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ORIGINAL PAPER

A ground crew shift rostering model for Santiago International Airport

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Abstract
A mixed integer linear programming model is presented for personnel planning of ground handling crews at Santiago International Airport in Chile. The model generates employee shift rosters for an entire month assuming heterogeneous workers (to reflect different skills demanded at specific times) that satisfy various constraints relating to legal restrictions, personnel demand, worker welfare criteria (fair shift assignments, elimination of undesirable shift patterns), and pre-existing work group assignments for achieving task synergies. Solutions are generated using a commercial solver, standardizing the shift assignment process and improving both personnel availability and worker welfare by objective standards compared to previous manual method solutions.

Keywords Personnel planning · Rostering · Ground handling crews · Mixed integer programming

Mathematics Subject Classification 90C11

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1 Introduction

The aviation business is characterized by high capital costs and low operating margins, resulting in a very competitive environment. This implies that firms in the industry must constantly seek time and cost reductions through the efficient use of resources and technologies in order to maintain profitability while delivering a quality of service at the level demanded by customers. A core function in the aviation sector is airport ground handling, a series of activities that play a primary role in flight schedule compliance and asset management efficiency. Which in turn means that resource assignments in personnel, equipment and inputs are all key elements in ensuring ground operations are carried out efficiently and effectively.

In this light, optimizing ground handling processes and improving ground crew working conditions is fundamental, especially at large international airports where high traffic volumes render these operations all the more complex. The present article is based on the real case of ground handling at Santiago International Airport in Chile as it was shortly before the separate operations of LAN Airlines and TAM Linhas Aereas were fully integrated following their merger as LATAM. Part of a larger project undertaken during 2013–2015 to improve all aspects of ground operations at the airport, this study focused on two main goals: first, the development of a simulation model for the baggage loading area that would define operating and response protocols for baggage handling incidents (Cavada et al. 2017), and second, the development and computer-based implementation of an optimization model to handle personnel planning for all ground crew. It is the work on the latter goal that will concern us here.

Personnel planning is a critical task for ground handling operators, due not just to its very significant impact on cost structures but also the scarcity of qualified workers given the considerable flight experience they must accumulate to obtain the necessary certifications. Furthermore, not always having the right personnel on duty as contractually required can lead to heavy fines that would turn labor costs into a major burden. Proper management of staff is thus of primary importance if operators are to be successful both operationally and financially in this extremely competitive and fragile market.

This paper reports on the implementation of an integer linear programming model for the personnel planning of Santiago International Airport's ground crew, which consists of more than 800 workers employed in 22 different ground operation job categories. Associated with these categories is a range of qualifications, skills and pre-existing work group assignments as well as employee-level restrictions relating to training, holidays, medical leave, assignable shifts as defined under employment agreements, etc. The problem to be solved by the model consists in generating monthly shift assignments in the form of 28 day rosters for all operating personnel that satisfy an array of legal, operational, human resource and employee welfare constraints as exemplified in Fig. 1.

Solving the problem presents a range of difficulties that stem not only from its size but also the challenge of appropriately incorporating the complexities

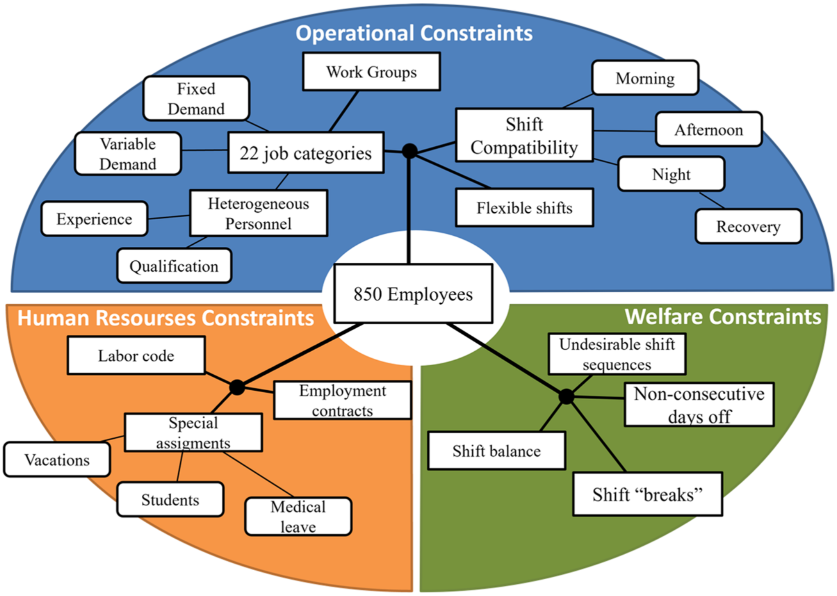

Fig. 1 Constraint map for ground crew personnel planning problem

and connections between all of the pre-conditions (Fig. 1) involved in the ground operations' 24/7 rotating shift structure. Furthermore, it is crucial that the problem capture the ultimate objective of the rostering process, meaning that the objective function must be carefully specified. We opted to express it as a weighted sum of staff assignment and welfare conditions indicators.

The principal contribution of this article thus lies in the design of a mixed integer optimization model that, when used in conjunction with a state-of-the-art commercial solver, can generate an exact solution of a real-world problem of planning the monthly rosters for a heterogeneous ground handling crew at an airport working under a 24/7 rotating shift system with multiple and diverse operational, welfare and human resources constraints reflecting the complexities in the operation. The global problem is broken down by job and explicitly includes conditions relating to employee welfare. A remarkable feature of the model is its flexibility, considering that a user of the tool could add new sequences agreed between workers and company without touching the whole structure of the model.

The model was implemented as part of a computer system known as ANDROS (for "Andes Rostering System") installed by the Santiago airport ground services operator that allows the user to add and remove constraints to reflect prohibited as well as required shifts in order, for example, to maximize the coverage of day and shift personnel demand for an entire one-month planning period. Results will be presented for the implementation of the system used to generate the rosters, with special reference to the impact of the new rostering structure on the system's overall functioning since it replaced the former manual scheduling methods.

The remainder of this paper is organized into five sections. Sections 2 reviews the related literature; Sect. 3 introduces the problem, explaining various considerations relating to legal shift definitions, operating conditions and worker welfare criteria; Sect. 4 develops the rostering model with its objective function and constraints; Sect. 5 sets out the model results, compares them to those of the previously used manual rostering method and briefly discusses the model's implementation in the airport personnel planning system; and finally, Sect. 5.3 summarizes and concludes.

2 Literature review

The cost of labor in many industries, particularly for highly specialized operations, has meant that previous research has focused on improvements to rostering optimization models in which personnel is recognized as the main component of the total cost structure (Ernst et al. 2004; Burke et al. 2004; Van den Bergh et al. 2013). In this section, we first discuss previous works on scheduling of airport group operations, then we review some relevant rostering works in other industries and finally, some recent works incorporating fairness and welfare in the context of personnel scheduling are presented.

In the area of airport ground handling, several works are particularly worthy of note. In one of the first contributions in this area, Dowling et al. (1997) provide a formulation of the rostering problem in the context of airline ground-staff decided monthly, along with a simulated annealing method to solve a two-stage optimization problem: the first stage decides monthly rosters while the second one allocates specific tasks on specific days to the staff assigned by the roster phase. Their system was able to solve a monthly roster for 500 staff in about 5 h. Soukour et al. (2013) present a staff scheduling problem in airport security service solved in three steps: days-off scheduling, shift scheduling, and staff assignment. The authors propose a memetic algorithm combined with an evolutionary algorithm and local search techniques to solve the staff assignment step. Kuo et al. (2014) build an integer linear programming model to handle customer service personnel planning at multiple airports. Their staff scheduling problem can handle different skills requirements through a multidimensional representation of them in the model and includes lunch and rest breaks. They are able to solve their model for a real problem using proper valid inequalities, which is compared with a benchmark heuristic. Fahle et al. (2016) specify and solve a cyclic roster planning problem, defined as the sequences of shifts designed for a group of employees, who switch cyclically from one week to the next. Then, in this scheme, several fairness aspects are considered in the construction; the authors present a local search post-processing step to obtain a fair cyclic plan without altering the final cost of a non-cyclic optimal shift plan. Kutschka et al. (2016) define the monthly rostering problem including qualification constraints plus several roster rules as well as fairness criteria; they use a branch-and-price (B&P) approach with temporal decomposition, solving the problem for seven instances where employees range from 130 to 304. Zeng et al. (2019) consider hierarchical skills for a problem of ground personnel scheduling. In their setting, staff with higher level skills is permitted to cover demands of lower levels (downgrading). They propose a B&P approach to solve the model. Shiau et al. (2020) propose a hybrid personnel scheduling model, which could be seen as an integrated rostering that include pre-assignments and specific requests in the construction of individualized work lines for each employee, based on a fair and equal share principle satisfying specific quality preferences associated with workload. For a given staff, the resulting scheduling meets demand while the cost of manpower is minimized. This model can also be used as a simulation tool for decision making support.

Personnel planning analysis frequently arises in the literature on crew scheduling and optimization models in other industries such as health and manufacturing. Beliën et al. (2013) study the problem of building schedules of an aircraft maintenance company, based on an enumeration approach, in which shift patterns are assigned using a mixed integer linear optimization model, solved for each combination of team sizes. Côté et al. (2013) use a B&P approach to assign shifts that assumes heterogeneous employees executing multiple activities. The subproblems are formulated using grammars and solved through dynamic programming; the B&P algorithms provided good-quality integer solutions for almost all tested instances. Boyer et al. (2014) solve a model using B&P with a heterogeneous work force and variable shift lengths. In this work, the employees have different qualifications, preferences and availabilities. The subproblems are also formulated using grammars to model the complex rules involved in the creation of feasible shifts for each employee. Restrepo et al. (2015) propose a similar model to those discussed previously (Côté et al. 2013; Boyer et al. 2014) to solve personalized tour scheduling problems in a multi-activity context assuming heterogeneous personnel. The problem is solved using a B&P approach based on two flexible enough formulations to incorporate different start times, patterns, multiple breaks, among other conditions. Lapègue et al. (2013) present a model to build employee timetables to cover the demand associated with a set of tasks, which is based on constraint programming pursuing the optimality criterion of balancing the workload sharing in the context of a pharmaceutical firm. Wong et al. (2014) design a two-stage heuristic algorithm to schedule nurses at a Hong Kong hospital, which combines a shift assignment heuristic with a sequential local search. Gérard et al. (2016) develop a model that is solved by column generation in a context with heterogeneous staff and highly variable work demand. Four heuristic methods are proposed to tackle the problem, providing good quality solutions for real size instances in short time. Finally, a model due to Alp et al. (2019) solves a real-world personnel scheduling problem, where the objective is to assign the workers in a fair manner, satisfying weekly personnel demand with the best tours, and providing fair distribution among employees. The application of the model in the company resulted in much better-quality schedules in terms of fairness.

The last decade has witnessed the incorporation of the heterogeneous personnel phenomenon in which a specific task can only be carried out by specific workers, and the idea of fairness or worker welfare is also increasingly being addressed. The recognition of this last notion varies from employer to employer and its integration into shift assignment techniques is, according to Wolbeck et al. (2019), a work in progress. A number of examples can be cited. Stockwell-Alpert et al. (2015) develop a two-stage heuristic for the pharmaceutical industry context that defines a generic roster which iteratively improves the worst case and accommodates fairness both in shift assignment and workload. Gross et al. (2018) propose two models to schedule hospital physicians and operating rooms that include fairness and doctors' preferences. Breugem et al. (2019) find crew rostering solutions for a Dutch railway company that consider fairness in workloads and shift structures using a three-phase heuristic based on a neighborhood search algorithm. Finally, there is Rea et al. (2021), who analyze equality and fairness concepts in shift assignments and propose a number of techniques for their incorporation.

Although the research on personnel scheduling is extensive, we were unable to find works addressing in an integrated way all the features present in our specific rostering problem. Namely: (i) personalized shift assignment scheme; (ii) preferred but not fixed working groups; (iii) existence of understaffing (personnel shortfall) and overstaffing during certain periods; (iv) heterogeneous workforce and skill requirements; (v) temporary position upgrades and substitutions; (vi) fairness and welfare considerations. Table 1 shows the presence of these features in the different articles previously discussed.

As shown in the table, most of the studies define shifts or schedules for workers with different skills and assume some fairness concept in the assignments. However, we could not find works that tackle rostering problems where understaffing and

Table 1 Relevant features of the rostering problem found in previous works

	Personalized Shifts	Not fixed working groups	Under/over staffing	Heterogeneous workforce (skills)	Temporary substitutions	Welfare and fairness
Dowling et. al (1997)	✓			✓		
Côté et al. (2013)	✓			✓		
Lapègue et al. (2013)	✓			✓		✓
Soukour et al. (2013)	✓		✓	✓		
Boyer et al. (2014)	✓		✓	✓		
Kuo et al. (2014)	✓		✓	✓		
Wöng et al. (2014)	✓			✓		✓
Stockwell-Alpert & Chung (2015)						✓
Fähle and Vermohlen (2016)						✓
Kutschka and Herbers (2016)			✓	✓		
Restrepo et al. (2016)	✓		✓			
Gérard et al. (2016)	✓		✓	✓		
Gröss et al. (2018)				✓		✓
Alp & Alkaya (2019)						✓
Breugem et al. (2019)		✓				✓
Zeng et al. (2019)	✓		✓	✓	✓	
Shiau et al. (2020)	✓					✓

overstaffing were combined with temporary upgrades and substitutions of workers' roles. The way in which we integrate these concepts in our model is a valuable contribution of the present work.

Next, we describe the practical problem and develop a solution approach based on the solution of a series of mixed-integer programming models that adequately capture the particularities of the different configurations observed in the real-settings of the case study.

3 Description of the problem

Before the implementation in 2013 of the ANDROS rostering system and the model presented here, the ground handling services operator (Andes Airport Services S.A., a private firm hereafter denoted "the operator" or "the company") drew up the rosters assigning employees to shifts using manual methods, a process that required excessive amounts of staff time and effort. The problem as it was at that time involved assigning the shifts for an entire month and for all operating personnel, taking into account legal requirements and operating conditions such as personnel demand for each job, demand for personnel with given skills, pre-existing work groups, special requests, and holidays and training sessions, as well as quantifiable employee welfare considerations.

An important aspect of ground operations is that certain activities are performed on the airport apron and thus require tight coordination of personnel with different jobs and skills so that they are always available when needed. This involves a range of factors and conditions that must be treated simultaneously, as in the three ground services illustrated in Fig. 2. The right-hand side of the figure shows the case of apron services for a flight, which just for the flight group requires rostering a group leader, two handlers, a conveyor and a cargo loader. These considerations, which are planned as a function of daily and monthly flight schedules, must be incorporated into the monthly rostering for each job as indicated in the figure.

The optimization problem addressed by the model to be introduced in Sect. 4 was built around three classes of interrelated constraints on the ground handling operations illustrated in Fig. 1 that must be reflected in the rostering. As described in turn below, the three classes are: shift structure and related legal considerations, operating conditions, and employee welfare conditions.

(a) **Shift structure and related legal considerations**

Shifts are defined in terms of the activity assigned to an employee for each day on the roster. There are three such activities: a work shift, on which an employee carries out his or her normal duties in the workplace; a non-work shift, on which an employee is attending training sessions or on medical leave and thus not available for work but is paid; and an off shift, referring to "free" days on which the employee is neither at work, in training or on medical leave.

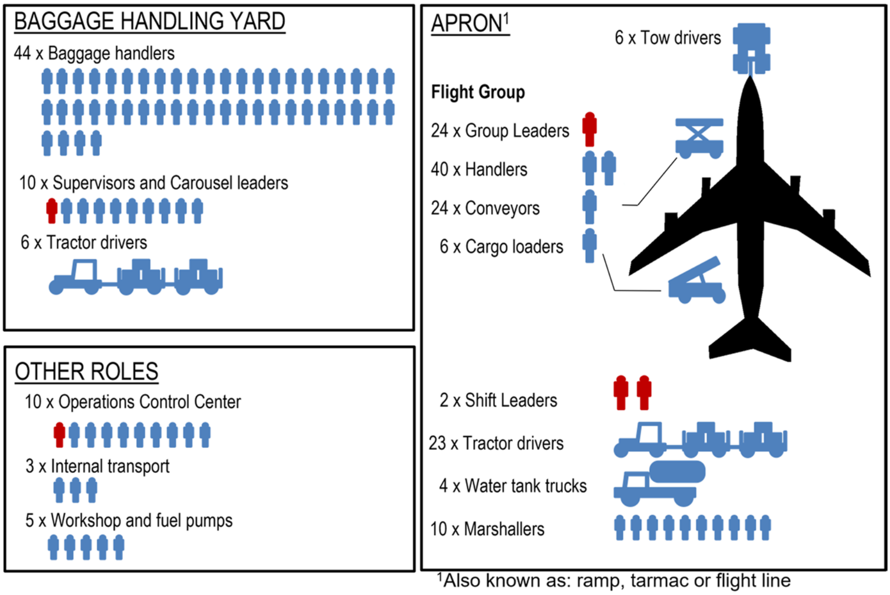

Fig. 2 Coordination and interaction of jobs in ground services rostering. The numbers indicate the average number of employees per shift in each job. The exact size and configuration of a flight group may vary depending on the type of aircraft being served, a typical flight group is formed by 1 leader, 2 handlers, 1 conveyor and 1 cargo loader. Leader positions are highlighted in red (online version) (color figure online)

The Chilean Labor Code limits the work week to no more than 45 h, with mandatory rest periods of 11 h between shifts. The Code also prohibits employees from working more than 6 consecutive days and further requires that two of the weekly days off in a month be Sundays. Working days for the ground crew employees are defined by three shift types: morning (M), from 4 am to 12 noon; afternoon (A), from 12 noon to 8 pm; and night (N), from 8 pm to 12 midnight. After working any sequence of night shifts, an employee is assigned a recovery day (R) before an off shift (O), the former being paid but not worked as explained above. This usually means 5 shifts per week including the recovery day when required. This setup is captured by the forward shift structure illustrated in Fig. 3.

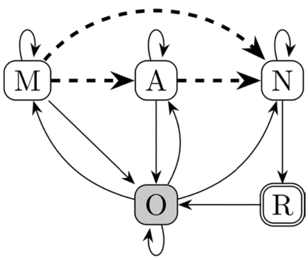

Fig. 3 "Forward" shift structure. As an example, a morning shift (M) can be followed on the very next day by another morning shift, an afternoon shift (A), a night shift (N) or an off shift (O) whereas a night shift (N) can only be followed by another night shift (N) or a recovery day (R)

(b) **Operating conditions**

The following conditions reflect the company's operating rules:

1. Personnel requirements. There are 22 different jobs that must be planned for the complete set of ground handling operations. The company's Capacity Planning Area makes estimates of the number of workers required for each shift over the month in each job, and since the ideal personnel solution cannot always be satisfied, it also estimates a "critical" or minimal requirement to be satisfied by each shift wherever possible.
2. Work groups. Although most jobs are independent of each other, some are organized in groups. For example, the team in charge of baggage is composed of a group leader, a cargo loader/driver and various baggage handlers (Fig. 2). The methodology considers the fact that, if possible, we intend to match the work group assignments in a pre-process, in such a way that the model privileges the formation of pre-assigned groups of workers that normally work together in jobs that require a team of employees with different skills and responsibilities to be executed.
3. Specific skills. Workers doing the same job are not homogeneous. They may differ as regards specific qualifications (e.g., certified for work on wide-body aircraft), permits to work with certain airlines, or simply levels of experience. All of these attributes will be included here under the heading of skills. The Capacity Planning Area's personnel estimates for each job on each shift specify the required number of workers with each skill.
4. Non-productive days worked. Workers frequently have shifts in which they do not carry out any duties, yet they are considered to have worked those shifts even though they have not contributed to satisfying personnel demand. This most commonly occurs when a worker: (a) must attend training sessions during working hours; (b) is on medical leave; or (c) is on holiday.

(c) **Employee welfare conditions**

Ground handling activities are considered to be heavy work. It is therefore in the interest of the company to incorporate certain welfare criteria into the rostering, which in concrete terms means that rosters should reflect a fair and appropriate distribution of workloads across personnel. The following objective and measurable criteria for regulating workloads were thus agreed with the company's Human Resources Area:

1. Rolling week. In any seven-day sequence there must be at least 2 days off, not necessarily consecutive. By contrast, the Labor Code stipulates that there must be 2 days off in each calendar week (Monday through Sunday).
2. Consecutive days off. Although as noted in the previous point, the 2 days off in any 7 days need not be consecutive, in the interest of employee welfare they must in fact be consecutive at least twice in a month.

3. Fair shift distribution. To ensure the workload is distributed across employees in the same job as fairly as possible, the number of shifts of each type (M, A, N) assigned to each employee should be similar.
4. Shift breaks. Over a series of days worked, shift rotations can only go in the forward direction. These rotations are known as shift breaks, and although permitted, are somewhat undesirable. They are shown as dashed lines in Fig. 3.
5. Special shift sequences. Certain combinations of shifts are obligatory or prohibited, mainly because of legal provisions or employment agreements.

The next section specifies in detail the mixed integer linear optimization model developed to define the monthly rosters while satisfying the various constraints just described above.

4 Mixed integer linear optimization model

As explained in the previous section, the optimization model considers personnel demand (for homogeneous workers as well as those with particular skills), their special requirements, legal considerations and operating conditions (training sessions, holidays, medical leave, etc.) and employee welfare. The objective of the model is to find a solution that minimizes understaffing (personnel shortfall) both global and in skills as well as unfair shift assignments. The formulation of the model is set out in detail in the following subsections.

(a) **Definitions and notation**

The sets, variables and parameters of the model and their notation are defined below in Tables 2, 3 and 4, respectively.

(b) **Objective function**

The objective function (1) is the weighted sum of five terms. The first term is the worst personnel shortfall ratio; the second term is the sum of the day and shift shortfalls; the third term is the sum of the day and shift skills shortfalls; the fourth term is the sum of the number of employees assigned to a day and a shift; finally, the last term represents fairness in the number of shifts assigned to each employee.

$$\begin{aligned} \min\ & \alpha_1 r + \alpha_2 \sum_{d\in D} \sum_{t\in T^{work}} l_{dt}^{pos} + \alpha_3 \sum_{d\in D} \sum_{t\in T^{work}} \sum_{s\in S} l_{sdt}^{skill} \\ & + \alpha_4 \sum_{d\in D} \sum_{t\in T_e^{work}} \sum_{e\in E} y_{edt} + \alpha_5 \sum_{e\in E} \sum_{t\in T_e^{work}} \left(u_{et}^{+} + u_{et}^{-}\right) \end{aligned} \tag{1}$$

(c) **Shift assignment and legal consideration constraints**

- Every employee must be assigned to a shift each day.

Table 2 Optimization model sets

Set	Description
E	Employees
T	Shifts
$T^{work} \subset T$	Worked shifts: morning, afternoon, night and recovery day
$T^{non-work} \subset T$	Shifts that do not contribute to the satisfaction of personnel demand (e.g., training sessions, holidays, etc.)
$T^{free} \subset T$	Off shifts
$T_e \subset T$	Shifts assignable to employee e
$T_e^{work} \subset T$	Worked shifts assignable to employee e
$T_e^{non-work} \subset T$	Non-contributing shifts assignable to employee e
D^{all}	Days
$D \subset D^{all}$	Days to be scheduled
$D^{-} \subset D^{all}$	Days of the previous month already set
$D^{saturday} \subset D^{all}$	Saturdays to be scheduled
$D^{sunday} \subset D^{all}$	Sundays to be scheduled
$D_{\mathrm{i}} \subset D^{all}$	Days in the i^{th} week of the month. The first day will always be a Monday and the last a Sunday
W_{all}	Weeks in the month
S	Skills
$E_s \subset E$	Employees with skill s

Table 3 Optimization model variables

Variable	Description
y_{edt}	Binary; equal to 1 if employee e is assigned to shift t on day d
x_{esdt}	Binary; equal to 1 if employee e is assigned to shift t to cover skill s on shift t
l_{dt}^{pos}	Shortfall in number of personnel relative to demand for day d and shift t
l_{sdt}^{skill}	Shortfall in number of personnel with skill s relative to demand for day d and shift t
r	Worst personnel shortfall ratio, defined as the shift with the lowest ratio of assigned employees to employee demand
f_{ed}	Binary; equal to 1 if employee e has day d and $d+1$ off
g_{ei}	Binary; equal to 1 if employee e has a sequence of two consecutive days off in the i^{th} week of the month
q_e	Number of shift breaks in employee e assignments over the planning period
u_{et}^{+}	Number of shifts t assigned to employee e in excess of the expected number
u_{et}^{-}	Number of shifts t assigned to employee e falling short of the expected number

$$\sum_{t \in T_e} y_{edt} = 1 \qquad e \in E, d \in D \tag{2}$$

- No employee may work more than τ_e days each week.

Table 4 Optimization model parameters

Parameter	Description
α_i	Weight of ith term in objective function
τ_e	Upper bound on number of shifts an employee e can work in a week
ρ_e	Upper bound on number of consecutive days an employee e can work
δ_{dt}^{pos}	Number of employees demanded on day d and shift t
δ_{sdt}^{skill}	Number of employees demanded with skill s on day d and shift t
ϕ_{dt}^{pos}	Upper bound on the shortfall in employees on day d and shift t
ϕ_{sdt}^{skill}	Upper bound on the shortfall in employees with skill s on day d and shift t
ω_e	Lower bound on Sundays off assigned to employee e
η_e	Lower bound on weekends off assigned to employee e
ς_e	Lower bound on sequences of two consecutive days off assigned to employee e
θ_e	Upper bound on shift breaks assigned to an employee e
μ_{et}^{+}	Upper bound on expected number of shifts t to be assigned to employee e over the planning period
μ_{et}^{-}	Lower bound on expected number of shifts t to be assigned to employee e over the planning period
M_e	Length of the rolling week of an employee e
χ_e	Upper bound on days an employee e can work in a rolling week

$$\sum_{t\in T_e^{work}\cup T_e^{non-work}} \sum_{d\in D_i} y_{edt} \leq \tau_e \quad e\in E, i\in W^{all} \tag{3}$$

- No employee may work more than ρ_e consecutive days.

$$\sum_{t\in T_e^{work}\cup T_e^{non-work}} \sum_{d=d'}^{d'+\rho_e} y_{edt} \leq \rho_e \quad e\in E, d'\in D^{all} : d' \leq |D| - \rho_e \tag{4}$$

- Every employee must have a minimum number of Sundays off in a month.

$$\sum_{d\in D^{sunday}} \sum_{t\in T^{free}} y_{edt} \geq \omega_e \quad e\in E \tag{5}$$

(d) **Operating condition constraints**

- The assigned number of employees must equal the demand for each shift and day.

$$\sum_{e\in E} y_{edt} + l_{dt}^{pos} \geq \delta_{dt}^{pos} \quad \forall d\in D, t\in T^{work} \tag{6}$$

The assigned number of employees with specific skills ($E_s \subset E$) must equal the demand for each shift and day.

$$\sum_{e \in E_s} x_{esdt} + l^{skill}_{sdt} \geq \delta^{skill}_{sdt} \quad \forall d \in D, t \in T^{work}, s \in S \tag{7}$$

- An employee can only cover one skill per assigned shift.

$$x_{esdt} \leq y_{edt} \quad \forall d \in D, t \in T^{work}_e, s \in S, e \in E_s \tag{8}$$

- A maximum personnel shortfall is set for each shift.

$$l^{pos}_{dt} \leq \phi^{pos}_{dt} \quad \forall d \in D, t \in T^{work} \tag{9}$$

- A maximum personnel shortfall is set for each skill and shift.

$$l^{skill}_{sdt} \leq \phi^{skill}_{sdt} \quad s \in S, d \in D, t \in T^{work} \tag{10}$$

- The maximum relative personnel shortfall on each shift is calculated.

$$l^{pos}_{dt} \leq \delta^{pos}_{dt} r \quad \forall d \in D, t \in T^{work} \tag{11}$$

(e) **Employee welfare conditions**

- Every employee must have a minimum number of weekends off in a month. Constraints (12), (13) and (14) identify the employee's sequences of two consecutive days off:

$$f_{ed} \leq \sum_{t \in T^{free}} y_{edt} \quad e \in E, d \in D^{all} : d \leq |D| - 1 \tag{12}$$

$$f_{ed} \leq \sum_{t \in T^{free}} y_{e(d+1)t} \quad e \in E, d \in D^{all} : d \leq |D| - 1 \tag{13}$$

$$f_{ed} + f_{e(d+1)} \leq 1 \quad e \in E, d \in D^{all} : d \leq |D| - 1 \tag{14}$$

To count the number of weeks in which employees have two consecutive days off, the variable g_{ei} is incorporated for each week i:

$$\sum_{d \in D_i} f_{ed} \geq g_{ei} \quad e \in E, i \in W^{all} \tag{15}$$

- Every employee must have at least ς_e weeks with consecutive days off.

$$\sum_{i \in W^{all}} g_{ei} \geq \varsigma_e \quad e \in E \tag{16}$$

- Of the consecutive days off in the previous item, η_e must be on weekends.

$$\sum_{d \in D^{saturday}} f_{ed} \geq \eta_e \quad e \in E \tag{17}$$

– The number of shift breaks is counted:

$$y_{edt} + y_{e(d+1)t'} \leq 1 + q_{ed} \; t, t' \in T^{work} : t \neq t', e \in E, d \in D : d \leq |D| - 1 \tag{18}$$

– The number of shift breaks is bounded:

$$\sum_{d \in D} q_{ed} \leq \theta_e \quad e \in E \tag{19}$$

– Fairness is incorporated in shift assignments through two parameters μ_{et}^{-} and μ_{et}^{+} that define a band of values for the number of shifts per employee which should ideally be assigned, and which are minimized in the objective function.

$$\sum_{d \in D} y_{edt} \geq \mu_{et}^{-} - u_{et}^{-} \quad e \in E, t \in T_e^{work} \tag{20}$$

$$\sum_{d \in D} y_{edt} \leq \mu_{et}^{+} + u_{et}^{+} \quad e \in E, t \in T_e^{work} \tag{21}$$

– An upper bound is set for the number of days worked by an employee within a window of M_e consecutive days:

$$\sum_{d=d'}^{d'+M_e-1} \sum_{t \in T_e^{work} \cup T_e^{non-work}} y_{edt} \leq \chi_e \quad e \in E, d' \in D : d' \leq |D| - M_e + 1 \tag{22}$$

(f) **Special shift sequences** Certain conditions relating to consecutive shift combinations on a roster are modeled with the help of special shift sequences. These sequences consist of two concatenated subsequences of shifts, the first one known as the prefix and the second one as the suffix. Thus, a given special sequence $p = \left(p_0, p_1, p_2, p_3, p_4\right)$may be composed of prefix$p^{-} = (p_0, p_1, p_2)$ and suffix $p^{+} = \left(p_3, p_4\right)$. Such combinations may be either obligatory or prohibited.

An obligatory sequence p represents the condition that if the sequence p^{-} occurs on an employee's roster (the prefix), then the sequence p^{+} must immediately follow (the suffix). For each obligatory sequence the model incorporates the following constraints:

$$\sum_{i=0}^{|p^{-}|-1} y_{e,d+i,p_i^{-}} \leq |p^{-}| - 1 + y_{e,d+|p^{-}|+j,p_j^{+}} \quad e \in E, d \in D, j \in \left\{0, \dots, |p^{+}| - 1\right\} : d \leq |D| - |p| \tag{23}$$

A prohibited sequence p represents the condition that if the sequence p^{-} (the prefix) occurs on an employee's roster, then the sequence p^{+} (the suffix) must *not* immediately follow. For each prohibited sequence the model incorporates the following constraints:

Table 5 Obligatory and prohibited shift combinations

p_1	p_2	Type	Description
M	R	Prohibited	Shift compatibility
A	M	Prohibited	Shift compatibility
A	R	Prohibited	Shift compatibility
N	A	Prohibited	Shift compatibility
N	M	Prohibited	Shift compatibility
N	O	Prohibited	Shift compatibility
R	O	Obligatory	Shift compatibility
NNNN	ROO	Obligatory	Employment agreement
MO	MO	Prohibited	Undesirable (planner can eliminate them)
MO	AO	Prohibited	Undesirable (planner can eliminate them)
ROO	MO	Prohibited	Undesirable (planner can eliminate them)
ROO	AO	Prohibited	Undesirable (planner can eliminate them)

$$\sum_{i=0}^{|p^-|-1} y_{e,d+i,p_i^-} + \sum_{j=0}^{|p^+|-1} y_{e,d+|p^-|+j,p_j^+} \leq |p| - 1 \quad e \in E, d \in D : d \leq |D| - |p| \tag{24}$$

Note that the constraints associated with compatibility between shifts are among the conditions incorporated into the model through special sequences. The use of these sequences facilitates the shift planner's task of incorporating new conditions without changing anything else in the model. Most of the constraints incorporated in this manner are listed in Table 5.

(g) **Execution, planning horizon and border conditions**

The presented model should be executed for each job separately, as except for multi-job work groups there is no dependency between any pair of jobs.

The order in which the jobs are executed follows a logic that was motivated by the fact that one of the original problems of the company was to find the best way to operate some shifts with less personnel than what was asked (personnel shortfall), which is acceptable until certain threshold or minimum staffing, but under which the problem becomes infeasible (refer to the description of the feasibility problem in next section).

Then, to reduce the possible effects of understaffing, the problem was split by treating the different jobs sequentially, solving the rostering model first for the critical and leadership job. For example, a group leader, who oversees the flight group (as the example shown in Figure 2), is a critical job, therefore a shortfall for that job is in fact not possible. Different is the case of a handler that works together with other two workers in the same flight group, having more slack to react if a shortfall is observed. As these more restricted jobs are assigned first, we could decide to upgrade personnel from less restricted jobs to more restricted ones in specific shifts, choosing workers with the required skills to cover the potential shortfalls according to the required capacity in these jobs with no slack.

Regarding the treatment of work groups, as discussed above in the description of the operating conditions, these groups are predefined so to the extent possible the group members must be assigned together. To address this issue, first the leader job is solved, and then when solving the other jobs, for each employee e in a work group the variable y_{edt} is set to 1 if the leader has also been assigned to this shift.

To achieve good results, adequate border conditions must be provided to the model. When solving the model, the planning horizons used for any given month include two extra weeks: one week before and one week after the analyzed month. The set D^{-} represents the group of days already set before the current month and their corresponding variables are fixed as a border condition. The extra week after the month is used to avoid myopic solutions that could make it difficult to get the solution on future scenarios.

5 Implementation and results

This section presents the results of the operator's implementation of the rostering model developed in the previous section. We begin as in a case study by making direct comparisons between the solutions generated by the model and those drawn up manually by company planners, thus revealing the model's ability to generate benefits. This is followed by a description of the implementation at the airport and the computational difficulties that were encountered. Finally, we discuss the qualitative impact of the implementation on the complete roster generation process in the personnel department and other related departments of the company.

5.1 Case study: comparison with previous manual scheduling

Three factors shaped the before-and-after performance analysis carried out to compare the roster solutions generated by the model with those drawn up under the previous manual techniques.

i. The operating conditions at the airport change considerably from month to month, so comparisons based on consecutive months, or even the same month in different years, may not constitute a valid test. As a result, we compared indicators relating to the manual and model-generated solutions for the same month.
ii. The company's rostering is subject to frequent revisions and last-minute adjustments, any of which may impact one or more performance indicators. We therefore compared the model-generated roster to the initial manual roster drawn up before any revisions or adjustments were made.

Table 6 Comparison of manual and model-generated schedules

KPI (April 2013)	Manual	Model
(1) % of non-compliant schedules	3%	0%
(2) Special request satisfaction	84%	> 99%
(3) Average days off per employee	9.8	9.62
(4) Average % of personnel assigned daily	62.7%	64.3%
(5) Employees assigned no consecutive days off	7%	0%
(6) Fair schedules	55%	71%
(7) Employees assigned extra shifts	62%	54%
(8) Job coverage (no. of employees)		
Group leader (60)	86%	91%
Ramp handler (150)	82%	83%
Aircraft tow driver (31)	94%	98%

iii. The actual implementation of the models by the company was carried out gradually. The rosters designed during this transition period thus do not faithfully reflect the results of either the manual methods or the models.

In light of the foregoing, we inputted the data used in drawing up the last manually produced roster to our models and on that basis generated rosters for three critical jobs. These rosters were then compared to those for the corresponding manual solutions before revisions or adjustments (details in Table 6 below).

The first result of note is that unlike the manual methods, the model was able to find rosters that complied with all labor and employment agreement conditions for all personnel. Special requests (medical leave, specific shift requests, training sessions, etc.) were also covered by the model in almost every case, a considerably better result than for the manual methods. Indicators (3) and (4) in Table 6 reveal that the model generated more efficient personnel assignments. The reduction in days off was compensated by assignments that ensured every worker's 2 days off per 7 day sequence were consecutive at least once a month. An employee is considered to have a fair schedule if the number of shifts of each type t falls inside the interval $[\mu_{et}^{-}, \mu_{et}^{+}]$. Indicator (6) in Table 6 shows that the model increased the percentage of employees with only fair shifts obtained under the manual system by 16 percentage points.

Turning to operating indicators, the model cut the number of extra shifts that had to be assigned by 8 percentage points, an improvement whose impact was all the more significant given that most of the reduction was felt on Sundays when days off are most appreciated. As regards job coverage (i.e., demand versus assigned), with the model the percentage increased for all three job categories tested. This result was particularly notable in the case of ramp agents given that wherever possible they must be scheduled for the same shifts as their crew chiefs, thus considerably reducing their shift assignment flexibility.

In general terms, then, the model improved significantly on the results of the manual methods. In what follows we discuss the implementation of the model and some results obtained during the first months of its application.

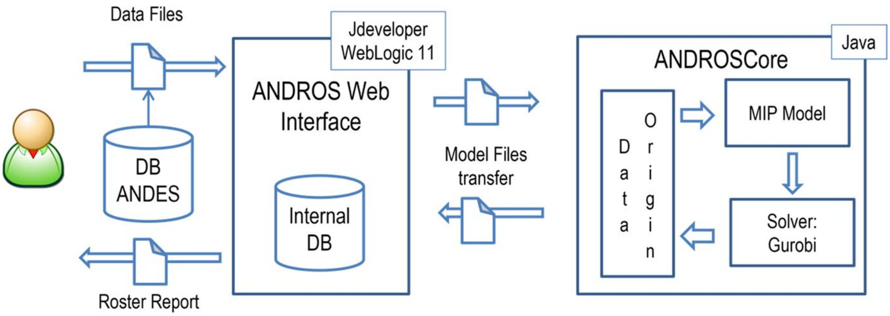

Fig. 4 ANDROS platform architecture

5.2 Implementation

The model went into operation in December 2014 as part of the ANDROS web platform, the support system for ground handling planning and management decisions installed by the company that links the various personnel services (human resources, operations, planning, etc.). Any additional requirements or constraints can be coded and introduced into the platform by the planners (see Fig. 4).

The construction of the rosters is executed by the AndrosCore subsystem. Developed in Java, its principal components are Data Origin, which processes and validates the input parameters; MIPMODEL, where the models are implemented in GLPK; and the Gurobi® optimization solver. The decision to implement the models separately from the solver was made by the company. In the original setup, AndroSCore was installed on an Intel i7-3770 K 3.5 GHz processor with 16 GB of RAM.

A flowchart illustrating the AndrosCore rostering procedure is presented in Fig. 5. For each job the procedure starts by reading the related data (staffing level, demand, requests, etc.) and then retrieves the personnel requirements according to shift start time, which are therefore grouped at this stage by shift type (M, A, N). For employees with special requests (vacations, courses, medical leaves, etc.) their corresponding shifts are preset. Next, the procedure reads the optimization parameters (solver time limit, optimality gap target and objective function weights) that have been parameterized for each job. Before solving the model, a *relaxed feasibility* version is built and used to determine whether or not a feasible solution exists (see

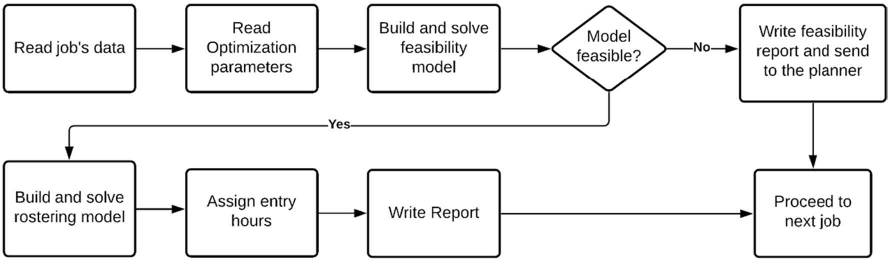

Fig. 5 AndrosCore rostering procedure

Feasibility Model next). If a feasible solution does not exist, a report on possible problems is generated to support the planner's ultimate decision and the procedure moves on to the next job (see under next heading). If, on the other hand, there is a solution, the model is executed, an algorithm assigns the shift start time and the procedure concludes on the job with the generation of a report.

The order in which the different jobs are executed in the AndrosCore rostering procedure in Fig. 5 is explained in previous Sect. 4 part g) where the details of the execution of the model are highlighted.

5.3 Feasibility model

In cases where no feasible solution exists it may be difficult to identify the reasons, especially if the cause is the interaction of two or more constraints. To facilitate the planner's task, a modified version of the model checks each constraint individually and every combination known to produce frequent conflicts, and delivers a report on the findings. The usual conditions that can lead to an infeasible model are:

(a) Previous month border conditions, infeasibilities occur when a preset shift conflicts with the last week of the previous month.
(b) Preset shifts, corresponding to special shifts requests are the most common source of infeasibilities. It can be because a conflicting request (e.g., an employee with a course set that also received a medical leave for the same period) or because a request leaves a shift without enough staff to operate.
(c) Workgroup assignments, similar to case b) regarding preset shifts, employees that belong to a workgroup are preassigned to the same shifts that their group leader; if such assignment is not possible (by a special shift request for example) the model would become infeasible.
(d) Minimum staffing and skills requirements, shown by constraints (9)-(11). While these are a very common reason for infeasibility, they result normally as a consequence of other conflicts. Therefore, we check this condition last.

The first step is to search for an initial feasible solution of the complete problem. If the problem fails to find such a solution, then for each of the previous conditions a unique feasibility model is solved. This model consists of relaxing the problematic constraint by adding a slack variable to it and minimizing the sum of all slack variables.

To identify all infeasible conditions, first the relaxed model is solved for each set of problematic constraints independently. If none of these problems lead to an infeasible solution in the relaxed model, then the cause must be in the interaction of two or more constraints. In that case, new models are built, systematically testing for conditions in pairs (ex.: special shift requests plus workgroups). Finally, all positive slack variables are reported to the planner so he/she can address the problem as needed.

5.4 Optimization parameters

The following parameters are defined to reflect the criticality of each job and its computational complexity: (1) weights on the objective function terms ($\alpha_1, \alpha_2, \alpha_3, \alpha_4, \alpha_5$), calibrated by experimentation in accordance with each job's rostering considerations; (2) the solver time limit T_L, which varies between 300 s for simple cases and four hours for more complex and/or critical ones; (3) the optimality gap target, defined initially as 0.05 for all cases. Note that finding an optimal solution is not a priority given that the rosters will be tweaked manually before being published in final form in order to accommodate last-minute changes.

To estimate a job's computational complexity, two factors were taken into account: the staffing level and the ratio of shift supply to shift demand (both in number of shifts), denoted u. The first factor is obtained by multiplying the staffing level by the number of shifts hired (e.g., 20 employees by 5 weekdays) and then subtracting holidays, medical leave and training sessions. The result is the upper bound on the coverage that can be achieved.

A real example of the results of a model run for 18 jobs is summarized in Table 7. As regards the column headings, "supply" indicates the number of shifts available if all personnel were available; "H.L.T." is the sum of holidays, medical leave and training sessions; "net supply" is the difference between the two; and u is the upper bound on coverage.

The "Time" column presents time in seconds needed to reach the target gap and those marked by an asterisk (*) are the cases where the time limit T_L was reached before getting the target gap.

An interesting result revealed in this table is that even for cases where $u < 1$, the coverage level is still very close to that upper limit. As observed in the Table 7, the main factor that is preponderant in adding complexity to the solution of the model is the understaffing; the less employees are present in a shift, the more difficult the model becomes to be solved, in both time and quality of solution. The second factor that is observed relevant in increasing the complexity of the solution of the model is the number of employees of the job, which means that the model applied to jobs with a larger volume of manpower requires more computational time to obtain a good-quality integer solution than other jobs with just few employees required. Note that in some instances the actual coverage reaches the upper bound on coverage, in which case the model can be stopped early even though the gap obtained is not good enough (e.g., shift leader). Overall, the model obtains consistently good coverages given the observed availability of employees in most of the real instances.

Once the optimization of the rosters is complete, the results may be outputted in the form of a spreadsheet for consultation and possible tweaking by planners and distributed to other company areas and departments. This report will also include all of the operating and welfare indicators. An example of such output is given in Fig. 6.

In the report shown in the figure, the description in A) identifies the name of the job, its code, date and number of employees to be scheduled. Below left in sector A) a detail in the rows of the IDs and names of the employees is also deployed. Section C) describes the different shifts assigned to each employee over the entire

Table 7 Model run results for 18 jobs, February 2015

Job title	Staff level	Demand	Supply	H.L.T	Net supply	*u* (Supp/Dem)	Time (s)	GAP	Coverage
Baggage counter monitor	5	91	100	14	86	0.95	1800*	0.15	0.86
Baggage handler	143	2373	2860	153	2707	1.14	3600*	0.06	1.00
Baggage yard supervisor	6	91	120	0	120	1.32	300*	0.09	1.00
Cargo loader	24	448	480	30	450	1.00	3600*	0.20	0.98
Carrousel leader	20	343	400	79	321	0.94	600	0.02	0.91
Conveyor operator	78	1134	1560	81	1479	1.30	300	0.02	1.00
Group leader	68	1246	1360	210	1150	0.92	3572	0.04	0.91
Handler	146	3045	2920	200	2720	0.89	10,801*	0.18	0.85
Internal transport driver	12	182	240	30	210	1.15	600	0.06	1.00
Marshaller	7	91	140	29	111	1.22	1800	0.03	1.00
Operations Control Center	15	238	300	10	290	1.22	60	0.07	1.00
Shift leader	12	238	240	54	186	0.78	600*	0.49	0.77
Tow driver	31	546	620	116	504	0.92	2171	0.06	0.92
Tractor driver (baggage yard)	34	546	680	76	604	1.11	1800*	0.05	1.00
Tractor Driver (Cargo)	26	357	520	80	440	1.23	1793	0.03	1.00
Tractor driver (ramp)	69	1183	1380	224	1156	0.98	2157	0.05	0.97
Tractor Driver (ULD)	7	147	140	30	110	0.75	150	0.03	0.74
Water tank truck driver	13	294	260	24	236	0.80	1047	0.00	0.80

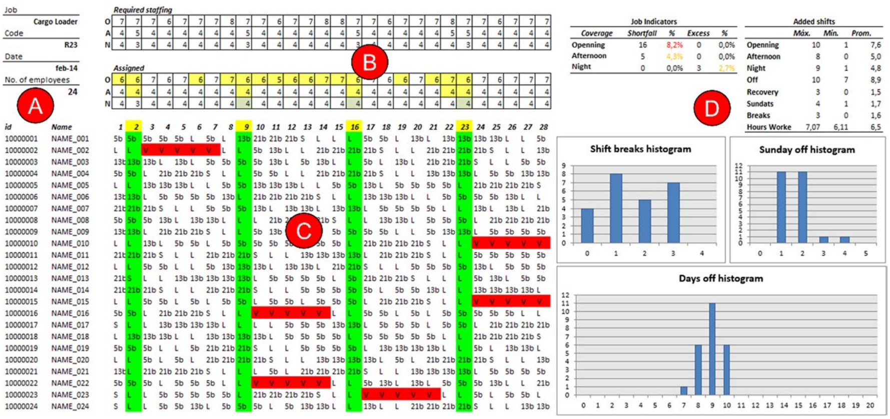

Fig. 6 Example of complete rostering report outputted by model

month for this job. How the model responds to a job staffing shortfall is illustrated in sector B) of the spreadsheet: the upper table shows the required staffing for the three shifts (Morning, Afternoon and Night) and the assignment of the model is in the lower table. In this instance, the quantity of scheduled H.L.T. implies a maximum coverage of $u = 1.0$ but the model does not attain that level. It does, however, equalize absences in order that no shift be left uncovered. The fact that all night shifts are covered is due to a constraint applied to that job. Sector D) of the report

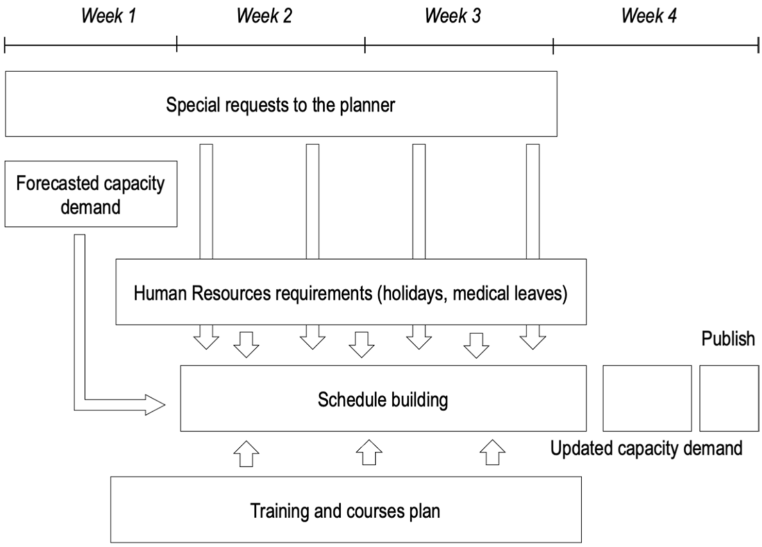

Fig. 7 Ground handling personnel planning and rostering process before implementation of ANDROS

shows global as well as specific indicators of the roster: coverage, detail of shifts, shift breaks, Sundays off, days off.

5.5 Impact on company rostering process

Upon implementing the ANDROS system, the company had to conduct a review of its rostering process and all of the agents involved in it. A flowchart of the process before implementation is given in Fig. 7. As can be seen, the process lasts four weeks and is fed by four inputs. The main input is the personnel demand estimates for each job drawn up by the Capacity Planning Area based on the airlines' flight schedules and historical data. The planners then use this information to construct the rosters, starting with those that show the least variance. Meanwhile, other company areas have until the third week to submit any special requests, which are incorporated into the rosters as they are received. In the fourth week, the Capacity Planning Area finalizes the requests, leaving a few days for the planners to review the rosters and publish the definitive versions.

To arrive at a satisfactory implementation of ANDROS, all human resource and training staff had to shorten the deadlines for submitting new personnel requests. Since the roster construction period was curtailed, the time allowed for estimating personnel demand was extended, particularly for the more complex jobs, so the predictions would be as accurate as possible. Although under these arrangements the planners have less than two weeks to put together the rosters, the real execution time for the models is about 48 h, leaving the remaining days for reviewing the results, resolving schedule conflicts and identifying possible data errors. In the end this proved to flexibilize the whole process, leaving enough time to make any manual

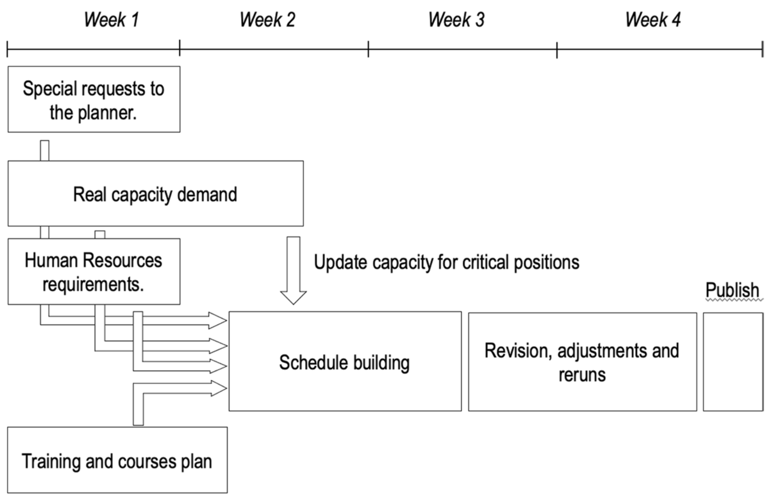

Fig. 8 Ground handling personnel planning and rostering process after implementation of ANDROS

changes that might be required to deal with contingencies. The new set of procedures is flowcharted in Fig. 8.

6 Discussion and conclusions

Ground operations are a key set of tasks in the proper functioning of a large airport. Given the relatively high cost of qualified personnel and the growing use of sophisticated technology, ground operation personnel planning must be carried out in a rigorous and efficient manner. The specialized qualifications required by ground crews mean that understaffing is always a potential problem, so minimizing understaffing is a central objective. In addition, there are a series of conditions and restrictions that must be met, some of which are legal or operational in nature while others relate to worker welfare or quality of life and in many cases are enshrined in employment contracts.

This study presented a mixed integer linear programming model to design shift rosters for heterogeneous ground operation workers that solve the personnel planning problem as it arises at Santiago International Airport in Chile. The model addresses employee demand per day and shift and worker welfare criteria, and allows the user to add constraints specifying obligatory and prohibited shift patterns that reflect changes over time in employment contract provisions and operating conditions. Thus, the model involves many complexities in the operation formulated and solved considering welfare, operational and human resources constraints in a flexible scheme useful for further applications.

Regarding the constraints associated with special shift sequences, the compatibility between shifts was considered in the model through special sequences, in the way it was explained in Sect. 4, subsection f). As discussed there, the use of such sequences as part of the model facilitates the planner´s task of incorporating new conditions without changing the model. Then, in case the union reaches new labor agreements with the company, the planner can add the new sequences agreed between workers and company without touching the whole structure of the model, and that is a major feature and novelty of this formulation that adds flexibility to the system.

Once gradual implementation of the model at the airport was completed in June 2013, solutions were generated for all ground operation jobs using the Gurobi® solver. The result was an improvement in job coverage averaging 3% over the solutions drawn up using the former manual methods, without any deterioration in worker welfare conditions such as fair shift assignments or the number of shift breaks. Use of the model also brought about a reduction in the amount of time devoted to roster design. It should further be noted that the solver solutions were exact without resorting to heuristics.

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Declarations

Conflict of interests The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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