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Impact Analysis of a Flexible Air Transportation System

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The paper provides analytical evidence of the added-value of flexibility for air transportation systems. More specifically, the impact of a new innovative modular aircraft on the operations of an airline is deeply analyzed. The impact analysis is carried out with an integrated schedule planning model which presents a combination of appropriate optimization and behavioral modeling methodologies. The results show that the flexible system uses the transportation capacity more efficiently by carrying more passengers with less overall capacity. Moreover, it is observed that the flexible system deals better with insufficient transportation capacity. Furthermore, the scheduling decisions are robust to the estimated cost figures of the new system. For the analyzed range of costs, it is always carrying more passengers with less allocated capacity compared to a standard system.

Keywords: Flexible transportation, Integrated schedule planning, Itinerary choice, Modularity, Multi-modality, Spill and recapture effects.

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1. Introduction

According to the statistics provided by the Association of European Airlines (AEA), air travel traffic has grown at an average rate of 5% per year over the last three decades (AEA, 2007)[5]. Consequently, sustainability of current transportation systems is threatened by increased energy consumption and its environmental impacts. Moreover, the increased mobility needs are inducing major disruptions in operations. Regarding air transportation, there is an increased number of landings and takeoffs from airports, resulting in frequent congestion and delays. The trade-off between the sustainability of transportation and the mobility needs justifies the investigation of new concepts and new solutions that can accommodate the increased demand with a minimal impact on the environment and the economy. The building stone of such new concepts is the introduction of various aspects of flexibility in transportation systems in general, and in air transportation systems in particular.

1.1 Flexibility in transportation systems

"Flexibility" is defined as "the ability of a system to adapt to external changes, while maintaining satisfactory system performance." (Morlok and Chang, 2004). Flexibility is a key concept for the robustness of transportation systems and studies on flexible transportation systems have an increased pace during the last decade. We refer to the work of Morlok and Chang (2004) for the techniques to measure the flexibility with a focus on capacity flexibility. Similarly, Chen and Kasikitwiwat (2011) develop network capacity models for the quantitative assessment of capacity flexibility.

Flexibility is studied for different transportation systems including land, rail, ship and air transportation. Brake et al. (2007) provide examples of Flexible Transportation System (FTS) applications that aim to improve the connectivity of public transport networks in the context of land transportation. Crainic et al. (2010) work on the flexibility concept with Demand-Adaptive Systems which combine the features of traditional fixed-line services and purely on-demand systems. Errico et al. (2011) provide a review on the semi-flexible transit systems where different flexibility concepts are introduced on the service areas and the time schedule. Zeghal et al. (2011) studies flexibility for airlines in terms of the active fleet and departure time of flights. An airline can increase or decrease the fleet size renting or renting out planes. Departure times can be adjusted within a given time-window. These flexibilities facilitate the integration of schedule design, fleet assignment, and aircraft routing decisions.

The nature of flexibility already embedded in transportation systems differs considerably. For example, in rail transportation, there is a natural capacity flexibility which rises from the modularity in fleet. In maritime transportation, the usage of standard unit load facilitates a more efficient practice of multi-modality with an efficient transfer between ships, trucks and trains. In this paper we are investigating what impacts such flexibility may have in air transportation.

Rail transportation

Flexibility in rail transportation rises from modular carrying units and several operations research techniques are applied to improve this flexibility. We refer to Huisman et al. (2005) for a review on the models and techniques used in passenger railway transportation for different planning phases. Kroon et al. (2009) discuss the construction of a new timetable for Netherlands Railways which improves the robustness of the system decreasing the delays. Similarly, Jespersen-Groth et al. (2009) study the disruption management problems in passenger railway transportation drawing the analogies with airline disruption management.

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[5] The source is included as an example for year 2007 but there are yearly releases available

Maritime transportation
Multi-modality is widely studied in the context of freight transportation where standard unit loads are transferred between maritime, land and rail transportation systems. In freight transportation, each movement of a loaded vehicle generates an empty flow and for the efficient use of the transportation system these empty flows need to be taken care of. We refer to Dejax and Crainic (1987) for a review of empty vehicle flow problems and proposed models on the subject. They also point out the potential advantages of an integrated management of loaded and empty vehicle movements. In maritime transportation Crainic et al. (1993) present models for the repositioning of empty containers in the context of a land transportation system. Olivo et al. (2005) study the repositioning problem in a multi-modal network where empty containers are transported by both maritime and land transportation. Di Francesco et al. (2009) consider empty container management problem under uncertainty and present a multi-scenario formulation regarding different realizations of uncertain parameters.

Air transportation
In the context of air transportation, airlines have dedicated a lot of efforts in increasing the flexibility through demand and revenue management (Talluri and van Ryzin, 2004a). Flexibility is obtained namely from differentiated fare products offered to different customer segments with the objective to increase the total revenue. Recently, additional attention has been paid to better represent the demand through advanced demand models. Coldren et al. (2003) work on logit models for travel demand, Coldren and Koppelman (2005) extend the models of the previous work using GEV, particularly nested logit model. Koppelman et al. (2008) apply logit models to analyze the effect of schedule delay by modeling the time of day preferences. Carrier (2008) and Wen and Lai (2010) work on advance demand modeling that enable customer segmentation with the utilization of latent class choice modeling. We refer to the work of Garrow (2010) for a comprehensive presentation of different specifications of choice behavior models.

Advanced demand models are integrated into optimization models in different levels of the airline scheduling process. Talluri and van Ryzin (2004b) integrate discrete choice modeling into the single-leg, multiple-fare-class revenue management model. Authors provide characterization of optimal policies for the problem of deciding which subset of fare products to offer at each point in time under a general choice model of demand. Sch¨on (2006) develops a market-oriented integrated schedule design and fleet assignment model with integrated pricing decisions. In order to deal with the non-convexity that is brought by the pricing model, an inverse demand function is used. The final model is a mixed integer convex problem and preliminary results are provided over a synthetic data. More recently Atasoy et al. (2012) introduces an integrated scheduling, fleeting and pricing model where a demand model, which is estimated on a real data, is explicitly included in the optimization model. The explicit representation of the demand model allows for further extensions of the framework with disaggregate passenger data. They also consider spill and recapture effects based on the demand model.

In addition to revenue management, schedule planning of airlines are more and more designed to be robust to unexpected disruptions, such as aircraft breakdowns, airport closures, or bad weather conditions (Lan et al., 2006; Gao et al., 2009), and associated recovery strategies are applied after the occurrence of these disruptions (Lettovsky et al., 2000; Eggenberg et al., 2010). The application of robust schedule planning models increases the profitability of airlines introducing flexibility to adapt to unexpected disruptions. In the literature, robustness is introduced for different subproblems of airline scheduling. Rosenberger et al. (2004) study a robust fleet assignment model that reduces the hub connectivity and embeds cancellation cycles in order to decrease the sensitivity to disruptions and they obtain a better performance compared to traditional fleet assignment models. Shebalov and Klabjan (2006) work on robust crew scheduling models where they introduce robustness by maximizing the number of crew pairs that can be swapped in case of unexpected situations. Lan et al. (2006) present two approaches to minimize passenger disruptions: a robust aircraft maintenance routing problem where they aim to reduce the delay propagation and a flight schedule re-timing model where they introduce time windows for the departure times of flight legs. Similarly, Weide (2009) studies an integrated aircraft routing and crew pairing model where the departure time of flights are allowed to vary in a time window. Inclusion of time windows in the schedule is shown to increase the flexibility of the model having improved results.

As mentioned previously, in air transportation the improvements are mostly investigated through decision support systems. Although these efforts are promising it is limited to the definition of the system itself. In this paper we introduce and analyze a new way to bring flexibility into air transportation, based on the concept of a modular aircraft, called Clip-Air. The objective is to provide analytical evidences of the added-value of flexibility for air transportation systems.

1.2 A modular flexible aircraft: Clip-Air

A new family of modular aircraft, called Clip-Air, is being designed at the Ecole Polytechnique Fédérale de Lausanne (EPFL, LeonBier11). Figure 1 illustrates the new design. Clip-Air is based on two separate structures: a *flying wing*, designed to carry the engines and the flight crew, and *capsules*, designed to carry the payload (passengers and/or freight). The wing can carry one, two or three capsules with a clipping mechanism which facilitates the separate handling of capsules. This modularity is the foundation of the Clip-Air concept for flexible transportation.

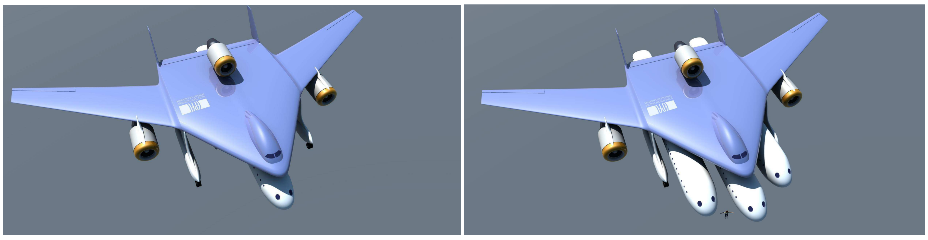

Figure 1. Clip-Air wings and capsules

The Clip-Air project started in 2010. The project is now in its second phase called “feasibility studies” which is planned to be finished in 2013. The feasibility studies involve various research groups from EPFL that work on the aerodynamic structure, the energy aspects, the tests of Clip-Air in a simulation environment etc. Our research group is interested in the impact of the flexibility of Clip-Air on transportation systems. This impact analysis is important for understanding the potential of introducing flexibility and is expected to motivate the studies on various aspects of flexibility in other transportation systems, such as railways and transit systems.

The Clip-Air project introduces a new concept in aircraft design. But its potential impact is significantly more far-reaching. Indeed, the flexibility provided by the new aircraft modifies the fundamental operations of multi-modal transportation systems.

Clip-Air broadens the flexibility with its innovative design. In the first place, the decoupling of the wing and capsules brings the modularity of railways to airline operations. This decoupling provides several advantages in terms of operations. The capacity of Clip-Air can be adjusted according to the demand by changing the number of capsules to be attached to the wing. This flexibility in transportation capacity is highly important in case of unbalanced demand between airports. As another example, Clip-Air’s modularity is expected to significantly improve the operations in hub-and-spoke networks where the itineraries connect through the hub airport. The flexibility of interchanging the capsules attached to the wings at the hub airport provides a better utilization of the capacity and simplifies the fleeting operations.

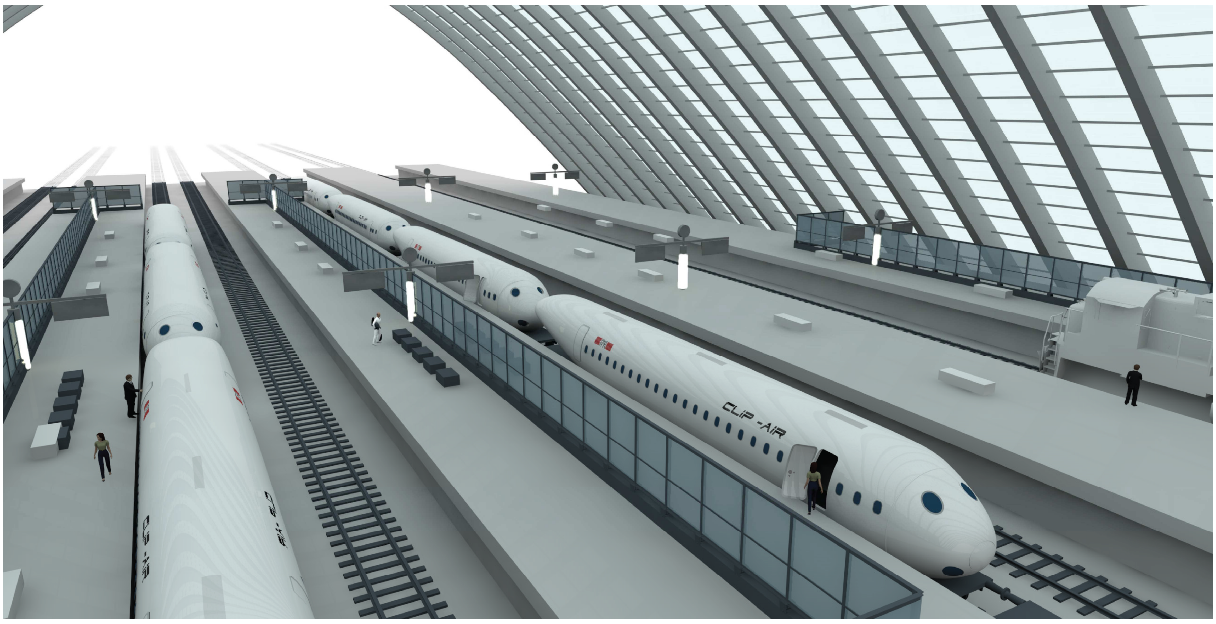

Figure 2. Demonstration of Clip-Air capsules at a railway station

Secondly, Clip-Air imports the concept of standard unit loads from freight to passenger transportation thanks to the structure of the capsules. The capsules are easy to transfer and store which facilitates their move by other means of transportation. As an illustration, in case of unbalanced demand in the flight network, the empty capsules can be transfered by railways in order to better respond to the demand in busy airports. A similar notion is also provided for passenger transportation by the design of Clip-Air. A passenger can board the capsule at a railway station (Figure 2), and the loaded capsule is attached to the wing at the airport. Such a concept brings new dimensions for multi-modal transportation. Furthermore, Clip-Air is designed for both passenger and freight transportation. A capsule containing freight can fly under the same wing with passenger capsules so that mixed passenger and freight transportation can be operated without any compromise in comfort. This flexibility enables airlines to better utilize their capacity according to the variable demand pattern they are facing. All in all, the integration of air transportation in multi-modal networks, for both passenger and freight transportation, is expected to be strengthened by the design of Clip-Air.

The Clip-Air system combines the mentioned flexibility aspects in terms of modularity and multi-modality with the efficient demand management and robust scheduling methods of airlines. Therefore, the four types of flexibility (demand management, robustness and recovery, modular capacity, and multi-modality) are brought together in an integrated transportation system.

1.3 Impact analysis of the flexibility of Clip-Air

The objective of this paper is to analyze the impact of Clip-Air's flexibility from an airline's perspective through the application of appropriate methodologies. For the concept of flexibility we focus on modularity and demand management. The design of Clip-Air has impact on many processes of air transportation. We focus on fleeting since Clip-Air's modularity alters the fleet assignment process considerably and the impact of flexibility can be directly observed through fleeting.

The fleet assignment problem has studied in the literature with several extensions. The trend in fleet assignment literature consists in the integration of supply-demand interactions into the model where the demand is treated at the itinerary level. We follow this trend in order to address the flexibility in demand management. Yan and Tseng (2002) develop a model that simultaneously decides the flight schedule and the fleet assignment with path-based demand considerations. With a similar idea of itinerary-based demand, Barnhart et al. (2002) build an integrated schedule design and fleet assignment model where they consider spill and recapture effects in case of insufficient capacity. Their model considers fare class segmentation so that passenger demand is represented separately for each fare class. Barnhart et al. (2002) build a similar model with the network effects including the demand adjustment in case of flight cancellations.

The novelty of the presented model is that it captures the modularity of Clip-Air by a simultaneous decision on the two levels of assignments: the assignment of wing to the flights and the assignment of capsules to the wing. This integrated model is combined with behavioral modeling in order to explicitly integrate supply-demand interactions. Lohatepanont and Barnhart (2004) model supply-demand interactions with demand corrections based on the Quality of Service Index. We represent the supply-demand interactions through an advance itinerary choice model which is estimated using a real dataset. The utilities of the alternative itineraries are defined by their price, departure time of the day and the number of stops. These utilities define the recapture ratios for the spilled passengers. Therefore the model has the flexibility to change the allocated capacity to the flights, including the option of canceling, by redirecting passengers whenever it is more profitable.

Beyond the analysis of Clip-Air itself, the contribution of the paper is the analysis of flexibility in transportation systems in general based on real data and through optimization models that integrate supply demand interactions. The non-trivial integration of the models proposed in the paper is used to carry out a comparative analysis between a standard and a flexible system. In return, the introduction of flexibility provides promising advantages and motivates the analysis of flexibility in other modes of transportation as well as the analysis of other flexibility notions. All conservative assumptions and the design of experiments are detailed constituting a valuable reference for flexible transportation systems to be designed in the future.

2. Integrated schedule planning

As mentioned at the end of section 1.3 we focus on the aspects of modular capacity and demand management in the context of airline operations.

Modular capacity is provided by the design of Clip-Air and we analyze the impacts of modularity on fleet assignment process. As illustrated in section 1.2 capsules can be detached from the wing. This feature generates an additional level of assignment decisions to be made in comparison to the assignment problem of standard planes. Therefore we build an integrated schedule design and fleet assignment model which enables the appropriate assignment of wing and capsules (section 2.1).

As for the demand management dimension, we integrate supply-demand interactions into the fleet assignment problem through spill and recapture effects. In case of insufficient transportation capacity the movement of spilled passengers is driven by an itinerary choice model based on the attributes of the itineraries (section 2.2).

2.1 Integrated schedule design and fleet assignment model

We present an integrated schedule design and fleet assignment model which facilitates the modularity of Clip-Air. This integrated model optimizes the schedule design, the fleet assignment, the number of spilled passengers and the seat allocation to each class. Since we want to come up with a comparative analysis between standard planes and Clip-Air, the model is developed for both cases.

The most important difference of Clip-Air from standard planes is that the fleet assignment includes both the assignment of wing and capsules. A flight can not be realized if there is no wing assigned to that flight. When a wing is assigned there is another decision about the number of capsules to be attached to the wing. Secondly, the operating cost allocation is different such that the costs are decoupled between wing and capsules. Flight crew cost is related only to the wing and cabin crew cost is related to the capsules. As will be explained in section 3.1, some other cost figures are also decoupled according to the weights of wing and capsules.

In this section we present the model for a fleet composed of Clip-Air wings and capsules, which considers a single airline. Schedule design is modeled with two sets of mandatory and optional flights such that schedule design decision is to operate the optional flights or to cancel them. The decision about the subset of flights to be flown could be integrated with a different convention based on the importance of flights. The proposed demand model is flexible to take into account different level of priorities for flights provided that the data is available to estimate the associated parameters. In case of such an extension, the schedule planning model will decide on the flights to be flown based on this additional information.

Let F be the set of flights, mandatory flights and optional flights are represented by the sets of F^M and F^O. A represents the set of airports and K represents the set of aircraft types which can be a Clip-Air wing with one, two or three capsules. The schedule is represented by time-space network such that $N(a,t)$ is the set of nodes in the time-line network, a and t being the index for airports and time respectively. $In(a,t)$ and $Out(a,t)$ are the sets of inbound and outbound flight legs for node (a,t). H represents the set of cabin classes which is assumed to consist of economy and business classes. S^h is the set of market segments for class h, which is taken as distinct origin and destination pairs in this study. For example, all the available business class itineraries for Geneva-Paris represent a market segment. I_s represents the set of itineraries in segment s. We include a set of no-revenue itineraries $I'_s \in I_s$ for each segment s which stands for the itineraries offered by other airlines. This set of itineraries is included in order to better represent the reality by considering the lost passengers to competitive airlines.

The objective (1) is to minimize the operating cost and loss of revenue due to unsatisfied demand. Operating cost for each flight f, has two components that correspond to operating cost for wings and capsules which are represented by C_f^w and $C_{k,f}$ respectively. These are associated with binary decision variables of x_f^w and $x_{k,f}$. x_f^w equals one if there is a wing assigned to flight f. $x_{k,f}$ represents the number of capsules assigned to flight f in such a way that it is one if there are k capsules assigned to flight f. The decision variable on the number of capsules could also have been defined as an integer variable. However the proposed formulation allows for more modeling flexibility. For example, it would allow to extend the model to capture the possible nonlinear relation between cost and the number of capsules. $t_{i,j}$ is the decision variable for the number of passengers redirected from itinerary i to itinerary j typically when there is insufficient capacity. $b_{i,j}$ is the proportion of passengers who accept to be redirected from itinerary i to j. The price of itinerary i is represented by p_i.

Constraints (2) ensure that every mandatory flight should be assigned at least one capsule. Optional flights are not exposed to such a constraint which forms the decision on the schedule design. Constraints (3) maintain the wing capsule relation such that if there is no wing assigned to a flight, there can be no capsule assigned to that flight. On the other hand if there is a wing assigned there can be up to three capsules flying. Constraints (4) and (7) are for the flow conservation of wings and capsules. y_{a,t^-}^w and y_{a,t^-}^k represent the number of wings and capsules at airport a just before time t respectively. Similarly y_{a,t^+}^w and y_{a,t^+}^k stand for the number of wings and capsules just after time t respectively. Constraints (5) and (8) limit the usage of fleet by the available amount which is represented by R_w and R_k for wings and capsules respectively. $minE_a^-$ represents the time just before the first event at airport a and CT is the set of flights flying at count time. In this study it is assumed that the number of wings and capsules at each airport at the beginning of the period, which is one day, is the same as the end of the period. Constraints (6) and (9) ensure this cyclic schedule property, where $maxE_a^+$ represents the time just after the last event at airport a.

Constraints (10) ensure the relation between supply and capacity. Decision variables $\pi_{f,h}$ represent the allocated seats for flight f and class h. δ_f^i is a binary parameter which is one if itinerary i uses flight f and enables us to have itinerary-based demand. The left hand side represents the actual demand for each flight taking into account the spilled and recaptured passengers (see section 2.2), where D_i is the expected demand for each itinerary i. Therefore, the realized demand is ensured to be satisfied by the allocated capacity. Similarly, these constraints maintain that when a flight is canceled, all the related itineraries do not realize any demand. We let the allocation of business and economy seats to be decided by the model as a revenue management decision. Therefore we need to make sure that the total allocated capacity for a flight is not higher than the physical capacity of Clip-Air and this is represented by the constraints (11). The capacity of one capsule is represented by Q and the total capacity can be up to $3 \times Q$. Constraints (12) are for demand conservation for each itinerary saying that total redirected passengers from itinerary i to all other itineraries in the same market segment should not exceed its expected demand.

$$Min \sum_{f\in F} \Big(C_f^w x_f^w + \sum_{k\in K} C_{k,f} x_{k,f}\Big) + \sum_{h\in H} \sum_{s\in S^h} \sum_{i\in(I_s\setminus I_s')} \Big(\sum_{j\in I_s} t_{i,j} - \sum_{j\in(I_s\setminus I_s')} t_{j,i} b_{j,i}\Big) p_i \qquad (1)$$

$$s.t. \sum_{k\in K} x_{k,f} = 1 \qquad \forall f \in F^M \quad (2)$$

$$\sum_{k\in K} x_{k,f} \le x_f^w \qquad \forall f \in F \quad (3)$$

$$y_{a,t^-}^w + \sum_{f\in In(a,t)} x_f^w = y_{a,t^+}^w + \sum_{f\in Out(a,t)} x_f^w \qquad \forall [a,t] \in N \quad (4)$$

$$\sum_{a\in A} y_{a,minE_a^-}^w + \sum_{f\in CT} x_f^w \le R_w \qquad (5)$$

$$y_{a,minE_a^-}^w = y_{a,maxE_a^+}^w \qquad \forall a \in A \quad (6)$$

$$y_{a,t^-}^k + \sum_{\substack{f\in In(a,t)\\ k\in K}} k\ x_{k,f} = y_{a,t^+}^k + \sum_{\substack{f\in Out(a,t)\\ k\in K}} k\ x_{k,f} \qquad \forall [a,t] \in N \quad (7)$$

$$\sum_{a\in A} y_{a,minE_a^-}^k + \sum_{\substack{f\in CT\\ k\in K}} k\ x_{k,f} \le R_k \qquad (8)$$

$$y_{a,minE_a^-}^k = y_{a,maxE_a^+}^k \qquad \forall a \in A \quad (9)$$

$$\sum_{s\in S^h} \sum_{i\in(I_s\setminus I_s')} \delta_f^i D_i - \sum_{j\in I_s} \delta_f^i t_{i,j} + \sum_{j\in(I_s\setminus I_s')} \delta_f^i t_{j,i} b_{j,i} \le \pi_{f,h} \qquad \forall f \in F, h \in H (10)$$

$$\sum_{h\in H} \pi_{f,h} \leq \sum_{k\in K} Q\ k\ x_{k,f} \sum_{j\in I_s} t_{i,j} \leq D_i \qquad \forall f \in F \quad (11)$$

$$\textstyle\sum_{j\in I_s} t_{i,j} \leq D_i \qquad \forall h \in H, s \in S^h, i \in (I_s \backslash I_s^{'}) \quad (12)$$

$$x_f^w \in \{0,1\} \qquad \forall f \in F \quad (13)$$

$$x_{k,f} \in \{0,1\} \qquad \forall k \in K, f \in F \quad (14)$$

$$y_{a,t}^w \geq 0 \qquad \forall [a,t] \in N \quad (15)$$

$$y_{a,t}^k \geq 0 \qquad \forall [a,t] \in N \quad (16)$$

$$\pi_{f,h} \geq 0 \qquad \forall f \in F, h \in H \quad (17)$$

$$t_{i,j} \geq 0 \qquad \forall h \in H, s \in S^h, i \in (I_s \backslash I_s^{'}), j \in I_s \quad (18)$$

2.2 Spill effects

Although the purpose of the fleet assignment is to optimize the assignment of aircraft to the flight legs, capacity restrictions and the uncertainties in demand may result with lost passengers or under utilized capacity. In case of capacity shortage some passengers, who can not fly on their desired itineraries, may accept to fly on other available itineraries in the same market segment offered by the company. This effect is referred as spill and recapture effect. The airlines can make use of the information on spill and recapture for a better planning of the fleet. There is an increasing interest in the literature to include these network effects in airline fleet assignment models (Lohatepanont and Barnhart, 2004).

In this paper we model the spill and recapture effects through a behavioral model. We assume that the spilled passengers are recaptured by the other itineraries with a recapture ratio based on a logit choice model. Choice of an itinerary is modeled by defining the utilities of the alternatives. To explain the utilities, the variables *price*, *travel time*, *departure time of the day*, and *the number of stops* were found to be important in the context of itinerary choice in the studies of Coldren et al. (2003), Coldren and Koppelman (2005) and Garrow (2010).

The choice situation is defined for each segment s and the set of available itineraries in the segment, I_s, represents the choice set. The index $i \in I_s$ carries the information on the cabin class, therefore we do not use any class index for the itineraries. The choice model is defined separately for economy and business classes. The utility of each alternative itinerary i, including the no-revenue options, is represented by V_i. The estimation of the model is carried out based on a mixed RP/SP dataset. Both RP and SP datasets are based on real data. The RP data is a booking data from a major European airline provided in the context of ROADEF Challenge 2009[6]. The SP data is based on an Internet choice survey collected in 2004 in the US. The details on the model and the estimation methodology is described in Atasoy and Bierlaire (2012). Here we provide the utilities of economy and business itineraries with the estimated parameters:

$$\begin{aligned} V_i = & -[2.23(-3.48) \times nonstop_i + 2.17(-3.48) \times stop_i] \times \ln(p_i/100) \\ & -[0.102(-2.85) \times nonstop_i + 0.0762(-2.70) \times stop_i] \times time_i \\ & +0.0283(1.21) \times morning_i \qquad \forall i \in I_s, s \in S^{econ.}, \end{aligned}$$

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[6] http://challenge.roadef.org/2009/en

$$V_i = -[1.97(-3.64) \times nonstop_i + 1.96(-3.68) \times stop_i[\times \ln(p_i/100)$$
$$-[0.104(-2.43) \times nonstop_i + 0.0821(-2.31) \times stop_i] \times time_i$$
$$+0.0790(1.86) \times morning_i \qquad \forall i \in I_s, s \in S^{bus.},$$

where p_i is the price (euro) and $time_i$ is the travel time (h) of itinerary i. If itinerary i is a nonstop itinerary, the $nonstop_i$ variable is 1, otherwise $stop_i$ is 1. Finally, $morning_i$ is a dummy variable for the time of day which is 1 if departure time is between 07:00-11:00 and 0 otherwise. The price is included with a log transform in order to capture the nonlinear relation between price and utility. The increase in price does not affect the utility of passengers in the same way for different levels of the price. The values in the brackets are the t-test values and except the parameter of morning for economy class all the parameters are significant at a 90% confidence level.

One of the main observations regarding the parameter values is that economy passengers are more sensitive to price and less sensitive to travel time compared to business passengers as expected (Belobaba et al., 2009). Moreover the utility is higher for morning itineraries and business itineraries are more sensitive to this time of the day variable compared to economy itineraries. In order to better understand the underlying behavior, elasticities and willingness to pay are analyzed by Atasoy and Bierlaire (2012). As an example, for a business nonstop itinerary the price elasticity is -1.86. For the economy class counterpart of the same itinerary in the same market segment, the price elasticity is -2.03. This is an example to show the differences in the sensitivity to price for economy and business passengers. The details can be found in Atasoy and Bierlaire (2012).

The logit model allows us to calculate the recapture ratios $b_{i,j}$ which represent the proportion of recaptured passengers by itinerary j among $t_{i,j}$ spilled passengers from itinerary i. The recapture ratio is calculated for the itineraries that are in the same market segment as given in equation (19) where the desired itinerary i is excluded from the choice set. Therefore lost passengers may be recaptured by the remaining alternatives of the company or by the no-revenue options which represent the alternatives provided by competitors. Since no-revenue itineraries are out of the network we assume that no spill exist from them.

$$b_{i,j} = \frac{\exp(V_j)}{\sum_{k \in I_s \setminus \{i\}} \exp(V_k)} \qquad \forall h \in H, s \in S^h, i \in (I_s \setminus I'_s), j \in I_s, \tag{19}$$

We illustrate the concept with the itineraries in an arbitrary market segment A-B including the no-revenue itinerary A-B ′. The attributes for the itineraries can be seen in Table 1 together with their resulting utility values. Using the logit formulation, recapture ratios are calculated as given in Table 2. These ratios are given as an input to the integrated schedule planning model.

Table 1. A-B itineraries

	class	nonstop	morning	time	price	V
A-B $_1$	E	0	1	250	300	-2.67
A-B $_2$	E	0	0	250	300	-2.70
A-B $_3$	E	1	0	80	200	-1.68
A-B $_4$	E	1	1	80	200	-1.65
A-B ′	E	1	1	80	225	-1.92

Table 2. Recapture ratios for A-B

	A-B $_1$	A-B $_2$	A-B $_3$	A-B $_4$	A-B ′
A-B $_1$	-	0.113	0.314	0.323	0.250
A-B $_2$	0.116	-	0.314	0.322	0.248
A-B $_3$	0.146	0.141	-	0.403	0.310
A-B $_4$	0.147	0.143	0.396	-	0.314

The ratios in Table 2 show that, in case of capacity shortage for itinerary 2, 11.6% of the passengers will accept the offer when redirected to itinerary 1. This ratio is 31.4% and 32.2% for itineraries 3 and 4 respectively and 24.8% for competitive airlines. The recapture ratio from itinerary 2 to itinerary 1 is the lowest since it is expensive and not a nonstop itinerary. The ratio from itinerary 2 to itinerary 4 is the highest being a nonstop and morning itinerary.

The logit model for the estimation of recapture ratios is estimated based on a dataset where the flights are flown by standard aircraft. For the comparative analysis between standard aircraft and Clip-Air we assumed that the utilities would be the same for the flights regardless of the considered fleet. For the passenger acceptance of Clip-Air, a further study should be carried out with the help of a stated preferences survey. The data provided by such a survey would enable to extend the demand model in order to take into account the potential impact of Clip-Air on the demand.

3. Results on the potential performance of Clip-Air

For carrying out the comparative analysis between standard planes and the Clip-Air fleet we work with a dataset from a major European airline which is the same dataset used for the spill effects as mentioned in section 2.2. Data provides information for the sets of airports, aircraft, flights and itineraries. Apart from these we need the estimated cost figures for Clip-Air wings and capsules which are explained in section 3.1. As Clip-Air exists only in a simulated environment we make the following assumptions for the comparison with standard planes:

- The results for the standard fleet have been obtained by letting the model select the optimal fleet composition from a set of different available plane types. On the other hand Clip-Air capsules are of the same size. This is an advantage for standard fleet since it is able to adjust the fleet composition according to the characteristics of the network. We only impose that the overall capacity is the same for both standard fleet and Clip-Air.
- In the set of different fleet types, the aircraft that are close to the capacities of 1 capsule, 2 and 3 capsules are kept present in the experiments (A320 - 150 seats, A330 - 293 seats, B747-200 - 452 seats). As mentioned in section 3.1, Clip-Air is more expensive compared to these aircraft except when flying with 3 capsules. Standard fleet and Clip-Air have almost the same set of aircraft sizes. This experimental design is meant to minimize the impacts of the differences in size and to reveal to a larger extent the impact of modularity. This is clearly in favor of the standard fleet. Having higher costs, Clip-Air can only compete with its modularity and flexibility.
- Total available transportation capacity in number of seats is sufficient to serve all the demand in the network for all the analyzed instances. It is explained in section 3.5 that this is in favor of the standard fleet and whenever the capacity is restricted, Clip-Air performs significantly better than the standard fleet in terms of the number of transported passengers.
- The schedule is assumed to be cyclic so that the number of aircraft/wings/capsules at each airport is the same at the beginning and at the end of the period, which is one day. This a limiting factor for Clip-Air since the modularity of the capsules is not efficiently used in such a case. The repositioning of the capsules by other means of transport modes could lead to more profitable and efficient schedules. However, we do not take into account the repositioning possibility in this study.

- As explained in section 3.1, we adjust only the fuel costs, crew costs and airport navigation charges. However the design of Clip-Air is expected to considerably decrease the maintenance costs due to the simple structure of the capsules. The capsules do not necessitate critical maintenance since all the critical equipments are on the wing. Furthermore, the overall number of engines needed to carry the same amount of passengers is reduced. Consequently, maintenance costs can be further reduced. These potential savings are ignored in this study.
- We challenge Clip-Air against a schedule conceived for a standard fleet. However the decoupling of wing and capsules is expected to reduce the turn around time and this advantage is ignored in this study.
- Clip-Air is designed for both passenger and cargo transportation. When the demand is insufficient to fill three capsules, additional revenue can be generated by using a capsule for freight. This is not considered in this study.
- As shown in sections 3.2-3.5, Clip-Air is found to allocate less capacity to carry the same amount of passengers compared to standard fleet. In other words, the flight network is operated with less number of aircraft due to the modularity of Clip-Air. It means that the total investment for the airline is potentially less important for a Clip-Air fleet than for a standard fleet. In this study we do not take this into account. Therefore the potential of Clip-Air in reducing the investment costs is ignored.
- Finally, we assume that the unconstrained demand for the itineraries (D_i) and the demand model for the recapture ratios are the same when the fleet is changed to Clip-Air. The overall impacts of the new system on passenger demand is not analyzed being out of scope of this paper.

The assumptions above lead to a conservative comparison between Clip-Air and standard fleet. Therefore, the results presented below provide lower bounds on the expected gains that a Clip-air fleet may provide to the airline.

We have implemented our model in AMPL and the results are obtained with the GUROBI solver. We first present a small example to illustrate the advantages of the enhanced flexibility of the Clip-Air system. Then we present the results for different scenarios about the network configuration, fleet size, fleet type and the costs of the Clip-Air fleet. The presented results include productivity measures in order to show the efficiency of the utilization of the capacity:

- Available seat kilometers (ASK): The number of seats available multiplied by the number of kilometers flown. This is a widely used measure for the passenger carrying capacity. Since our data does not provide information on the kilometers flown for the flights, we convert the total flight duration to kilometers with a speed of 850 kilometers per hour.
- Transported passengers per available seat kilometers (TPASK): A productivity measure which we adapt to compare the standard fleet and Clip-Air. It is the total number of transported passengers divided by the available seat kilometers and measures the productivity of the allocated capacity.

3.1 Cost figures for Clip-Air

As mentioned previously Clip-Air exists only in a simulated environment. Therefore estimated values are used for the operating cost of Clip-Air using analogies with the aircraft A320. The capacity of Clip-Air is designed to be 150 seats, the same as the capacity of an A320. In Table 3 we present the weight values for Clip-Air flying with one, two and three capsules in comparison to one, two and three aircraft of type A320. As seen from the Table, Clip-Air is 78% heavier than one

A320 plane when it is flying with one capsule, and 11% heavier than two A320 planes when flying with two capsules. However when flying with three capsules Clip-Air is 11% lighter than three A320 planes. We use these weight differences to proportionally decrease/increase the fuel cost and air navigation charges since both depend on the aircraft weight. The airport charges are usually applied depending on the weight class of the aircraft rather than being directly proportional (ICAO, 2012). However to be on the conservative side we apply an increase which is proportional to the weight.

Table 3. Clip-Air configuration

		Clip-Air	A320
Maximum Capacity		3x150 (450 seats)	150 seats
Engines		3 engines	2 engines
Maximum Aircraft Weight	1 (plane/capsule)	139t (+78%)	78t
	2 (planes/capsules)	173.5t (+11%)	2x78t (156t)
	3 (planes/capsules)	208t (-11%)	3x78t (234t)

Furthermore we make adjustment on the crew cost due to the decoupling of wing and capsules. Flight crew cost is associated with the wing, and the cabin crew cost is associated with the capsules. Clip-Air flies with one set of flight crews regardless of the number of capsules used for the flight. It is given by the study of Aigrain and Dethier (2011) that flight crew constitutes 60% of the total crew cost for the A320. Therefore Clip-Air decreases the total crew cost by 30% and 40% when flying with two and three capsules respectively.

The adjusted cost figures sum up to 56% of the total operating cost of European airlines: fuel cost 25.3% (IATA, 2010), crew cost 24.8% (IATA, 2010), airport and air navigation charges 6% (Castelli and Ranieri, 2007). The remaining operating cost values are assumed to be the same as the A320 for the utilization of each capsule.

3.2 An illustrative example

We present results for a small data instance to illustrate the flexibility provided by the Clip-Air system. The network consists of four flights with the demand and departure-arrival times given in Figure 3. There is an expected demand of 1200 passengers which is generated by 4 itineraries between airports A-C, B-C, C-A and C-B. The available fleet capacity is not limited and the circular property of the schedule is ignored for this example. For the standard fleet, it is assumed that there are three types of planes which have 150, 300 and 450 seats. Clip-Air capsules are assumed to have a capacity of 150 seats as presented in Table 3.

In order to fully satisfy the demand with standard planes, 2 aircraft with 300 seats each should depart from the airports A and C. At airport B an aircraft with 450 seats is needed for the departure to airport C and an aircraft with 150 seats for the departure to airport A. Therefore 4 aircraft are used with 1200 allocated seats. Clip-Air is able to cover the demand with 2 wings. The wings depart from airport A and C with 2 capsules each. At airport B, 1 capsule is transfered to the flight that departs to airport C. Therefore the flight B-C is operated with 3 capsules and the flight B-A is operated with 1 capsule. The total number of allocated seats is 600 which means that Clip-Air is able to transport the same number of passengers with 50% of the capacity of the standard fleet. This change in the fleet assignment operations leads to several simplifications in the operations. Since the same type of aircraft is used for all the flights the type of crew does not need to be changed for different flights. The airport operations are also simplified since the same type of aircraft can be assigned to the flights with necessary adjustments in the number of clipped capsules.

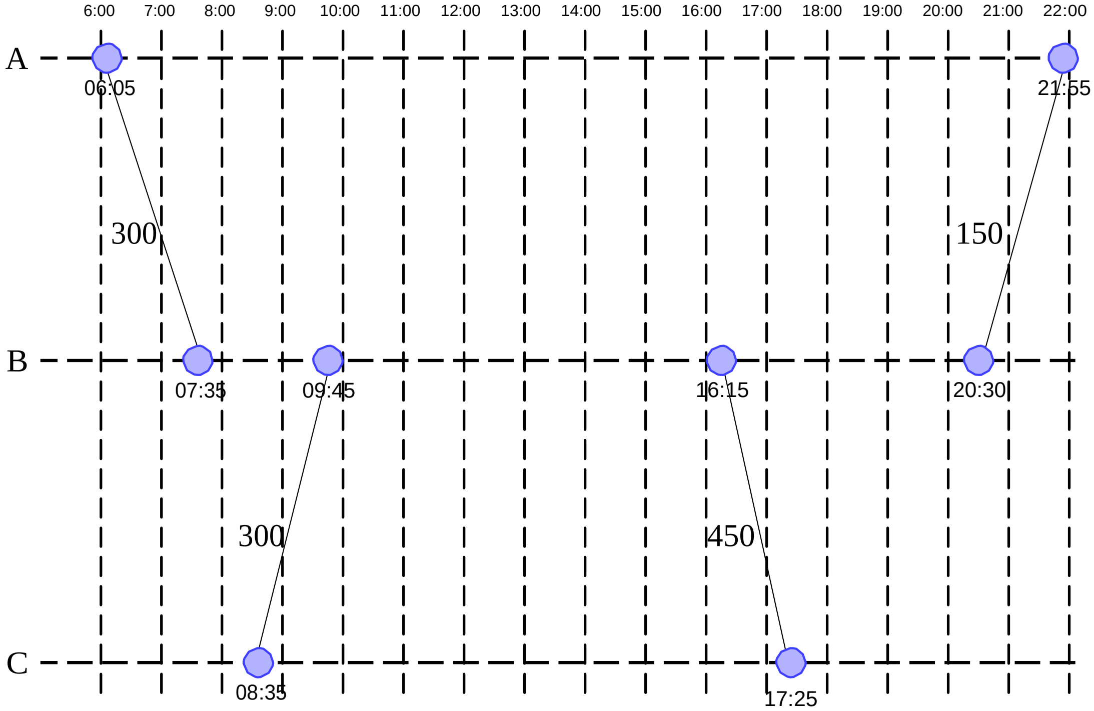

Figure 3. Time-line network for the illustrative example

We can analyze the same data instance with a limited capacity of 600 seats for standard planes and Clip-Air. In that case 2 aircraft with 300 seats each will be operated from the airports A and C to airport B. The same aircraft will depart from airport B which will result with a loss of 150 passengers on the flight B-C and with an excess capacity of 150 seats on the flight B-A. However Clip-Air covers the demand without any loss or excess capacity with its flexible capacity.

This illustrative example gives the idea of the potential savings with Clip-Air which is quantified with the experiments presented in the continuation of this section.

3.3 Network effect

The type of the network is an important factor that needs to be analyzed for quantifying the performance of Clip-Air. For this matter, we present results for three different network structures: airport pair, hub-and-spoke network with single hub and peer-to-peer well connected network. Flight densities of these networks are different from each other which affects the performance of Clip-Air.

Airport-pair network

We present a network with 2 airports and 38 flights which are balanced for the two routes. The description of the data set is given in Table 4 and the results are provided in Table 5. It is observed that Clip-Air carries 7% more passengers compared to a standard fleet. The increase in the number of transported passengers is also reflected by the spill cost which is higher for standard fleet. Therefore the profit is 5% higher when flying with Clip-Air. The allocated capacity is similar for the two cases. The average demand per flight does not favor the usage of 3 capsules therefore the operating cost for Clip-Air is higher. This is compensated by the increased revenue due to the flexibility of Clip-Air on the allocated transportation capacity.

Table 4. Data instance for the airport-pair network

Airports	2
Flights	38
Density (Flights/route)	19
Passengers	13,965
Itineraries	45
Standard fleet types	A320(150), A330(293), B747-200(452)

Table 5. Results for the airport-pair network

	Standard fleet	**Clip-Air**
Operating cost	1,607,166	1,725,228
Spill costs	604,053	448,140
Revenue	2,419,306	2,575,219
Profit	812,140	849,991 (+4.66 %)
Transported pax.	10,276	11,035 (+7.39 %)
Flight count	38	38
Total flight duration	3135 min	3135 min
Used fleet	2 A320	7 wings
	5 A330	12 capsules
Used aircraft	7	7
Used seats	1765	1800
ASK	78,388,063	79,942,500
TPASK (× 10^{-5})	13.11	13.80

Hub and spoke network with a single hub

The behavior of the Clip-Air system is analyzed for a hub-and-spoke network with a single hub where all the flights need to connect through the hub. Details for the data instance are given in Table 6. With Clip-Air, less flights are operated and there is a 14% increase in total transported passengers allocating a similar capacity as the standard fleet. The increase in the transported passengers with less number of flights is reflected through the TPASK measure. Since the flight density is low, which is 3.25 flights per route, and since the connections are only possible through the hub, the profit with Clip-Air is 7% less compared to the standard fleet. However we are still using two aircraft less with Clip-Air which will reduce the number of flight crews and simplify the ground operations for airports. We need to mention that in this particular instance the incoming and outgoing flights from the hub are balanced in terms of the demand for each spoke airport. Therefore a standard fleet can also perform well in this situation.

Table 6. Data instance for the hub-and-spoke network

Airports	5
Flights	26
Density (Flights/route)	3.25
Passengers	9,573
Itineraries	37
Standard fleet types	A320(150), A330(293), B747-200(452)

Table 7. Results for the hub-and-spoke network

	Standard fleet	Clip-Air
Operating cost	817,489	938,007
Spill costs	484,950	393,677
Revenue	1,247,719	1,338,992
Profit	430,230	400,985 (- 6.80 %)
Transported pax.	5,031	5,721 (+ 13.71 %)
Flight count	24	22
Total flight duration	1850 min	1700 min
Used fleet	5 A320	6 wings
	2 A330	12 capsules
	1 B747	
Used aircraft	8	6
Used seats	1788	1800
ASK	46,860,500	43,350,000
TPASK (× 10^{-5})	10.74	13.20

Well connected peer-to-peer network

In this section we present results for a peer-to-peer network where the airports are well connected with 98 flights and 28,465 expected passengers as seen in Table 8. Clip-Air transports 2.8% more passengers with a 21.3 % reduction in the allocated capacity compared to the standard fleet. This means that Clip-Air uses the capacity more efficiently which is also supported by the increased TPASK measure. When we look at the used number of aircraft we see that there is a clear difference between standard fleet and Clip-Air. Therefore the minimum number of flight crews is 35% less for Clip-Air which is important for the crew scheduling decisions. The density of the network is higher compared to the hub-and-spoke instance and all the airports are connected pairwise. The possibility to change the number of capsules at airports is utilized more efficiently. Therefore this type of network reveals more prominently the advantages of the flexibility of Clip-Air.

Table 8. Data instance for the peer-to-peer network

Airports	4
Flights	98
Density (Flights/route)	8.17
Passengers	28,465
Itineraries	150
Standard fleet types	A320(150), A330(293), B747-200(452)

Table 9. Results for the peer-to-peer network

	Standard fleet	Clip-Air
Operating cost	3,189,763	3,117,109
Spill costs	982,556	978,683
Revenue	5,056,909	5,060,782
Profit	1,867,146	1,943,673 (+ 4.1 %)
Transported pax.	20,840	21,424 (+ 2.8 %)
Flight count	91	84
Total flight duration	6650 min	6160 min
Used fleet	7 A320	13 wings
	10 A330	28 capsules
	3 B747	
Used aircraft	20	13
Used seats	5336	4200 (- 21.3 %)
ASK	502,695,667	366,520,000
TPASK (× 10^{-5})	4.15	5.85

3.4 Effect of the standard fleet configuration

Clip-Air is composed of modular capsules, the standard fleet can be composed of any aircraft type and the model has the opportunity to select the best fleet composition. Therefore it is important to see the effect of the fleet configuration when comparing with the performance of Clip-Air. This analysis enables us to figure out which type of airlines may profit better from the Clip-Air system.

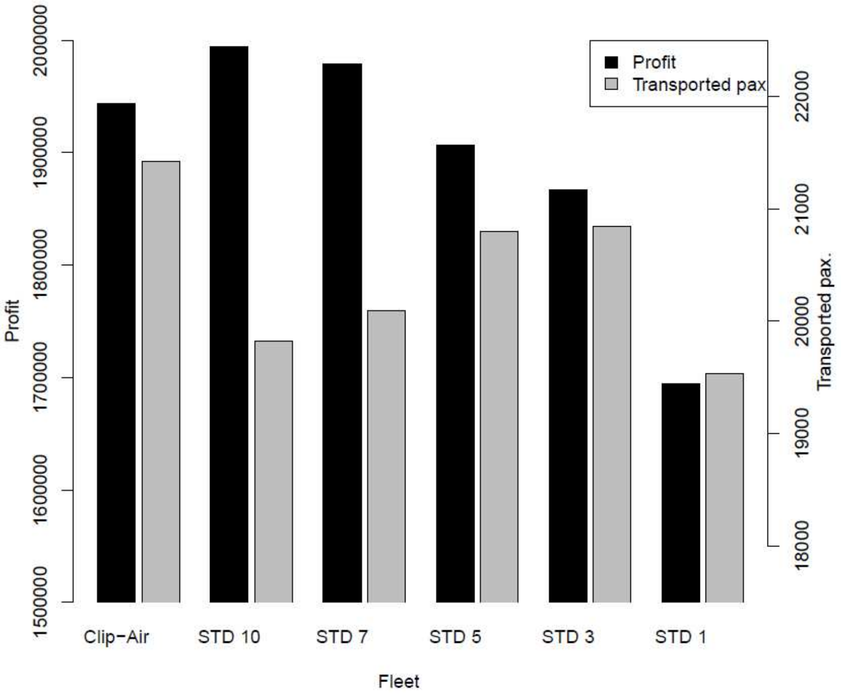

Figure 4. Profit and transported passengers for different fleet configurations

We use the same data instance as the peer-to-peer network given in Table 8. We change the available standard fleet configuration by gradually decreasing the fleet heterogeneity. The total transportation capacity is kept high enough to serve the whole demand for all the tested instances. The first scenario is designed to be composed of a highly heterogeneous fleet which is representative of the existing aircraft types in the European market. The gradual decrease afterwards is carried out in such a way that the remaining set of aircraft have enough variation in terms of size. Therefore the aircraft which have a similar counterpart in the fleet are selected to be removed which is done to have a fair comparison between Clip-Air and standard fleet.

The results for Clip-Air and standard fleet with different fleet configurations are provided in Table 10. It is observed that the richer the fleet configuration, the better the performance of standard fleet. When the standard fleet has 10 or 7 plane types available, the profit is higher compared to Clip-Air. However the transported number of passengers is always higher for Clip-Air although it is allocating less capacity. The profit and the transported passengers dramatically decrease when the fleet configuration is highly restricted with one type of plane. When we look at the results with 1 plane type, which has the same capacity as 2 capsules, the decrease in profit is 12.8% and 8.8% less passengers are carried. The change of profit and total number of transported passengers with the fleet configuration can be seen more clearly in Figure 4. Furthermore, the measure of TPASK is better for Clip-Air for all the cases except the last case where the utilization of the capacity is very high due to the insufficient capacity allocation. In this last case, standard fleet operates significantly less flights since the flights are not profitable with a single type of aircraft.

Table 10. Results with varying standard fleet configuration

		Standard fleet				
	Clip-Air	10 plane types	7 plane types	5 plane types	3 plane types	1 plane type
Operating cost	3,117,109	2,950,195	2,994,783	3,174,240	3,189,763	2,949,697
Spill costs	978,683	1,094,892	1,066,190	958,428	982,556	1,395,316
Revenue	5,060,782	4,944,573	4,973,275	5,081,038	5,056,909	4,644,150
Profit	1,943,673	1,994,378 (+2.6%)	1,978,492 (+1.8%)	1,906,798 (-1.9%)	1,867,146 (-3.9%)	1,694,453 (-12.8%)
Transported pax.	21,424	19,823 (-7.5%)	20,096 (-6.2%)	20,796 (-2.9%)	20,840 (-2.7%)	19,533 (-8.8%)
Flight count	84	93	94	93	91	77
Total flight duration	6160	6,780	6,875	6,780	6,650	5,705
Used fleet	13 wings 28 capsules	1 A318(107) 2 A319(124) 3 A321(185) 8 A330(293) 5 A340(335) 2 B737(128) 2 B777(400) 1 B747-400(524) 3 ERJ135(37) 2 ERJ145(50)	1 A319(124) 4 A321(185) 9 A330(293) 5 A340(335) 2 B737(128) 4 B777(400) 4 ERJ145(50)	5 A319(124) 2 A320(150) 10 A330(293) 5 A340(335) 2 B747-200(452)	7 A320(150) 10 A330(293) 3 B747-200(452)	12 A330(293)
Used aircrafts	13	29	29	24	20	12
Used seats	4200	6720 (+60%)	7232 (+72%)	6429 (+53%)	5336 (+27%)	3516 (-16%)
ASK	366,520,000	645,456,000	704,366,667	617,505,450	502,695,667	284,166,050
TPASK ($\times 10^{-5}$)	5.85	2.99	2.85	3.37	4.15	6.87

3.5 Effect of the available transportation capacity

All the previous results are obtained without any limit on the total capacity so that it is enough to cover the total expected demand. However in reality there may be capacity shortage in case of unexpected events, weather conditions or in high season. Therefore it is important to test the performance of Clip-Air compared to standard fleet when there is limited capacity. The data instance seen in Table 11, that consists of 100 flights, is used for the tests. Available capacity is decreased gradually and the results corresponding to each level of capacity is presented in Table 12.

For the unlimited capacity case, Clip-Air is able to carry 7% more passengers with 25% less transportation capacity. In all of the cases Clip-Air is able to carry more passengers compared to the standard fleet. In case of capacity restrictions, this advantage of Clip-Air over a standard fleet becomes more evident as the restriction becomes harder to overcome. This can also be observed from the TPASK measures which state that the productivity is higher for the allocated capacity compared to standard fleet.

As mentioned previously, there are mandatory flights which need to be served. Our dataset does not include information about the mandatory flights and to be able to represent the schedule design decision we randomly select a percentage of the flights to be mandatory. In this instance 50% of the flights are assumed to be mandatory. As the capacity restriction becomes more severe, Clip-Air flies with one capsule in order to operate these mandatory flights. This significantly increases the operating cost of Clip-Air and decreases the resulting profit. In the last case in Table 12 the standard fleet has 16% more profit due to the explained phenomenon. In order to see the effect of the mandatory flights, the same instance with an available capacity of 1950 seats is analyzed, where all the flights are assumed to be optional. In such a case Clip-Air has 9% more profit and carries 5% more passengers compared to a standard fleet. Indeed, when all the flights are optional, Clip-Air can select the most profitable flights where the level of demand enables to avoid the usage of one capsule flights.

When the available capacity is decreased further neither the standard fleet nor Clip-Air can serve the mandatory flights which makes the problem infeasible.

Table 11. Data instance for the tests with different available capacity

Airports	5
Flights	100
Density (Flights/route)	6.25
Passengers	35,510
Itineraries	140
Standard fleet types	A319(124), A320(150), A321(185), A330(293), A340(335), B737-300(128), B737-400(146), B737-900(174), B747-200(452), B777(400)

Table 12. Results with varying available capacity

			Clip-Air		
	Not limited	**4500 seats**	**3750 seats**	**3000 seats**	**1950 seats**
Operating cost	3,737,841	3,547,651	3,321,567	2,837,159	2,063,607
Spill costs	764,078	1,028,581	1,420,982	2,201,731	3,801,355
Revenue	6,120,255	5,855,752	5,463,351	4,682,602	3,082,978
Profit	2,382,414	2,308,101	2,141,783	1,845,443	1,019,371
Transported pax.	27,061	25,682	23,722	19,851	12,810
Flight count	93	93	89	82	72
Total flight duration	7110	7110	6780	6240	5460
Used fleet	18 wings 39 capsules	17 wings 30 capsules	17 wings 25 capsules	16 wings 20 capsules	14 wings 13 capsules
Used aircrafts	18	17	17	16	14
Used seats	5850	4500	3750	3000	1950
ASK	589,241,250	453,262,500	360,187,500	265,200,000	150,832,500
TPASK (× 10¯5)	4.59	5.67	6.59	7.49	8.49

			Standard Fleet		
	Not limited	**4500 seats**	**3750 seats**	**3000 seats**	**1950 seats**
Operating cost	3,656,793	3,510,037	3,168,626	2,651,208	1,741,825
Spill costs	1107237	1,326,018	1,787,240	2,526,149	3,958,092
Revenue	5,777,096	5,558,315	5,097,093	4,358,184	2,926,241
Profit	2,120,303 (-11%)	2,048,278 (-11%)	1,928,467 (-10%)	1,706,976 (-8%)	1,184,416 (+16%)
Transported pax.	25,136 (-7%)	23,926 (-7%)	21,647 (-9%)	17,794 (-10%)	11,294 (-12%)
Flight count	93	93	91	87	88
Total flight duration	7110	7110	6945	6585	6,700
Used aircrafts	26	17	16	15	14
Used seats	7832	4498	3750	3000	1949
ASK	788,878,200	453,061,050	368,953,125	279,862,500	184,992,583
TPASK (× 10¯5)	3.19	5.28	5.87	6.36	6.11

3.6 Sensitivity analysis on the costs of Clip-Air

Since the Clip-Air system does not exist yet, sensitivity analysis needs to be carried out for the assumed operating cost of Clip-Air. As mentioned in section 3.1, we estimated the crew cost, fuel cost, airport and air navigation charges for Clip-Air. Therefore we present a sensitivity analysis of these cost figures. Fuel cost, airport and air navigation charges are analyzed with the cases of 10%, 20%, 30% and 50% higher values compared to the base values we have initially used. The crew cost does not depend on the weight of the aircraft. Clip-Air always flies with one set of flight crews regardless of the number of capsules used. Therefore, Clip-Air crew cost savings depend on the repartition of overall crew costs between flight and cabin and we analyze the sensitivity of the results to this repartition. As mentioned in section 3.1, we assume that flight crew and cabin crew constitute 60% and 40 % of the total crew cost respectively. Therefore 60% represents the base case for the flight crew cost throughout the analysis. We consider two other cases where flight crew constitutes the 50% and 70% of the total crew cost. The 50% case implies a reduction in the potential savings of Clip-Air and the 70% case is in favor of Clip-Air where the crew cost is further decreased.

The analysis is carried out for the same data instance used for the analysis of the effect of transportation capacity in section 3.5. The results in Table 13 are presented in comparison to the results for standard fleet given in Table 12 for the case of unlimited capacity.

It is observed that the scheduling decisions are the same for almost all of the cases having 18 assigned aircraft and allocating 25% to 29% less capacity compared to the standard fleet. This is a good indicator which says that our model is robust in the analyzed range and the general conclusions remain valid.

The number of transported passengers is higher for Clip-Air for all the analyzed cases and the range of this increase is between 4.5%-8.3%. The highest increase in profit is 14.8% which occurs when all the cost values are in favor of Clip-Air. On the other hand, the lowest profit of Clip-Air (20.9% lower than standard fleet) is observed when all the cost figures are in favor of the standard fleet.

When we further analyze the results in Table 13, we can draw conclusions on the relative impacts of each cost figure on the resulting profit and transported passengers. When all the other cost values are at their base levels, even a 50% increase in airport and air navigation charges does not affect the superiority of Clip-Air over a standard fleet. A 30% increase in the fuel cost decreases the profit of Clip-Air below that of a standard fleet even when all other costs are at their base levels. The impact of different percentages for flight crew cost is more evident when the fuel cost is increased. For example, when there is a 20% increase in fuel cost, the profit of Clip-Air may become inferieur to a standard fleet depending on the flight crew percentage. When it is 70% Clip-Air is still more profitable even for a 30% increase in airport and air navigation charges. However when the flight crew percentage is 50% Clip-Air is less profitable even for the base case.

It is observed that both the increase in the fuel cost and the increase in airport and air navigation charges decrease the profit as expected. However the total number of transported passengers is not considerably affected by the change of the costs. When the percentage of the flight crew cost increases, Clip-Air uses the advantage of the decoupling of wing and capsules and reduces the crew cost considerably. Although the number of carried passengers is not highly affected, it is increased when the flight crew percentage is high. It can be concluded that crew cost and fuel cost are more critical compared to airport and air navigation charges in terms of the profit and the number of transported passengers, although there is not a significant effect on the scheduling decisions.

Table 13. Sensitivity analysis for the cost figures of Clip-Air

Fuel cost			**Base**			**+10%**			**+20%**			**+30%**			**+50%**		
Flight crew %			**50%**	**60%**	**70%**	**50%**	**60%**	**70%**	**50%**	**60%**	**70%**	**50%**	**60%**	**70%**	**50%**	**60%**	**70%**
Airport & air navigation charges	Base	Profit (%):	+9.9	+12.4	+14.8	+4.9	+7.3	+9.8	-0.1	+2.3	+4.7	-5.1	-2.7	-0.3	-15.0	-12.8	-10.4
		Pax. (%)	+6.9	+7.7	+8.3	+6.9	+6.9	+7.7	+6.2	+6.9	+7.7	+6.2	+6.9	+6.9	+4.5	+6.2	+6.9
	+10%	Profit (%):	+8.7	+11.2	+13.6	+3.7	+6.1	+8.6	-1.3	+1.1	+3.5	-6.3	-3.9	-1.5	-16.2	-14.0	-11.6
		Pax. (%)	+6.9	+7.7	+8.3	+6.9	+6.9	+7.7	+6.2	+6.9	+7.7	+6.2	+6.9	+6.9	+4.5	+6.2	+6.9
	+20%	Profit (%):	+7.5	+10.0	+12.4	+2.5	+4.9	+7.4	-2.5	-0.1	+2.3	-7.5	-5.1	-2.7	-17.4	-15.2	-12.8
		Pax. (%)	+6.9	+7.7	+7.7	+6.9	+6.9	+7.7	+6.2	+6.9	+7.7	+5.7	+6.9	+6.9	+4.5	+6.2	+6.9
	+30%	Profit (%):	+6.3	+8.7	+11.2	+1.3	+3.7	+6.2	-3.7	-1.3	+1.1	-8.7	-6.3	-3.9	-18.6	-16.4	-14.0
		Pax. (%)	+6.9	+7.7	+7.7	+6.9	+6.9	+7.7	+6.2	+6.9	+7.7	+4.5	+6.9	+6.9	+4.5	+5.7	+6.9
	+50%	Profit (%):	+4.0	+6.3	+8.8	-1.1	+1.3	+3.7	-6.1	-3.7	-1.3	-11.0	-8.7	-6.3	-20.9	-18.7	-16.4
		Pax. (%)	+6.9	+6.9	+7.7	+6.2	+6.9	+7.7	+6.2	+6.9	+6.9	+4.5	+6.2	+6.9	+4.5	+4.5	+6.2

4. Conclusions and future directions

In this paper, the added value of flexibility in air transportation systems is analyzed. We have focused on the flexibility brought by the modularity of a new type of aircraft, Clip-Air, which is currently being designed. It is clearly shown that bringing flexibility helps to both better respond to the network demand and to increase revenues. The analysis of flexibility in this paper is not limited to Clip-Air and can be a reference for future studies on flexible transportation systems. This study is a promising step towards the integration of different types of flexibility in various transportation systems.

In order to quantify the added value of flexibility, a comparative analysis is carried out between the Clip-Air system and an existing standard configuration. For this purpose an integrated schedule design and fleet assignment model is developed for both Clip-Air and a fleet with standard planes. Sustainability of transportation systems is closely related to the demand responsiveness and this can not be achieved without introducing demand orientation in transportation models. For that matter, supply-demand interactions are integrated in the model through an itinerary choice model which represents spill and recapture effects. Therefore the presented methodology is an integration of advanced optimization and demand modeling methods for airlines.

Since the Clip-Air system does not exist yet, the estimation of the cost is based on reasonable assumptions. In order to perform a conservative comparison, our scenarios include some advantages for the standard fleet compared to Clip-Air. For instance, we do not allow Clip-Air to use different types of capsules, while the standard fleet can rely on different plane types.

Different scenarios are analyzed to quantify the performance of Clip-Air. The scenarios are designed to test the effects of the network type, fleet size, fleet configuration and the estimated cost of the Clip-Air system. In all analyzed cases, Clip-Air is found to carry more passengers allocating less capacity compared to the standard fleet. This is supported by the high TPASK measures which means that Clip-Air uses the available capacity more efficiently than the standard fleet. The scenarios show that the potential advantages of Clip-Air are more evident in a large network where the flight density is high and the airports are well connected. In such a network, airlines fly with different types of aircraft as a strategy to capture various demand patterns. Clip-Air is more efficiently responding to the demand with a single capsule type due to its flexibility. Therefore, airlines that operate over a large network with a high density of flights are expected to gain the most by switching to a Clip-Air fleet.

As mentioned previously, the cost estimation for the Clip-Air system is based on various assumptions. Therefore a sensitivity analysis is presented for crew cost, fuel cost and airport and air navigation charges. It is seen that scheduling decisions are not sensitive to the cost in the range of our analysis. Clip-Air is found to always perform better in terms of the number of carried passengers. In terms of profit, Clip-Air becomes less advantageous mainly when the fuel costs are increased above 20%.

The overall results show that Clip-Air has a significant potential for an efficient use of the capacity, as well as an increase of the airline profits. The conservative nature of the scenarios and the sensitivity analysis suggest that these reported improvements will be outperformed by a real implementation of the system.

The Clip-Air system can be analyzed from different perspectives thanks to its design. For instance, a standardization of the Clip-Air capsule would give a multi-modal dimension to the system. The capsules could be carried on railways and on trucks, allowing passengers to board outside of the airport. Since the capsules are of simple structure, their storage and transfer is relatively easy. We believe that the repositioning possibility will increase the flexibility of Clip-Air and help to show more clearly how it can adapt to different situations of the capacity and demand. Moreover, the modularity of Clip-Air allows to have freight and passenger loaded capsules on the same flight which opens up new frontiers to mixed passenger and cargo transportation. Furthermore, it is more realistic for an airline company to have only part of the fleet composed of Clip-Air wings and capsules the rest being composed of standard aircraft. Therefore, a model with mixed fleet is crucial to see what types of aircraft should be replaced by Clip-Air. A dynamic business plan for companies can be obtained with the inclusion of the fixed cost for the purchase of the Clip-Air wings and capsules. Furthermore, a business model where the companies operating the wings are different from the companies operating the capsules should be analyzed.

The Clip-Air concept opens the door to a wide range of new research opportunities in the context of flexible transportation. Analogies and differences among the existing transportation modes can be utilized better in order to design new concepts. In this paper, modularity, which is a flexibility we are used to see in railways, is shown to be significantly advantageous in airline operations. Therefore, the presented analysis is a promising step towards the new flexibility concepts without being confined in the boundaries of the existing systems.

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