Optimizing Air Cargo Handling at an International Airline Hub for AbOvo

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Abstract

In this study, we solve an operational planning problem in the air cargo industry. In an international airline hub, all shipments which arrive at the airport and have to go to another destination need to go through two processes, namely, breaking down of the unit load devices (ULDs) that arrived in and building up of ULD for their destination flight. The final goal is that all shipments have to catch their connecting flight on time. Due to the complexity of the overall problem, current practices at airlines are to split up the problem into two smaller and thus simpler problems. The goal of this paper is to solve the full planning problem using a single model. Working with our industrial partner AbOvo, we solved the problem of scheduling the break down and build up process according to the departure timings of the destination flights to ensure that all shipments catch the flight. Assignment of ULDs to bread down (BD) zones and shipments to workstations in each build-up (BU) zone is done using theory of 'scheduling jobs with precedence constraints'. We formalize its requirements and the objectives.

Furthermore, we develop and evaluate two different solution approaches. One is called the main model and the other solution is named as the alternative model. The BD zone part of the model for both the solution approaches is the same. The difference between these two approaches is only regarding the BU zone assignment process and hence we describe only the alternative BU zone model for the second approach. We solve the full planning problem by using integer linear programming.

Keywords: *Time Discretization, Scheduling with precedence constraints.*

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1 Introduction

An international airline hub needs to plan the air cargo movement so that all shipments catch their connecting flights or road connections. Air cargo shipments are transported in so-called unit load devices (ULDs). It allows a large quantity of cargo to be bundled into a single unit like a pallet or a container. A ULD may contain many shipments which need to go to different final destinations. Hence, at the first step of the whole process as seen in Figure 1 below, the incoming ULDs are broken down on arrival. Here in the breakdown zone (BD), ULDs have to be unpacked and separated. The separate shipments are then transported to the warehouse and stored there. These shipments are then moved to the packing area which is called buildup zone (BU). Finally, the outbound ULDs are constructed from these shipments, and they are taken to the outbound flight for loading. Each zone has different attributes such as capacity for BD zone, the number of workstations for BU zone, transportation times between zones and the warehouse and handling times for process in each zone. Shipments have different attributes namely shipment id, destination flight number, date of arrival and departure, type of shipment and weight. Using all the attributes , we formulate the problem as an Integer linear program by writing constraints and the parameters which are stated in detail in the problem description section. The goal of the optimization process is to build up all ULDs such that there is sufficient time available for them to catch their flight connections.
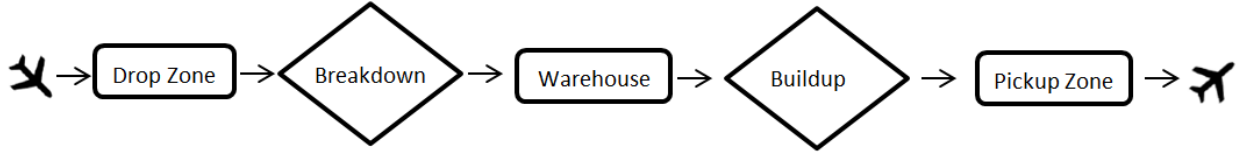

Figure 1: The process that takes place at a hub

2 Problem Description

In the given problem, shipments arrive in the form of a ULD at four types of drop zones (DZ) in the airport. ULDs are unloaded from an aircraft by the ground handling agent and placed in one of the drop zones. The decision to assign the DZ is not a part of our planning problem in this paper as it has already been given in the data associated with each shipment. From the drop zone, each ULD has to be transported to the breakdown zone to be broken down into shipments. The decision of allocating an ULD to a BD zone has to be taken at this point.

In BD zone, ULDs are separated into shipments. There are 12 different BD zones in the hub that are located at different places of the airport. Attributes related to BD zones are:

- Type of shipment a BD zone handles. For example, some of the BD zones handle only ULDs containing animals, some of them handle only cooled products and others handle regular ULDs.

- Capacity of the BD zone.

- Transportation times from DZ and to Warehouse.

- Handling time per ULD.

The inbound ULDs are classified into product categories of, 'cooled' (CLD), 'normal' (NRML) and 'animals'(NML). When the shipments are unpacked, depending on the scheduled departure time of the connection flight it is booked for, it is either stored temporarily in the warehouse or directly sent to the build up process. The warehouse (WH) is fully automated and with the assumption that there are never capacity constraints in the WH. As soon as enough stock is available in the storage WH to build up one ULD for a specific aircraft, these can be requested to be provided to the BU zone.

In a next step, shipments are built up into ULDs depending on their connecting flight. This is done in a build up zone (BU zone). A departing aircraft type has a link to a specific BU zone. So with the provided information on which aircraft the shipment should go on, the BU zone is known. There are 8 different BU zones and each BU zone has different number of workstations in it. At each workstation only one ULD can be built up at any given time. The shipments are provided from the storage WH to the chosen workstation. Transportation times for ULDs are different from each BU zone to a flight. In addition to this, there are different pre-processing times for each flight which is also given in the data. The maximum capacity by weight that each built up ULD can have is given as 400 kg.

Some other requirements are that if the building up of two ULDs for the same aircraft are planned at one workstation, it is not allowed to build up a ULD for a different aircraft in between, even if there is some idle time. The reason is that after building up one ULD there might be some shipments with the same destination left. It should be avoided to move those around, so they would stay at the workstation for the build up of the next ULD for the same aircraft. Listed below are attributes associated with BU zone

- Handling times to buildup a ULD

- Transport times from the WH

- Number of workstations

- Flights list associated with each BU zones and the transportation time between the flight and the BU zone.

- Pre-processing buffer times for the flights.

The goal is to build up all ULDs before the given buffer time so that allof them can catch the connections.

3 Mathematical Model for the Problem

Our mathematical model for this problem is a combination of two problems namely, the break down zone and the build up zone assignments. The overall view of the general process can be seen in Figure 2.
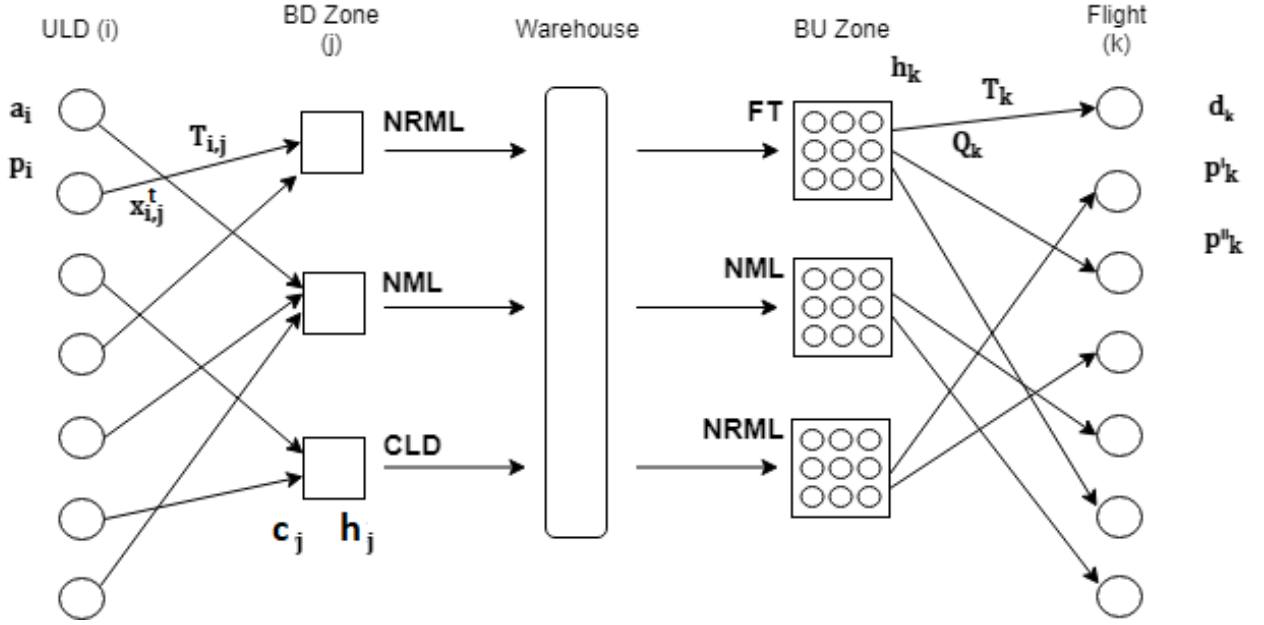
Figure 2: Overall view for the aircargo process

3.1 Break Down Process

Each ULD is a part of the ULD set I and each BD zone is a part of the BD zones set J. Time is discretized into minutes in set T.

ULD i ∈ I = {1,2,3,...,N}

BD zone j ∈ J = {1,2,3,...,M}

Time horizon t ∈ T = {1,2,3,...,T}

Shipments l in ULD i ∈ Li = {1,2,3....,L}

a_i : Arrival time of ULD i in drop zone
d_i : Earliest Departure time of a shipment in ULD i
c_j : Capacity of BD zone j
h_j : Handling time in BD zone j
T_{ij} : Time taken to transport an ULD i to BD zone j
T_j : Time taken to transport shipments from i to BD zone j to Warehouse

3.1.1 Decision Variables for Break Down Process

In the Break Down zone, the decision needs to be taken on which ULDs should be assigned to which BD zone at which time. For this reason, the decision variable has to be binary. The decision variable takes value 1 if the ULD i is assigned to BD zone j at time t and value 0 if the ULD i is not assigned to BD zone j at time t.
$x_{ij}^t \in \{0,1\}, \forall i \in I, j \in J, t \in T$: if a ULD i is assigned to BD zone j at time t or not.

3.1.2 Constraints for Break Down Process

The constraint (1) ensures that the ULD is assigned at a feasible time, the constraint (2) ensures that all ULDs have to be assigned to exactly one BD zone.

The time at which Break down of ULD i starts, $t_{i,start} = \sum_{j \in J} \sum_{t=a_i}^{d_i} t \cdot x_{ij}^t$

Each ULD takes i T_{ij} time to travel to its assigned BD zone j, therefore the following constraint ensures that the start time of ULD i is greater than the sum of its arrival time and transportation time :

$$\sum_{j \in J} \sum_{t=a_i}^{d_i} (t - T_{ij}) \cdot x_{ij}^t \geq a_i, \qquad \forall i \in I \tag{1}$$

Each ULD i must be assigned to a BD zone j before the earliest departure time of the shipment it contains. We will further tighten this time limit in other constraints that follow. The following constraint ensures that each ULD is assigned to a BD zone :

$$\sum_{j \in J} \sum_{t=a_i}^{d_i} x_{ij}^t = 1 \qquad \forall i \in I \tag{2}$$

For the special case given in this problem, where we have multiple drop zones, then such ULDs have to be assigned to multiple BD zones associated with it. In constraints (3) and (4), we assign such ULDs having multiple drop zones to their respective BD zones i.e animal BD zone and normal BD zone.

$$\sum_{j \in J_{NML}} \sum_{t=a_i}^{d_i} x_{ij}^t = 1 \qquad \forall i \in I \tag{3}$$

$$\sum_{j \in J_{NRML}} \sum_{t=a_i}^{d_i} x_{ij}^t = 1 \qquad \forall i \in I \tag{4}$$

In the constraint (5), we meet the requirement given to us that for multiple drop zone ULDs, animal BD zone has to be assigned before the regular shipment BD zone.
$J_{NML} \bigcup J_{NRML} = J$

$$\sum_{j \in J_{NML}} \sum_{t=a_i}^{d_i} (t + h_j) \cdot x_{ij}^t \leq \sum_{j \in J_{NRML}} \sum_{t=a_i}^{d_i} (t) \cdot x_{ij}^t \tag{5}$$

The constraint (6) is the capacity constraint. In the constraint (6), we check that if ULD's in subset i are started to be processed at time t, no more ULDs than the remaining capacity of the BD zone j can start before $t + h_j$, because the process of breaking down the current ULDs needs to be completed. If ULDs in subset i start at t in BD zone j, then other ULDs are in $u \in I \setminus \{i\}$. In the first part of the constraint, we are calculating the remaining capacity for the BD zone at time t . For the second part

of the constraint, we are stating that ULDs assigned in next time period $t + h_j$ should be less than or equal to remaining capacity in the BD zone.

$$c_j - \sum_{i \in I} x_{ij}^t \geq \sum_{u \in I \setminus \{i\}} \sum_{\tau=t+1}^{t+h_j-1} x_{ij}^\tau \qquad \forall t \in T, \forall j \in J \tag{6}$$

The effect is that no more ULDs than the capacity of BD zone are assigned at any given time. The same equation can be simplified if we initially discretize time in a coarse manner i.e instead of discretizing time in minutes, if we discretize time in handling time intervals of the BD zone and define the decision variable only at those discretized time values, then we can rewrite the equation as follows:

$$c_j - \sum_{i \in I} x_{ij}^t \geq 0 \qquad \forall t \in T, \forall j \in J \tag{7}$$

The above simplified form of equation ensures that at any given time t in the set T, which contains time values discretized according to handling time intervals, the capacity of BD zone is never violated.

ULD i is broken down at time, $t_{i,end} = \sum_{j \in J} \sum_{t=a_i}^{d_i} (t + h_j).x_{ij}^t$

Now, let's consider the journey of each shipment as shown in Figure 3. Each ULD i has $l \in L_i$ shipments in it. If ULD i is assigned at time t to BD zone j, then $x_{ij}^t = 1$ and it also means that all shipments in ULD i are assigned at that time t to BD zone j. Therefore we use the information given in the data set to map ULD number i to the shipment number l and we can then see when a shipment was assigned to a BD zone as shown below:
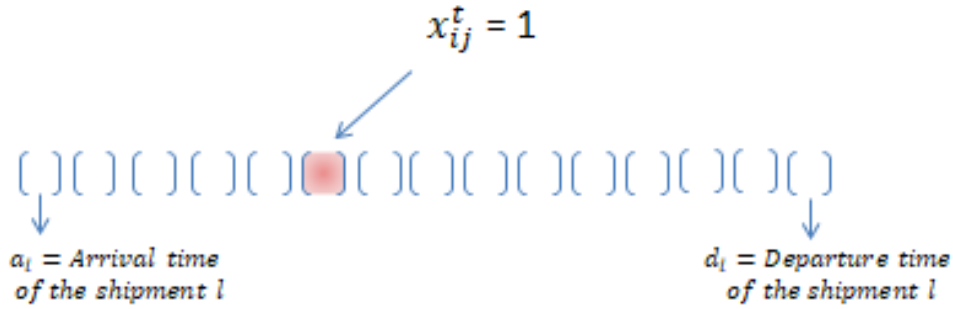

Figure 3: Journey of Shipment

3.2 Build Up Process

We define parameters for flights and Build up zones :

Flight k ∈ K = {1,2,3,...,K}

BU zone for flight k has Workstations m $\in M_k = \{1,2..,M\}$

Capacity of ULD in Kgs (W)= 400

Weight of each shipment= w_l

Time taken to build up a ULD in BU zone for Flight k= b_k

Pre-processing time for each Flight k= p_k

3.2.1 Decision Variables for Build Up Process

In the Build Up zone model, the decision needs to be taken regarding which shipments should be assigned to which workstation at what time in a given Build Up zone. For this reason, we introduce a decision variable: z_{lm}^t

Shipment l having departure flight k is assigned to one of "m" workstations in its BU Zone.

$$z_{lm}^t \in \{0,1\}, \forall i \in I, l \in L_i, m \in M_k, t \in T$$

The second decision we need to take is regarding the number of workstations that need to be allocated to a flight to start its ULD build up process. For this purpose we introduce the second decision variable in BU zone as follows:

Q_{mk}^t is our binary decision variable to decide if the Workstation m is assigned to build ULD for Flight k at time t or not.

$$Q_{mk}^t \in \{0,1\}, \forall k \in K, m \in M_k, t \in T$$

3.2.2 Constraints for Build Up Process

All shipments must be assigned to a workstation in its designated Build up zone.

$$\sum_{m \in M} \sum_{t=a_l}^{d_l} z_{lm}^t = 1 \qquad \forall k \in K, \forall l \in L_k \tag{8}$$

If shipments in subset $l \in L_k$ start at t in m^{th} workstation, other shipments in subset $p \in L_k \setminus \{l\}$ cannot start before $t + b_k$

$$Q_{mk}^t \cdot W - \sum_{l \in L_k} z_{lm}^t \cdot w_l \geq \sum_{p \in L_k \setminus \{l\}} \sum_{\tau=t+1}^{t+b_k-1} z_{pm}^\tau \cdot w_l, \qquad \forall k \in K, \forall m \in M_k, \forall t \in T \tag{9}$$

The above simplified form of equation ensures that at any given time t in the set T, which contains time values discretized according to handling time intervals, the capacity of BU zone is never violated.

The number of workstations in the Build up zone that are to be assigned to build ULDs for flight k shall not exceed the number of ULDs that go into the flight and hence we need the following constraint to take care of this.

$$\sum_{m \in M_k} \sum_{t=a_l}^{d_k} Q_{mk}^t \leq \frac{\sum_{l \in L_k} \sum_{m \in M} \sum_{t=a_l}^{d_k} z_{lm}^t w_l}{W} + 1, \qquad \forall k \in K \tag{10}$$

If a workstation 'm' in a buildup zone is assigned to flight k at time t, then no other flight can start building its ULDs in that workstation before time t+bk.

$$1 - Q_{mk}^t \geq \sum_{q \in K \setminus \{k\}} \sum_{\tau=t}^{t+b_k} Q_{mq}^t, \qquad \forall k \in K, \forall m \in M_k, \forall t \in T \tag{11}$$

The above equation can also be simplified as follows, when we consider a coarse time discretization as discussed earlier.

$$1 - Q_{mk}^t \geq Q_{mq}^t, \qquad \forall k \in K, \forall q \in K \setminus \{k\}, \forall m \in M_k, \forall t \in T \tag{12}$$

In the entire timeline of a shipment from its arrival to departure as in Figure 4, we have a precedence constraint on processes a shipment goes through. The Break down process precedes the Build up process and hence The assignment for BD zone should happen before Workstation assignment in a BU Zone.
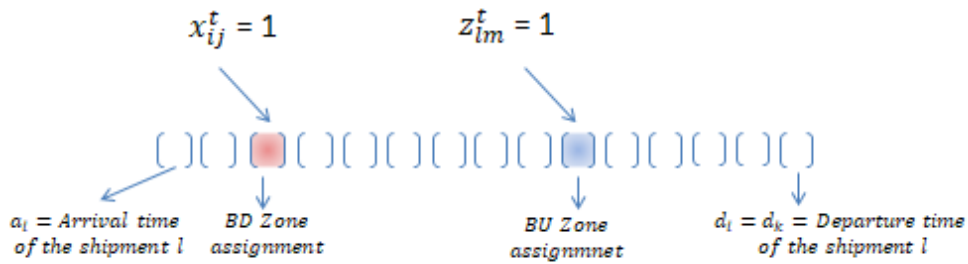

Figure 4: Journey of Shipment - 2

The end time of ULD i in Break down process and the summation of transportation time needed to reach Warehouse shall be less that the time at which the shipment l is assigned to a workstation 'm' in Build up zone of flight k.

$$\sum_{j \in J} \sum_{t=a_l}^{d_i} (t + h_j + T_j) \cdot x_{ij}^t \leq \sum_{m \in M_k} \sum_{t=a_l}^{d_l} z_{lm_k}^t \cdot t \qquad \forall i \in I, \forall l \in L_i \tag{13}$$

For Multiple DZ ULDs we have to consider only NRML BD zone assignments for writing precedence

constraint :

$$\sum_{j \in J_{NRML}} \sum_{t=a_l}^{d_i} (t + h_j + T_j) \cdot x_{ij}^t \leq \sum_{m \in M_k} \sum_{t=a_l}^{d_l} z_{lm_k}^t \cdot t \qquad \forall i \in I, \forall l \in L_i \tag{14}$$

Slack for each shipment is given by difference in departure time and the time at which shipments are built up into ULDs. Let this slack time for each shipment be greater than s_{min}

$$(d_l + p_k) - (\sum_{t=a_l}^{d_l} z_{lm_k}^t \cdot (t + b_k)) \geq s_{min} \qquad \forall i \in I, \forall l \in L_i, \forall k \in K, \forall t \in T \tag{15}$$

$$s_{min} \geq 0 \tag{16}$$

3.3   Objective Function

By maximizing the minimum slack of all shipments, we ensure that each shipment is ready well before its departure time.

$$\max s_{min}$$

3.4   Alternate Model for Build Up Process

In this section we define the alternate model for ULD build up process. We will start by listing down the used input parameters and decision variables followed by defining the constraints and objective function.

3.4.1   Input Parameters

The model consider two set of entities. Let K denote the set of flights and T denote the set of time horizons. We use the respective lower case indices to represent single entities: $k \in K, t \in T$.

$avail_{kt} \in \mathbb{R}$: weight of all shipments available for flight k at time period t

$due_k \in \mathbb{R}$: build-up due time for flight k

$dem_k \in \mathbb{R}$: weight of all shipments booked for flight k

$split_k \in \mathbb{N}$: maximum number of ULDs to build simultaneously for flight k

$uld_k \in \mathbb{N}$: total number of ULDs to schedule for flight k

$dur_k \in \mathbb{N}$: number of time periods to build an ULD for flight k

$cap \in \mathbb{R}$: capacity of an ULD (given data: 400 kgs)

$open_t \in \mathbb{N}$: number of workstations that can build ULD during time period t

While the parameters dem_k and due_k provides the information on total weight of shipments that should be sent in flight k and the time at which they should be packed as ULDs respectively, $avail_{kt}$ tells the weight of shipments available for flight k at time period t.

The data on available workstations at a time period t and how many can be used for flight k are presented by the parameters $open_t$ and $split_k$ respectively. Though we can use all the available workstations to build ULDs for flight k, in practice it is effective and efficient to limit the number of ULDs built in parallel. This leaves more options and time to react to operational problems during build-up and allows to build the ULDs on close-by workstations. And as enforcing a hard limit in practice might lead to offloads for flights where the shipment arrives rather late such that the limit is too low to build all ULDs on time, we want to set a less restrictive limit.

So, we choose the maximum required parallel build-ups, between any build-up period and the scheduled departure period of the flight, for which all shipments can be packed as the suitable limit. For each period t, we determine the shipment weight arriving in the future $(dem_k - avail_{kt})$ and the weight that could be packed in the remaining time, if no parallel build-ups are allowed. Note that the number of ULDs that can be built sequentially in the time between t and due time for flight k, can be determined as $((due_k - t - 1)/dur_k)$. The ratio of both gives us the required parallelism and its maximum over the periods the sought limit. If the required parallelism is less than the desired maximum split, we allow maximum split to be built in parallel.

The parameters uld_k, dur_k and cap has details on the number of ULDs to be sent in flight k, time taken to build each ULDs and the capacity of the ULD which is 400 kgs in our case.

3.4.2 Decision Variables for Build Up Process

The primary decision made by the model is the number of ULDs to start building at each period. To calculate the objective value, we introduce further decision variables. One part of the objective is to load as much as possible. There are two reasons that might prevent us from achieving this goal: First, if not all ULDs can be scheduled for build-up. Second, if a ULD is scheduled before enough shipment is available. We capture the effect of each reason in one variable.

$start_{kt} \in \mathbb{N}$: number of ULDs started to build at time period t for a flight k ($t \leq due_k$ - dur_k)

$offload_k \in \mathbb{N}$: number of not scheduled ULDs for flight k

$dead_{kt} \in \mathbb{R} \geq 0$: weight of lost shipments on flight k's ULDs if they are built before enough shipments available at time period t

3.4.3 Constraints for Build Up Process

We have defined the following constraints to construct a feasible build-up schedule.

Parallel build-ups There is no technical reason to restrict the number of ULDs that are built in parallel for a segment. However, in practice there might occur problems during a build-up when an item cannot be packed onto the planned ULD. In this case, the load planner has to find another ULD with enough remaining capacity under massive time pressure. The more ULDs that are not started yet, the more options and time he has for replanning. Furthermore, if only a few ULDs for a segment are built in parallel, they can be assigned to spatially close workstations. This might reduce transport

distances and improve overview during build-up. We note that, during a time period t, the ULDs that were started during period (t − dur_k + 1) to period t are still work in progress. For each flight k we limit the number of simultaneously built ULDs by $split_k$ as:

$$\sum_{\substack{t' \in T \\ \text{t - } dur_k \leq t' \leq t}} start_{kt'} \leq split_k \qquad \forall k \in K, \forall t \in T \tag{17}$$

Workstation availability The number of usable workstations is limited. As each workstation can process one ULD at a time, we limit the number of simultaneously processed ULDs during period t by $open_t$. To calculate this number for a point in time, we sum up the ULDs of all flights that have been started during earlier periods and are not finished yet:

$$\sum_{k \in K} \sum_{\substack{t' \in T \\ \text{t - } dur_k \leq t' \leq t}} start_{kt'} \leq open_t \qquad \forall t \in T \tag{18}$$

3.5   Objective Function for Alternate model

While satisfying all the given constraints we want to have an objective function that helps meeting the objective of the problem which is to load as many shipments as possible. To maximize the loading of shipments, we schedule the build-up of ULDs in such a way that it minimizes the early build up of ULDs and the number of ULDs building up unassociated to the departing flight.

$$\min \qquad (\sum_{k \in K} \sum_{t \in T} dead_{kt} + \sum_{k \in K} offload_k) \tag{19}$$

4   Solution and Discussion

We implemented all above presented variables and constraints in python using Jupyter notebook. We checked the notebook in both Linux and Windows 64-bit operating systems and it compiled without any errors in both. As a MIP solver we used Gurobi in version 8.1.0. For data cleaning Pandas(0.24.0) and Numpy(1.15.4) was used. All the graphs generated using matplotlib(3.0.2).

We perform our testing in two machines. One machine had Intel Core i7-4500U processor with 2 cores clocked at 1.8 GHz and equipped with 4 MB cache running on a 64-bit Ubuntu 18.04. Another machine had Intel Core i7-6500U processor with 2 cores clocked at 2.5 GHz and equipped with 4 MB cache running on a 64-bit Windows 10. Each machine had 8 GB main memory and all the experiments were performed under full load.

First model takes three hours to build the entire model and for the second model takes around two hours to build entire model, probably due to a very fine time discretization that we used (We can reduce the time by using a coarse discretization of time). In the solution, we see that all shipments catch their flights on time as was our goal in this project. To choose a planning time horizon that fits our needs, we evaluated different planning time horizons with respect to the solution quality and runtime. For the BD zones, first we determined the planning horizon as one minute but it took a lot of time for the solution. Then we decided to discretize the time using handling time intervals for each BD zone. For the BU zones, time is discretized in one minute intervals but we can change this too for faster processing of model.

To perform this analysis we took some assumptions. Those are

- Shipments arriving after departure not included.

- If a shipment contains an animal and normal items, first it goes to the NML BD zone and then goes to the NRML BD zone.

- Shipments above 400kg do not go into the BD and BU processes.

- If a ULD with the same ID number arrives in 4 hours after the previous one, it is removed.

- Departure flight number can appear once in a day.

- Only flights which have already been assigned to the BU zone are considered.

4.1 Break down zone results

The results for the BD zones are visualized in both Figure 5 Figure 6. Most number of ULDs allocated to BD NRML-1 because transportation time and the handling time for this particular BD zone are less than the others. Similarly this is applied to the ULD which is containing animals. For this ULDs BD NML-3 was selected most. Hence, our model picked the best BD zone. As per the data we received it used only three normal break down zones and three animal break down zones. Other break down zones are not picked by our model for this data.
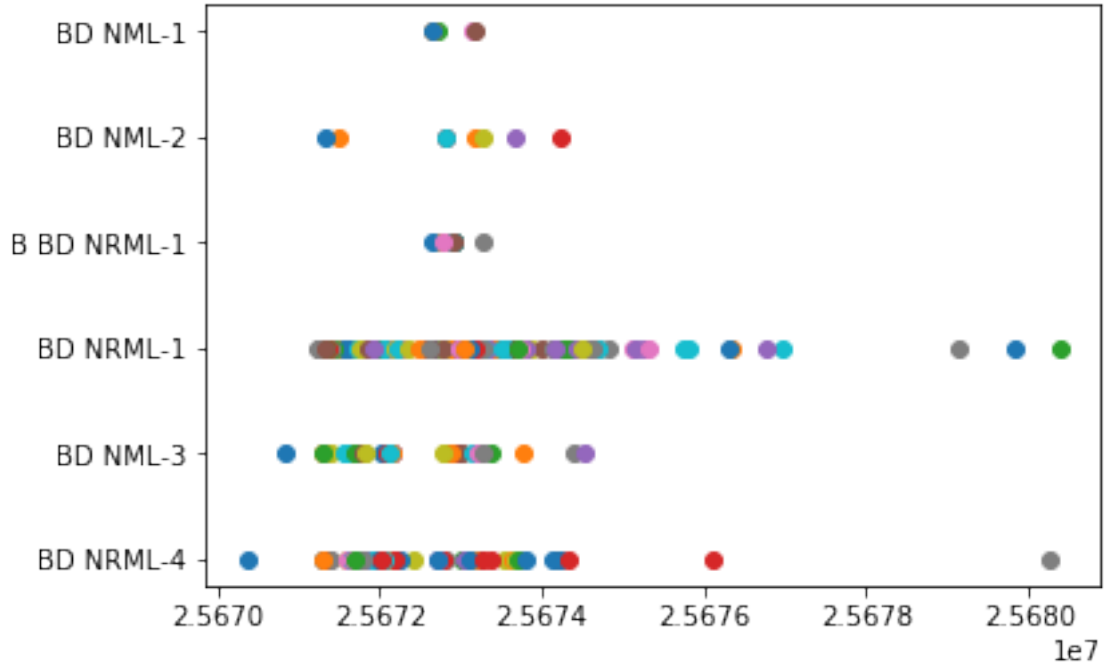

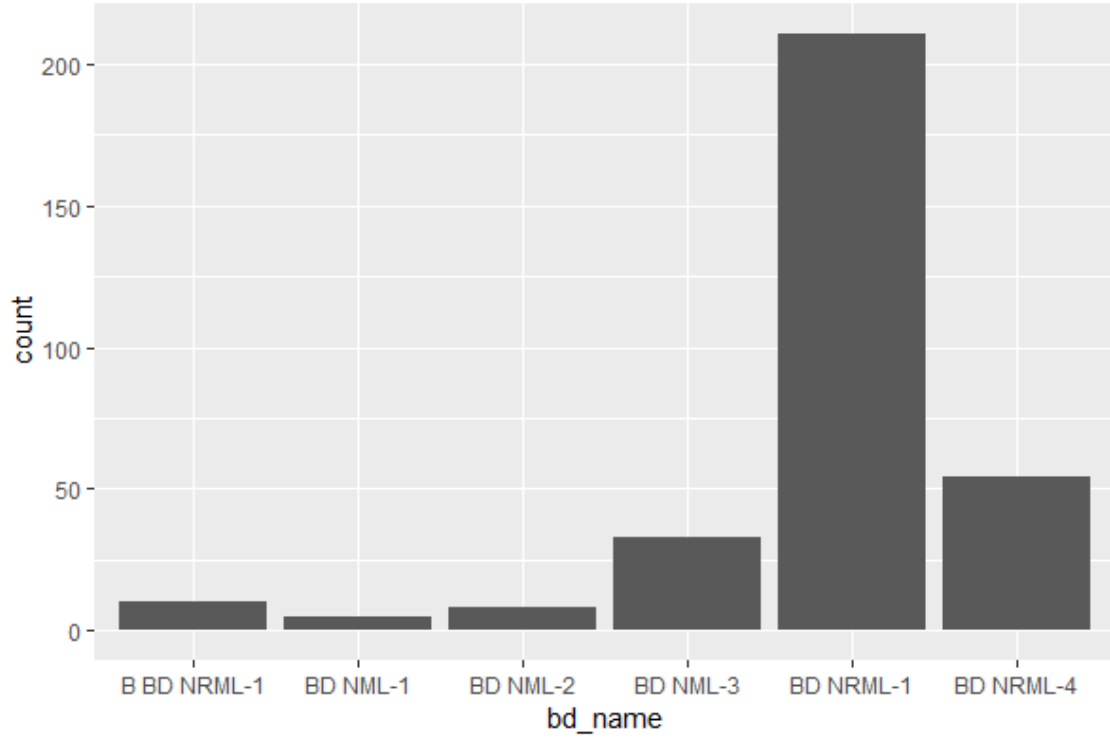Figure 5: Shipment Arrival Times (X-axis) and BD Zones (Y-axis)

Figure 6: BD zones (X-axis) and ULD count (Y-axis)

4.2 Build-up zone results - main model

The results for the BU zones are visualized in both Figure 7 and 8. Most number of ULDs are built in BU FT-1. Since we already allocated all the flights to BU zone before it arrives we don't need to make a decision about the BU zone but the decisions our model is making is about the number of workstations that need to be used in the BU zone and at the time at which it has to be used such that there are no conflicts.
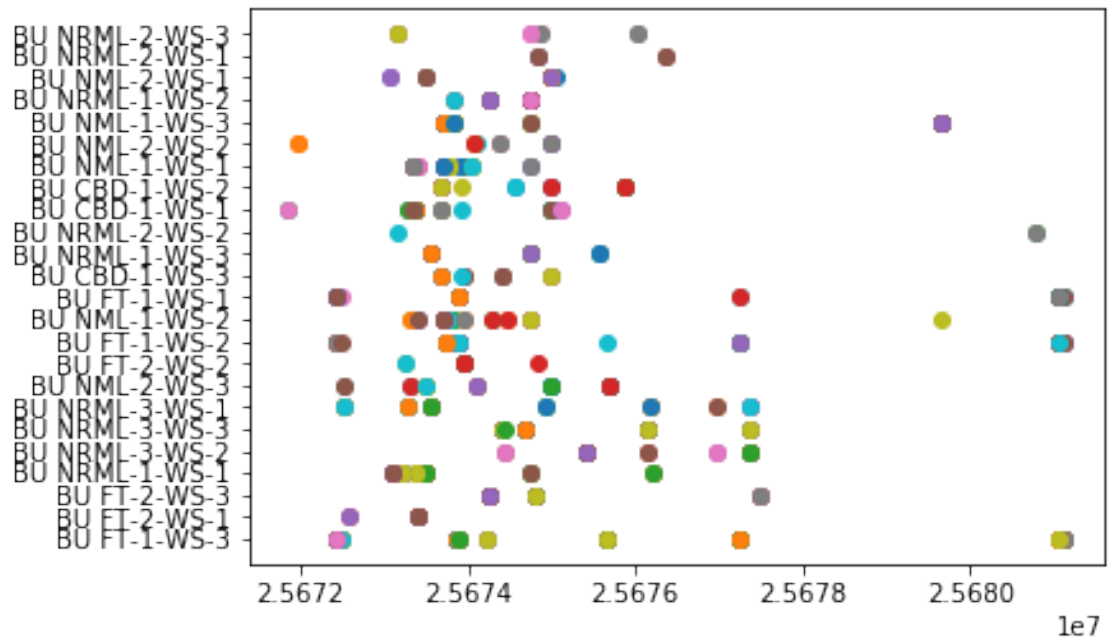

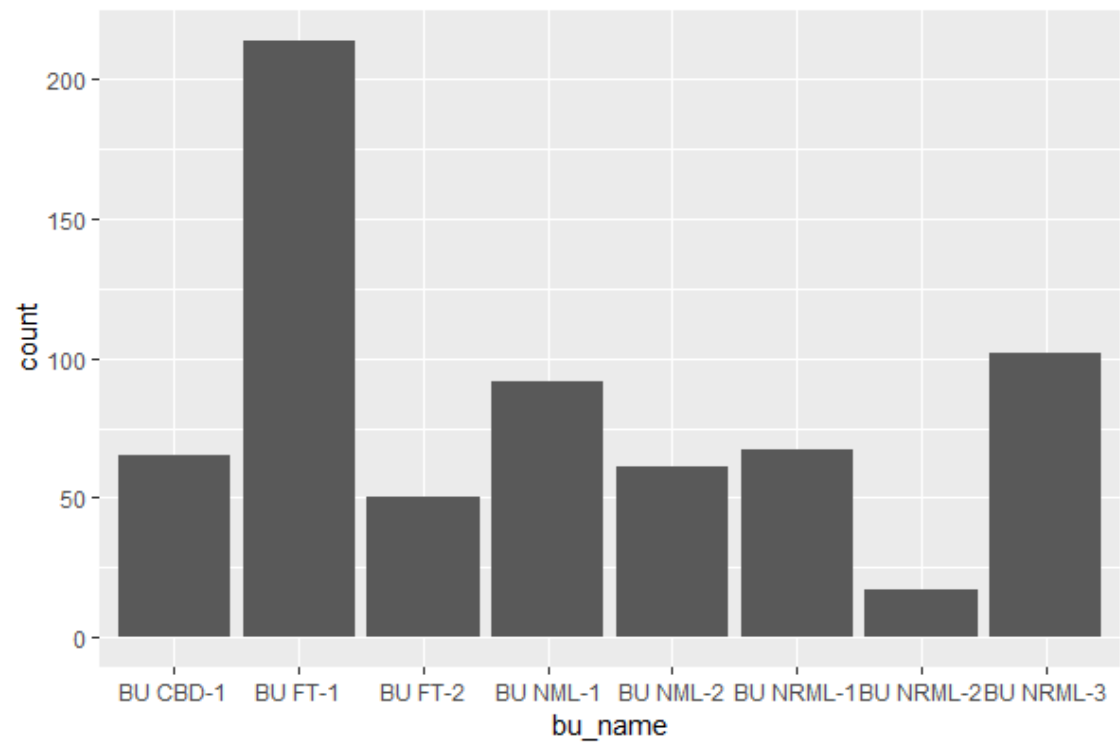Figure 7: Shipment Arrival Times (X-axis) and BD Zones (Y-axis)

Figure 8: BD zones (X-axis) and ULD count (Y-axis)

4.3 Build-up zone results - alternative model

The results of the alternative model is visualized in Figure 9. The primary decision this model is giving is for a given flight what is the optimal time to start the build up process. Other decision variables are not useful for this data because all the shipments are catching the flights.
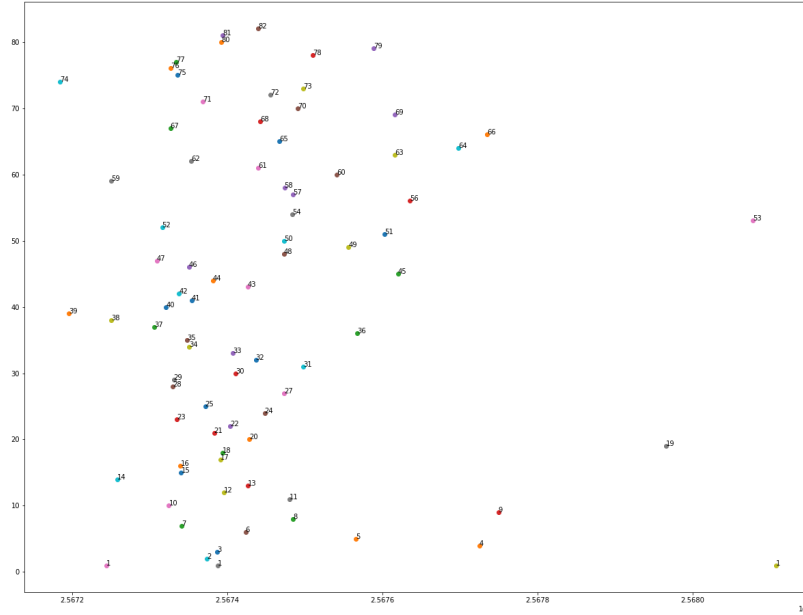

Figure 9: Shipment Arrival Times (X-axis) and BD Zones (Y-axis)

4.4 Sensitivity analysis

The data provided to us has shipment durations ranging from 4 hours to 6 days. To perform sensitivity analysis the shipment which is having only below 10 hours duration is selected. For these shipments the build up zones and departure flights are already decided. But there might be a chance for the incoming flights to be delayed. To get better results we reduce the inbound flight arrival time by 2 hours. The results show that we now assign the ULDs to a new break down zone compared to the old one. You can see the visualization below.
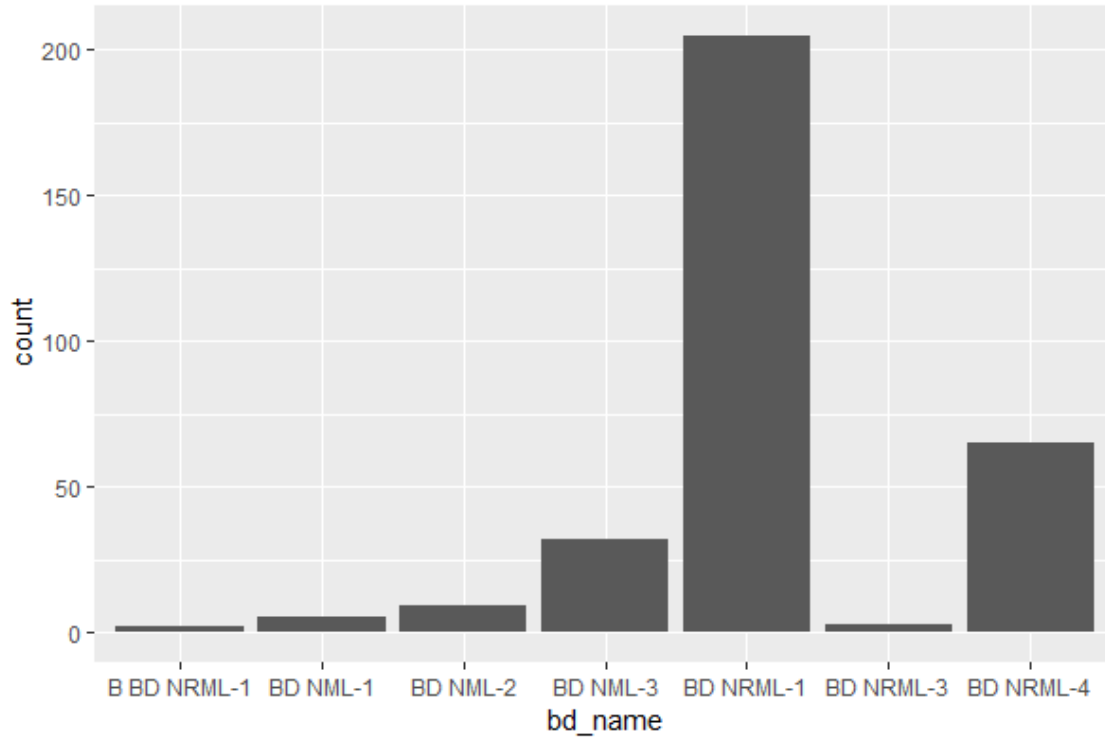

Figure 10: Shipment Arrival Times (X-axis) and BD Zones (Y-axis)

References

[1] FELIX BRANDT (2017) *The Air Cargo Load Planning Problem* Karlsruher Instituts für Technologie (KIT).

[2] FELIX BRANDT AND STEFAN NICKEL (2018) *The air cargo load planning problem - a consolidated problem definition and literature review on related problems* European Journal of Operational Research, 275(2), 399-410.