_{s=1}^{S} C_s P\, Z_s + \sum_{k=1}^{K}\sum_{j=1}^{N}\sum_{i=1}^{N} Vec\_c_{ijk} D_{ij}\, CPM_k$
where,

$\sum_{j=1}^{N}\sum_{i=1}^{N} Z_{ij} D_{ij} RC$: represents the total relocation cost of workers from “j” to “i”.

$\sum_{s=1}^{S} C_s PZ_s$: represents the total penalty cost if a package “s” is delivered late.

$\sum_{k=1}^{K}\sum_{j=1}^{N}\sum_{i=1}^{N} Vec\_c_{ijk} D_{ij}\, CPM_k$: represents the total operating cost of the vehicles.

3.4 Constraints

3.4.1 *C1:* One Vehicle Constraint:

$\sum_{k=1}^{K} \sum_{n=1}^{V_k} P_{sijkn} = Part\_trav_{sij}$ (s=1..S, i=1..N, j=1..N)

This constraint is added to made sure that a package “s” going from “i” to “j” is assigned to only 1 vehicle of type “k”. For example, if a package 1 is being assigned such that it will be delivered from the center “1” to center “2” and assuming right now, we only have 2 vehicles available of Truck (k=1) and 1 vehicle of type Train (k=2) and Plane (k=3). Then our constraint will be defined as:

$(P_{1,1,2,1,1} + P_{1,1,2,1,2} + P_{1,1,2,2,1} + P_{1,1,2,3,1}) = Part\_trav_{1,1,2}$

Because of this, if package “1” has to be transported from Center 1 to Center 2, the RHS will be 1 and it will be only assigned to one vehicle out of Truck1, Truck2, Train1, and Plane1. Also, if no package is being transported from “i” to “j” then the package won’t be assigned to any vehicle.

3.4.2 C2: Tracking Route Assigned to each Vehicle

$\sum_{s=1}^{S} P_{sijkn} \leq 0+M3*(y2_{i,j,k,n})$ (i=1..n, j=1..n, k=1..k, n=1..V_K)

$Vec\_R_{i,j,k,n} \geq 1-M4*(1-y2_{i,j,k,n})$ (i=1..n, j=1..n, k=1..k, n=1..V_K)

As mentioned above, we have created a binary Decision variable $Vec\_R_{i,j,k,n}$ to track if vehicle number “n” of type “k” is assigned to the route “i” to “j”.
We created an if-then constraint and then converted it to Either – Or constraint.
Logic is that, if any of the packages are assigned to a particular vehicle number of type “k” going from center “i” to center “j”, then $Vec\_R_{i,j,k,n}$ will be 1 else it will be 0. For example, suppose we have 4 packages and even if one of them is going on truck 1 from 1 to 2, which is Package 2 then LHS for 1st part of the constraint will be:

$(P_{1,1,2,1,1} + P_{2,1,2,1,1} + P_{3,1,2,1,1} + P_{4,1,2,1,1}) = 1$ (as $P_{2,1,2,1,2} = 1$).

So, to ensure that constraint will be held up $y2_{1,2,1,1}$ will have to be assigned 1. And then in the 2nd constraint if $y2_{1,2,1,1}$ is assigned 1 then $Vec\_R_{1,2,1,1}$ will have to become 1 (since it is a binary variable it can only be 1 or 0).

3.4.3 C3: Vehicles can be assigned to only 1 route

$$\sum_{i=1}^{N} \sum_{j=1}^{N} Vec\_R_{ijkn} \leq 1 \qquad (k=1..K,\ n=1..V_k)$$

This constraint is used to ensure that a vehicle "n" of a particular type "k" should be assigned to only one route "i" to "j" at a time. For example, suppose we have 3 centers, then for Truck 1 i.e., k=1 and n=1 our constraint will be like this:

$$Vec\_R_{1,2,1,1} + Vec\_R_{1,3,1,1} + Vec\_R_{2,1,1,1} + Vec\_R_{2,3,1,1} + Vec\_R_{3,1,1,1} + Vec\_R_{3,2,1,1} <= 1$$

Using this, if any part is assigned to truck 1, we will restrict it to one route only.

3.4.4 C4: Vehicles Allocated to Center i

$$Vec_{ik} = \sum_{j=1}^{N} \sum_{n=1}^{V_k} Vec\_R_{i,j,k,n} \qquad (i=1..N,\ k=1..K)$$

This is not a constraint but the calculation to determine the number of vehicles of particular type "k" are allocated (by allocated we refer to those vehicles only to which any packages for delivery are assigned) to each center. This is calculated by summation of "Vec_R" variable and summing it for each center (acting as destination node) and number of vehicles of type "k". For example, if we know that for 2 Trucks(k=1) are allocated to travel from center 1 to center 3 and 1 truck to travel from center 1 to center 4 then,

$Vec_{1,1} = Vec\_R_{1,3,1,1} + Vec\_R_{1,3,1,2} + Vec\_R_{1,4,1,3}$ and all other will be 0.

(Note that for each route different "n" is used to signify the importance of previous constraints that a particular vehicle can be assigned to only 1 route).

So, based on this constraint we can determine that 3 vehicles of type k=1 will be allocated at center 1.

3.4.5 C5: Vehicle Allocated to route i to j

$$Vec\_c_{ijk} = \sum_{n=1}^{V_k} Vec\_R_{ijkn} \qquad \text{(i=1..N, j=1..N, k=1..K)}$$

This one is also not a constraint imposed by OOPS, but just like C4, this will help us in defining further constraints. This is similar to “C4: Vehicles allocated to center ‘i’” and here we are basically finding the number of vehicles of type “k” being assigned to a particular route (i to j).

3.4.6 C6: Total Vehicles Allocated

$$\sum_{i=1}^{N} Vec_{ik} \leq V_k \qquad \text{(k=1..K)}$$

This constraint is to ensure that sum of number of vehicles of each type that are allocated (by allocated we mean that packages to be delivered are assigned to it) to each center must be less than the Total Number of vehicles of each type “k” available to OOPS at the start of the day.

3.4.7 C7: Weight Capacity

$$\sum_{s=1}^{S} \sum_{i=1}^{N} \sum_{j=1}^{N} W_s P_{sijkn} \leq W\_cap_k \qquad \text{(k=1..K, n=1..}V_k\text{)}$$

This constraint is to ensure that packages are assigned to vehicles in such a way that the sum of weights of packages does not exceed the truck capacity**.** For example, let us take the case that we have only 2 vehicle types, truck (k=1, weight capacity = 250 kg) and train (k=2, weight capacity = 1000kg). And we have 2 packages: (both packages have weight of 225 kg and have to be transported from C1 to C4). So, there are 2 options depending on other factors as well like cost, timely delivery etc.

1) both packages either allocated to train or
   W1*P1,1,4,2,1 + W1*P2,1,4,2,1 = 225+225 = 450 (still less than 1000kg which is weight capacity of train)

2) We use 2 trucks to deliver.
W_1*$P_{1,1,4,1,1}$ + W_1*$P_{2,1,4,1,1}$ = 225 + 225 = 450 (exceeding the 250 kg truck capacity, so packages will be assigned to different trucks)

3.4.8 C8: Incompatibility Constraint

$P_{sijkn} + P_{sijkn} \leq 1$ (i=1..N, j=1..N, k=1..K, n=1..V_k)

This constraint to ensure that Incompatible packages that need to be delivered via same route (i.e., same originating and same destination center) should not be assigned to same vehicle. For example: suppose OOPS has to deliver 2 packages from center 1 to center 3 and package 1: gunpowder and package 3: lighter fluids are incompatible with each other. Then the packages will not be allocated to same vehicle for example truck 1 (k=1, n=1):

LHS, $P_{1,1,3,1,1}$ + $P_{2,1,3,1,1}$ will have to be less than or equal to 1.

So, only 1 package can be allocated to truck 1 going from Center 1 to Center 3. This constraint will be added for each pair of packages that are defined as incompatible by OOPS.

3.4.9 C9: Maximum Vehicles that can be Loaded (allocated) at each center

$\sum_{k=1}^{K} \sum_{i=1}^{N} \sum_{j=1}^{N} Vec\_c_{ijk} \leq ML_i$ (i=1..N)

This constraint is to ensure that the sum of a number of vehicles that are loaded(allocated) at each center should be less than the max number of vehicles that can loaded at that center as per the parameter given by Oops.
For example, 2 vehicles each of truck (k=1) and train (k=2) are required to travel from center 1 to center 3. And maximum number of vehicles loaded at C1 is 5.

LHS, $Vec\_c_{1,3,1}$+$Vec\_c_{1,3,2}$ = 2+2 =4 <= RHS (ML_1 = 5)

3.4.10 C10: Maximum Vehicles that can be Unloaded at each center

$$\sum_{k=1}^{K} \sum_{i=1}^{N} Vec\_c_{ijk} \leq MUL_j \qquad (j=1..N)$$

This constraint is to ensure that sum of number of vehicles that are unloaded at each center is less than the maximum number of vehicles that can be unloaded at that center as per the parameter given by Oops.
For example, 2 vehicles each of truck (k=1) and train (k=2) are required to travel from center 1 to center 3. And maximum number of vehicles that can be unloaded at C3 is 4.
LHS, $Vec\_c_{1,3,1}$+$Vec\_c_{1,3,2}$ = 2+2 =4 <= RHS, MUL_1 = 4.

3.4.11 C11: Relocation Variable Constraint

$$Z_{ii} = 0 \qquad (i=1..N)$$

We created decision variable "Z" to determine the number of vehicle operators who need to be relocated from one center to another. So, it does not make sense to relocate vehicle operators from one center to that center itself. That is why diagonal in the matrix Z will be 0.

3.4.12 C12: Number of operators needed at each center

$$NW_i - \sum_{j=1}^{N} Z_{ij} + \sum_{j=1}^{N} Z_{ji} \geq \sum_{k=1}^{K} Vec_{ik} \qquad (i=1..N)$$

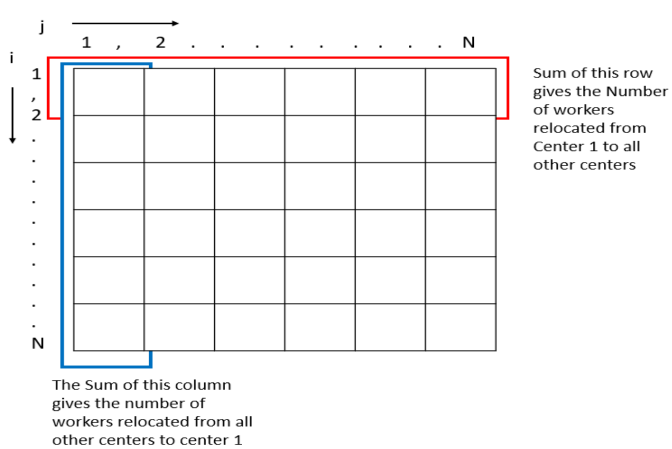

Fig 4: Representation of allocation of operators

This constraint is added to make sure that each center has enough number of workers (including both original workers present + number of workers relocated from other centers to this center) should be sufficient to handle all the vehicles (irrespective of type) assigned to that center. So, for each center we are calculating:

LHS, NW_i (Number of workers available at center i) - $\sum_{j=1}^{N} Z_{ij}$ (Number of workers relocated from center i other centers – *the row (marked by the red box in figure*) + $\sum_{j=1}^{N} Z_{ji}$ (Number or workers relocated from other centers to center i -*the column (marked by the blue box) in the figure*) >= RHS, the sum of all vehicles irrespective of type allocated (assigned to delivery of packages) to center i.

3.4.13 C13: Tracking of packages being delayed

This pair of constraint is to track which packages are being delivered after their deadline as separate Penalty cost needs to be paid. So, if package "s" is being delivered late (comparing the time it takes to deliver a package "s" if its going from "i" to "j" on a particular vehicle "n" of type "k" –

$$Delivery\ Time = \frac{Distance\ btw\ node\ i\ and\ j}{Speed\ of\ vehicle - package\ is\ allocated\ to}$$

and then comparing this delivery time with package's deadline).

$\sum_{k=1}^{K} \sum_{n=1}^{V_k} P_{sijkn} SP_k PT_s \geq D_{ij} Part\_trav_{sij} - M^*(y_s)$ (s=1..S, j=1..N, i=1..N)

This constraint is to ensure that if a package is being delivered on time (To avoid non-linearity we have multiplied speed of vehicle on both sides) then "y" will be 0 and otherwise 1.

$PZ_s \geq 1\text{-}M2(1\text{-}y_s)$ (s=1..S)

If "y" is assigned 1 means package "s" was delivered late and thus "PZ" for package "s" will also be assigned 1.

3.4.14 C14: Package cannot be assigned from same center to same center

$P_{siikn} = 0$ (s=1..S, i=1..N, k=1..K, n=1..V_k)

This constraint is added to make sure that that no packages are assigned to a route such that it has same shipping and destination center.

3.4.15 C15: Non-Negativity and Binary Constraint

This constraint is added to ensure that MILP model gives correct optimal value and for that to happen all our decision variables should be greater than or equal to 0 (to have logically correct solution) along with few that have been restricted to have only 2 values 0 or 1 – hence are constrained as binary.

4.0 Solving Sample Problem:

To ensure that the proposed MILP model developed by us satisfies all the constraints defined by Oops for their Middle Mile Logistics problem and to determine the optimum solution at a minimized cost, AMPL software was used for testing purposes, and the Model file (".txt format") and Data file (".txt format") was passed as input to AMPL and then solved by using the CPLEX solver.
We created a sample problem to check for validity and show how the MILP model works.

Sample Problem: To check for validity, we created a sample problem wherein the state of Texas has 5 centers located at Amarillo, Fort Worth, Houston, Laredo, and Odessa, and the central depot is in Austin (have marked the locations approximately on Texas Map). And 7 packages need to be shipped while ensuring that all constraints set by Oops are held at the minimum cost. We created input parameters for our problem logically shown in Table 1 – 5 below.
Also, to ensure that the incompatibility constraint is working correctly we have assigned that packages 1 and 2 traveling from center 1 (C1) to center 5 (C5) are incompatible because of safety reasons and hence should be assigned to different vehicles.

Number of centers: N	5
Number of packages: S	7
Relocation cost per mile: RC	40
Number of vehicle types: K	3
M1 parameter	max (Dist)
M2	1
M3	7
M4	1

Table 1: Parameters

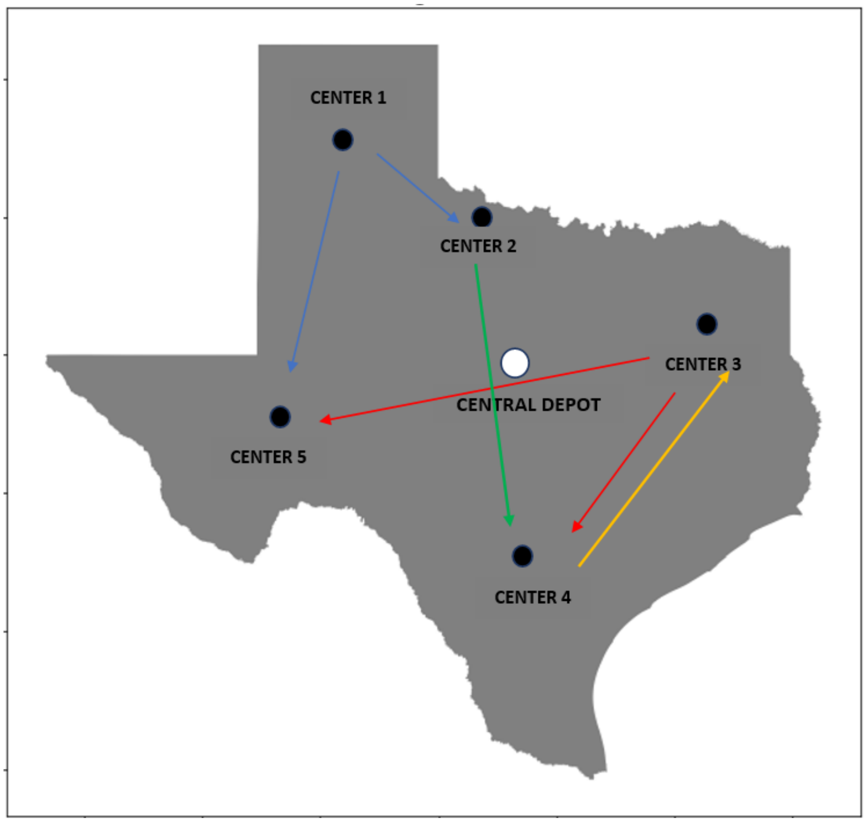

Fig5: Sample problem of Middle-Mile Logistics in Texas State

Vehicle Type	**K**	**Speed (Miles/Hr)**	**Weight Capacity (Kg)**	**Number of vehicles**	**Cost per mile (CPM)**
Truck	1	30	300	2	3.5
Plane	2	100	600	2	15
Train	3	50	800	3	10

Table 2: Vehicle info

Center Number	City	Max Loading	Max Unloading	Number of workers
1	Amarillo	3	1	2
2	Fort Worth	2	3	2
3	Houston	3	2	1
4	Laredo	2	3	2
5	Odessa	1	4	4

Table 3: Shipping center info

Package	Origin shipping center	Destination center	Weight (Kg)	Deadline (Hr)	Penalty Cost ($)
1	C1	C5	100	12	1000
2	C1	C5	75	10	250
3	C1	C2	75	12	400
4	C3	C5	150	8	500
5	C3	C4	200	9	600
6	C3	C4	300	10	700
7	C4	C3	50	9	500

Table 4: Package Info

$Dist_{i,j}$	C1	C2	C3	C4	C5
C1	0	339	600	626	260
C2	339	0	260	424	321
C3	600	260	0	315	532
C4	626	424	315	0	425
C5	260	321	532	425	0

Table 5: Distance between each shipping center (from Google Maps)

4.1 Output check from MILP Model:

Package	Origin Shipping Center	Destination Center	Vehicle Type	Vehicle Number
1	C1	C5	Plane (k=2)	n=1
2	C1	C5	Train (k=3)	n=3
3	C1	C2	Truck (k=1)	n=2
4	C3	C5	Truck(k=1)	n=1
5	C3	C4	Train (k=3)	n=2
6	C3	C4	Train (k=3)	n=2
7	C4	C3	Train (k=3)	n=1

Table 6: Output from decision variable "P_{sijkn}"

Observations:

1. From this table, we can see that even though packages 1 and 2 have to be shipped via the same route (i.e., center 1 (C1) to center 5 (C5)) and their total weight capacity (100+75 = 175) can be satisfied by any vehicle type, they are assigned to different vehicles because of incompatibility constraint.
2. As packages 5 and 6 are both transported from center 3 (C3) to center 4 (C4), they are assigned to the same vehicle train 2.
3. As the number of vehicles allocated at all the centers (truck = 2, train =3, and plane =1) is less than the total vehicles of each type available at the central depot. Also notice that our model assigns the costliest mode of transport: A plane to the route which has the smallest distance (C1 to C5).

Shipping center number	No. of trucks	No. of planes	No. of trains	Total vehicles allocated	ML	MUL
C1	1	1	1	3	3	1
C2	0	0	0	0	2	3
C3	1	0	1	2	3	2
C4	0	0	1	1	2	3
C5	0	0	0	0	1	4

Table 7: Output from decision variable Vec_{ik}

Observations:

1. From this table we can see that the total vehicles allocated (loaded) at each center are less than their maximum loading limit.
2. Also, we can see that 3 vehicles had to be unloaded at center 5 (C5) which is less than 4, similarly we can see that all other centers also satisfy the maximum unloading constraint.

Vehicle Type : Truck

Center	C1	C2	C3	C4	C5
C1		1			
C2					
C3					1
C4					
C5					

Table: 8.1

Vehicle Type : Plane

Center	C1	C2	C3	C4	C5
C1					1
C2					
C3					
C4					
C5					

Table: 8.2

Vehicle Type: Train

Center	C1	C2	C3	C4	C5
C1					1
C2					
C3				1	
C4			1		
C5					

Table: 8.3

Table 8: Output from decision variable Vec_c_{ijk}

This basically shows that a particular vehicle is only assigned to 1 route and is not repeated in any other route.

Package	PZ: Package delivered late
1	0
2	0
3	0
4	1
5	0
6	0
7	0

Table 9: Output from decision variable PZ_s

This is to keep track of which packages are delayed. In our problem only package 4 is delivered beyond its deadline because package 4 is assigned to a truck and it's scheduled to be delivered from center 3 (C3) to center 5 (C5), then the estimated time of delivery is:

$time = \frac{distance\ (=532)}{speed\ of\ truck\ (=30)}$ = 17.73 Hrs.(approx.), whereas deadline is of 8 hours.

Center	C1	C2	C3	C4	C5
C1					
C2			1		
C3					
C4					
C5	1				

Table 10: Output from decision variable Z_{ij}

This is to understand how many operators are relocated from one center to the other. From the output table, we see that one operator is relocated from center 2 (C2) to center 3 (C3) and one worker is relocated from center 5 (C5) to center 1 (C1).

This is because initially only 2 operators were available at center 1 and 3 vehicles are allocated to that center. So, that is the reason why one operator was relocated from center 5 (C5) to center 1 (C1) (smallest distance – so will have minimum relocation cost) similarly only 1 operator was available at center 3 (C3) and as 2 vehicles are loaded at center 3 (C3), one worker is relocated from center 2 (C2) to center 3 (C3) (again C2 has the smallest distance to C3 as compared to any other center).

4.2 Objective value:

From our model, we got the minimum cost to be 37148.5

$$\text{Total Cost: } \underbrace{\sum_{j=1}^{N}\sum_{i=1}^{N} Z_{ij} D_{ij} RC}_{\text{Relocation Cost}} + \underbrace{\sum_{s=1}^{S} C_s P Z_s}_{\text{Penalty Cost}} + \underbrace{\sum_{k=1}^{K}\sum_{j=1}^{N}\sum_{i=1}^{N} Vec_{cijk} D_{ij} CPM_k}_{\text{Operating Cost of Vehicles}}$$

Please refer to section 3.3 for a detailed explanation.
This is the summarized form of how this cost is actually calculated.

Relocation cost: From table 10 we can see that $Z_{2,3}$ =1 and $Z_{5,1}$=1 and the rest are 0.
So, cost = 260*1*40 +260*1*40 = $ 20800

Penalty Cost: From table 9 we can see that only package 4 was delivered beyond its deadline so the cost is $ 500.

Operating cost: From table 8 we can see which vehicle is allocated to which route.

Cost = $Vec\_c_{1,2,1}*D_{1,2}*CPM_1 + Vec\_c_{1,5,2}*D_{1,5}*CPM_2 + Vec\_c_{1,5,3}*D_{1,5}*CPM_3 + Vec\_c_{3,5,1}*D_{3,5}*CPM_1 + Vec\_c_{3,4,3}*D_{3,4}*CPM_3 + Vec\_c_{4,3,3}*D_{4,3}*CPM_3$
=1*339*3.5 + 1*260*15 + 1*260*10+1*532*3.5+1*315*10+1*315*10
= 15848.5

So total cost = 20800 + 500 + 15848.5
= 37148.5

5.0 References

Cover image reference:

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