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A study on the optimal aircraft location for human organ transportation activities

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Abstract

The donation-transplant network's complexity lies in the need to reconcile standardized processes and high levels of urgency and uncertainty due to organs' perishability and location. Both punctuality and reliability of air transportation service are crucial to ensure the safe outcome of the transplant. To this scope, an Integer Linear Programming (ILP) model is here proposed to determine the optimal distribution of aircraft in a given set of hubs and under the demand extracted from the Italian transplant database. This is an application of uncapacitated facility location problems, where aircraft are facilities to be located and organ transportation requests represent the demand. Two scenarios (two hubs versus three hubs) are tested under the performance point of view and over different time periods to assess the influence of variations in demand pattern and time period length on the solution.

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Keywords: human organ; aircraft allocation; air transportation; transplantation; Integer Linear Programming.

1. Introduction

The donation-transplant network is a strategic asset of the Italian Healthcare system where many players interact in real time in a scenario led by urgency, unpredictability of time and location of organs, and reliability to be

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ensured. A human organ eligible for transplantation needs to be brought, in the shortest possible time, to the transplant centre where the recipient is. Therefore, for long distances, transportation activities are often performed by air, with road transportation segments between the airports and the healthcare facilities involved.

As reported in Mantecchini et al. (2016), the Italian regulatory framework for transportation of organs, patients, and medical teams (2015) enables the Regions to handle organ (and patient) shipping activities under the provision of minimum operative requirements, in order to frame the topic of organ transportation in a homogeneous context of call for services on a national level. The Italian healthcare and transplant network is composed of 44 Transplant Centres (TCs in the followings), while each hospital equipped with an intensive care unit is a potential Donor Centre (DCs in the followings). In the same context, the national territory is split into macro-areas and regional areas. Transplant operations take place within the same area (approximately 65% of the total, see data in column “Transplant from death donor” in Table 1) or between two different areas (both within Italy or from/to a foreign country), according to the data supplied by the Italian Transplantation Centre (Centro Nazionale Trapianti, CNT in the followings). Table 1 below shows the figures of organ transplantation activities in year 2016.

Table 1. Transplant activity in Italy in 2016 (Source: CNT, 2016).

	N° donors employed	Transplants from death donor	Kidney	Liver	Heart	Lung	Pancreas
National activity	1,298	3,411	1,796	1,213	266	147	67
Extra-regional activity	601	1,095	340	369	149	105	26

The urgency of transplantation activities depends on the Cold Ischemia Time (CIT in the followings) which starts from the picking up of the organ from the donor’s body and ends when the organ is transplanted. Within this time – which ranges from 5 hours for heart to up to 36 hours for kidney (source: CNT) – the organ is perfused and shipped from origin (DCs) to destination (TCs), where the transplant takes place. Mishandling of organs as well as violation of CIT rule affect inversely the chances of a successful transplantation and healthy follow-up of the patient, as stated – among others - in Banner et al. (2008) and Uehlinger et al. (2010). Kidney and liver transplantation activities take often place within the same area, whereas organs with shorter CIT are treated on the basis of transplantation urgency programs at the national level. In addition, waitlists for kidney and liver are much longer than those of the other organs (see Table 2 below); thus, there is a higher possibility to find internally a match donor-receiver. Preliminary data from 2017 highlight a relevant increase in the clinical assessment of potential donors which would hopefully result in a reduction of patient waitlist (source: Author elaboration from CNT data).

Table 2. Waitlist and average permanency in waitlist for each organ (source: CNT, 2016)

Year	People in waitlist				Average permanency in waitlist (years)			
	Heart	Liver	Lung	Kidney	Heart	Liver	Lung	Kidney
2010	711	1,171	343	6,686	2.36	2.04	1.86	3.01
2015	697	1,016	375	6,945	2.80	2.00	2.30	3.10
2016	748	1,030	348	6,793	3.10	1.50	2.40	3.10

The design of the network (DCs, TCs, transportation alternatives and the location of nodes – i.e. airports and high-speed railway stations - within the network), the continuous monitoring of transportation data on extra-regional base and the optimization of performances are key aspects to be assessed and evaluated to efficiently model the logistic chain. A large share of CIT is spent during transportation phases, as shown in Mantecchini et al. (2017) for the Italian case-study. Around 58% of extra-regional organ transportation events took place by air, 66% of which “accompanied by medical team", with the remaining 34% “unaccompanied". The transportation alternative chosen depends on the distance to be covered and the CIT: for these reasons, heart and lung travel by air - respectively - in the 75% and 66% of the cases; finally, the shorter the CIT, the more frequently the organs travel “accompanied by medical team” (100% for heart and lung, less than 10% for kidney shipped by air). The main airport nodes – where a larger share of organs is handled – are Rome Ciampino (CIA), Palermo (PMO) and Milan Linate (LIN), which is obviously related to the location of the main TCs of the national healthcare system (see Figure 1 below).

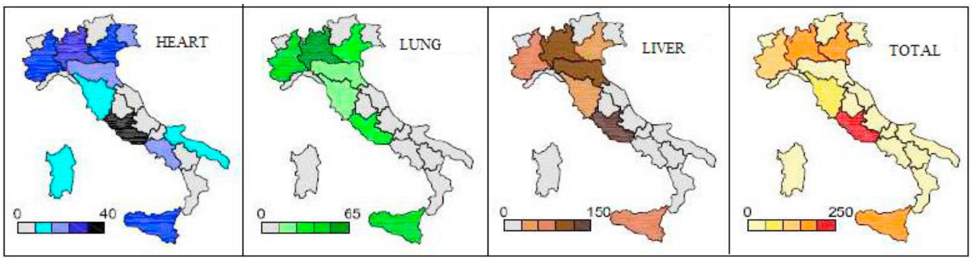

Fig. 1. Heatmap of organ destination 2015-2016. All kind of organ, air transportation.

In this work, we evaluate the opportunity of shifting from regional to national management of organ transportation activities by air, highlighting the connected potential benefits and drawbacks. In particular, the number and location of bases (hubs) and the number of aircraft to be based at each hub are taken into account. The hub location is solved a-priori since both Italian airport network and TCs' locations are known; therefore, the chosen airport hubs will be those attracting the larger number of organs on the basis of the Italian transplant database. Subsequently, the problem of determining the optimal number and allocation of aircraft at each hub is solved by means of an Integer Linear Programming (ILP) model. This problem falls in the category of Uncapacitated Facility Location Problem (UFLP) (see Laporte et al., 2015). In our context, the objective function minimizes a combination of the travelled distance and the number of aircraft (see Section 4.3). This problem has some peculiarities if compared to other UFLPs in scientific literature: indeed, more than one aircraft can be located in the same hub, and incompatibility restrictions must be respected for organ transportation requests that overlap in time. The basic hypothesis are:

- demand is given on input from the Italian transplant database which provides information on organ type, the nodes of transportation (where the organ and the receiver are) and the relevant times of the transportation chain;
- only air transportation events within Italy have been considered;
- air transportation events have been modelled as if they had been operated by a private contractor[*];
- en-route distances and flight times are known for each O/D pair with reference to a typical business jet for medical transportation services, such as the Bombardier Learjet 45
- the start and end times of aircraft occupation are computed for each event and each airport hub, based on the requirements provided by law (see Section 4.1);
- data have been pre-processed in order to filter out events which occur very rarely; in particular we neglect simultaneous requests when the corresponding peak occurred only in less than 5% of the total set of events; the request(s) eventually filtered out would be diverted to on-call providers such as military or scheduled commercial flights (see Section 4.2);
- model solutions will be evaluated on the basis of number of required aircraft (N_A), Total Distance covered (TD), Distance covered on Ferry flights (FD), aircraft Occupancy Time (OT), percentage of aircraft Occupancy Time (%OT), and finally CO_2 polluting emission based on the methodology issued by U.S. Energy Information Association and ICAO Aircraft Engine Emissions Databank (ICAO, 2017) (see: https://www.eia.gov).

2. The Italian context of transportation of organ, medical teams and patient for transplantation activities

The Italian transplantation network is made of DCs and TCs and a series of coordination and operational bodies,

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[*] This is true for accompanied organs, while un-accompanied organs - thanks to longer CIT – actually are mainly flown on scheduled flights; finally, eventually, also military flights are allowed to ship organs.

with a pyramidal structure of management and information chain going both bottom-to-top and top-to-bottom. Each level has primary duties and tasks to pursue in order to keep and improve the performance of the system as a whole.

The coordination of explant and transplant activities at the national level is carried out by the CNT, in close cooperation with the Permanent Technical Board – which develops nation-wide guidelines - and the Operational CNT (CNTO in the followings) which is in charge of the organ allocation with regard to waitlist, real time emergencies, exchanges of organs (i.e. compensation) between the three macro-regions and with foreign countries. The local coordination level collects and reports information about potential donors and promotes awareness campaigns on transplantation topics. The Regional level manages the regional waitlists, coordinates organ picking and reanimation activities and carries out organ and donor assessment. The excess of organs between macro-regions is handled by the Interregional coordination level in cooperation with CNTO.

The following activities take place between the organ availability notice and the transplant: after the death has been assessed according to the Ministerial Decrees n° 578/1993 and 582/1994, the data of the potential donor are transmitted and tests are carried out in order to run the matching organ-receiver on the basis of compatibility and either regional waitlists or national emergency program. In case of a no-match within the region, the organ is put at CNTO's disposal. Then, the transportation is organized; the difference between "accompanied" and "un-accompanied" air transportation trips is analysed in Section 4.1. If the organ assessment fails, the organ is discarded, otherwise it is eligible for transplant. The transplant takes between 2 and 15 hours, depending on the complexity of the surgery.

Other relevant policy documents on transplantation topics are national Guidelines and Technical Annex on storage units, aircraft, providers, cabin crews, and stretched patients (charged to regions since 2016), as well as EU Regulation and Directive on standards for organ transplantation activities which are described in Mantecchini et al. (2017). National policy is aligned with the latest reform of call for special services within the EU. According to the Technical Annex, air transportation providers must guarantee early availability of the aircraft at the departure node (within 120 min from the notification), 365/24/7 operation irrespectively of adverse weather conditions, and aircraft equipped to allocate safely and monitor organ storage units during the flight. In this framework, a national management of organ transportation requests, as suggested by this work, would increase the system's safety and responsiveness by means of a careful assessment of transportation solutions and aircraft location.

3. Literature review

Healthcare Facility Location (HCFL) has received a large attention in the scientific literature, as poorly located or over/under dimensioned facilities affect customer perception as well as costs. Ahmadi-Javid et al. (2017) split non-emergency from emergency location management, then introduce a categorization according to ten descriptive dimensions such as uncertainty, multi-period setting, particular input/setting, objective function, decision variables, constraints, basic discrete location problem, mathematical modelling approach, solution method, and case study inclusion. Daskin and Dean (2004) classified HCFL models into accessibility (maximizing coverage or minimizing distance), adaptability (modelling resiliency to different scenarios) and availability (modelling the supply of services in shortage capacity scenarios) models. In general terms, two groups of facility location problems exist:

- covering-based problems: set covering problems (demand originates within a specified travel/time distance from the servers and either the number of servers or the total location cost is minimized), maximal covering problems (the solution maximizes the demand covered within a specified distance), and p-center problems (travel/time distance between demand origins and the servers is minimized);
- median-based problems, which minimize the weighted average distance costs between demand and servers: p-median location problems locate facilities minimizing the total demand weighted travel distance/time. Constraints impose that each request is assigned to only one facility, the number of facilities is limited, and assignments are restricted to open facilities only. In addition, fixed charge facility location problems attempt to minimize the total cost of facility opening and travel times.

According to Daskin and Dean (2004)'s classification, our work falls in the first category.

Location-allocation models on transplantation logistic topics have been applied to investigate optimal hospitals and TCs location, organ allocation, and transportation modes. Recent works include the design of robust health service networks proposed by Zarrinpoor et al. (2018) and the minimization of the total costs incurred by the National Health Service for transplantation proposed by Caruso and Daniele (2018) who modelled the following cost items as a function of the numericity of operations carried out: transportation costs of the medical teams, organ removal costs at each DC, organ transportation costs, the costs incurred at TCs, and the costs for special waste disposal of discarded organs at both DCs and TCs. Consolidated contributions on TCs location have been proposed by Daskin & Dean (2004), Kong et al (2010), Belien et al. (2013) and Zahiri et al. (2014, a). The first two works pursue the optimal location of TCs, DCs and organ procurement organizations, either giving for granted or re-designing the infrastructure network. The last one is a fuzzy model for a long-term dynamic location-allocation to minimize the total costs, further extended by Zahiri et al. (2014, b) to include alternative transportation modes as well as uncertainty in demand and supply in a multi-objective location-queuing model. The methodology proposed by Belien et al. (2013) is applied to Belgium and pursues the minimization of the sum of the weighted time components of the transportation chain under limited budget. CIT limits the maximum allowed travel time and TCs are open on the basis of demand and number of beds available; if a TC is closed, its demand is shifted to the immediate closest alternate compliant with the CIT constraint, whereas this might result in longer displacement for patients. The result is the optimal combination of TCs to be opened for each organ, given the demand and supply as well as the travel times between DCs and TCs pairs and from/to airports. The opening of a TC reduces travel time and allows a better covering of the territory; on the other hand, increased costs and responsiveness are expected.

The effectiveness of organ allocation and matching algorithms has been the research focus of Bruni et al. (2006), Rogrilie and Shi (2007), Alagoz et al. (2009) and Rais et al. (2011) on parameters such as blood compatibility, region, age, urgency, waitlist and territorial extent analysed.

Our work has a different focus, since DCs, TCs and transportation nodes' location are given, and the goal to pursue is aircraft allocation with the aim of minimizing the distance covered as well as the number of aircraft. In this phase, the costs of opening and keeping an aircraft base (take-off/landing taxes, reservation of parking slots on the airport's airside, fuelling, personnel, and maintenance) have not been taken explicitly into consideration as they differ with regard to airport, fleet composition and size. In addition, our study has been carried out from the point of view of the coordinator of the transplantation logistic chain and not from the transportation service providers'.

4. Methodology

Prior to going through the structure of the ILP model proposed, a short description of the Italian transplant database and of the set of data to run the model is needed. The database structure has been jointly developed by the authors and the Italian CNTO and is thoroughly described in Mantecchini et al. (2016). In the time period taken into consideration in this study (one year, from June 2015 to May 2016), 505 donors for a total of 868 organs have been counted for extra-regional transplantation activities; then requests involving either a foreign country or road transportation have been discarded. Thus, the population is 262 donors, 351 transportation requests by air and 476 organs (1 donor can generate more than 1 transportation request which in turn can supply more than 1 organ at a time). To our tasks, origin and destination, route choice, transportation nodes and relevant time instants are enumerated, such as:

- date/time of notification;
- date/time of arrival of the medical team to the airport appointed for the DC ("DC airport" for conciseness);
- date/time of picking end;
- date/time of take-off from the same airport;
- date/time of landing to the airport appointed for the TC ("TC airport" for conciseness);
- date/time of transplant start.

4.1. Computation of aircraft occupancy time

The computation of aircraft occupancy time for each request introduces the existence of overlapping transportation requests, which will be dealt with by the model and explained in the sub-Section 4.2. According to the Technical Annex to Italian Guidelines, the contractor must comply in due time with the aircraft requests made by either the CNTO or the Region involved.

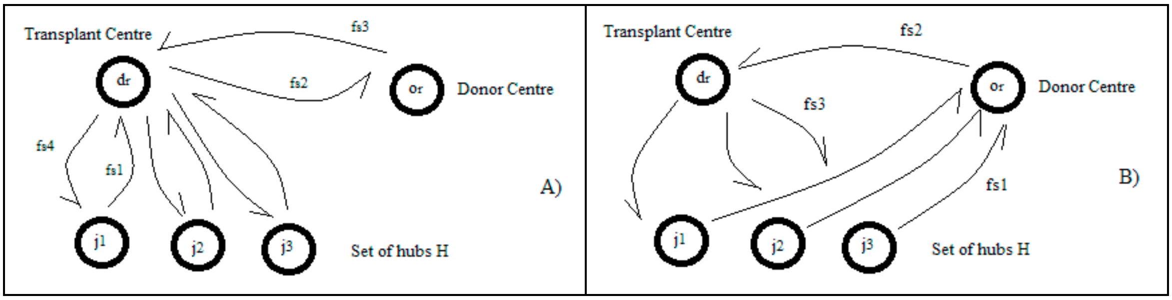

Fig. 2. Flight segments (fs) involved for (A) “accompanied”; (B) “un-accompanied” transportation events (Source: Authors).

With reference to Fig. 2 above, a short description of each Flight Segment (FS) of the transportation chain is here provided. If an “accompanied” organ is involved (Fig. 2A), the aircraft travels from the contractor’s hub (which we label *j*) to the TC airport to collect the medical team (FS1 - ferry flight), then to the DC airport (FS2) and backwards (FS3) with the organ and then again to the contractor’s hub *j* (FS4 - ferry flight). The aircraft status “occupied” is computed from the landing time of FS2 brought backwards by an amount of time equal to FS2’s flight time and 120 min (time foreseen by the Technical Annex to comply with the aircraft request) during which FS1 must be performed. If an “un-accompanied” organ is involved (Fig. 2B), FS1 is a ferry flight linking the hub airport *j* to the DC airport, FS2 ships the organ from the DC to the TC airport and FS3 is a ferry flight from the TC airport to the hub *j*. In this context, the aircraft status “occupied” starts 120 min before the take-off time from the DC airport. In both cases, as FS1 has to be performed “within 120 min from the notification” and the time needed to cover even the maximum O/D distance within the Italian airspace is less than 120 min, we can assume that the aircraft status “occupied” is irrespective from the hub choice. After the organ transportation chain has been performed, the aircraft status is turned to “available” at a time instant equal to the take-off time from the TC airport plus the flight time needed to perform either FS4 in Fig. 2A or FS3 in Fig. 2B. Thus, this time instant is “hub-dependent”.

4.2. Data pre-processing and filtering-out of peak demand

Two transportation requests at a given hub, where the “occupied” status of the latter lies between the “occupied” and “available” status of the former are defined as “overlapping”. Overlapping transportation requests within the set have been numbered-out by means of a frequency distribution and ranked according to the following criteria in order to filter-out peaks of overlapping requests that occur very rarely:

- requests from/to either Sicily or Sardinia are given priority, as air transportation is likely the only one compliant with the CIT;
- air transportation priority is given to organs with short CIT;
- in case of further uncertainty, air transportation priority is given to long-range displacements.

According to these criteria, 11 requests are neglected as part of a restricted panel with more than 4 overlapping requests (which make up around 3% out of the 351 requests) and are considered as diverted to either road, high speed train, military flights, commercial flights, helicopter.

The O/D distance and flight time between all airport pairs have been computed with reference to a LJ45 aircraft by means of the freeware tool Greatcirclemapper (see www.greatirclemapper.net) for both the scenarios with two hubs (Rome CIA and Milan LIN) and three hubs (by adding Palermo PMO). CIA – LIN – PMO are the IATA callsigns of the three airports taken into consideration (see Fig. 3 below). Flight times for each O/D pair have been increased of 5 min at each airport to compute taxi-in/out time (the value has been increased to 10 min at Rome Fiumicino and Milan Malpensa to account for the complexity of the airside).

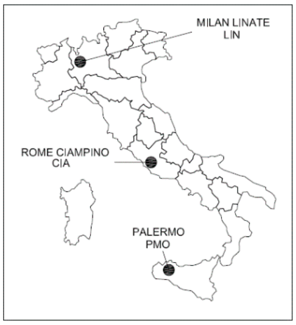

Fig. 3. Set of airport hubs chosen (Source: Authors).

4.3. Model formulation

We call H the given set of hubs, A the set of aircraft, and R the set of human organ transportation requests. Each request $r \in R$ is characterized by its origin o_r (DCs) and its destination d_r (TCs). Each request must be performed by an aircraft located at a hub. $H_r \subseteq H$ is the subset of hubs that can serve request $r \in R$. We call s_{rj} the start time and e_{rj} the end time of request r if using an aircraft based in j ($r \in R, j \in H_r$), which limit the "occupied" and "available" status of the aircraft. As mentioned in Section 4.1, in the Italian case s_{rj} is not dependent from the hub choice j but the index is here shown in order to keep the generality of the model. Two transportation requests r, r' overlap in time if served from hub $j \in H_r \cap H_{r'}$ if $e_{rj} > s_{r'j}$ and $s_{rj} < e_{r'j}$; thus, they must be served by different aircraft. Let L_j be the set of pairs of requests that overlap if served from hub $j \in H$. Finally, we let c_{rj} be the distance travelled by an aircraft serving a request r from the hub j ($r \in R, j \in H_r$).

The following binary variables are introduced (7): y_{ij} assuming value 1 if aircraft $i \in A$ is based at hub $j \in H$ (0 otherwise); x_{ri} assuming value 1 if request $r \in R$ is served by aircraft $i \in A$ (0 otherwise), and z_{rj} assuming value 1 if request $r \in R$ is served by an aircraft based at hub $j \in H$ (0 otherwise). The ILP model reads as follows:

$$\min \alpha \sum_{i \in A} \sum_{j \in H} y_{ij} + \sum_{r \in R} \sum_{j \in H_r} c_{rj} z_{rj} \tag{1}$$

$$\sum_{j \in H} y_{ij} \le 1 \qquad \forall i \in A \tag{2}$$

$$\sum_{i \in A} x_{ri} = 1 \qquad \forall r \in R \tag{3}$$

$$x_{ri} + x_{r'i} \le 2 - y_{ij} \qquad \forall i \in A, j \in H_r \cap H_{r'}, (r, r') \in L_j \tag{4}$$

$$x_{ri} \le \sum_{j \in H_r} y_{ij} \qquad \forall i \in A, r \in R \tag{5}$$

$$z_{rj} \ge x_{ri} + y_{ij} - 1 \qquad \forall i \in A, r \in R, j \in H_r \tag{6}$$

$$y_{ij}, x_{ri}, z_{rj} \in \{0;1\} \qquad \forall i \in A, r \in R, j \in H \tag{7}$$

The objective function (1) minimizes a weighted sum of the number of used aircraft and the total travelled distance, where α is the weight given to the first term. Constraints (2) ensure that each aircraft is located at most in one hub and constraints (3) impose that each request is executed by an aircraft (after the pre-processing and filter-out of exceeding data carried out previously). With constraints (4) we require to use different aircraft for requests that overlap in time. If the two overlapping requests shall be served by the same hub, the value given to α would steer the decision between adding a new aircraft in that hub and diverting the request to the closest hub where an aircraft with "available" status is based. Constraints (5) link the x and y variables: if a request r is served by an aircraft i, then the aircraft must be located in one of the hubs in H_r. Finally, constraints (6) link the x y z variables: if request r is served by aircraft i ($x_{ri} = 1$) and aircraft i is based at hub j ($y_{ij} = 1$), then $z_{rj} = 1$, i.e. request r is served by an aircraft based at hub j. In this way, the travelled cost is properly counted in the objective function.

5. Discussion of the Results

Model (1) - (7) has been developed in AMPL and solved by Cplex, while Python has been used to list the pairs of overlapping requests within the given time period. By multiplying the matrix of the z variable values in the optimized solution with the matrices relative to flight time and distance travelled for each request, and extending the sum to all requests, the following performance indicators are derived:

- distance travelled in ferry (positioning) flights by aircraft based at each hub (FD);
- total distance covered by aircraft based at each hub (TD);
- aircraft Occupancy Time (OT);
- percentage of occupancy time (% OT); and
- number of aircraft (N_A).

The process has been iterated for both scenarios (2 and 3-hubs) by optimizing a single month (1M), four-month periods (4M), six-month periods (6M) and the year (12M) to assess the influence of variation in demand pattern and time period length on the number of aircraft allocated to each hub. Tables 3 and 4 summarize the results.

Table 3. Results of the optimization for different time periods under a 2-hubs scenario

2-HUBS SCENARIO	CIA airport			LIN airport			OT [hours]	% OT
	TD [10^3km]	FD [10^3km]	N_A	TD [10^3km]	FD [10^3km]	N_A		
1M	279.4	110.5	3	196.4	57.1	3	2,926.1	33.31%
4M	278.1	109.4	4	193.3	53.9	2	2,918.6	33.24%
12M	277.6	109.0	4	191.9	52.4	2	2,917.0	33.21%

In Table 3 above, the results of 1M and 4M optimizations are the sum of the single contributions of the performance indicators extended to 1 year period. Data are thus made comparable to the result of 12M optimization. In Table 4 below, the results of 6M – 1st semester (6M -1) and 6M – 2nd semester (6M – 2) are presented separately to highlight the relevant traffic increase (notably at LIN and PMO airports) during the 2nd semester due to the increase in transportation demand. The sum of the two contributions is highly comparable to the result of 12M optimization, assessing the goodness of the hypothesis of stabilization of the optimized solution in the medium-to-long term.

Table 4. Results of the optimization for different time periods under a 3-hubs scenario.

3-HUBS SCENARIO	CIA airport			LIN airport			PMO airport			OT [hours]	% OT
	TD [10^3km]	FD [10^3km]	N_A	TD [10^3km]	FD [10^3km]	N_A	TD [10^3km]	FD [10^3km]	N_A		
6M - 1	64.3	19.4	2	64.0	16.2	2	51.0	15.5	2	1,207.6	27.5
6M - 2	64.1	19.7	2	113.8	29.3	1	66.5	15.6	2	1,641.2	37.4
12M	128.4	39.1	2	177.8	45.5	2	117.6	31.0	2	2,848.7	32.4

As far as computation time is concerned, all optimizations in the 3-hubs scenario require more time than in the 2-hub scenario. We observed a relevant difference on 6M optimization for 3-hubs scenario (172 sec for the 1st semester and 1,055 sec for the 2nd semester) meaning that the higher number of requests and the choice on whether to move an aircraft or use a new one has played a relevant role.

The aircraft allocation is strictly linked to the time period inspected and, thus, to the number of requests and their geographic provenience: data from 1M optimization present a huge fluctuation of the solution, which is dissipated by enlarging the time period: i.e. the worst scenario for a single month optimization foresees a total of 7 aircraft (respectively 4 and 3 aircraft in CIA and LIN airports) but at a very low %OT, which would mean a waste of resources. Indeed, 12M optimization returns an allocation providing lower values of total distance (TD) and occupancy time (OT) if compared to 1M and 4M optimizations (see Table 3). Then, during the 2nd semester, both the number of overlapping requests and multi-organ events have increased and the trend is rebated from preliminary figures of the following periods. For this reason, optimization on a time window shorter than 6 months should not be taken into consideration to design the service on a national basis.

In addition, it is worth mentioning the relevant difference in total distance (TD) between the hubs: in the 2-hubs scenario, aircraft based in CIA cover central-southern Italy and the two main islands while those based in LIN cover only the north of Italy, where a larger share of transplantation events take place. Nevertheless, the average distance flown by LIN-based aircraft is higher, given the lower number of aircraft here based (2 against 4 in CIA). The 3-hubs scenario confirms the total number of aircraft allocated, proposing an equal distribution between CIA and PMO, while LIN keeps its basin. From Table 4, we see that 6M optimization on the 2nd semester allocates only one aircraft in LIN which thus has a higher occupancy time (OT); as a consequence, one of the aircraft based in PMO airport supports on call transportation activities in the north, which is highlighted by the notable increase in total distance (TD) flown by PMO-based aircraft with respect to the 1st semester.

As a whole, from the comparison of 12M solution from Tables 3 and 4, the average distance flown by LIN-based aircraft is around 30% higher than the same value for CIA and PMO-based aircraft. The total distance (TD) is reduced from $469.6 \cdot 10^3$ km to $423.8 \cdot 10^3$ km (around -10%), which reflects in a reduction of more than 25% of distance travelled on ferry flights (FD). This is ascribable to the high number of requests towards Palermo and southern Italy's TCs which, with 2 aircraft based in PMO airport, would no longer need positioning flights from/to CIA airport. The shorter TD translates itself in a saving of around 68 hours of Occupancy Time (OT).

Finally, the *z* matrix and the matrices returning flight time and distance travelled for each request are useful to derive the information on the fuel burnt during the organ transportation activities by air and the relative CO_2 emission. Taking into consideration the fact that the aviation contribution to the total share of CO_2 pollution ascribable to transportation is deemed to increase in the next future (EEA, 2013 and ICAO, 2017) and based on manufactures' fact sheets and publication of notable institutions within air traffic industry, we assume that a fleet made of average jets such as LJ45 (Bombardier, 2009) would impact in the following terms (see Table 5 below).

Table 5. Estimate of CO2-induced pollution

	TD [10^3 km]	CO_2 emission [t]	OT [hours]	Fuel burnt [10^3 l]
2-hubs scenario	469.6	829.3	2,917.0	1,688.9
3-hubs scenario	423.8	748.4	2,848.7	1,507.0
% Reduction 3-hubs vs 2-hubs	-9.74%		-2.34%	

6. Conclusions and future development

An ILP model developed in AMPL and solved by Cplex has been proposed to optimize the allocation of aircraft devoted to organ transportation activities in Italy in a chosen set of hubs based on historic demand. This is a real-world problem arisen at the CNT in a case study inspecting the feasibility of shifting the transportation chain management at national level, to promote the establishment of a common framework and a cost-efficient usage of available resources. As transplantation activities can actually save and extend patients' life, the key aspect of the activity is not saving money but making the best use of the resources available, by investing in optimization, process re-engineering, research and informative campaigns to raise population's awareness on the topic.

The two scenarios proposed (with, respectively two and three hubs) cover transportation requests with six aircraft, amount deemed sufficient to cope with growing trends of transplantation activities' figures issued (see http://www.trapianti.salute.gov.it/cnt/cnt.jsp). Both optimized scenarios would allow reduction of resources' duplication; indeed, the current regional management seems likely to result in higher number of operating aircraft and reduced Occupancy Time, which is already quite low even by considering all events performed by contractors as proposed by this study. The allocation of aircraft among a larger number of hubs would in turn permit a reduction of total distance (TD) flown and a diminished fuel consumption and polluting emission. To summarize, an equilibrium point could be reached with a restricted number of nationwide call for services with candidate contractors encouraged to join forces and let free to decide on aircraft allocation on the territory.

To push further the scope of the research, wider time periods can be analysed and new elements introduced within the model, such as additional costs for the contractors and the possibility to serve a sequence of requests without heading back to the hub, once each request has been completed. This option would allow a reduction of ferry flight segments, provided that cabin crew shifts allow this practice. Finally, the evaluation of alternative transportation modes to optimize transportation time and costs is still a valuable research field in this context.

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