Decision Support for an Optimal Choice of Subsidised Routes in Air Transportation

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***Abstract*—In reaction to the deregulation of air transportation, countries have adopted different subsidy schemes to ensure accessibility of air services by small and/or remote regions. Subsidy schemes such as Public Service Obligation (PSO) that are provided by countries in the European Economic Area (EEA), and the Essential Air Service (EAS) program in the USA aim to achieve an optimal network of subsidised routes based on defined criteria, for example, accessibility to a major city, advanced healthcare or an international airport. The aim of the work presented here is to develop a mathematical model that can assist decision-makers in selecting the optimal network of subsidised routes. We use a budget-constrained maximum coverage model that is capable of maximising multiple objectives, corresponding to different accessibility criteria. This paper also presents a method to estimate the cost of subsidising new routes. Sweden is used as a case study and we explicitly model two of the criteria used by Trafikverket (the Swedish Transport Administration). The results show that that it is possible to significantly improve the accessibility, without increasing the subsidisation cost; they also show that the model is capable of producing practically useful solutions and can be applied to other countries.**

***Keywords*—Decision Support; Public Service Obligation; Optimisation; Air Transportation**

The deregulation of air transportation (1978 and 1987 in the United States and Europe, respectively) gave airlines the liberty to choose new profitable routes to operate and abandon the unprofitable ones. Consequently, routes with insufficient passenger demand, although crucial in regional economic development, are often ignored by airlines [1], [2]. In reaction, countries adopted subsidy schemes to guarantee accessibility to and from small communities or regions with insufficient demand for commercial air services. Examples of subsidy schemes include Public Service Obligations (PSO) provided by countries in the European Economic Area (EEA), and the Essential Air Service (EAS) program in the United States. Subsidy schemes are implemented to provide scheduled air services in communities where commercial air services are considered unprofitable by airlines. These subsidised services usually aim to link a target community to a potential destination such as a hub airport or a major city. The routes can either be domestic or international; however, according to [3], 90% of subsidised routes are domestic.

The subsidy schemes in air transportation aim to achieve an efficient transportation network based on defined criteria, for example, accessibility to a) a major city, b) advanced health care, c) a hub or an international airport, d) a university, or e) a tourist site. Based on one or more of these criteria, authorities need to make decisions about which routes to subsidise. The criteria are usually specified as travel time-related targets. For example, it should be possible to access a capital city within four hours. There are variations in how these subsidy schemes are implemented because countries use different assessment methods for defining the subsidy scheme criteria and their associated targets. This is very evident among the EEA member states despite of the European regulations [4] that suggest a unified implementation of the subsidy scheme (PSO scheme) [5].

Apart from the criteria and the associated target, there may also be other requirements on the subsidised routes. According to [3], [6], the commonly used requirements on PSO routes are: (1) minimum number of round trips per day; (2) minimum seat capacity per day; (3) maximum number of stops; (4) time table requirements, for example, number of days per year with no service; (5) size of aircraft; (6) air emissions of specified substances; and (7) maximum one-way fares. In the United States, the EAS has requirements such as service with no more than one connection, flights at reasonable times taking into account the needs of passengers with connections, and aircraft seat capacity [7].

The set of defined criteria and targets of a subsidy scheme aim to achieve efficient air transportation services for the entire population. An efficient transportation network allows a society to achieve the largest possible amount of benefits from the available resources.

Achieving an optimal transportation network under a subsidy scheme involves making decisions about which routes to subsidise based on a budget, with respect to the defined criteria. Defining a criterion avoids ad-hoc decision-making by the authorities, eliminates wasteful resource allocation through inefficient transportation networks and is used as a foundation for efficient transportation service provision [6].

The aim of the work presented in this paper is to develop a decision-support tool that can assist decision-makers in selecting an optimal network of subsidised routes. The paper has three major contributions. First, we present an estimation method for the cost of subsidising new routes. This provides the data required by the model for assessing the selection of

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a new route to the network of subsidised routes. Secondly, we develop a budget-constrained optimisation model that can assess the current network and suggest an optimal network of subsidised routes. Thirdly, we use the model to evaluate the current PSO network in Sweden, and suggest a new set of routes that improve the accessibility.

The rest of the paper is as follows. Section I presents previous related work. Section II presents the method used; it includes an explanation of the basic modelling assumptions in Section II-A, the cost estimation in Section II-B, route-demand estimation in Section II-C, a reformulation of our problem as a *MaxCoverage problem* and the corresponding Integer Programming (IP) model (Section II-D and Section II-E, respectively), modelling approaches to multiple accessibility targets, a description of the case study and data in Sections II-F, II-G and II-H, respectively. The results in Section III are followed by the discussion and the conclusions in Sections IV.

I. Related work

Bråthen [6] developed a method for assessing the level of service (LOS) on individual subsidised routes (PSO routes) in Norway through comparison of the socio-economic profitability of the subsidised routes with the best-alternative mode of transportation. A situation close to social optimum may be achieved by setting wise subsidy scheme targets. Pita et al. [8] assessed the subsidised routes of Azores using an integrated flight-scheduling and fleet-assignment model. The objective of their optimisation model was to minimise the incurred social cost of satisfying a given target demand which is set as a subsidy scheme criteria.

Wittman [9] assessed the accessibility of available air service in United States metropolitan regions by evaluating their quantity and quality. He used a connectivity index to generate accessibility scores at a regional level, and proposed a methodology to construct U.S. regional airport catchment areas using the United States Census Bureau Primary Statistical Areas (PSAs). Grubesic and Wei used data-envelopment analysis with a geographic information system to evaluate the efficiency of EAS at the community level [10]. They also discussed policy implications and suggested strategies to improve the EAS program.

The debate of whether a subsidy scheme such as EAS is essential or superfluous has existed since the deregulation of airlines. Cunningham and Eckard [11] used hypothesis testing to statistically analyse the impact of using subsidies to provide air services to small communities. They compared the airfares and service levels in certain cities for the period of 1978 to 1984, and concluded that the EAS subsidy program was superfluous because it had a negligible improvement in the level of air services in small communities. However, a later study by Özcan [12] concluded that air passenger traffic is indeed essential as it contributes to the per-capita income of the communities. Özcan [12] used a 2-stage least-squares model to evaluate the economic contribution of EAS flights on small and remote U.S. communities. These two conflicting results, in different time periods, further motivate the need for continuous evaluation of the benefits of subsidy schemes.

There has been quite a lot of work analysing the PSO system and EAS system from various angles, for example, [6], [8], [9], [10], [11], [12], and an extensive literature compilation by [2]. However, the studies most similar and relevant for this paper are [13] and [14].

Flynn and Ratick [13] used a maximal-covering model to evaluate options for the continuance of the EAS program. The model used two objectives to maximise coverage and minimise the system-wide cost. Using a case study of communities in North and South Dakota (USA), the model selected an optimal EAS network with its associated population coverage and minimum total cost. The model further identified the communities, which would continue to receive services, which would have discontinued service, which needed more service and the type of service. Similar to our paper, the paper by Flynn and Ratick [13] also maximised the population covered/accessibility with consideration of the cost.

Pita et al. [14] presented a socially-oriented flight-scheduling and fleet-assignment (SFSFA) optimisation model. They called it an alternative style of cost-benefit analysis with application to the Norway PSO network. The model sought for a PSO network that minimises the social cost while satisfying the demand. The social cost accounted for the operating costs and revenues of all stakeholders, i.e., passengers, airlines, airports and government. Our paper is similar to [14] because it compares the existing network with the optimal network at a given budget.

This paper however differs from the previous work in four ways:

1) The model by Flynn and Ratick [13] was not designed to capture the operational characteristics of the present network but rather to assess alternative plans for future EAS networks. Our model can both assess the current network of subsidised flights and suggest an optimal network.
2) Instead of euclidean distance (like in [13]), we used ground transportation travel times such that the ground travel time to the airport is also considered.
3) Pita et al. [14] considers the existing PSO network (but not new possible PSO routes), their associated cost and demand, while this paper presents a method of estimating the cost of new and future subsidised routes.
4) In this study, we analyse the current PSO network in Sweden, and suggest ways of optimising it.

II. Method

The base for the decision-support tool is an optimisation model that selects the optimal set of subsidised routes that satisfies the defined criteria of a subsidy scheme.

A. Modelling assumptions

As mentioned previously, a subsidy scheme criterion is commonly associated with targets ensuring that some population can access a selected type of destination within a certain travel time, for example, if it is possible to reach the capital in less than four hours. People in a given population centre are considered as a single unit and they are assumed to make the same travel choice for each target; the population is aggregated into population centres, e.g. municipalities, and the ground travel time from these centres to the (centre of the) capital is calculated, for the different means of transportation. We illustrate this using an example in Fig. 1. For some municipality, it might be possible to travel by train, car, bus or plane; but for evaluation purposes, the mode offering the shortest travel time is of interest. Here, we consider adding travel options for the population by subsidising routes from existing Airport A to selected destinations, e.g. the capital. For example, consider one municipality where the quickest way to reach the capital currently takes five hours, by ground transportation (bus or train). By adding a subsidised route from a nearby Airport A to the capital, it may be possible to reduce the travel time to three hours, and thus achieve the defined target for that municipality.

We evaluate the quality (efficiency) of the suggested solutions by the associated increase in accessibility, which is obtained by counting the increase in the number of people that can take advantage of the benefits represented by the defined subsidy-scheme target. Considering a subsidised route, we categorise the journey into three phases: (1) Passengers travel from their population centres to the airport by ground transportation such as private cars, taxis or public transportation; (2) Flight from the departure airport to an arrival airport closest to the final destination. This phase includes the waiting and processing times at both airports; (3) The final phase is the possible use of ground transportation from the arrival airport to the final destination, unless the arrival airport is the final destination. The total travel time is the sum of the two ground travel times and the flight time. Thus, for each PSO target, the population in each center will choose the option that is within a given target time. Before solving the model (and adding PSO routes), it is possible to calculate the travel times for these options. Then, when a subsidised flight is added (e.g., through nearby Airport B in Fig. 1), the population in a center will utilise this new option if it improves the accessibility by satisfying a given target time.

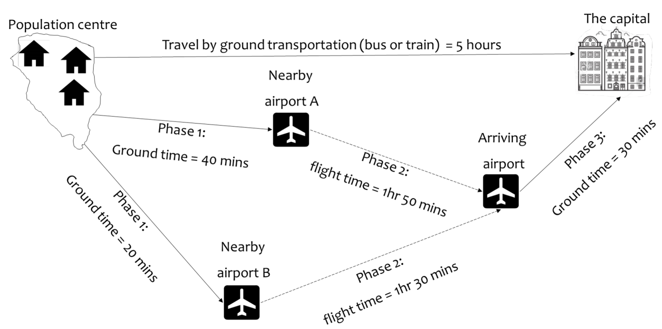

Figure 1: Effect of subsidised routes on travel options

B. Cost estimation

The cost of a subsidised route c_f (where a route is indexed by f) is the difference between the operating cost incurred by the associated airline and the total route-ticket revenue. Ticket revenue is the sum of airfares from the route demand (number of passengers) and it is generally proportional to the route demand. According to Swan and Adler [15], the flight operating cost can be approximated as a function of the available seat capacity and the total number of miles flown by an aircraft; their product gives the available seat miles (ASM) along a given route. We propose to estimate the cost of subsidising a route (i.e., Equation 1) using a linear regression model:

$$c_f = A + B \cdot Demand + C \cdot ASM + D \cdot (Demand/ASM) \tag{1}$$

The parameters A *to* D can be estimated by a least-squares estimation method using historical data on the existing routes. To obtain a better model, $Demand/ASM$, an interaction variable between the Demand and ASM, was used. This interaction variable was calculated as the Demand to ASM ratio.

C. Route-demand estimation

We assume that the ASM for both the current and new routes are known. The length of the route is estimated, and the available seat capacity in relation to the aircraft used along a given route is known. The cost of subsidising a route is dependent on its demand. Both the historical route demand and the cost of subsidising the current routes are known. However, to estimate the cost of subsidising a new possible route, we need to estimate its demand.

According to the basic gravity model used by [16], the total passenger volume between airports i and j can estimated using the following variables:

- Population P_{ij}: the product of the city populations P_i and P_j where the airports are located.
- Catchment size C_{ij}: the product of the populations C_i and C_j that is within 1 hour driving time of the two airports.
- Travel time T_{ij}: the average travel time between the two airports. This is the sum of the average ground access travel time for C_i and the flight time between the two airports.
- Stops S_{ij}: an indicator variable with 1 for one-stop routes and 0 for non-stop routes. This is an additional variable which was not used by [16].

We propose to use k-nearest neighbours (k-NN) regression, which is one of the simplest non-parametric methods [17] for estimation. It is non-parametric because it does not make any assumptions about the underlying data. We use the historical route data, i.e., passenger volumes y_o and the route characteristics/features x_o (i.e., the variables P_{ij}, C_{ij}, T_{ij} and S_{ij}) to estimate the passenger volumes y_N of the new possible route. The features x_N, also known as the prediction points of the new possible route are assumed to be known. The first step is to identify those observed passenger volumes y_o whose features x_o are most similar to the prediction point x_N; the similarity is measured using the euclidean-distance function $\sqrt{(\sum_{i=1}^{n}(x_N^i - x_o^i)^2}$ on each observation with n features. The euclidean distances are used to rank the observed passenger volumes y_o in ascending order. The second step is to select the k observed passenger volumes y_o with the smallest ranks, hence the name k-nearest neighbours. The average of these k observed passenger volumes gives an estimate of the passenger volumes y_N for the new possible route. The appropriate value of k can be obtained using model validation measures such as mean absolute percent error (MAPE).

D. Reformulation as MaxCoverage problem

We formulate our subsidised route-choice problem as a *Budgeted Maximum Coverage problem*. The input to the Maximum-Coverage problem consists of a set U (the *universe*), a collection $\mathcal{S}$ of subsets of U and a number K; the goal is to pick K subsets from $\mathcal{S}$ whose union contains as many elements of U as possible (i.e., covers as much of the universe as possible – hence the name MaxCoverage). In the Budgeted MaxCoverage problem, each element $u \in U$ has a weight w_u, every subset $s \in S$ has a cost c_s and instead of K, a budget B is used to limit the number of selected subsets. The goal is to pick the subsets from $\mathcal{S}$, maximising the total weight of the elements in the union of the subsets such that their total cost does not exceed the budget B. It is convenient to represent an instance of the MaxCoverage problem with a $|U| \times |\mathcal{S}|$ membership matrix A where each row corresponds to an element of U and each column s represents a subset in $\mathcal{S}$, and whose entry $A_{us} = 1$ or 0 depending on whether element $u \in s$ or not.

Our PSO route choice problem reduces to the Budgeted MaxCoverage problem as follows: The universe is the set P of the population centers; the weight D_p of a center $p \in P$ is the number of people living in p. The potential PSO routes F define the subsets of P: for each route $f \in F$, there is a subset $P_f \subseteq P$ of the population centers that are served by f within the target travel time. That is, we create the $|P| \times |F|$ matrix A whose entry $A_{pf} = 1$ or 0 depending on whether f provides a way to reach the destination from p within a given time or not.

E. IP for MaxCoverage

We use the following IP model:

$$\max\ Z = \sum_{p \in P} D_p y_p$$

subject to

$$\sum_{f \in F} c_f x_f \leq B$$

$$y_p \leq \sum_{f \in F} A_{pf} x_f \quad \forall p \in P$$

$$y_p \in \{0,1\} \quad \forall p \in P$$

$$x_f \in \{0,1\} \quad \forall f \in F$$

Here B is the given budget and x_f is the decision variable for whether the route f is chosen ($x_f = 1$) or not ($x_f = 0$). The constraint $\sum_{f \in F} c_f x_f \leq B$ ensures that the cost of the selected routes does not exceed B. The constraints $y_p \leq \sum_{f \in F} A_{pf} x_f$ work as follows: if no route serves a population center p, then the pth row in Ax is equal to 0, so the pth constraint in $y \leq Ax$ reads $y_p \leq 0$, implying that $y_p = 0$ and D_p is not counted in the objective function; on the contrary, if at least one route serves p, then the pth row in Ax is at least 1, so y_p may be equal to 1 (and it actually will be equal to 1, since it can only be 0 or 1) and D_p is counted towards the served population.

The demand and cost estimation is done under the assumption that the routes are independent, i.e. adding one specific PSO route, will not affect the demand for other PSO routes. While this is a reasonable assumption in most cases, it is not true for multiple routes through one and the same airport. These solutions might occur however, since adding one non-stop route and one one-stop route through one specific airport might be the mathematically optimal choice, given the independence assumption. Given a set of airports K and a set O_{fk} of flights f that pass through each airport k, we ensure that each airport has most one route passing through it by adding a constraint:

$$\sum_{f \in O_{fk}} x_f \leq 1 \quad \forall k \in K.$$

F. Multiple accessibility targets

When choosing PSO routes, it may be beneficial to look at more than one accessibility target. We consider several objectives, based on the required time limit to reach the destination. For example, for $t = 4, 5$ we define Z^t as the number of people who can reach the destination within t hours. Considering more than one target results in multi-objective optimisation, as we want Z^t to be large for all t.

There are several standard approaches for handling multiple objectives:

- Lexicographic optimisation [18] is used when it is possible to order the objective functions according to priority, so the higher-priority objectives are optimised before lower priority objectives. In our case, we may say that Z^5 is more important than Z^4 (optimising for the worst time is more important). We first solve the problem of maximising Z^5 and let Z^{5*} be the value of the optimal solution, then we add $Z^5 = Z^{5*}$ as a constraint to the problem, and solve the problem of maximising Z^4.
- Weighted optimisation [19] uses a linear combination of the objective functions. It is applied when it is difficult to organise the targets based on priority. One natural weighting scheme is to have equal weights for the targets, optimising, in our case $Z^4 + Z^5$.

G. Case study

To test our model, we use the PSO scheme in Sweden as a case study. The advertising and calls for PSO routes are done by Trafikverket (the Swedish Transport Authority), which assesses the need for subsidised routes by municipalities based on eight criteria [20]. We consider two of these eight criteria, i.e., access to Stockholm (the possibility for the population in the municipality to reach the capital within a target time), and access to an international airport. This generates five targets to be used in this study, which are presented in Table I. We calculate the accessibility for the situation without PSO routes and for the base case (the eleven current routes). We also use the model to find the optimal set of routes while varying the budget, and compare the obtained results.

H. Data

The data used in this study were gathered from multiple sources. Statistics Sweden [21] was the source of data on the Swedish geographical boundaries that were used in the study. This data included variables such as population-centre name known as "tätort", the municipality where they are located, location coordinates and the population. As of April 2016, there are 290 municipalities and 1979 population centres [22].

The data on airports were obtained from [23]. Only airports with an IATA code were included on assumption that it would be too expensive to open a PSO route to/from an airport that had not previously accommodated commercial traffic. The candidate PSO routes used in this paper included both non-stop and one-stop routes to Stockholm-Arlanda airport. In the base case (the situation at the time of the study), there are eight airports as origins for current PSO routes to Stockholm-Arlanda airport; this forms two non-stop and nine one-stop PSO routes. Furthermore, there are ten additional airports that could accommodate PSO routes, giving a total of 799 possible PSO routes to choose from. The current commercial flights was obtained from [24] whereas the possible PSO routes and current PSO routes were retrieved from [23] and [25], respectively.

The computation of ground travel times by private transportation to the airport was done using ArcMap's Network Analyst Toolbox. For longer trips such as trips to the capital, travel times by public transportation from the TravelTime platform [26] were used. The minimum travel times for each journey were obtained by considering various journey start times from 05:00 am to 11:00 am.

All the flight times were calculated based on a Saab 340 aircraft because it is the most common aircraft used along subsidised routes in Sweden. The *R* software was used to web scrap the great circle mapper website [27] for flight times of various routes.

Demand data: The annual historical passenger volume from 2000 to 2016 was obtained from Trafikverket; this gave us a dataset of 170 observations. The population data from and the estimated total travel time were used to estimate the variables P_{ij}, C_{ij}, T_{ij}; the variable S_{ij} was obtained from the characteristic of the route. These four variables were used as features x_o in the k-NN regression to estimate the route demand.

We chose k based on a 10-fold cross-validation, where the dataset was randomly duplicated into ten datasets, each with a different training sub-dataset of 153 observations and a testing sub-dataset of 17 observations. The lowest MAPE was 13.6% and it corresponded to $k = 2$ (see Table II). In Figure 2, the scatter plot of observed and estimated demand volumes for 2016 shows how well the 2-NN model can be used to estimate route demand. Therefore, the route demand for non-existing routes were estimated using a 2-NN model.

Cost data: For cost estimation, historical route data on the annual subsidisation cost (in Swedish Krona-SEK) for the period from 2011 to 2016, the corresponding passenger demand (number of people) and an indicator variable for one-stop and non-stop routes were obtained from an interview with Trafikverket. Additionally, the annual ASM was calculated as the product of the average number of seats of the aircraft used, flight frequencies per week and the annual miles travelled. From the Trafikverket report [25], some routes had zero annual subsidisation cost for time periods where the routes had agreements for no-subsidies; the zeroes were not considered as part of the data because our focus was to estimate the cost

TABLE I: THE CRITERIA AND TARGETS CONSIDERED IN THE STUDY

Accessibility criterion	Target
To Stockholm	1. Less than 4 hours
	2. Less than 5 hours
	3. Asynchronously prioritise Target 2 over Target 1
To an international airport[a]	4. Less than 4 hours
To Stockholm and an international airport[a]	5. Combine Target 1 and Target 4 using weights

[a] The international airports considered by Trafikverket are Stockholm-Arlanda, Gothenburg-Landvetter, Copenhagen Kastrup, Oslo Gardermoen and Trondheim Vaernes.

TABLE II: MAPE (%) FOR DIFFERENT VALUES OF K

k	1	**2**	3	4	5	6	7	8	9	10
MAPE	16.61	**13.55**	14.53	14.94	15.41	15.84	16.95	17.31	17.65	17.93

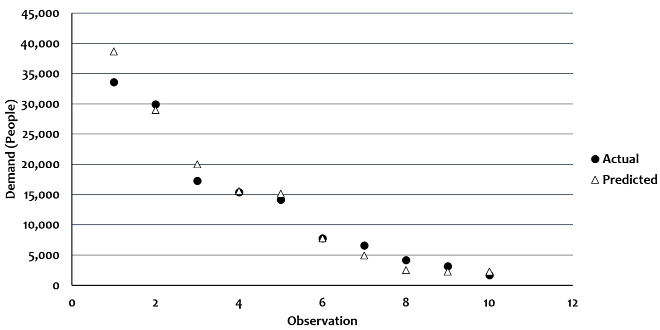

Figure 2: A scatter plot of actual and estimated demand volumes for 2016 using 2-NN

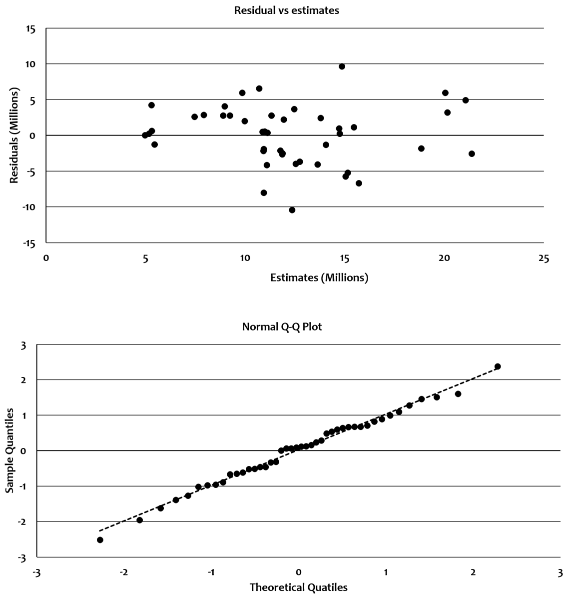

Figure 3: Residual plots for cost estimates.

of subsidisation. Additionally, having zeroes in the data gave poor cost estimates for new routes. This resulted in a dataset of 44 observations.

The route $Demand$, $log(ASM)$ and $Demand/ASM\ ratio$ were used as the explanatory variables in the cost estimation model, i.e. Equation 1. The ASM has large values; therefore for easier interpretation of the results, the logarithm of ASM was used. A step-wise linear regression was run to select the best combination of these three explanatory variables that can be included in the model; including all the three explanatory variables gave the highest Adjusted R-square of 90.8%.

The estimated parameters were $B = 658$, $C = 519,000$ and $D = -1.16e-5$. For our case, including the constant A gave negative cost estimates and thus it was excluded from the final model. The standard errors for parameters B, C and D were 134, $84,500$ and $1.76e-6$ respectively; all the three parameter estimates were significant at 99% level of confidence. The out-of-sample prediction accuracy of the model was tested using the leave-one-out cross-validation [28]. Fig. 3 shows that the model residuals are randomly scattered around zero and normally distributed, indicating that the model predictions would on average be correct, and not systematically too high or too low.

To provide a good base-case for comparison, the cost of the current eleven PSO routes[1] was re-estimated using our model and it produced a subsidisation cost of SEK 154.8 million.

The model had 2778 binary variables and 3200 constraints. It was implemented using AMPL (version 20171122) and solved with CPLEX 12.7.1.0 on a computational server. All problems were solved to optimality in a few seconds.

III. Results

A. Accessibility without PSO routes

Given our assumptions, and input data, 97.04% and 99% of the population can already reach Stockholm within four and five hours respectively, either by ground transportation or by a commercial flight. This implies that PSO route(s) can be used to increase the accessibility for the remaining 2.96% and 1% of the population, i.e., 295,371 and 99,788 people, respectively. Additionally, 98.39% of the population can already access an international airport within four hours, making it possible to improve the situation for 1.6% (i.e., 159,660) of the population. These remaining populations belong to small communities, which require accessibility to certain destinations and are the target for subsidised routes. Trafikverket aims to improve the accessibility for these communities. Therefore, the results will focus on the improvement measured by how many more people that can access the considered destinations within a target time.

B. Accessibility with current PSO routes

As can be seen in Fig. 4, the introduction of the current eleven PSO routes improves the accessibility for an additional 25,945 people to reach Stockholm within four hours, and 59,873 people to reach Stockholm within five hours. In the case of accessibility to an international airport within four hours, the current PSO routes improve the accessibility for 19,958 people.

The current eleven PSO routes have an estimated subsidisation cost of SEK 154.8 million. Below, this is compared to optimal solutions with a budget constraint of SEK 150.0 million.

C. Accessibility with optimal PSO routes

1) Targets 1 and 2: Targets 1 and 2 aim to separately maximise the number of people that reaches Stockholm in less than or equal to 4 hours, and less than or equal to 5 hours, respectively. Each target gives a single optimisation objective, i.e., to maximise the number of people covered within the target time.

The selected optimal set of routes given the considered criteria and assumptions, gives the results shown in Fig. 4. Replacing nine of the current PSO routes with nine new routes but at a cheaper cost of SEK 145.6 million, increased the number of people served with respect to Target 1 to 128,175. On the other hand, replacing eight (all one-stop routes) of the current PSO routes with eight (two one-stop routes and six non-stop routes) new routes would provide accessibility to 91,237 people with respect to Target 2, at a cost of SEK 146.1 million.

2) Target 3: Targets 1 and 2 are asynchronously (i.e., one after the other) considered to form Target 3, which results into the maximisation of two objectives. These two targets are organised in a hierarchical order with Target 2 prioritised higher than Target 1. This order can be motivated by the

[1]The current eleven PSO routes include are: Gällivare-Arvidsjaur-Arlanda, Torsby-Hagfors-Arlanda, Hemavan-Vilhelmina-Arlanda, Hemavan-Lycksele-Arlanda, Hemavan-Kramfors-Arlanda, Lycksele-Kramfors-Arlanda, Vilhelmina-Lycksele-Arlanda, Sveg-Mora-Arlanda, Sveg-Arlanda, Vilhelmina-Arlanda, Vilhelmina-Kramfors-Arlanda.

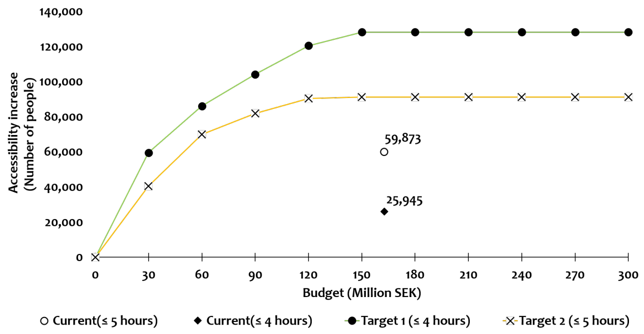

Figure 4: Improvement in accessibility of Targets 1 and 2 for each PSO budget value

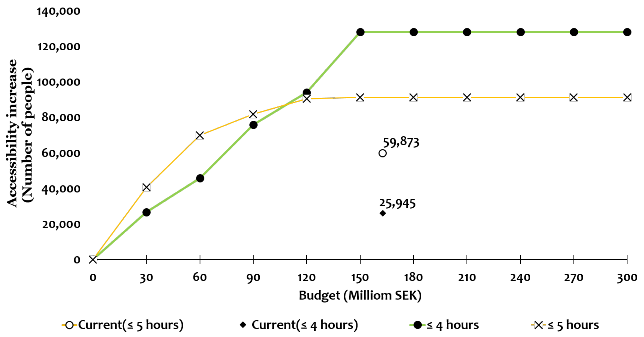

Figure 5: Improvement in accessibility for each PSO budget value used for Target 3.

need to first serve the population with longer travel times to Stockholm. We therefore use lexicographic optimisation to first maximise the accessibility for Target 2, followed by maximising the accessibility for Target 1.

Fig. 5 presents the improvement in accessibility (increase in the number of people served) under Target 3, for various PSO budget values. Asynchronous consideration of Target 1 and Target 2 gives a different characteristic of the improvement in accessibility for Target 1 (Fig. 5) compared to when the model individually optimises for Target 1 (Fig. 4), now that Target 2 is prioritised first.

With a budget greater than SEK 90 million, less improvement in accessibility within five hours is possible hence the focus is turned to increasing the accessibility within four hours. Having a budget greater than SEK 150 million would not increase the number of people whose accessibility is improved both within five hours and within four hours. In comparison to Target 1 and 2, optimising for Target 3 results in the same increase in the number of people served, with a PSO-budget of SEK 150 million. With this budget, the set of optimal routes under Target 3 is the same as that of Target 1.

3) Target 4: When optimising for Target 4, the model switches focus from trying to improve the accessibility to Stockholm, and instead tries to ensure that as many people as possible can reach an international airport within four hours. From a modelling perspective, this means focusing on multiple destinations, instead of just one.

Fig. 6 shows that having a budget of SEK 150 million

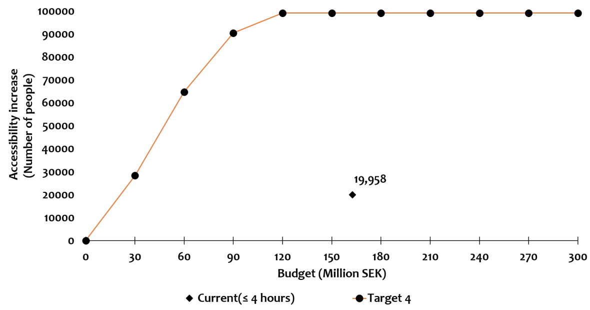

Figure 6: Improvement in accessibility under Target 4 for various PSO-budget values

improves the accessibility to an international airport for 99,137 people. The cost for the eight PSO routes in the solution amounts to 116.4 million, which is a significant improvement to the base case (which has eleven routes at a cost of 154.8 million).

4) Target 5: Target 5 is a combination of Targets 1 and 4, and it aims to maximise the number of people that can: (1) access Stockholm in less than 4 hours, and (2) access an international airport in less than four hours. Thus it is a combination of two different criteria but instead of using lexicographic optimisation, we choose to weight the two different objectives. Typically, weights are chosen by a decision-maker, who will make use of his or her expert knowledge in order to select proper values. When a set of results has been obtained, the weights can be altered to get new solutions to compare with. To illustrate this, we use a maximum budget of SEK 120 million and various weights; given an objective function as $W_t{\cdot}Target\ 1{+}(1{-}W_t){\cdot}Target\ 4$, lower weight parameter-W_t favours Target 4 more than Target 1 and vice-versa.

The value of $W_t = 0.1$ gives an improvement in accessibility for 115,123 and 97,026 people, to Stockholm and an international airport within 4 hours, respectively. However, a value of $W_t = 0.9$ results into a higher improvement in accessibility to Stockholm within 4 hours (i.e., 120,177 people) while there is a reduction in the number of people with improved accessibility to an international airport within 4 hours (i.e., 91,983 people).

IV. Discussion and Conclusion

The results indicate that the accessibility without PSO routes, as evaluated by the selected targets, is already quite good as more than 97% of the population can be considered covered by existing travel options. The remaining 300,000 people who would benefit from PSO routes are however significant, and are the focus for introducing PSO routes. The results also indicate that the current system of PSO routes increases the number of people who can conveniently access Stockholm central, and an international airport, but that it is possible to significantly improve this number, without increasing the cost.

The current budget seems to be appropriately set as the optimisation model cannot improve the situation with an increased budget. There are several possible explanations as to why the routes suggested by the optimisation model improve the accessibility so much more than the current routes. First of all, we only consider a subset of the criteria used by Trafikverket. It is reasonable to assume that the accessibility for some population centres might be worse when studying additional criteria, giving incentives to add routes which are not detected by our model. Secondly, some of the routes that can be used by the model might induce set-up costs, which are not considered. Still, the analysis made here clearly indicates that it might be possible to improve the accessibility significantly, using the same budget as today.

The case study suggests differences when PSO targets are considered asynchronously and simultaneously versus when they are considered individually. Although the model is tested using a case study of Sweden, the flexibility demonstrated by being able to consider different targets (i.e., accessibility to airports and/or capital city, and target travel times) means that the model can be applied to other countries with subsidy schemes in air transportation, for example PSO scheme in Europe and EAS scheme in the USA.

It can be concluded that the optimisation-based decision support tool that is developed in this study can be used to evaluate subsidy systems in air transportation. However, it can still be improved through further research. For example, more detailed flight scheduling, improved demand and cost modelling would increase the value of the information that can be produced using the model. It would also be interesting to rank the different criteria of a subsidy scheme based on the social benefits; this rank could also be used to compare the subsidy schemes of two or more countries.

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