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Integrating optimization and simulation to gain more efficient airport logistics

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Abstract— **In this paper we present airport logistics, which is a framework of resource management in the air transportation system. Focus is on the processes supporting turn-around. A detailed simulation model of various processes involved in turn-around is developed, by which the interaction between these processes are analyzed. We show that integrating optimization and simulation is a powerful tool to demonstrate efficiency improvements in airport logistics, using scheduling de-icing trucks as an example. An optimization algorithm for scheduling de-icing trucks is developed and simulations are performed comparing different schedules. The schedule obtained when considering total airport performance in the optimization algorithm gives minimum flight delay and waiting times in the simulations.**

Keywords-airport; logistics; simulation; optimization; de-icing, turn-around

I. INTRODUCTION

The air transportation system (ATS) is not only huge and complex; it also involves many actors with different and sometimes contradictory objectives which makes an overall flow management difficult to attain. Collaborative decision making (CDM) is an initiative trying to create a common ground for these actors. In short, the goal is to enhance the integration between airport, airline and air traffic flow management planning to enable collaborative decision-making through better use of real-time information exchange [1].

The airport is where most actors in the ATS interact, and therefore also where a system for CDM would have the greatest impact. The airport is also where most delays are generated. According to [2], only 16% of the air traffic delays are airborne, while the rest can be derived from gate (50%), taxi-out (26%) and taxi-in (8%).

This paper presents the *Airport logistics* framework. Airport logistics concerns resource management in the airport system and covers all logistic activities and sub processes – and the corresponding resources – that are involved in and influence the air transportation process. The vision with airport logistics is to develop a complete picture of all processes and activities at the airport; in particular a real-time overview and controllability over all resources in use, or available for supporting the ATS. With this information at hand, it would be possible to, at a tactical basis, optimize the planning and utilization of all the resources, and at an operational level, be able to reschedule due to disturbances in the system.

In this paper, we present the first steps towards the vision described above. A simulation model for the turn-around process at Stockholm Arlanda airport is developed to provide a complete picture of the logistic activities involved in turn-around. A tool for optimized planning of the de-icing trucks is constructed and integrated into the simulation model. Figure 1 highlights the process; a flight schedule is used as input data to the optimization algorithm which produces a schedule for the de-icing trucks. The same flight schedule is used as input data in the simulation model together with the schedule for the de-icing trucks. The overall objective is to investigate whether it is possible to obtain more efficient airport logistics by optimizing one of the turn-around services, while taking into account total airport performance. Performance is evaluated using indicators such as delay and waiting time.

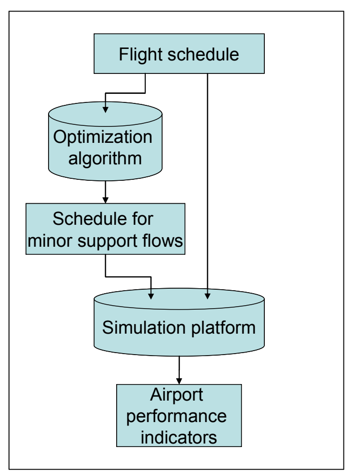

Figure 1. Integration of optimization and simulation

In the next section, we survey some of the related research, followed by a more thorough treatment of the concept airport

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logistics in Section III. Sections IV and V describe the simulation and optimization models, respectively. Computational results are presented in Section VI and Conclusions can be found in Section VII.

II. AIR TRAFFIC RESOURCE MANAGEMENT

Resource management in the ATS is nothing new and includes many well known research areas. Some of them are shown in Figure 2, categorized from the three of the main actors in the ATS: airlines, airports and air traffic control (ATC). In this context, ATC represent all actors responsible for Air Traffic Management (ATM), although this is a simplification. It is evident from Figure 2 that some planning tasks have to be accomplished jointly by more than one actor.

Resource management in general involves many scientific disciplines. Among them, a particularly important one is operations research (OR). We refer to [3] and [4] for surveys of OR applied in the ATS, and [5] that surveys the potential applications of OR to European air traffic flow management.

Resource management in airline operations is typically revenue/cost-driven and includes planning issues at all levels; schedule design [6], fleet assignment [7], maintenance planning [8], crew pairing and crew assignment [9] and revenue management [10]. Lately, there has been an increased interest in integrated management (e.g. combined fleet assignment and aircraft routing with maintenance [11], and crew scheduling and maintenance planning [12]), as well as in disruption management, i.e., to perform recovery when the planned schedule is disrupted due to delays and other unforeseen events [13].

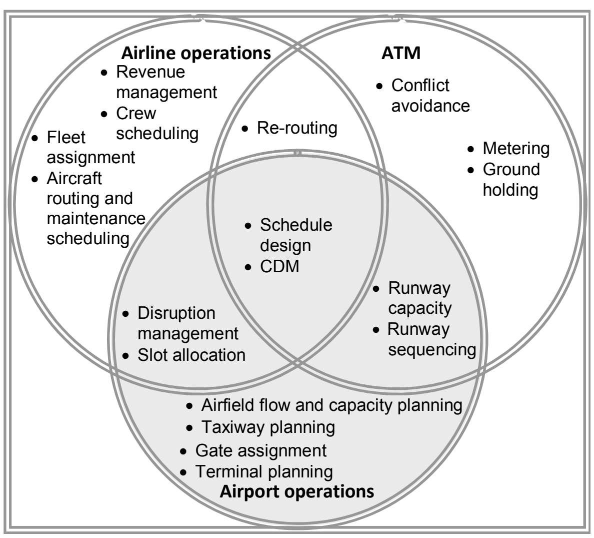

Figure 2. Resource management challenges and initiatives in the ATS

Previous work on resource management at airports is closely related to our concept of airport logistics. However, whereas most of the previous work cited below focus on a certain type of process at the airport, airport logistics is intended to capture the interaction between the processes, and more importantly, between the airport processes and ATM. Relevant elements in resource management at the airside of an airport include runway capacity [14], runway sequencing and taxiing [15], slot allocation [16] and gate assignment and scheduling [17]. At the landside and terminal areas of an airport, previous work has focused various analyses of terminal operations [18].

Simulation is a very powerful tool for modeling and analyzing the performance of airside operations. A number of airside simulation packages are available, such as SIMMOD [19], TAAM [20], The Airport Machine [21] and MACAD [22]. A recent development and trend is to integrate airside and landside simulation tools [23], which includes the platforms OPAL [24], THENA [25] and SPADE [26].

In addition to airline and airport operations, resource management is equally important in ATM. In the context of airport logistics, the most relevant operation of ATM is Air Traffic Flow Management, including the measures re-routing, metering, and ground holding [27].

III. AIRPORT LOGISTICS

Studying the ATS using a network flow representation, see Figure 3, the flows that generate value in the ATS are passengers, possibly traveling with baggage, and cargo. These flows may be viewed as *value flows*. In order to facilitate the value flows, *support flows* are necessary; the two most evident being the flows of aircraft and aircraft crew. These are also the only two support flows that connect the airports in the system. Many other support flows are perpendicular to the aircraft flow, e.g. the flow of fuel or maintenance services.

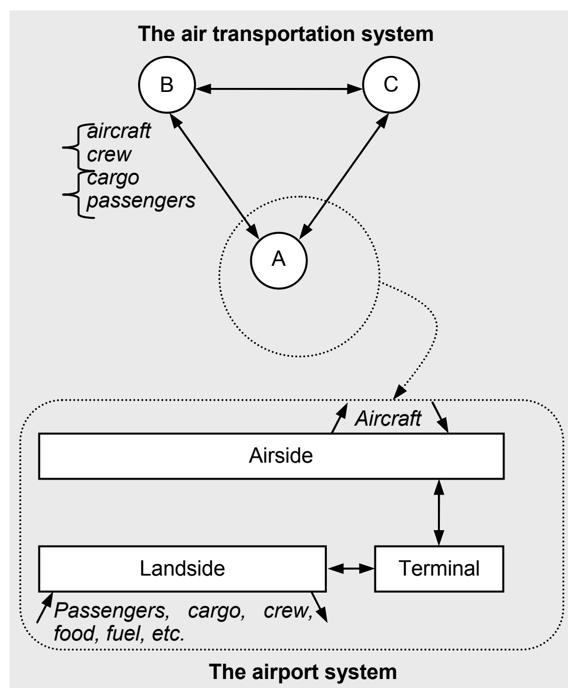

Figure 3. A conceptual view of the air transportation system.

Most users of the ATS interact at the airport. Apart from the airport, which may be regarded as an actor in the system, the users include airlines, handling companies, passengers, cargo owners and air traffic control (ATC). The overall efficiency of the system is a (complex) function of the individual efficiency of every single participant in the system. To maximize the overall efficiency, information about the operations of one actor should be made available to all other actors. This is also the core concept of CDM; airlines, airports, handling companies and ATC should all have access to the same information within the system. An actor should be able to influence decisions that will affect their operations, including decisions made by another actor.

The technical prerequisites for an effective CDM system, such as the possibility to create safe and secure communication channels, exist today. Furthermore, there exist solutions for navigation, surveillance and control of aircraft, which are superior to the radar based systems in use today. These technical advances result in an increasing amount of information to each actor in the ATS, which, correctly used, might lead to improved resource utilization, as well as reduced delays and waste. However, the growing amount of information also leads to a mounting complexity in the decision making process, as the number of options available for the decision makers grows. Thus, improvement in efficiency requires that each actor has the ability to handle and utilize the new information.

When a single airport is studied, the logistics of the ATS is limited to airport logistics. *Airport logistics is the planning and control of all resources and information that create a value for the customers utilizing the airport.* The customers in this aspect are the passengers and cargo service consumers, as well as airlines, restaurants, shops, and other actors operating at the airport. In the context of CDM, the goal of airport logistics is to utilize and process the information made available via CDM to achieve an efficient resource management.

Looking closer at airport A in Figure 3, the airport is divided into three geographical areas: landside, terminal and airside. These are commonly used notations, but the definitions vary. In some sources landside includes all activities on the ground and airside includes everything happening in the air, while other sources place the border between landside and airside at the security control. The definitions used here can be found in Table I.

TABLE I. DEFINITIONS OF AIRPORT AREAS

Airside	Airside is the area where activities related to aircraft movements, like approach, taxiing and take-off, as well as turn-around (e.g. fuelling, push-back and services by other types of vehicles), take place.
Landside	Landside includes the areas and the associated activities on the curb side of the terminal, like parking spaces and bus stops.
Terminal	Terminal includes the area and all activities occurring inside a terminal building. Note that this may be a cargo terminal as well as a passenger terminal.

Most of the flows enter and leave the ATS through landside (see Figure 3). The passengers may e.g. travel by car, train or buss to the airport, and will reach the landside area before entering a passenger terminal. Cargo often arrives by truck and might be unloaded at a cargo terminal. It may be argued that some support flows, like for example fuel or water for the aircraft, go directly from landside to airside. Here, for the sake of simplicity, it is however assumed that all flows going from landside to airside will pass through a terminal. The aircraft flow does not normally leave the ATS, but enters and leaves a single airport system through airside. The turn-around process is initiated when an aircraft touches down and lasts until it takes off again.

One way of increasing the resource utilization in the ATS is to reduce delays that occur in the turn-around process. During turn-around, several activities are performed; passengers and baggage have to be unloaded, and the aircraft has to be cleaned and fuelled. The toilets have to be emptied and the food supplies restocked. Sometimes snow and ice have to be removed before the aircraft can take off again. The efficiency of each of these processes has a direct impact on the turn-around time of the aircraft. The turn-around process is essential in the airport system, as most of the other relevant processes and activities connect to each other during the turn-around. This makes turn-around an excellent starting point for analyzing airport operations.

IV. MODELLING THE TURN-AROUND PROCESS

In the following section, activities during the turn-around process at Stockholm Arlanda airport (SA) are described. This is followed by a description of a simulation model of the turn-around process at SA.

A. Turn-around services

1) The Baggage loading and unloading process

Checked-in baggage can be stowed in the aircraft in two different ways. Either the bags are stowed in bulk (normally smaller aircraft) or in pre-packed containers (for larger aircraft). As the containers can be packed before the aircraft arrives to the airport, the time for loading baggage will be shorter with container loading than with bulk if the number of bags is large. [28]

2) The Catering process

The catering process involves removing leftover food from the previous flight and re-equipping the aircraft with new food. Catering can start when all passengers have left the aircraft, and the catering companies use high-loaders to get the cabinets on and off the aircraft. A specific high-loader can be used for a range of aircraft types. For types outside this range another high-loader have to be used. Thus, some planning is required to assign high-loader to flights.

Catering takes between 5 and 75 minutes depending on how much food that is needed and whether or not there are pre-packs (pre-ordered commodities placed on the seat). The catering teams need to go back to the depot between serving two aircraft to empty garbage and re-equip with new food. The catering coordinator makes a rough plan from the air traffic schedule of how many workers that are needed. The detailed planning of who is serving which aircraft is done manually during the day. [29]

3) The Cleaning process

The airlines can request different types of aircraft cleaning. During daytime the cleaning can take from 5 (just empty garbage) up to 40 (garbage, seat-pockets, belts, vacuum cleaning etc) minutes. The latter is only performed on aircraft with longer turn-around times. Longer and more thorough cleaning is performed during nighttime.

For most aircraft, cleaning and catering can be performed simultaneously. This is not always possible however, due to space constraints. In the latter case, it does not matter if cleaning or catering is performed first. The cleaning teams can go directly between two aircraft, but at breaks and when they need new material (like pillows and blankets) they have to go to the cleaning base. There is no significant difference between the cleaning teams so all teams can be assigned to all aircraft and types of cleaning. [30]

4) The Fueling process

At SA, fueling can be performed in two ways. There is a hydrant system with fuel pipes in the ground that dispenser trucks can connect to. At aircraft stands where the hydrant system is not available, fueling is performed by tankers. There are different types of dispenser trucks; the large type that can serve all kinds of aircraft and the smaller type that can only connect to smaller aircraft. However, the small dispensers are preferred when the area around the aircraft is tight. The tankers vary in size and can normally carry between 8 and 40 cubic meters of fuel.

Fueling cannot be performed simultaneously with baggage loading and unloading since these services require the same area around the aircraft. The area around the aircraft has to be planned so that the dispenser truck or tanker has a free way for evacuation. There are also some airline-specific rules about fueling while passengers are onboard. Most airlines allow this under certain conditions, e.g. there must be a fire engine ready in the immediate surrounding or there must be two way communications between apron and aircraft. At SA, fueling is not allowed if there is a thunderstorm.

The time it takes to refuel depends on the capacity of the pipes and, of course, of the amount of fuel needed. The pilot decides how much fuel that is needed and must report this to the fueling company before they can start to fill up the aircraft. Today, there is no preplanned schedule for which truck that will serve which flight. The fueling company coordinator allots the assignment to one of the workers as soon as the request is received from the pilot. [31]

5) The Water and Sanitation processes

The aircraft has to be released from waste water and be re-equipped with fresh water. This is performed by two different vehicles which most often are operating on the opposite side of the aircraft body than baggage handling and fueling. This means that water and sanitation can be performed simultaneously with baggage loading/unloading and fueling, but not simultaneously with each other. However, it does not matter which one of them that performs its service first. [32]

6) The De-icing process

Since even very thin layers of frost and ice on the aircraft have a negative effect on the lifting force and the control of the aircraft, de-icing is needed if any part of the aircraft is covered with snow or frost, or there is precipitation that could cause this to happen. At SA, the de-icing period is between October and April. The de-icing process is divided into two steps; during the first step, frost and ice are removed from the aircraft, usually by a warm, buoyant glycol mix (Type 1 fluid). The next step is called anti-icing and is performed to prevent new frost and ice from appearing on the aircraft before take off by a thicker fluid (Type 2 fluid). The time from anti-icing to take off (called hold-over time) is limited, as the effect of the Type 2 fluid wears off after a while. This means that it is not possible to de-ice an aircraft a long time before take off. The length of the hold-over time depends on the type of fluid, temperature and type of precipitation. [33]

The hold-over time makes it important to find a de-icing truck that can serve the aircraft on the "right" time. If the aircraft is served late, the turn-around time will increase, possibly resulting in a late departure. If the de-icing is performed too early, the procedure might have to be repeated. Even so, this would be a fairly uncomplicated planning problem, if only the time windows were known in advance and could be considered reliable. Today, the de-icing coordinator will plan tactically based on weather conditions and the flight schedule, and operationally – when a truck is dispatched – based on a request from the pilot [34]. When the coordinator gets the request, he or she decides which truck that should be allocated to the aircraft in question. Today, there is no preplanned schedule that the decision can be based on. This means that the truck drivers do not know in advance which aircrafts they are going to de-ice during the day.

The request from the pilot usually arrives at the beginning of the turn-around process, with the assumption that all activities will be performed on time. The de-icing truck will arrive at the aircraft a couple of minutes before the estimated departure time. [33]

B. A simulation model of Stockholm Arlanda airport

A detailed simulation model of all actors and activities involved in the turn-around process enables the assessment of various logistical operations involved in turn-around, as well as their interactions and their impact on airport performance.

The simulation model reflects SA. From an aircraft point of view, the model starts with touch down and taxiing into the stand, continues with the main processes during the turn-around and ends with taxiing out to the runway and taking off.

Since the turn-around process is very complex and contains both discrete and continuous functions, simulation is an appropriate method to use. There exist many commercial simulation packages on the market, some with special adaptation to different airport processes, e.g. terminal or runways. Other simulation software are more general and therefore available to use for modeling a wide range of different systems, e.g. all from manufacturing to queuing areas in a post office. To model the turn-around process, ARENA [35], which is a generic simulation package, is used. One reason for choosing ARENA is the possibility to integrate the optimization schedules into the model.

Figure 4 shows the conceptual model of the activities in the turn-around process embedded into the simulation model.

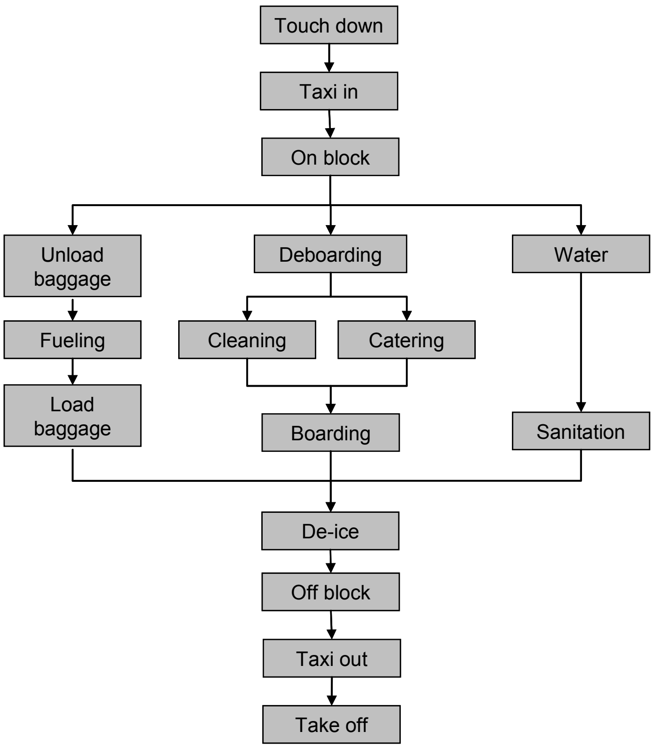

Figure 4. Turn-around activities included in the simulation model

The activities must be performed in the order of the arrows in Figure 4. If there is no arrow connecting two activities, they do not depend on each other and can be performed simultaneously. The conceptual model has some simplifications compared to reality:

- In the model, *cleaning* and *catering* can be performed simultaneously, which in reality is not the case for all aircraft types (predominantly not for IATA Code C aircraft).
- Some airlines do not allow *fueling* while passengers are on board, i.e. in some cases fueling must be performed between *deboarding* and *boarding*.
- For some (large) aircraft types, *fueling* can be performed simultaneously as *baggage* handling.
- In the conceptual model, *water* is always performed before *sanitation*. In the ARENA model, water is performed before sanitation if a water resource is available, otherwise sanitation is performed first. In the real case any of the two activities can be performed first as long as they are not performed simultaneously.

The number of resources available for each operator (e.g. catering trucks or high loaders), as well as which flights a particular operator have to serve, are specified as input to the model. All the support flows, e.g. cleaning teams and fuel trucks, are modeled as resources in the simulation. Since there are different operators performing the same turn-around service depending on which airline the flight belongs to, the resources are split into different service pools. An airline has a contract with only one of the service pools for each activity. A flight that should be served by cleaning team pool 1 can thus be delayed if pool 1 has too few resources, even if cleaning pool 2 has plenty of available resources.

In the simulation model, the duration time of the turn-around activities will depend on the aircraft type (number of seats, baggage loaded in bulk or containers, one or two escalators etc), although it is also possible to specify time for each aircraft individually. Transferring crew or passengers can be taken into consideration in the model. Suppose for example that crew from flight 1 are supposed to transfer to flight 2. Then it is possible to set a transfer time period, preventing the push-back of flight 2 until a certain time period has passed from the on-block of flight 1. In the current paper, this type of flight dependency is not used, since the necessary input data is lacking. For more information on the simulation model, see [36].

Validation of the model is done by some basic checks and by conferring with system experts at SA. One validation check is that the number of movements per hour in the model equals those in the flight schedule. A comparison is shown in Figure 5.

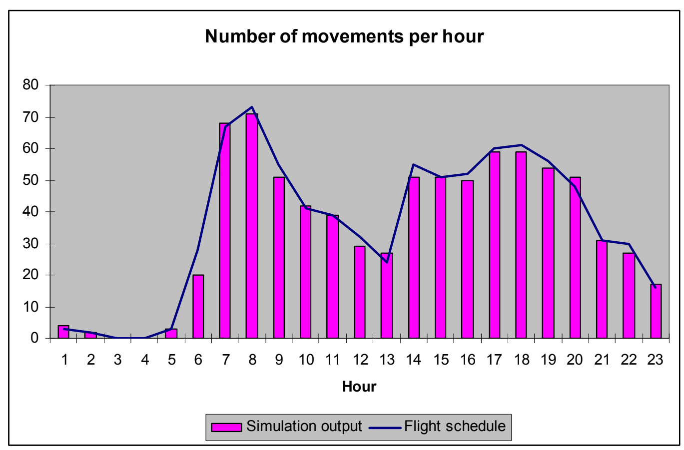

Figure 5. Comparison between flight schedule and simulation output

The total turn-around time as well as waiting time for support services should increase if the individual process times increase. Results from a simulation where the process times have been increased with 20%, show that this is also the case, as can be seen in Table II. The table shows the number of aircraft that have to wait for service as well as the maximum and average times for the waiting flights.

TABLE II. WAITING TIMES FOR SUPPORT SERVICES IN VALIDATION SCENARIOS

		Cleaning	Catering	Unload Baggage	Water	Sanita-tion	Fuel	Load Baggage
Normal case	*Number that has to wait*	13	11	4	3	1	5	9
	Percentage waiting	4%	3%	1%	1%	0%	2%	3%
	Max (minutes)	3	3	3	3	0	1	3
	Average (minutes)	1	1	2	2	0	1	2
Increased process times	*Number that has to wait*	20	18	15	6	7	20	21
	Percentage waiting	6%	6%	5%	2%	2%	6%	7%
	Max (minutes)	4	6	4	4	1	3	5
	Average (minutes)	2	2	2	2	0	1	2
Decreased number of resources	*Number that has to wait*	26	30	10	5	7	21	14
	Percentage waiting	8%	9%	3%	2%	2%	7%	4%
	Max (minutes)	5	6	3	3	1	4	3
	Average (minutes)	2	2	1	2	0	1	2

The total turn-around time as well as waiting time for support services should increase if the number of support service resources decrease. Results from a simulation where the number of support service resources have been decreased with 20% can be seen in Table II.

V. OPTIMIZING THE DE-ICING PROCESS

As mentioned in Section I, the aim of this study is to investigate whether it is possible to gain more efficient airport logistics by optimizing the airport processes. Here, the de-icing process is studied because it is more complex than many of the other support flows. The aim of the optimization approach is to develop a tool to assist with the planning and scheduling of the de-icing trucks. This includes deciding which truck that should serve a certain aircraft, and when a truck should visit the refill station.

The trucks start at a depot, drive to an aircraft to perform de-icing, and then travel directly to another aircraft, back to the depot or to the refill station. The refill station has to be visited when the truck has run out of de-icing fluid. The de-icing scheduling problem has all of the key components of a classical vehicle routing problem as well as some additional constraints. This means that it can be modeled as a route optimization problem.

A mathematical formulation of the de-icing scheduling problem is

$$\text{Min} \sum_{i=0}^{N} \sum_{j=0,j\neq i}^{N} \sum_{k=1}^{K} \sum_{r=1}^{R} (a*l_i + b*w_{ij}x_{ij}^{kr}) \qquad (1)$$

$$\text{s.t.} \sum_{i=1}^{N} x_{ih}^{kr} - \sum_{j=1}^{N} x_{hj}^{kr} = 0 \qquad h \in \{0,...,N\},\ k \in \{1,...,K\},\ r \in \{1,...,R\} \qquad (2)$$

$$\sum_{j=0}^{N} \sum_{k=1}^{K} \sum_{r=1}^{R} x_{ij}^{kr} = 1 \qquad i \in \{0,...,N\} \qquad (3)$$

$$\sum_{i=1}^{N} \sum_{j=1}^{N} d_i x_{ij}^{kr} \le q^k \qquad k \in \{1,...,K\},\ r \in \{1,...,R\} \qquad (4)$$

$$t_i + s + f_i + w_{ij} - M(1 - x_{ij}^{kr}) \le t_j \qquad i,j \in \{1,...,N\},\ k \in \{1,...,K\},\ r \in \{1,...,R\} \qquad (5)$$

$$p_i \ge t_i + s + f_i \qquad i \in \{1,...,N\} \qquad (6)$$

$$p_i \ge STD_i \qquad i \in \{1,...,N\} \qquad (7)$$

$$l_i \ge t_i + s + f_i - STD_i \qquad i \in \{1,...,N\} \qquad (8)$$

$$t_m^{stop} + f_0 - M(1 - z_{mn}^k) \le t_n^{start} \qquad m,n \in \{1,...,R\},\ k \in \{1,...,K\} \qquad (9)$$

$$z_{mn}^k \ge x_{i0}^{km} + x_{0j}^{kn} - 1 \qquad m,n \in \{1,...,R\},\ n>m,\ k \in \{1,...,K\},\ i,j \in \{0,...,N\} \qquad (10)$$

$$t_r^{stop} \ge p_j + w_{j0} - M(1 - x_{j0}^{kr}) \qquad j \in \{1,...,N\},\ k \in \{1,...,K\},\ r \in \{1,...,R\} \qquad (11)$$

$$0 \le t_r^{start} \le t_i - w_{0i} + M(1 - x_{0i}^{kr}) \qquad i \in \{1,...,N\},\ k \in \{1,...,K\},\ r \in \{1,...,R\} \qquad (12)$$

$$t_i \ge 0,\ p_i \ge 0,\ l_i \ge 0 \qquad i \in \{1,...,N\} \qquad (13)$$

where

K is the number of available de-icing trucks, $1 \le k \le K$.

N is the number of assignments, $0 \le h,i,j \le N$, during the time period. Assignment 0 is the refill station where also all routes start and end.

R is the number of routes, $1 \le m,n,r \le R$, performed by the trucks. A route is a sequence of assignments performed by a truck. R is large enough to accommodate the number of routes that the fleet can possible perform in a day, i.e. $R \le N$. Some of these routes might be empty.

q^k: Capacity of truck k. (liters)

w_{ij}: Traveling time, i.e. the time it takes to drive from assignment i to assignment j. (minutes)

f_i: De-icing duration time, i.e. process time, for assignment i. (minutes)

f_0: Refill time, i.e. the time it takes to fill up fluid at the refill station, which is denoted as assignment 0. (minutes)

STD_i: The scheduled time of departure for the aircraft corresponding to assignment i. (time point specified by minutes)

s: Set-up time, i.e. the time span from when a truck arrives to an assignment until the de-icing can start. (minutes)

M: An arbitrary large constant.

a: Weight of delay in the objective function.

b: Weight of traveling time in the objective function.

t_i: Arrival time to *assignment i*.

t_r^{start}: Start time for *route r*.

t_r^{stop}: Stop time for route r.

p_i: The time assignment i is finished.

l_i: Delay for the aircraft corresponding to assignment i. (minutes)

x_{ij}^{kr} = 1 if there is an arc from i to j on route r, i.e. if truck k is performing assignment j just after assignment i in route r, otherwise 0.

z_{mn}^{k} = 1 if truck k performs route m before route n, otherwise 0.

Equation (1) is the objective function of the problem, i.e. to minimize the delay of aircraft as well as the traveling time for the trucks. Equation (2) ensures that the same truck arrives to and leaves each assignment on its route. Equation (3) defines that every assignment is performed exactly once. Equation (4) makes sure that a de-icing truck is going to the refill station before it runs out of fluid. Equation (5) specifies that a truck can not arrive to an assignment before the previous one is completed and the truck has travelled between the assignments. The time an assignment is finished is calculated in equation (6) and (7). The possible flight delay is defined in equation (8). Equation (9) defines that the next route with the same truck can not start before it is re-equipped with de-icing fluid. Equation (10) guarantees that if an arc exists (i.e. if the x-value for an arc is 1) the z-value for the corresponding route is also 1. Equation (11) and (12) specifies the start and stop times for a route.

When CDM is implemented at SA, the de-icing companies will have information about where and when de-icing is needed. Then the request for de-icing from the pilot will not be needed anymore, which makes the use of the order time obsolete. Therefore order time is not used in the model, which means that delays caused by a late order time are avoided, and the finished time is calculated as:

$$p_i = \begin{cases} t_i + s + f_i & if \quad t_i + s + f_i \geq STD_i \\ STD_i & if \quad t_i + s + f_i < STD_i \end{cases},$$

corresponding to constrain (6) and (7) in the model. If p_i is lower than STD_i, STD_i is used as the new finished time for truck k. In reality the de-icing trucks sometimes might be available for the next assignment before STD_i, but since de-icing in general is one of the last things that is performed before take off (due to the hold-over time), this extra time will be very short and is therefore neglected here.

If $p_i > STD_i$, a delay, l_i, occurs:

$$l_i = \begin{cases} (t_i + s + f_i) - STD_i & if \quad (t_i + s + f_i) > STD_i \\ 0 & otherwise \end{cases},$$

as defined in equation (8) in the mathematical formulation.

The mathematical model is solved using a GRASP [37] heuristic. Two objectives are minimized in the model: accumulated total delay for the flights in the flight schedule, weighed by parameter a, in the objective function (1), and the total distance (time) travelled by the de-icing trucks, weighed by parameter b. By changing the values given to a and b, different solutions will be optimal for the model. In this paper, a is set to 1 and b is set to ½. This means that one minute of delay gives an equal objective function contribution as one kilometer of driving distance with an average speed of 30 km/h. These values are selected through computational testing, and give a good balance between the two objectives. The GRASP algorithm finds a number of different solutions while searching the solution space, and solutions dominating in either low delay or a short travelling distance are considered interesting.

In Table III three different solutions are presented. In the GWOAC solution, the closest truck is always selected for a new assignment, without regarding whether or not it is available. This gives a solution with a short (although not necessarily the shortest) accumulated travel time, but with an unacceptable level of delay since many flights have to wait for the de-icing service. The GRASP solutions offer a trade-off between delay and travel time; GRASP 1 might be considered the solution preferred by the de-icing company whereas GRASP 2 performs better in terms of total airport performance. It should be noted that a solution without any delay is not possible to find since some flights are delayed due to other reasons.

TABLE III. DIFFERENT SOLUTIONS TO THE DE-ICING SCHEDULING PROBLEM

Solution	Traveling time [minutes]	Delay [minutes]
GWOAC	842	340 270
GRASP 1	1020	295
GRASP 2	1066	207

VI. SIMULATION RESULTS

A. Scenarios

One aim with the simulation model is to compare the airport operations when using an optimized de-icing schedule to when simpler scheduling rules are used. To that end four scenarios have been created; the first one without de-icing, while the three other scenarios include de-icing. In all scenarios with de-icing, all the departing flights are de-iced. The number of de-icing trucks used is 18 in all these scenarios. In Scenario 2, de-icing is planned according to a simple rule of thumb, while de-icing in Scenario 3 and 4 are based on schedules from the GRASP heuristic.

1) Scenario 1: No de-ice

The first scenario is a base scenario to further validate the simulation against the flight schedule. In this scenario no de-icing is performed. The results are also useful for deriving which delays that are not due to de-icing, which is interesting to know in the other scenarios.

2) Scenario 2: De-ice with a "first-go-first-served" schedule

In the second scenario, the de-icing trucks are scheduled according to a simple rule of thumb priority. The scheduling rule is based on a kind of first-come-first-served procedure, where the de-icing is performed in the order of scheduled time of departure (STD) for the flights. In practice, this means that the flight with the earliest scheduled departure time is served first and so on.

3) Scenario 3: De-ice with a schedule that is optimized for the de-icing company

The de-icing in the third scenario is performed according to a schedule from the optimization algorithm, corresponding to solution GRASP 1 in Table III. This scenario can be seen as an example of what happens when individual actors are sub-optimizing their own processes.

4) Scenario 4: De-ice with a schedule optimized for the entire airport

In the fourth scenario the de-icing trucks are planned according to the schedule from the optimization algorithm that gives the lowest delay for the departing flights, i.e. GRASP 2 in Table III.

The number of replications needed to get reliable results depends on how much the results vary between the runs. The standard deviation as well as the mean value vary by output variable, which means that the number of required replications differ depending on which output variable that is studied. Looking at all the output variables from all scenarios, 50 replications is the highest number of replications required for an allowed deviation from the mean by 10%, with a confidence interval of 99% [38]. Therefore the simulation output is based on 50 replications of the model, for all scenarios.

B. Output

Delays are measured for touch down, stand and off block. A strict definition of delay is used in this work, where a delay is defined as any activity failing to begin within one second of the expected start time.

A touch down delay is the difference between the scheduled time of arrival (STA) in the flight schedule and the time that the flight touches down in the simulation model. The number of touch down delays presented here is in percentage of the total number of movements on the runway, i.e. not only the number of arrivals, since the departures also contribute to these delays.

A stand delay is the difference between the time the flight reaches the stand and the time the turn-around process can start, i.e. the waiting time for the stand if it is occupied by another aircraft when the aircraft arrives.

An off block delay is defined as the time difference between the completion of the turn-around process in the simulation and the STD in the flight schedule.

TABLE IV. DELAYS FOR THE DIFFERENT SCENARIOS

	Touch down			Stand			Off block		
	Percentage delay	Max delay	Average delay	Percentage delay	Max delay	Average delay	Percentage delay	Max delay	Average delay
Scenario 1	19%	3 min	44 sec	1%	7 min	4 min	8%	14 min	5 min
Scenario 2	19%	3 min	42 sec	2%	10 min	5 min	27%	32 min	8 min
Scenario 3	19%	3 min	42 sec	1%	7 min	3 min	26%	43 min	7 min
Scenario 4	19%	3 min	42 sec	1%	7 min	3 min	24%	20 min	6 min

The number of delays (in percentage) as well as the maximum and average values of the delays can be seen in Table IV. Notice that the average value is not the average of all flights but the average of all delayed flights.

The touch down delays are due to limited runway capacity. In reality, the capacity is often lower than the number of movements in the schedule for certain time periods. It is common that several flights are scheduled to touch down at the same time, e.g. 7 o'clock in the morning, although it is impossible to touch down more than one flight (unless two runways are in use for arrivals) at exactly that time. In reality, some flights arrive before STA while in the simulation no flight becomes active before STA. These factors are reasons for the relatively high percentage of touch down delays and the short delay time. However, some of the delays originate from delayed departing flights, since they are occupying the runway at a time when they are not scheduled to be there. The difference in the average delay between Scenario 1 and the other scenarios might also be due to the delayed departure flights. If some of the departures causing touch down delays in

Scenario 1 are delayed themselves, the number of touch down delays might decrease.

The stand delays depend on the off block delays, and are increase with the accumulated time that flights are occupying the gates. This is the reason why there occur more and longer stand delays in Scenario 2 than in Scenarios 3 and 4. The off block delays do not differ very much between Scenarios 2 and 3, but by studying the point in time when they occur, it becomes evident that most of the delays in Scenario 3 happen during the late evening. Off block delays in the end of the simulation period do not affect the stand delays to the same extent as off block delays during morning to afternoon.

Looking at the 8% off block delayed flights in Scenario 1, 65% of them is delayed due to touch down delays including taxi-in-times. The rest (35%) of the off block delayed flights have a simulated turn-around time longer than the scheduled. This also means that 8% of the off block delays in Scenarios 2-4 are not likely caused by de-icing.

In Scenario 1, for all of the off block delayed flights, the unload baggage - fueling - load baggage track (i.e. the left track in Figure 4) is the bottleneck. In Scenario 2-4, most of the off block delays can be derived to the de-icing process.

TABLE V. WAITING TIMES FOR SUPPORT SERVICES, SCENARIO 1

	Cleaning	Catering	Unload Baggage	Water	Sanita-tion	Fuel	Load Baggage
Number that has to wait	13	11	4	3	1	5	9
Percentage waiting	4%	3%	1%	1%	0%	2%	3%
Max (minutes)	3	3	3	3	0	1	3
Average (minutes)	1	1	2	2	0	1	2

Among other things, off block delays are caused by absent support resources, which means that the flight has to wait for them. Waiting time is defined as the difference between the time the aircraft is ready to be served by the support service and the time when the service starts. In Table V the number of aircraft that have to wait (in quantity and percentage) as well as the maximum and average waiting times for all the support services are shown for Scenario 1. Note that the average value is not the average of all flights but the average of all waiting flights.

The waiting times do not differ significantly between the scenarios, with the exception of the waiting times for the de-icing service. Waiting time for de-icing is an excellent measure of the quality of the de-icing schedule used in the scenario. In Table VI the number of aircraft (in percentage) that have to wait for the de-icing truck is presented. For the waiting aircraft, the maximum, average and total waiting times are given.

Studying the number of off block delays in Table IV the result of Scenario 4 is better than that of Scenario 3 which in its turn is better than Scenario 2. The stand delays are consistent with this result. The same holds for the average off block delay times, although the maximum off block delay that occurs is largest in Scenario 3. It is not obvious whether a small maximum delay or a small average delay is most desirable when considering airport performance. To a large extent, this depends on the flights being delayed.

TABLE VI. WAITING TIMES FOR DE-ICING TRUCKS

	De-icing			
	Percentage waiting	Max waiting time	Average waiting time	Total waiting time
Scenario 1	-	-	-	-
Scenario 2	23%	40 min	13 min	1181 min
Scenario 3	21%	47 min	10 min	808 min
Scenario 4	18%	33 min	9 min	646 min

Considering the time an aircraft has to wait for the de-icing trucks (Table VI), the situation is the same as for the off block delays. Scenario 3 is better than Scenario 2 due to number of delays as well as average and total delay time, while Scenario 2 has a lower maximum delay time than Scenario 3. Scenario 4 has lower figures for all the measured values.

Thus, the results presented in Table IV and VI, show that the de-icing schedule optimized for total airport performance (Scenario 4) gives better results than the schedule optimized for the de-icing company (Scenario 3) or the more simple rule of thumb schedule (Scenario 2). These results support the theory that trying to find solutions optimal for the entire airport will give a better airport performance than letting all actors try to find solutions optimal for their own activity.

VII. CONCLUSIONS

In this study, an optimization algorithm for scheduling de-icing trucks has been developed and integrated into a simulation model for the turn-around process at Stockholm Arlanda airport. The schedule based on an optimization solution where total airport performance is considered, gives the lowest flight delays and shortest waiting times.

These results are promising and suggest that scheduling tools for other turn-around activities should be developed in the future, to further increase the resource utilization at the airport. Implementing optimized schedules for all the support flows in the simulation model will also give a more complete picture of the logistic system at the airport, showing how all actors and processes are linked to each other.

Future research also include extending the simulation model to the final approach for arriving aircraft, as well as the taxiing and take off processes. By implementing these extensions, it will be possible to integrate more processes related to air traffic control operations into the simulation, e.g. runway sequencing and push-back clearance. These implementations will make it possible to investigate how the air traffic control related processes, together with the turn-around activities, affect the overall airport performance.

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