1 Introduction

During the last couple of decades, the operations research (OR) community has developed models and methods to not only solve static problems but also to tackle them in their natural dynamic environment. International (hub) airports with high passenger and flight traffic are an example of such an environment. In such environement a proper disruption management, giving an adequate answer on unforseen events, is crucial in order to maintain the daily operations according to some predefined standards. OR practitioners have primarily put their focus on the disruption management for the crew pairing problem which considers flight and crew schedules as well as passenger itineraries (see [8, 6, 9]), or the airports' runway planning problem (see [4]) and gate assignments problem (see [12, 5]). Though, it is one of the airports major and most challenging tasks, to date OR has paid little attention to the disruption management for the planning of outbound baggage handling.

Outbound baggage is the baggage that is brought in from check-in passengers (check-in baggage) or incoming flights (transfer baggage) and which has to be loaded into departing airplanes. The check-in baggage and transfer baggage are fed in into the Baggage Handling System (BHS) which is a conveyor belt network automatically transporting the bags to their destinations. To load the bags into bulk-containers, all departing flights are scheduled and assigned to handling facilities, called carousels. During a flight's baggage handling period, workers at the carousels load incoming bags from the carousel's conveyor belt into bulk-containers. At the end of the baggage handling period, usually 10 to 15 minutes before the flight's departure, all containers are transported to the corresponding airplane, where they are loaded into the airplane's cargo hold.

It is a major concern of the airport to decrease the proportion of mishandled bags, i.e. bags that cannot be transported with their designated flight. The number of bags waiting on the carousels conveyor belt for a given time period defines the carousel's workload. When the workload on a carousel exceeds the carousel's capacity, baggage can no longer be forwarded to that carousel until the workload decreases. Since the baggage instead remains within the BHS's conveyor belt network, the overall baggage traffic increases, leading to delays when transferring baggage to its destination.

As different carousels are often reached via the same lanes in the BHS, the backlog on one carousels has an direckt effect also to the other carousels. Hence, it becomes more likely, that bags do not arrive at the carousels in time, which causes mishandled baggage and therefore a poor level of the service. Consequently, planning the outbound baggage handling, airports seek to obtain a workload on the carousels below a given target value to guarantee that a backlog on carousels is avoided.

The baggage handling process is carried out in a very dynamic, unstable and volatile environment. From the very beginning, the arrival process of baggage at airports is characterized by uncertainty and is therefore hard to predict. [11] described the arrival profile of check-in passengers as rather stable. However, unforeseen events on the way to the airport or uncommon traveler group sizes flying together (e.g. during convention meetings, or national or international conferences) can alter this profile. Transfer baggage from incoming flights has a similar uncertain character. Flight arrival times, and hence the arrival time of transfer baggage at airports, can be delayed by malfunctions at the previous airport, bad weather conditions or aircraft landing sequencing decisions. Baggage handling operations are also disrupted by delayed outgoing flights, for instance due to technical problems or even natural phenomena. An example would be the volcanic eruption of Eyjafjallajökull in Iceland in April 2010, leading to a massive disturbance of baggage operations in Europe and other parts of the world. The last possible source for disruptions can be found within the baggage handling facilities, for instance malfunctions of the BHS or broken baggage screening devices.

After the airport has established a plan for flights' baggage handling, i.e. the airport has scheduled flights' baggage handling and has assigned flights to carousels, groundhandlers staff the carousels with workers loading the bags at the carousels into bulk-containers. The number of workers employed for a flight defines flight's loading rate and hence, directly influences the carousel's workload. In practice, the outbound baggage handling and the staffing of worker groups is done separately. Therefore, airport's calculated workload for each carousel, based on the generated plan for the outbound baggage handling, may not be reached due to a lack of workers. Groundhandlers plan their workforce for the next day on the basis of airport's proposed plan for the outbound baggage handling (see [7]). Thus, the coincidence of airport's and groundhandlers' planning becomes crucial when a change in airport's planning occur during the day.

The literature for outbound baggage handling is rather sparse. If we even restrict the literature review to a dynamic planning of outbound baggage handling, to the best of our knowledge the literature is empty. We therefore focus the literature review to static outbound baggage handling problems. [3] and [2] propose a greedy based sequential allocation heuristic to assign flights to handling facilities. However, neither of them consider the scheduling of the baggage handling nor they take into account the dynamics of the baggage arrival process. Our problem statement for the outbound baggage handling is similar to that of [7]. They present the first model formulation considering both, the scheduling of flights to carousels as well as the assignment of flights to carousel. It is shown that the consideration of the baggage arrival process within a daily planning leads to improved solutions. However, [7] consider the problem as a inter-day planning problem. They generate a plan for the planning of the next day such that groundhandlers can staff the carousels adequately. In our problem statement we consider the intra-day operation. To ensure that groundhandlers can staff the personnel for the day accordingly.

This paper focuses on a dynamic outbound baggage handling planning updating the plan during the course of the day such that the impact of disruptions is reduced. To the updated plan for outbound baggage handling subject to groundhandlers' available number of workers we present a integrated approach tackling the outbound baggage handling and the staffing of workers at the carousels. The methods of disruption management vary from fuzzy logic (***References) to robust methods from linear programming (***References). For outbound baggage handling with work-group pairings we propose a linear programming framework. As the time to update the plan is restricted at the problem is NP-hard to solve (see [7]), we will decompose the planning of outbound baggage handling and the staffing of personnel. To the best of our knowledge, this paper is the first which provides a disruption management framework for the outbound baggage handling process.

The paper is structured as follows: 2 provides a description of the outbound baggage handling problem and worker staffing at carousels. A mixed-integer model combining both problems is presented in 3. **??** provides the framework for the disruption management which is based on a sequential decomposition and column generation with a primal search heuristic. The computational study in **??** shows the performance of our proposed procedure in comparison to the current procedure employed at airports. A summary of the paper is given in **??**.

2 Problem description

We present the problem description for the general outbound baggage handling and the groundhandlers work-group pairing problem, i.e. staffing the workers to the carousels such that each flight is handled with the adequate number of workers in 2.1. The considered disruptions occurring during the baggage handling are discussed in 2.2.

2.1 Outbound baggage handling and work-group pairing

The problem description is separated into two parts. In the first part, "Outbound baggage handling", we explain the outbound baggage handling process in detail (compare **(author?)** [7]). In the second part, "Work-group pairing", groundhandlers staffing at the carousels is described.

Outbound baggage handling Once, a bag is fed-in into the BHS, it is transported via the conveyor belt network of the BHS to its destinations with a constant transport time to a baggage carousel or to the central storage system. As incoming flights, carrying a flight's transfer baggage, or passengers may arrive at the airport before the flight's baggage handling has been started, the BHS offers the possibility to store early baggage within a central storage system. Earliest when the baggage handling of a flight has started, which is, depending on flight's destination, two to three hours before scheduled departure time (QUELLE!), the stored bags are sent to the assigned carousel. Once the storage depletion has been started, the stored bags are directed to the assigned carousel with a constant transfer rate. An interruption of a flight's baggage handling as well as the storage depletion process is not allowed. At international airports it is common policy to have all stored bags depleted around 45 minutes before scheduled departure time of a flight.

Flight's baggage handling, i.e. the loading process of bags into bulk-containers, takes place at carousels (see Figure 1). A flight must not be split to multiple carousels, but a carousel can handle several flights simultaneously. The number of simultaneously handled flights is restricted by the number of parking positions, where one parking position can accommodate one bulk-container, and working stations. The number of containers required for a flight is provided by the airline. To guarantee the sorting criteria of a flight, e.g. for first class, economy class and transfer baggage (see **(author?)** [10]), all bulk-containers of a flight have to be placed at the carousel for the whole baggage handling period. To uniquely identity baggage worldwide, each bag is labeled with a secure massage. Workers match the right bulk-container for the baggage by scanning the secure massage and the bar-code on the containers. For that purpose every working stations is equipped with a scanner. The working stations divide the carousel into and even number of loading areas. To each working station at a carousel belongs the same number of parking positions. A flight can only be assigned to a working station, if at least one container is placed on one of the working station's parking position. However, a working station have not to be assigned to a working station if a bulk-container is placed on one of the working station's parking positions. Due to security reasons and to reduce the number of mishandled bags, a working station can handle one flight at a time. The number of required working stations depends on the number of flight's bulk-containers.

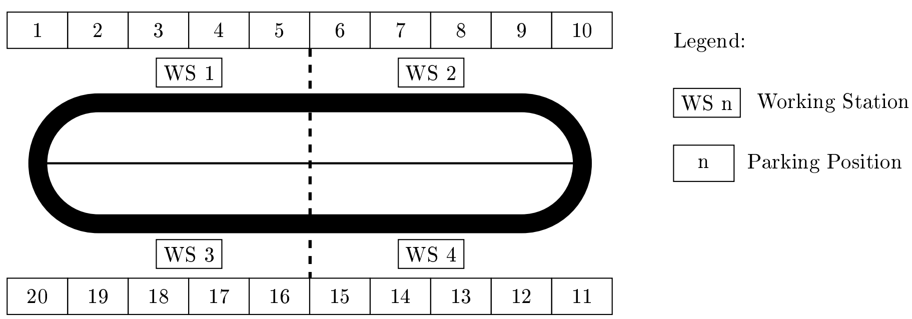


Figure 1: Carousel with 20 parking positions and 4 working stations

Work group pairings Since October 1996 the groundhandling market at European airports is open for companies (see **(author?)** [1]). Each airline makes an contract with a groundhandler offering service at the airport for one or several of its flights. A groundhandler can be responsible for more than one airline, and one airline contracts several groundhandlers for the offered flights.

However, one flight is handled by only one groundhandler.

A groundhandlers' workers have a fixed shift start time of the shift end time which results in a shift length which can vary between 3 to 10 hours. Moreover, each worker has the right of one 30 minute break during the day. Workers can only handle flights for which the groundhandler company has contracts for. If a working station is assigned for one flight, then a worker of the corresponding groundhandler has to be assigned to the working station. Moreover, as a working station is equipped with one scanning device, one worker can be maximal assigned. Hence, to guarantee the calculated workload for the outbound baggage handling, each groundhandler should assign as many workers for a flight as working stations are assigned.

2.2 Disruptions

Outbound baggage handling depends on different factors like the handling facilities, the incoming and outgoing flights and the groundhandlers. A failure of the BHS represents the worst case scenario. In this case no baggage can be transported through the terminal making the planning of outbound baggage handling impossible. Therefore, for this scenario we cannot provide an answer automatically. For all other scenarios, our procedure finds an adequate answer by updating flights outbound baggage handling. A breakdown of a working station can be caused by a defect scanning device. As a consequence, the total loading rate for the currently assigned flight gets reduced by the loading rate of that working station immediately and the working station capacity of that carousel gets reduced until the expected time of replacement of that scanner. Sometimes it is necessary to shut down a complete carousel for a while. This can be due to maintenance work such as replacement of crescent pallets. As such actions are planned a while before they are conducted, we can assume that they occur only after the baggage handling period for the currently assigned flights ended. Inbound flights arrive delayed or prematurely frequently (ON TIME STATS). As an effect, transfer baggage for connecting flights arrives not at the expected time and the expected baggage streams need to be updated.

Table 1 summarizes the different disruption types and their effects categorized by the three failure sources facilities, flights and groundhandlers.

Source	Type	Effect
Facilities	BHS	No bag transport
	Working station	Reduced loading rate for currently assigned flight Reduced capacities for future assignments
	Carousel	Reduced capacities for future assignments
Flights	Inbound delay	Altered baggage streams for all connecting flights
	Inbound cancellation	Reduced baggage streams for all connecting flights
	Outbound delay	Blocked capacities
	Outbound cancellation	Freed capacities
Groundhandlers	Unexpected worker absence	Reduced loading rate for currently assigned task Reduced capacities for future assignments

Table 1: Disruptions for the outbound baggage handling with work-group pairing

For example, if there is a failure at the infrastructure, the reason could be a breakdown of a carousel's working station, e.g. when a scanning device breaks. In this case, the working station can not be used for a flights anymore. But also the complete carousel could have a failure or has to be closed in the near future due to maintenance work. When a carousel has a failure, flights currently handled at a carousel are finished. Another reason for a disruption may be found at the groundhandler, when workers are absent.

3 Model formulation

In this section we present the mathematical models which are used to solve the dynamic OBBHP.

Baggage handling for the set of departing flights $\mathcal{F}$ is planned on a discrete planning horizon $\mathcal{T} = \{1, \dots, T\}$, that consists of T periods of equal length.

Each flight is assigned to a carousel $c \in \mathcal{C}$ and a number of working stations w. A carousel is characterized by its conveyor belt capacity measured in number of bags K_c^{b}, the number of parking positions K_c^{p}, the number of working stations K_c^{w} and its position in an Euclidean plane.

The number of required parking positions of flight i is denoted P_i.

A schedule for a flight $i \in \mathcal{F}$ consists of the start of the baggage handling $s_i^{\mathrm{h}} \in \mathcal{T}$, the start of the storage depletion $s_i^{\mathrm{d}} \in \mathcal{T}$ and the end of the baggage handling period $S_i^{\mathrm{E}} \in \mathcal{T}$. S_i^{E} is determined by the flight departure time, whereas s^{h} and s^{d} are matter of decision. Baggage handling can start at most three hours before the flight departure and storage depletion cannot start before the baggage handling period.

In general the number of working stations and the baggage handling schedule should be set such that all bags are depleted from the storage and loaded by the end of the baggage handling. In the face of disruptions, this is not always be possible. Therefore, we do not filter w-s^{h}-s^{d}-combinations where left bags are expected.

For simplicity, we represent the assignment of working stations and a schedule by tuple $\tau = \left(w_\tau, s_\tau^{\mathrm{h}}, s_\tau^{\mathrm{d}}, \phi_\tau^{\mathrm{lb}}\right)$ with ϕ_τ^{lb} as the number of left bags. Set $S_i$contains all possible τ for flight i,

Let $\left(\mathcal{A}_{i,t}\right)_{0 \leq t < S_i^{\mathrm{E}}}$ denote the estimated baggage arrival stream for flight $i \in \mathcal{F}$. $\mathcal{A}_{i,t}$ gives the estimated number of bags that arrive at a carousel in time period t.

Let r^{w} denote the constant loading rate per worker or working station and r^{s} the storage depletion rate, that is assumed to be constant per flight. $\phi_i^{\mathrm{s}}\left(t,\tau\right)$ yields the number of bags in the storage in time period t, if flight $i \in \mathcal{F}$ is scheduled with τ and $\phi_i^{\mathrm{w}}\left(t,\tau\right)$ yields the number of bags that are left on the carousel in time period t. Figure 2 illustrates the calculation of both functions.

When creating the sets S_i and the corresponding storage and workload functions, some tuples can be eliminated due to dominance criteria: if $w'_\tau \geq w_\tau$, $s_{\tau'}^{\mathrm{h}} \leq s_\tau^{\mathrm{h}}$, $\phi_{\tau'}^{\mathrm{lb}} \geq \phi_\tau^{\mathrm{lb}}$, $\phi_i^{\mathrm{s}}\left(t,\tau'\right) \geq \phi_i^{\mathrm{s}}\left(t,\tau\right)$ and $\phi^{\mathrm{w}}\left(t,\tau'\right) \geq \phi^{\mathrm{w}}\left(t,\tau\right)$ for all t and any $\tau \neq \tau'$,τ' can be removed from S_i. With that result, the earliest start of the baggage handling is set to $S_i^{\mathrm{ES}} = \min_{\tau \in S_i}\left(s_\tau^{\mathrm{h}}\right)$.

At each decision epoch $t_k \in \mathcal{T}$ we solve a static problem with respect to the current planning and updated information about disruptions and expected baggage streams. Time for (re-)optimization

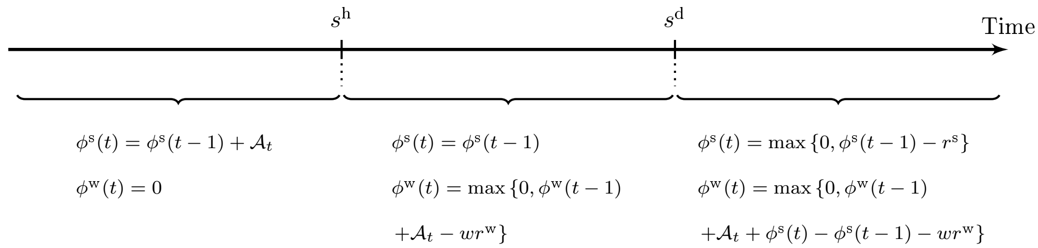


Figure 2: Functions $\phi_i^{\mathrm{s}}(t,\tau)$ and $\phi_i^{\mathrm{w}}(t,\tau)$

is limited to Δ^{opt} time periods. At time $t_k + \Delta^{\mathrm{opt}}$ the algorithm has to return a new solution. For communicating a new solution we reserve another Δ^{impl} time periods. Thus, a new planning takes effect at $t_k + \Delta^{\mathrm{opt}} + \Delta^{\mathrm{impl}} =: t_k^{\mathrm{impl}}$.

To increase the tractability of each static problem the planning horizon is limited by parameter Δ^{h}. The set of flights considered in the optimization problem at time t_k is

$$\mathcal{F}_{t_k} = \left\{ i \in \mathcal{F} \;\middle|\; t_k^{\mathrm{impl}} < S_i^{\mathrm{E}} \wedge S_i^{\mathrm{ES}} < t_k^{\mathrm{impl}} + \Delta^{\mathrm{h}} \right\}$$

and the problem is defined for the horizon $\left[t_k^{\mathrm{impl}}, \max_{i \in \mathcal{F}_{t_k}} \left(S_i^{\mathrm{E}}\right)\right]$.

Depending on the current time (t_k and t_k^{impl}) and currently implemented flight schedules, the flights in $\mathcal{F}_{t_k}$ are categorized by the following sets:

- $\mathcal{F}_{t_k}^{\mathrm{new}} := \mathcal{F}_{t_k} \setminus \mathcal{F}_{t_{k-1}}$
- $i \in \mathcal{F}_{t_k}^{\mathrm{pro1}} := \left\{ i \in \mathcal{F} \mid s_i^{\mathrm{h}} \leq s_i^{\mathrm{d}} < t_k^{\mathrm{impl}} < S_i^{\mathrm{E}} \right\}$
- $i \in \mathcal{F}_{t_k}^{\mathrm{pro2}} := \left\{ i \in \mathcal{F} \mid s_i^{\mathrm{h}} < t_k^{\mathrm{impl}} \leq s_i^{\mathrm{d}} < S_i^{\mathrm{E}} \right\}$
- $i \in \mathcal{F}_{t_k}^{\mathrm{pla1}} := \left\{ i \in \mathcal{F}_{t_k} \mid s_i^{\mathrm{h}} < t_k^{\mathrm{impl}} + \Delta^{\mathrm{c}} \right\}$
- $i \in \mathcal{F}_{t_k}^{\mathrm{pla2}} := \left\{ i \in \mathcal{F}_{t_k} \mid t_k^{\mathrm{impl}} + \Delta^{\mathrm{c}} \leq s_i^{\mathrm{h}} \right\}$

All flights in $\mathcal{F}_{t_k}^{\text{past}}$ do not influence the optimization at this decision epoch and can be neglected.

All flights in $\mathcal{F}_{t_k}^{\text{fut}}$ are not considered as they are far enough in the future.

All flights in $\mathcal{F}_{t_k}^{\text{new}}$ were not included in the previous decision epoch, i.e. there is no planning available. They are considered for the first time in the current decision epoch and can be planned without any restrictions.

For all flights in $\mathcal{F}_{t_k}^{\text{pro1}}$ baggage handling and the storage depletion is in progress, i.e. the planning cannot be changed, but they use resources and thus influence the current decision epoch.

For all flights in $\mathcal{F}_{t_k}^{\text{pro2}}$ baggage handling is in progress, but the storage depletion did not start yet. Therefore the decision regarding the start of storage deplation can be changed.

All flights in $\mathcal{F}_{t_k}^{\text{pla1}}$ and $\mathcal{F}_{t_k}^{\text{pla2}}$ were planned in the previous decision epoch, but their baggage handling has not started or starts at t_k^{impl}. Their planning can be altered, but lead time Δ^{c} regulates reassignment of flights to another than the planned carousel. If $t_k^{\text{impl}} + \Delta^{\text{c}} \leq s_i^{\text{h}}$ the flight may be reassigned to another than the previously planned carousel, otherwise reassigning is not allowed.

We divide the planning day in Q time segments $\mathcal{T}_q$, such that $\mathcal{T} = \biguplus_{1 \leq q \leq Q} \mathcal{T}_q$ and $t < t'$ for all $t \in \mathcal{T}_q$ and $t' \in \mathcal{T}_{q+1}$ with $q = 1, \ldots, Q-1$. To decrease the utilization at each carousel and during each time segment to or below target value u^{tar} we introduce threshold values $0 = u_0 < u_1 < \ldots < u_K$. A utilization u of $u_{k-1} + u^{\text{tar}} < u + u^{\text{tar}} \leq u_k + u^{\text{tar}}$ for $k = 1, \ldots, K$ incurs costs of p_k^{u} with $p_1^{\text{u}} < p_2^{\text{u}} < \ldots < p_K^{\text{u}}$.

$u_t^{\text{tar}} = u^{\text{tar}} - \left(\sum_{i \in \mathcal{F}^{\text{pro1}}} \phi_i^{\text{w}}(t, w, \tau) + \sum_{i \in \mathcal{F} \setminus \mathcal{F}^{\text{pro1}} : S_i^{\text{ES}} \leq t < S_i^{\text{E}}} \phi_i^{\text{w}}(t)\right) / K_c^{\text{b}}$

The assigned working stations need to be staffed with workers during the baggage handling period, i.e. for each flight $i \in \mathcal{F}$, we need to assign w_τ workers from s_τ^{h} to S_i^{E}. The set of workers is denoted $\mathcal{M}$. Dummy tasks o_m and s_m represent the shift start and end for each worker $m \in \mathcal{M}$, respectively, where $S_{o_m}^{\text{ES}} = S_{o_m}^{\text{E}} =: S_m^{\text{SS}}$ and $S_{s_m}^{\text{ES}} = S_{s_m}^{\text{E}} =: S_m^{\text{SE}}$. If a worker is assigned consecutively to two flights i and j, that are handled on carousel c_i and c_j respectively, he needs enough time to get from c_i to c_j. The carousel positions together with a constant worker travel speed lead to symmetrical traversal times δ_{c_l,c_k} for $c_l, c_k \in \mathcal{C}$. The duration to get to carousel c at the shift start is denoted $\delta_{o_m,c}$ and the duration to get from carousel c to the exit is denoted δ_{c,s_m}. The workers and the flights are partitioned into L disjunctive subsets $\mathcal{M}_1, \ldots, \mathcal{M}_L$ and $\mathcal{F}_1, \ldots, \mathcal{F}_L$, respectively and workers $m \in \mathcal{M}_l$ can only handle the flights $i \in \mathcal{F}_l$. Set $\mathcal{F}_m = \left\{ i \in \mathcal{F}_l \mid S_m^{\mathrm{SS}} \leq S_i^{\mathrm{E}} \leq S_m^{\mathrm{SE}} \right\}$ contains all flights a worker can handle. Precedence relations of flights' baggage handling allows for defining all possible worker transitions as $\mathcal{E}_m \coloneqq \left\{ (i,j) \mid i \in \mathcal{F}_m \cup \{o_m\}, j \in \mathcal{F}_m \cup \{s_m\}, S_i^{\mathrm{E}} < S_j^{\mathrm{E}} \right\}$.

The workers that are available in decision epoch t_k are

$$\mathcal{M}_{t_k} = \left\{ m \in \mathcal{M} \mid S_m^{\mathrm{SE}} > t_k^{\mathrm{impl}} \wedge S_m^{\mathrm{SS}} < \max_{i \in \mathcal{F}_{t_k}} \left(S_i^{\mathrm{E}} \right) \right\}.$$

For each worker $m \in \mathcal{M}_{t_k} \cap \mathcal{M}_{t_{k-1}}$ we have a set of tasks $\widehat{\mathcal{F}}_m$ from the previous solution.

Depending on the current time and the tours, there are three situations to consider:

- $\mathcal{M}_{t_k}^{\mathrm{busy}} \coloneqq \left\{ m \in \mathcal{M}_{t_k} \mid m \text{ is assigned to a flight } i \in \mathcal{F}_{t_k}^{\mathrm{pro1}} \cup \mathcal{F}_{t_k}^{\mathrm{pro2}} \right\}$
- $\mathcal{M}_{t_k}^{\mathrm{move}} \coloneqq \left\{ m \in \mathcal{M}_{t_k} \setminus \mathcal{M}_{t_k}^{\mathrm{busy}} \mid m \text{ is on his way to a flight } i \in \mathcal{F}_{t_k}^{\mathrm{pla1}} \cup \mathcal{F}_{t_k}^{\mathrm{pla2}} \right\}$
- $\mathcal{M}_{t_k}^{\mathrm{idle}} \coloneqq \mathcal{M}_{t_k} \setminus \mathcal{M}_{t_k}^{\mathrm{busy}} \setminus \mathcal{M}_{t_k}^{\mathrm{move}}$

For changing worker tours, we need to determine the location and time of availability of the workers. If a worker is busy, his position is the carousel of the current task. As we may reduce the number of working stations of the corresponding flight, he can be removed and reassigned immediately at time t^{impl} . If a worker has spare time between tasks (or shift start or end), we assume that he waits at the previous location until he has to move towards the next location to get there in time. Therefore a worker with spare time gets idle at first and his location is obvious. Finally, once a worker is moving towards the location of a task, we calculate his position at t^{impl} using the rectangular coordinates of his starting position and the destination carousel and the proportion of the total distance traveled. The worker can be rerouted from that position.

The initial capacity of the central storage is given by K^{s}. For all flights $i \in \mathcal{F}_{t_k}^{\mathrm{pro1}}$ storage depletion time is known. Furthermore for all other flights $i \in \mathcal{F}_{t_k} \setminus \mathcal{F}_{t_k}^{\mathrm{pro1}}$, we know that all bags that arrive before S_i^{SE} are fed into the storage, regardless of the storage depletion time. Therefore, we can reduce the initial storage capacity to the residual storage capacity $K_t^{\mathrm{s}} = K_t^{\mathrm{s}} - \sum_{i \in \mathcal{F}_{t_k}^{\mathrm{pro1}}} \phi_i^{\mathrm{s}}(t,\tau) - \sum_{i \in \mathcal{F}_{t_k} \setminus \mathcal{F}_{t_k}^{\mathrm{pro1}} : t < S_i^{\mathrm{ES}}} \phi_i^{\mathrm{s}}(t,\tau)$.

The initial capacities of carousel c are given by K^{p}_c and K^{w}_c. For all flight in $\mathcal{F}^{\mathrm{pro1}}_{t_k}$ and $\mathcal{F}^{\mathrm{pro2}}_{t_k}$ the start of the baggage handling is known. Therefore, K^{p}_c can be reduced to $K^{\mathrm{p}}_{c,t} = K^{\mathrm{p}}_c - \sum_{i \in \mathcal{F}^{\mathrm{pro1}}_{t_k} \cup \mathcal{F}^{\mathrm{pro2}}_{t_k}}$

Table 2 summarizes the notation used in the models.

Table 2: Notation

Sets:	
$\mathcal{T}$	Time period starting times
$\mathcal{F} = \mathcal{F}_1 \uplus \ldots \uplus \mathcal{F}_L$	Flights that are relevant for the current decision epoch
$\mathcal{F}^{\mathrm{pro1}}$	Flights where BH is in progress and storage depletion is in progress
$\mathcal{F}^{\mathrm{pro2}}$	Flights where BH is in progress and storage depletion is planned
$\mathcal{F}^{\mathrm{pla1}}$	Flights that are planned and cannot be assigned to another carousel
$\mathcal{F}^{\mathrm{pla2}}$	Flights that are planned and can be assigned to another carousel
$\mathcal{F}^{\mathrm{new}}$	Flights that are considered for the first in the current decision epoch
S_i $(S_i(w))$	Set of start time tuples for flight i (with w working stations)
$\mathcal{C}$	Carousels
$\mathcal{M} = \mathcal{M}_1 \uplus \ldots \uplus \mathcal{M}_L$	Workers

$\mathcal{E}_m$	Possible transitions for worker m
$\mathcal{F}_i^- / \mathcal{F}_i^+$	Predecessors and successors of flight i
Indices:	
$t = 1, \ldots, T$	planning horizon
$i, j = 1, \ldots, F$	flights
$c = 1, \ldots, C$	carousels
$q = 1, \ldots, Q$	time segments
$k = 0, \ldots, K$	workload bounds
$m = 1, \ldots, M$	workers
$l = 1, \ldots, L$	flight and worker subsets
Flight parameters:	
P_i	Number of required containers
S_i^{E}	End of baggage handling
$W_i^{\max}$	Maximal number of assignable working stations
w	Number of assigned working stations
$\left[S_i^{\mathrm{ES}}, S_i^{\mathrm{LS}}\right]$	Time window for the start time of the baggage handling
$\tau = \left\langle s^{\mathrm{h}}, s^{\mathrm{d}} \right\rangle$	Start time tuple
$\phi_i^{\mathrm{lb}}(w, \tau)$	Number of left bags depending on w and τ
Carousel parameters:	
K_c^{b}	Capacity of the conveyor belt
K_c^{p} ($K_{c,t}^{\mathrm{p}}$)	Number of available parking positions (at time t)
K_c^{w} ($K_{c,t}^{\mathrm{w}}$)	Number of available working stations (at time t)
$\delta_{c,c'}$	Traversal time to get from carousel c to c'
Storage parameters:	
K^{s} / K_t^{s}	Initial storage capacity / Residual storage capacity at time t
Worker parameters:	

S^{ss}_m / S^{se}_m	Shift start / end
o_m / s_m	Dummy task representing the shift start / end
Objective function parameters:	
u_k, p^{u}_k	workload bound and applied penalty
p^{b}	penalty per unloaded bag
Decision variables:	
$x_{i,c,w,\tau}$	1, if flight i is assigned to carousel c with w working stations and start time tuple τ, 0 otherwise
$y_{c,q,k}$	1, if workload bound k, is violated on carousel c in time interval q, 0 otherwise
$f_{m,i,j}$	1, if worker m handles flight j directly after flight i, 0 otherwise

3.1 Time indexed formulation

In the time-indexed formulation, binary decision variable $x_{i,c,w,\tau}$ is equal to one if flight i's baggage handling is assigned to carousel c with w working stations and scheduled with start time tuple τ. For the staffing of workers, binary flow variable $f_{m,i,j}$ is equal to one, if worker m handles flight i directly before flight j. The assignment and scheduling problem for outbound baggage handling with work group constraints (OBBHWG) can be stated as

$$\begin{aligned} \min \quad & \sum_{c\in\mathcal{C}} \sum_{q=1}^{Q} \sum_{k=1}^{K} p^{\mathrm{u}}_k \cdot y_{c,q,k} \\ & + \sum_{i\in\mathcal{F}} \sum_{c\in\mathcal{C}} \sum_{\tau\in\mathcal{S}_i} p^{\mathrm{b}} \cdot \phi^{\mathrm{lb}}_{\tau} \cdot x_{i,c,\tau} \end{aligned} \tag{1}$$

subject to

$$\sum_{c\in\mathcal{C}}\sum_{\tau\in\mathcal{S}_i} x_{i,c,\tau} \geq 1 \qquad \forall i \in \mathcal{F}\setminus\mathcal{F}^{\mathrm{pro1}} \tag{2}$$

$$\sum_{i\in\mathcal{F}\setminus\mathcal{F}^{\mathrm{pro1}}\setminus\mathcal{F}^{\mathrm{pro2}}}\ \sum_{\tau\in\mathcal{S}_i:s^{\mathrm{h}}_{\tau}\leq t<S^{\mathrm{E}}_i} P_i\cdot x_{i,c,\tau} \leq K^{\mathrm{p}}_{c,t} \qquad \forall c\in\mathcal{C}, t\in\mathcal{T} \tag{3}$$

$$\sum_{i\in\mathcal{F}\setminus\mathcal{F}^{\mathrm{pro1}}\setminus\mathcal{F}^{\mathrm{pro2}}}\ \sum_{\tau\in\mathcal{S}_i:s^{\mathrm{h}}_{\tau}\leq t<S^{\mathrm{E}}_i} w_\tau\cdot x_{i,c,\tau} \leq K^{\mathrm{w}}_{c,t} \qquad \forall c\in\mathcal{C}, t\in\mathcal{T} \tag{4}$$

$$\sum_{\substack{i\in\mathcal{F}\setminus\mathcal{F}^{\mathrm{pro1}}\\ S^{\mathrm{ES}}_i\leq t<S^{\mathrm{E}}_i}}\ \sum_{c\in\mathcal{C}}\sum_{\tau\in\mathcal{S}_i} \phi^{\mathrm{s}}_i(t,\tau)\cdot x_{i,c,\tau} \leq K^{\mathrm{s}}_t \qquad \forall t\in\mathcal{T} \tag{5}$$

$$\sum_{\substack{i\in\mathcal{F}\setminus\mathcal{F}^{\mathrm{pro1}}\\ S^{\mathrm{ES}}_i\leq t<S^{\mathrm{E}}_i}}\ \sum_{\tau\in\mathcal{S}_i} \frac{\phi^{\mathrm{w}}_i(t,\tau)}{K^{\mathrm{b}}_c}\cdot x_{i,c,\tau} - \sum_{k=0}^{K} u_k\cdot y_{c,q,k} \leq u^{\mathrm{tar}}_t \qquad \forall c\in\mathcal{C}, q\in\mathcal{Q},\ t\in\mathcal{T}_q \tag{6}$$

$$\sum_{k=0}^{K} y_{c,q,k} \leq 1 \qquad \forall c\in\mathcal{C}, q\in\mathcal{Q} \tag{7}$$

$$\sum_{m\in\mathcal{M}_l(i,j)\in\mathcal{E}_m} f_{m,(i,j)} \geq \sum_{c\in\mathcal{C}}\sum_{\tau\in\mathcal{S}_j} w_\tau\cdot x_{j,c,\tau} \qquad \forall 1\leq l\leq L, j\in\mathcal{F}_l \tag{8}$$

$$\sum_{(o_m,j)\in\mathcal{E}_m} f_{m,(o_m,j)} \leq 1 \qquad \forall 1\leq l\leq L, m\in\mathcal{M}_l \tag{9}$$

$$\sum_{(j,i')\in\mathcal{E}_m:i'=i} f_{m,(j,i')} = \sum_{(i',j)\in\mathcal{E}_m:i'=i} f_{m,(i',j)} \qquad \forall 1\leq l\leq L, m\in\mathcal{M}_l,\ i\in\mathcal{F}_l \tag{10}$$

$$T\cdot f_{m,(i,j)} + \sum_{\tau\in\mathcal{S}_i} S^{\mathrm{E}}_i\cdot x_{i,c,\tau} - \sum_{c'\in\mathcal{C}}\sum_{\tau\in\mathcal{S}_j}\left(s^{\mathrm{h}}_j-\delta_{c,c'}\right)\cdot x_{j,c',\tau} \leq T \qquad \forall m\in\mathcal{M},\ (i,j)\in\mathcal{E}_m, c\in\mathcal{C} \tag{11}$$

$$T \cdot f_{m,(o_m,j)} + S^{\text{ss}}_m - \sum_{c \in \mathcal{C}_j} \sum_{\tau \in \mathcal{S}_j} \left(s^{\text{h}}_j - \delta_{o_m,c} \right) \cdot x_{j,c,\tau} \leq T \qquad \forall m \in \mathcal{M}, j \in \mathcal{F}_m \tag{12}$$

$$T \cdot f_{m,(i,s_m)} + \sum_{c \in \mathcal{C}_i} \sum_{\tau \in \mathcal{S}_i} \left(S^{\text{E}}_i + \delta_{c,s_m} \right) \cdot x_{i,c,\tau} \leq T + S^{\text{se}}_m \qquad \forall m \in \mathcal{M}, i \in \mathcal{F}_m \tag{13}$$

$$x_{i,c,\tau} \in \{0,1\} \qquad \forall i \in \mathcal{F}, c \in \mathcal{C}, \tau \in \mathcal{S}_i \tag{14}$$

$$y_{c,q,k} \in \{0,1\} \qquad \forall c \in \mathcal{C}, 1 \leq q \leq Q, 0 \leq k \leq K \tag{15}$$

$$f_{m,(i,j)} \in \{0,1\} \qquad \forall m \in \mathcal{M}, \tag{16}$$

$$(i,j) \in \mathcal{E}_m \tag{17}$$

Objective function (1) minimizes the penalty costs for violating threshold values on the relative workload on every carousel and in every time interval and applied penalty costs for each left bag. The assignment and scheduling of flights to handling facilities is modeled in constraints (2) to (7). Cover constraints (2) require each flight to be assigned at least once. The available parking positions and working stations are restricted by constraints (3) and (4). The storage capacity is bounded in constraints (5). Utilization of the carousel capacities is measured in constraints (6) and (7). Auxiliary variable $y^{\text{u}}_{c,q,k}$ is set to one, if the utilization at carousel c is between threshold u_{k-1} and u_k, which incurs costs of p^{u}_k in the objective function.

The staffing of the assigned working stations is modeled in constraints (8) to (13). Constraints (9) connect the number of assigned working stations with the number of staffed workers. Constraints (9) ensure that each worker can only start a single tour at his origin and constraints (10) force each worker to transfer through tasks once he started a tour. Due to constraints (**??**) workers must leave their origin in order to handle flights. Constraints (11) avoid the overlapping of sequential tasks for a worker by considering the required transfer time $\delta_{c,c'}$ to move from carousel

c to carousel c'. Due to constraints (12) and (13), each worker has to start and end their shift with the dummy task o_m and s_m, respectively. Finally, constraints (14) to (16) give the variable domains.

The OBBHWG has $\mathcal{O}\left(X^4\right)$ variables where X is the maximum cardinality of the relevant sets and $\mathcal{O}\left(X^3\right)$ constraints. The problem of scheduling flights´ baggage handling and to assign flights to carousels is NP-hard to solve. With model formulation (1) – (16) we could not solve any real-world instance. We will therefore present a sequential decomposition into two subproblems and a Dantzig-Wolfe decomposition for the first subproblem.

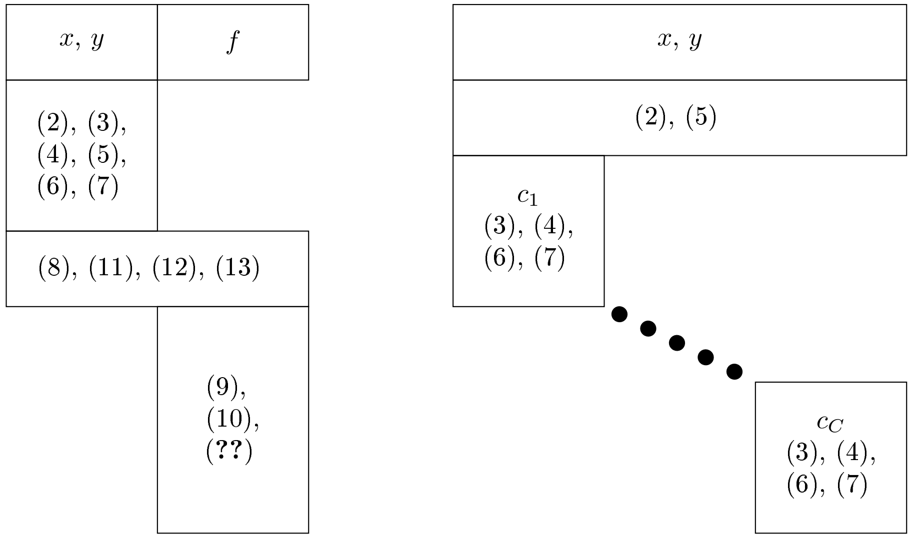
3.2 Sequential and Dantzig-Wolfe decomposition

Model (1) – (16) has a dual block-ladder structure (see Figure 3a) with x as the linking variables. We may decompose the problem by means of Benders decomposition and modify the subproblem to obtain a totally unimodular constraint matrix. Thus Benders cuts can be generated by solving the subproblem as a linear program. But as the master problem suffers from symmetry we use a more rigid sequential decomposition (Formulierung ändern, evtl. ganz auf die duale block ladder Struktur verzichten?). The problem of assigning flights to carousels and scheduling their baggage handling is separated from the problem of staffing workers to the flights. The stage 1 problem has a block ladder structure (see Figure 3b). It will further be decomposed by means of Dantzig-Wolfe decomposition resulting in a Master Problem and a subproblem for each carousel (see Figure 3b).

3.2.1 Master problem

The Master Problem (MP) assigns flights to carousels and sets the flights‘ baggage handling schedule. In the MP, a duty d is defined as a feasible assignment of flights to a carousel and their scheduling for the baggage handling. Moreover, the following parameters are used:

- $\Phi^{\text{ass}}_{d,i}$ – Equal to one if flight $i \in \mathcal{F} \setminus \mathcal{F}^{\text{pro1}}$ is assigned to duty d, zero otherwise
- $\Phi^{\text{sto}}_{d,t}$ – Number of stored bags in duty d during time period t due to all flights i with $\Phi^{\text{ass}}_{d,i} = 1$
- $\Phi^{\text{wor}}_{d,l,t}$ – Number of required workers of subset l at time t due to all flights i with $\Phi^{\text{ass}}_{d,i} = 1$



(a) Dual block ladder structure

(b) Primal block ladder structure

Figure 3: Structure of model (1) – (16)

- $K^{\text{wor}}_{l,t}$ – Number of available workers of subset l at time t for all flights $i \in \mathcal{F} \setminus \mathcal{F}^{\text{pro1}} \setminus \mathcal{F}^{\text{pro2}}$
- C_d – Cost for using duty d

In the MP binary decision variable z_d is equal to one, if duty d is selected, and zero otherwise. The MP can be stated as:

$$\min \quad \sum_{d \in \mathcal{D}} C_d \cdot z_d \tag{18}$$

subject to

$$\sum_{d \in \mathcal{D}} \Phi^{\text{ass}}_{d,i} \cdot z_d \geq 1 \qquad \forall\, i \in \mathcal{F} \setminus \mathcal{F}^{\text{pro1}} \tag{19}$$

$$\sum_{d \in \mathcal{D}} \Phi^{\text{sto}}_{d,t} \cdot z_d \leq K^{\text{s}}_t \qquad \forall\, t \in \mathcal{T} \tag{20}$$

$$\sum_{d \in \mathcal{D}} \Phi^{\text{wor}}_{d,l,t} \cdot z_d \leq K^{\text{wor}}_{l,t} \qquad \forall\, l \in \mathcal{L}, t \in \mathcal{T} \tag{21}$$

$$\sum_{d \in \mathcal{D}_c} z_d \leq 1 \qquad \forall\, c \in \mathcal{C} \tag{22}$$

$$z_d \in \{0,1\} \qquad \forall\, d \in \mathcal{D} \tag{23}$$

The accumulated costs for using duties are minimized in objective function (18). In constraints (19) each flight is assigned to at least one selected duty. The storage capacity at time t is bounded in constraints (20). Due to convexity constraints (22) only one duty is selected for each carousel.

As the MP contains an exponential number of duties which makes the problem practically intractable, the set of duties is restricted to subset $\mathcal{D}' \subset \mathcal{D}$. The MP containing only the duties in $\mathcal{D}'$ is called restricted MP (RMP). Because RMP does not necessarily yield an optimal solution to MP, new duties are generated by means of column generation. Hence, we solve the linear relaxed RMP and use dual variables $\lambda_i^{\text{ass}} \geq 0, \lambda_t^{\text{sto}} \leq 0$,

$\lambda_{l,t}^{\text{wor}}$ and $\lambda_c^{\text{con}} \leq 0$ of constraints (19), (20), (**??**) and (22), respectively to identify new duties with negative reduce costs.

Let $P(\mathcal{D}_c)$ be the convex polyhedron for all duties $\mathcal{D}_c$. A duty $d_c \in \mathcal{D}_c$ of carousel c is represented by binary variable vector $x_c^{\text{d}} = \left(x_{i,w,\tau}^{\text{d}}\right)_{i \in \mathcal{F}, 0 \leq w \leq W_c^{\max}, \tau \in \mathcal{S}_i(w)}$. Binary variable vector $y_c^{\text{d}} = \left(y_{q,k}^{\text{d}}\right)_{q \in \mathcal{Q}, k \in \mathcal{K}}$ determines the penalties for violating the threshold values u_k (see constraints (6) and (7)). The most promising duty for carousel $c \in \mathcal{C}$ is the solution of the pricing problem (PP)

$$\underset{x_c^{\text{d}}, y_c^{\text{d}}}{\operatorname{argmin}} \left\{ z_c^{\text{PP}} = C_d - \left(\sum_{i \in \mathcal{F}} \sum_{w=0}^{W_{i,c}^{\max}} \sum_{\tau \in \mathcal{S}_i(w)} (\lambda_i^{\text{ass}} + \rho_{i,\tau} + \rho_{i,w,\tau}) \cdot x_{i,\tau,w}^{\text{d}} + \lambda_c^{\text{con}} \right) \;\middle|\; d \in x^{\text{d}} \in P(\mathcal{D}_c) \right\} \tag{24}$$

with

- $\rho_{i,\tau} = \sum\limits_{t \in \mathcal{T}} \lambda_t^{\text{sto}} \cdot \phi_i^{\text{s}}(t,\tau)$,

- $\rho_{i,w,\tau} = \begin{cases} 0 & \text{if } i \in F^{\text{pro1}} \cup F^{\text{pro2}} \\ w \cdot \sum_{l:i\in\mathcal{F}_l} \sum_{s^{\text{h}}_{\tau} \leq t < S^{\text{E}}_i} \lambda^{\text{wor}}_{l,t} & \text{otherwise} \end{cases}$ and

- $C_d = \sum\limits_{q=1}^{Q} \sum\limits_{k=0}^{K} p^{\text{u}}_k \cdot y^{\text{d}}_{q,k} + \sum_{i\in\mathcal{F}} \sum\limits_{w=0}^{W^{\max}_i} \sum\limits_{\tau\in\mathcal{S}_i(w)} p^{\text{b}} \cdot \phi^{\text{lb}}_i(t, w, \tau) \cdot x^{\text{d}}_{i,w,\tau}$.

The generated duties are added to the MP and the process repeats until no duty with negative reduced can be found. The found solution is than optimal for the linear relaxation of MP. An integer solution may be obtained using branch-and-price. This does not guarantee a feasible solution in acceptable time though. Therefore, we apply a primal search heuristic with local search techniques as described in Chapter **??** to find a feasible solution.

3.2.2 Work Group Pairing Problem

In the following, let duty subset $\mathcal{D}^* \subseteq \mathcal{D}'$ represent the found solution for RMP. Given solution $\mathcal{D}^*$, the assigned carousel, the number of assigned working stations and the start of baggage handling is determined for each flight. Hence, we have the parameters

- $\hat{s}^{\text{h}}_i$ – Fixed start time of the baggage handling for flight i
- $\hat{w}_i$ – Fixed number of working stations assigned to flight i
- $\hat{c}_i$ – Assigned carousel for flight i

The Work Group Paring Problem (WGPP) assigns workers to tasks. In the WGPP we use binary variable $f_{m,i,j}$ of model (1) – (16). Additional slack variable r_i measures the lack of workers for each flight i. The WGPP can be modeled as a network flow problem with underlying graph $G = (\mathcal{F}, \mathcal{E})$. The tasks are the nodes and each task i and j is connected via an arc $e = (i, j)$, iff task j can be handled after task i.

$$
\begin{aligned}
\text{(WGPP)} \qquad & Z(x) = \min \quad \sum_{i \in \mathcal{F}} r_i && && (25)\\
& \text{subject to} \\
& (9), (10), \\
& (\textbf{??}), (16) \\
& \sum_{m \in \mathcal{M}} \sum_{j \in \mathcal{F}_m} f_{m,j,i} + r_i \geq \hat{w}_i && \forall i \in \mathcal{F} && (26)\\
& T \cdot f_{m,i,j} \leq T - S_i^{\mathrm{E}} - \delta_{\hat{c}_i,\hat{c}_j} + \hat{s}_j^{\mathrm{h}} && \forall m \in \mathcal{M}, i, j \in \mathcal{F}_m && (27)\\
& T \cdot f_{m,out_m,j} \leq T - S_m^{\mathrm{ss}} - \delta_{c_{out},\hat{c}_j} + \hat{s}_j^{\mathrm{h}} && \forall m \in \mathcal{M}, j \in \mathcal{F}_m && (28)\\
& T \cdot f_{m,i,in_m} \leq T - S_i^{\mathrm{E}} - \delta_{\hat{c}_i,c_{in}} + S_m^{\mathrm{se}} && \forall m \in \mathcal{M}, i \in \mathcal{F}_m && (29)
\end{aligned}
$$

Constraints (26) penalize the lack of workers at the assigned working stations for all flights. The sequence of tasks, the shift start and end are modeled in constraints (27) – (29). The span of time between two consecutive tasks is modeled by constraints (27). Each worker can only be assigned to tasks after his shift started (see (28)) and before his shift ends (see (29)).

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