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Baggage dissociation for sustainable air travel: Design study of ground baggage distribution networks

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ABSTRACT

Dissociation of passenger travel from baggage delivery has been proposed as one of the radical innovations in future air travel. This concept is still relatively new and largely unexplored, so there are many issues that need to be resolved. For instance, a complete end-to-end baggage dissociation will require the ground distribution networks to deliver passenger luggage to and from the departing and arriving airports. This paper proposes to design such networks as the existing parcel delivery networks. In particular, baggage sorting centers (BSCs) can serve as local hubs for creasing a scalable, multi-level topology of the delivery network in order to manage baggage flows in a given geographical area around the selected airports. Assuming the population density as a proxy for estimating the baggage delivery service demands, the optimum locations of BSCs are determined by formulating and solving the standard p-median and the maximal covering location problems. The numerical results were obtained for Greater London, and also for the whole UK assuming all its major civilian airports. The Greater London area could be served by 36 BSCs to achieve a full service coverage. The 90% service coverage of the whole UK can be achieved by about the same number of BSCs, provided that the coverage distance is increased. In practice, the actual number of required BSCs crucially depends on the operational and capital costs, and the maximum processing capacity of each BSC. These findings have direct implications on the long-term planning and innovations in future air transport.

Introduction

The largest and the busiest airports are struggling to meet the increasing travel demands, since they were dimensioned to handle a certain maximum number of arriving and departing flights per day (Snowdon et al., 1998). Even at busy airports, the number of flights and passengers and the luggage volumes vary substantially in the course of the day as shown in Fig. 1 for the case of four main London airports in the UK. The busy hours with peak demand for the airport services determine the required airport capacity. Moreover, costly delays negatively affect the travel experience (Zhang & Zhang, 2006; Wang and Loo, 2019), which has a significant impact on sustainability of airports and air transport in general (Li & Loo, 2016). For instance, the baggage delivery systems at airports had to handle 4 billion travelers and 4.27 billion luggage in 2018 alone (SITA, 2019). Moreover, there will be more than 20 airports operating near their capacity limits by 2035, compared to only 3 such airports in 2012 (Dg Mobility and Transport, 2015).

A new concept of dissociating passengers from delivery of their luggage has been recently proposed as a possible solution to lacking airport capacity. The idea originated in one of the Baggage Working Group meetings of the International Air Transport Association (IATA) in 2013 (Loskot & Ball, 2015). The baggage dissociation envisions future air travel when passengers will be incentivized to travel independently of their heavy luggage (Al-Hilfi et al., 2018). The ultimate aim is to send heavy luggage from the point of departure to the final destination using separate delivery channels. Passenger luggage would be collected from their premises shortly before their departure to the airport, or passengers could drop their luggage at the baggage collection points established, for example, in local supermarkets and post offices. The luggage should be delivered to the final destination shortly after the arrival of passengers. Such end-to-end baggage dissociation will require not only providing many new baggage delivery services around and at the airports, but also allocating extra capacity to allow delivering baggage on

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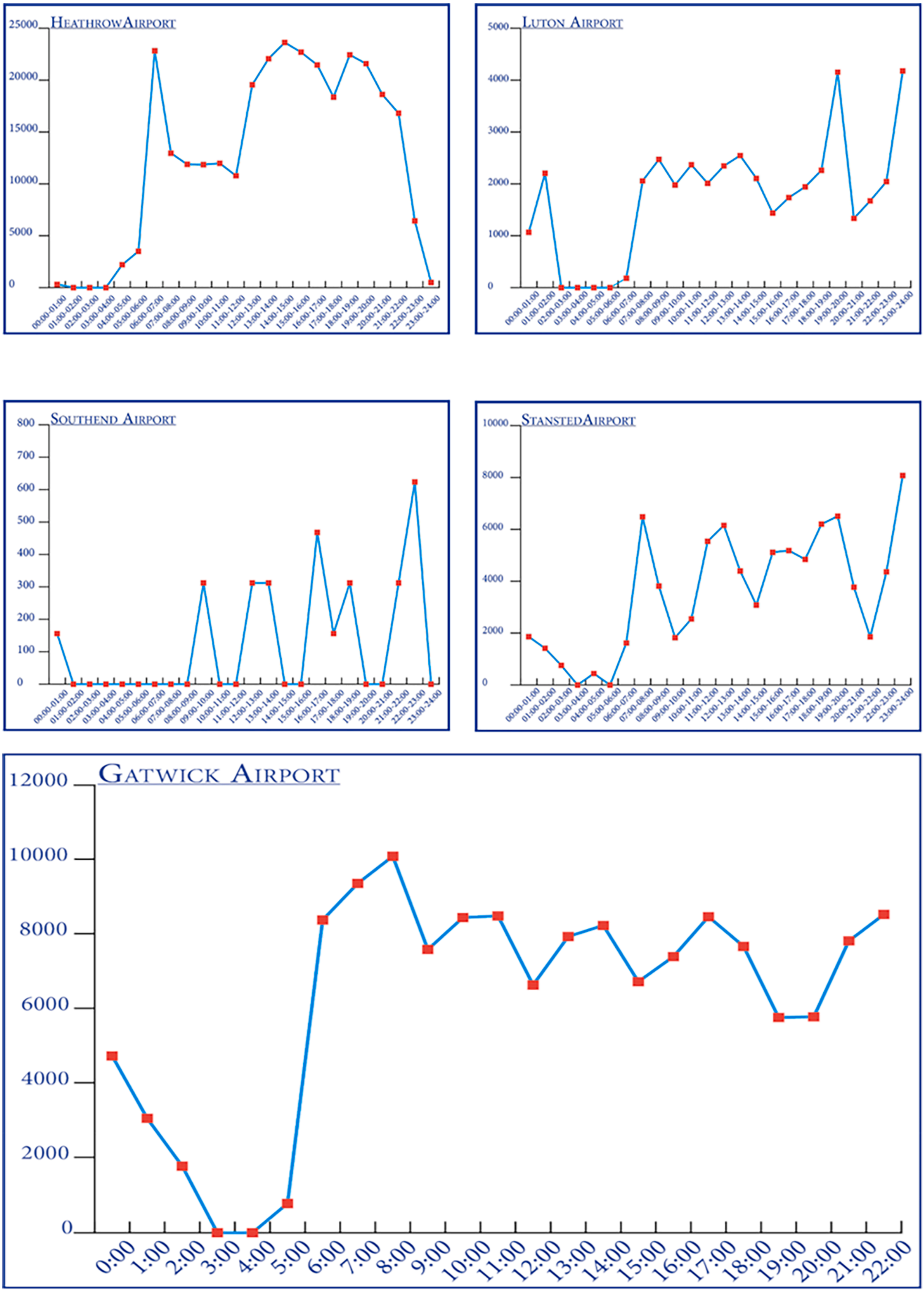

Fig. 1. The daily variations of the number of arriving passengers at the selected airports in London, UK.

dedicated flights.

There are still many unsolved challenges in realizing baggage dissociation (Al-Hilfi et al., 2018). It is also important to understand the drivers of such a disruptive change. The present consensus seems to be that baggage dissociation can substantially enhance the travel experience by avoiding carrying heavy luggage. Passengers can be then encouraged to use more ecological public transport, which can solve the curb-side congestion at airports during peak hours. The other benefits are simplified check-in and arrival procedures as well as designing new passenger-only airports, terminals and aircrafts. Passenger-only aircraft would be lighter, faster, and more fuel efficient, which provides new opportunities for aircraft manufacturers. On the other hand, baggage dissociation creates many new issues concerning security, safety, insurance, and business planning. It will require creating or modifying the supporting services, processes, and infrastructure. For instance, an overlay network of flights dedicated to delivering luggage may need to be established.

The baggage dissociation in the ground segment must be considered before attempting to provide the complete end-to-end dissociation service. At present, baggage delivery services to and from the airports are offered by a few private companies in some cities. Several major airlines offer such services for an extra fee. Although delivery of delayed luggage from the arrival airport to passenger premises is offered by default by most airlines, it is a special and small-scale service provided over a very simple distribution network.

The basic concept of baggage dissociation was introduced in (Loskot & Ball, 2015). The departing and arrival flights data at the largest airport hubs collected over one week in July 2016 were compared and analyzed in (Al-Hilfi & Loskot, 2016). A novel concept of satellite passenger terminals that can alleviate the airport capacity problems and directly benefit from baggage dissociation was presented in (Al-Hilfi & Loskot, 2017). The paper (Al-Hilfi et al., 2018) outlined the challenges and benefits of baggage dissociation and estimated expected volumes of baggage flows to and from the airports serving Greater London in the UK.

In this paper, our objective is to design a hierarchical two-tier baggage ground distribution network considering the scenario of six airports serving Greater London, and then the scenario involving all main civilian airports across the UK. In particular, assuming the population density to estimate the baggage delivery service demands, the optimal locations of baggage sorting centers (BSCs) are determined by formulating and solving the standard location optimization problems. Numerical results can be then evaluated in light of the anticipated future developments in air transport.

The specific contributions of this paper are:

1. We design a two-tier distribution network to enable new ground baggage delivery services around main airports, and determine the optimum locations of BSCs to offer the required level of service in given geographical areas.
2. We identify the BSC locations that are more critical, since they appear in different design strategies. In addition, we determine which BSCs can be shared by multiple airports in order to reduce the capital costs.
3. The case studies provide insights for policy and decision makes about the infrastructure needs and highlight the key issues involved in offering new ground baggage distribution services.

The rest of this paper is structured as follows. Baggage ground distribution networks are introduced in Section 2. The optimization problems for optimum placement of BSCs are formulated in Section 3. The case studies are presented in Section 4. The results are discussed and evaluated in Section 5. Finally, Section 6 concludes the paper.

Baggage ground distribution networks

The concept of baggage dissociation could be included into Transportation-as-as-Service (TaaS) and Mobility-as-a-Service (MaaS), which intend to provide modern integrated transport services in highly populated urban areas (Jang et al., 2021). Their aim is to provide a better travel experience while benefiting from increasingly popular goods distribution networks (Goodall et al., 2017). The IATA promotes the development of a Baggage-as-a-Service (BaaS) ecosystem to provide comprehensive services related to baggage handling and delivery in air transport. Extending BaaS with baggage dissociation services will likely forever change how the personal travel is organized and perceived. Provided that luggage can be delivered end-to-end and completely independently from passenger travel, its delivery becomes akin to parcel delivery. Since parcel delivery services and the underlying infrastructure have been evolving over decades, they are already well established. They can inspire the design of baggage delivery services to enable a new era of travel, similarly to as the online retailing stimulated expansion of the logistics networks (Xing et al., 2011).

The dissociation of passenger travel and baggage delivery can be realized only within the ground segment (to and from the airports), only in the air segment (passengers and their luggage can be put on different flights), or as a complete end-to-end service. The main challenge of any baggage dissociation service is reconciliation of passengers with their luggage at the destination. This will require adding sufficient storage capacity for luggage at airports, or providing such storage outside the airports closer to passenger premises in residential areas and city centers. The latter is preferred, since it can be used regardless whether passenger or luggage arrived first. This leads us to the following reasoning.

- Baggage dissociation in air segment causes the reconciliation problem at the destination airport.
- The reconciliation problem at the destination airport can be resolved by offering off-airport baggage ground distribution service.
- The baggage ground distribution network provided around the destination airport can be also utilized by passengers departing from the same airport.

In this paper, we only consider the design of ground baggage distribution networks. The ground segment is utilized to collect and deliver luggage from passenger premises to the departure airport, and to also bring luggage from the arrival airport back to passengers after they have reached their final destination.

Any flow-type network generally faces three main challenges: scalability, congestion, and management of transport resources. These issues are strongly affected by the adopted network architecture and topology. It is common to design transport networks with multiple levels of hierarchy, so that high-capacity hubs at the center are served by the last-mile delivery sub-networks at edges. However, since providing network services in sparsely populated areas is usually not economically viable, the ubiquitous service provisioning generally requires appropriate government policies and incentives.

Hence, it is useful to understand how parcel delivery networks are organized and structured, and then reuse these principles for designing ground baggage distribution networks. In particular, parcel delivery networks have a distinct hierarchical topology (Baumung et al., 2015). The consolidation centers or consolidation points (CP) and distribution stations (DS) are both crucial for achieving the delivery efficiency. The delivery vehicles are stationed at distribution or delivery centers to provide the last-mile delivery. The sorting centers (SC) act as gateways for parcel delivery to and from the distribution centers, and they are interconnected via a network of long-haul transportation links and hubs. Moreover, whereas the last-mile sub-networks are often in operation during the day, from early morning until late evening, the long-haul transportation networks for delivering parcels between DCs are utilized mainly overnight.

The parcel delivery networks consist of the following sub-networks (Cetiner, 2010).

- Mail collection sub-network is used for collecting and delivering letters and parcels to sorting centers. For larger geographical areas, consolidation points (CoP) can be used to switch from small to bigger delivery vehicles before reaching the sorting centers.
- The sorting centers (SC) are large and often fully automated facilities. They perform sorting of the incoming mail, and route it towards destination sorting centers, which then provide last-mile delivery to a final destination. The SCs are interconnected by long-haul transportation links utilizing larger vehicles for consolidated delivery among hubs either by road and rail, or by air and road.
- The distribution sub-network is responsible for distributing mail from sorting centers to mini-hubs referred to as delivery stations (DS) for letters, and delivery bases (DB) for parcels. They perform final sorting towards the assigned delivery districts (DD).
- The last-mile sub-network within every delivery district is served by a postal worker over a pre-defined route in order to make the final delivery.

The parcel delivery networks are usually designed in several steps. In the first step, the decision is made on the number and location of network hubs (SC and DS). The parcel flows are then optimized in the second step. The country-wide parcel delivery service usually relies on 10′s of sorting centers, 100′s of delivery stations, and 1000′s of delivery vehicles to reach the capacity of about 100′s millions of parcels delivered every year. The corresponding optimization problems for designing parcel delivery networks are parameterized by a large number of variables and constraints expressing various requirements. Even at such large scales, and assuming multiple conflicting objectives, which give rise to various trade-offs, the optimization problems can be often solved efficiently (Campbell & O'Kelly, 2012). The solutions of these optimization problems yield more specific design requirements such as the required number of vehicles, the route to be travelled during delivery, scheduling the deliveries, and the customers to be visited.

Design of baggage distribution networks

The envisioned baggage ground delivery network inspired by the parcel delivery network is depicted in Fig. 2. The network needs to have at least two-tier topology. It should also fully exploit the existing baggage handling systems (BHS) at airports. The BHS perform the first level sorting of baggage arriving to airports, and the routing towards appropriate baggage sorting centers (BSCs) outside the airport. The BSCs

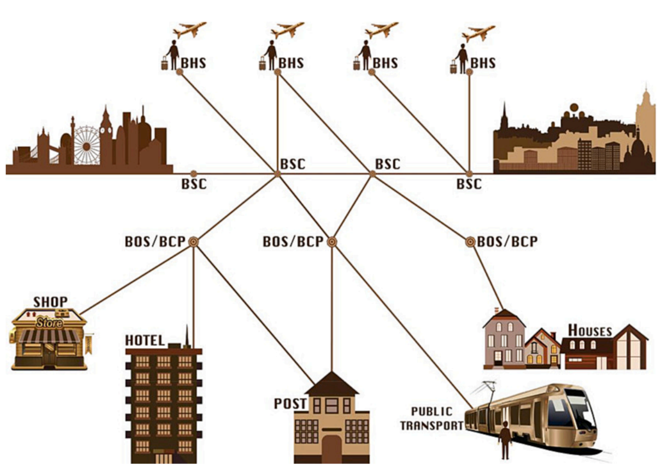

Fig. 2. The architecture of baggage collection and distribution ground network in urban areas.

perform the second-level sorting, and they can be shared by multiple nearby airports. The BSCs can also provide longer-term storage of baggage, since sufficient capacity is not normally available at the airport's BHS. In case there are multiple airports within the same geographical area, baggage should never be routed directly between BHS, but always through a BSC. Likewise, baggage destined for other cities would be routed via a BSC sub-network. Moreover, different service classes with different routing, delivery delays and pricing levels can be offered for high-priority and leisure passengers.

The BSCs feed directly into the second-tier sub-networks formed by the baggage delivery stations (BDS) for the last-mile delivery. As before, BDS are always connected via BSCs. The transport capacities between BHS and BSCs, between different BSCs, and between BSCs and BDS need to be determined carefully. Baggage transport can be realized, for example, by trains and dedicated truck vehicles. The BSCs must be spread out throughout the city in order to provide sufficient service coverage matching the service demand in the area. The baggage delivery service also requires defining the admissible delivery end-points such as homes, shopping malls, stores, post offices, and hotels (Hakimi, 1965). This provides another opportunity for creating differentiated services with different pricing levels.

Methodology

The design of baggage delivery networks is fundamentally a logistics problem. It requires defining baggage flows to and from the airports with intermediate storage and sorting facilities under qualitative and quantitative service requirements. In this paper, the optimization problems are formulated to obtain the optimum locations of BSCs in baggage distribution networks in Greater London, and then also in the whole UK. This is the first crucial step towards designing new baggage delivery services and the supporting infrastructure. The BSC locations determine baggage flow patterns and their characteristics as well as the capital and operational costs. Therefore, the optimal placement and assignment of BSCs is critical for making new baggage delivery services to be economically and technically viable (Sule, 2001).

A baggage distribution network is a type of service network. These networks are usually designed using a two-stage decision process. The first step is to choose the optimal locations over a set of possible alternatives. In the second stage, the users are assigned to respective service facilities, so that the total operating costs of the network are minimized. The first stage decision is a general service location problem assuming the following key factors: size of the geographical area, distribution of users and demands in this area, and the service quality requirements (Eiselt & Laporte, 1995). The distances within the service area are either known, or they are estimated. Although the distribution and the number of service users are often not known, they can be estimated, for example, as being proportional to the population density. Moreover, there could already be existing service facilities in the area, and the task then becomes how to add more facilities or resources to increase the capacity for provisioning of the new service. In addition, it is important to choose suitable metrics for evaluating the expected service quality and accessibility.

The facility location problems were studied in the literature for decades. This led to various model variants, solution algorithms, and application areas (Campbell & O'Kelly, 2012.). Even then, assuming the transportation and logistics decisions in the facility location problems is increasingly attractive (Saldanha-da-Gama, 2022). Incorporating new elements and constraints improves the modeling accuracy with real-world features (Alumur et al., 2021). For instance, the location models and optimizations of drone delivery networks were investigated in (Chauhan et al., 2019). The development, evaluation, and benchmarking of the optimization algorithms for location problems are reported in (Wandelt et al., 2022).

The general facility location problem can be defined assuming any of the following four location models and their combinations (Hakimi, 1964).

- Analytic modeling approach adopts many simplifying assumptions such as a uniform distribution of the service demand, and equal costs for delivering the service at each service facility.
- Continuous model does not constrain locations of the service facilities, whereas the service demands are assumed to originate only at certain specific locations.
- Network modeling approach associates the users and service facilities with network nodes. The service provisioning costs are a function of the service link properties connecting the service demand locations to the service facilities.
- Discrete model assumes discrete locations for both the service demands and the service facilities. This approach leads to combinatorial optimization problems.

Discrete service facility location problems

In this paper, the optimum locations of BSCs for baggage ground distribution networks are determined as discrete service location problems. These designs usually associate weights with all the demand points as well as candidate locations of the service facilities. They can be formulated as the *p*-median or as the *p*-center location problem.

The p-median location optimization problem

The *p*-median problem is one of the most studied location optimization problems. It has been used for improving the service accessibility under limited resources (Daskin & Maass, 2015). The main objective of the *p*-median problem is to minimize a weighted sum of distances from all demand points to the opened *p* service facilities. The main assumptions are that the number of facilities *p* to be optimally located is given and fixed, and the service users are assigned to the geographically closest service facilities. The *p*-median problem was first defined to find the optimum locations of switching centers in a telecommunication network (Hakimi, 1965). Since then, many variants were considered in the literature for different scenarios such as optimally placing warehouses, industrial plants and other public facilities (Daskin, 1995). It was also used to station the minimum number of police cars to patrol a highway network (ReVelle & Eiselt, 2005). More recent research efforts focused on improving the computational effectiveness by developing new solution strategies and algorithms (Church & Wang, 2020) including heuristic methods (Gwalani et al., 2021).

To define the *p*-median problem, let I denote a set of demand points of cardinality $n=|I|$, and J be the set of $p=|J|$ service facilities such as BSCs in the baggage delivery networks. An auxiliary variable, h_i, denotes the service demand at location, i, and d_{ij} denotes the distance between the demand point i and the service facility j. The symbol Y_{ij} denotes the normalized intensity of the service demand at point i assigned to facility j. The symbol x_j is a binary decision variable, which equals to 1, if the service facility is located at the candidate location j, and 0, otherwise. The *p*-median problem minimizes the objective:

$$\min \sum_{j\in J}\sum_{i\in I} h_i d_{ij} Y_{ij} \tag{1}$$

subject to:

$$\sum_{j\in J} Y_{ij} = 1\ \forall i\in I,\ \sum_{j\in J} x_j = p,\ Y_{ij}\leqslant x_j\ \forall i\in I, j\in J \tag{2}$$

where

$$x_j\in\{0,1\}\ \forall j\in J,\ \text{and},\ Y_{ij}\in\{0,1\}\ \forall i\in I, j\in J. \tag{3}$$

Objective (1) minimizes the demand-weighted total distance between the service facilities and the demand points, so passengers can access the respective BSCs. Constraints (2) ensure, respectively, that all the demand points are assigned, the number of service facilities to be located is fixed, and the facilities are assigned only to those sites that are still available. Conditions (3) restrict the decision variables to binary values. These conditions can be relaxed in order to allow that a demand point can be served by multiple service facilities, which creates alternatives in choosing the best BSCs, i.e.,

$$0\leqslant Y_{ij}\leqslant 1\ \forall i\in I, j\in J. \tag{4}$$

The p-center location optimization problem

This model is typically assumed in specifying the optimum locations of emergency service centers, cloud computing centers, hospitals, public transport stations, parks in the city, and similar such facilities. The *p*-center location optimization problem is a mini-max problem that determines the locations of *p* facilities minimizing the maximum distance over all the demand points to their nearest service facility (Çalık et al., 2019; Hakimi, 1965). Denote such a maximum distance as D, and let χ_{ij} be equal to 1, if the demand point i is served by the service facility j, and 0, otherwise. Consequently, the objective is:

$$\min D \tag{5}$$

subject to:

$$D\geqslant \sum_{j\in J} d_{ij}\chi_{ij}\ \forall i\in I,\ \sum_{j\in J} Y_{ij}\chi_{ij} = 1\ \forall i\in I,\ \chi_{ij}\leqslant Y_{ij}\ \forall i\neq j \tag{6}$$

$$\sum_{j\in J}\chi_{ij} = p\ \forall i\in I,\ \chi_{ij}\in\{0,1\}\ \forall i\in I, j\in J.$$

Constraints (6) are similar to the constraints assumed for the *p*-median problem. For $p = 1$, the optimization problem is referred to as an absolute center problem. If there are weights h_i associated with each demand point, for example, representing the achievable service quality at the service points, the constraint in (6) can be modified as (Daskin, 1995),

$$D\geqslant h_i \sum_{j\in J} d_{ij}\chi_{ij}\ \forall i\in I. \tag{7}$$

The maximal covering location optimization problem

Coverage is an important factor to consider when deciding locations of the service facilities in order to ensure that the service is reachable, i.e., within a specified maximum distance over the whole area of interest (Owen and Daskin, 1998). In terms of the resources availability, the covering problems can be categorized into the set covering location problems (SCLP) and the maximum covering location problems (MCLP) (García & Marín, 2015). Assuming that there are a limited number of service facilities, which can be deployed, the coverage model for the optimum facility locations has been defined in (Church & ReVelle, 1974). This model maximizes the demand coverage served by the facilities. Similarly to the classical *p*-median problem, the MCLP is a resource-constrained service facility location problem where the service level is highly sensitive to the number of service facilities opened. In the context of baggage distribution networks, the MCLP seeks the maximum user population that can be served within a stated distance or time by the limited number of BSCs.

Mathematically, the MCLP is formulated in terms of the set of demand points I, the set of potential facility locations J, the maximum distance (or, equivalently, the maximum time) to respond to the service request, S, for every service facility, the demand intensity w_i at point i, the distance d_{ij} between the facility j and the demand point i, and $N_i = \{ j \in \mathrm{J} \mid \mathrm{d_{ij}} \leq \mathrm{S} \}$ is the set of potential facility locations covering the demand point i. In addition, it is assumed that at most p service facilities can be opened to satisfy the service demands. The corresponding decision variables are defined as:

$$\chi_i = \begin{cases} 1, & \text{facility is located at point } i \\ 0, & \text{otherwise} \end{cases}, \text{ and, } Y_i = \begin{cases} 1, & \text{point } i \text{ is covered} \\ 0, & \text{otherwise} \end{cases}. \quad (8)$$

Note that the demand point i is covered, provided that, $Y_i = 1$, if $\exists j : \chi_j = 1$ and $j \in N_i$. The resulting optimization problem has the objective:

$$\max \sum_{i \in I} \chi_i Y_i \quad (9)$$

subject to:

$$\sum_{j \in N_i} \chi_j \geqslant Y_i \ \forall i \in I, \ \sum_{i \in I} \sum_{j \in N_i} \chi_j = p, \ \chi_j \in \{0,1\} \ \forall j \in J, \ Y_j \in \{0,1\} \ \forall j \in J. \quad (10)$$

Objective (9) maximizes the demand coverage, which can be served by all the service facilities, i.e., BSCs. Constraints (10) require, respectively, that at least one service facility is located within the pre-defined maximum distance from all the demand points i, the total number of service facilities is exactly equal to p, and the decision variables χ_i and Y_i are binary. The optimum locations of BSCs in the MCLP can be determined by maximizing the number of potential users served by the network within a pre-defined service radius.

Solving the optimization problems

Extensive efforts were expended to solve location optimization problems in computationally effective ways (Church & Wang, 2020). Nowadays, commercial optimization solvers such as CPLEX, Gurobi, Xpress and many others can deal with very large-scale such problems. However, in order to provide a framework that can be potentially used by a variety of different stakeholders, our choice was a free add-in for Microsoft Excel, called *OpenSolver*, which has been proven to be sufficient and effective in finding numerical solutions for the location optimization problems considered in our case studies.

OpenSolver is empowered by the open-access COIN-OR engine. It is a CBC solver, which has been successfully integrated into several modeling frameworks including AMPL, so the solutions can be readily compared with other commercial solvers. *OpenSolver* provides a powerful capability for solving both linear and mixed integer optimization problems (Mason & Dunning, 2010). The add-in has a built-in visualizer to import decision variables, objective functions, and constraints directly into the spreadsheet. It also supports fast re-solving after the model parameters have been updated. The users access the solver remotely. In particular, the actual calculation is submitted by *OpenSolver* add-in over the Internet to the computing server in a cloud. Once the server sends the results back, the results are automatically loaded into the spreadsheet. *OpenSolver* can check the obtained results for linearity, whether the objective behaves as expected, whether all the constraints are satisfied, and it alerts the user, if any problems were detected.

Case studies of baggage distribution network design

In this section, the design guidelines for optimally locating BSCs in the baggage ground distribution network are given assuming airports in the UK. In particular, the first scenario investigates the locations of BSCs in Greater London. It is a large and highly populated area served by six international airports. The second scenario is concerned with the optimum deployment of BSCs around the main civilian airports across the whole UK.

In both scenarios, the service demand intensity is assumed to be proportional to the population density. The BSC location problem is first discretized by defining a regular grid to partition the geographical area of interest into equal-size square cells to make the problem computationally tractable (Yu and Solvang, 2018). The partitioning was performed by the ArcGIS software. The minimum number of BSCs required to cover the whole area is determined by gradually increasing the number of BSCs until the desired coverage has been reached. It is assumed that there is at most one BSC located in each cell, and one BSC is allowed to serve multiple neighboring cells. In practice, the exact locations of BSCs can be further optimized by incorporating the real-road data in each cell.

The distances between demand sites and their respective BSCs are calculated using the Manhattan distance. Thus, having points (x_1, y_1) and (x_2, y_2), their distance is computed as, $|x_1 - x_2| + |y_1 - y_2|$, where $|.|$ denotes the absolute value.

Scenario 1: Greater London area

With the population of over 9 million, London is the largest city in the Western Europe, and it is also the largest aviation hub in the world. The six international airports around London are: Heathrow, Gatwick, Stansted, Luton, City, and Southend Airport. These airports handled over 177 million passengers in 2018, while Heathrow airport alone processed 53 million pieces of luggage. In our study (Al-Hilfi et al., 2018), it was estimated that the combined baggage flows among these airports and the city center would reach the intensity of 100′s of luggage per hour in both directions during busy hours on the weekdays in the summer.

The Greater London area was partitioned into 173 cells of size 5.5 km × 5.5 km. The number of cells was determined by initially considering the division into only 33 boroughs (small suburbs) using the ArcGIS. However, assuming only 33 cells cannot provide sufficient demand coverage. Moreover, excessive demand aggregation also negatively affects the accuracy and the confidence of the analysis. Therefore, the number of cells was gradually increased to 173 cells by further subdividing each of the 33 boroughs. The population sizes in each cell were then calculated by the ArcGIS using the population data obtained from (Greater London Authority, 2020).

The MLCP problem assumes the demand sites, $I=\{1,\ldots,173\}$, and a subset of the service facility sites (i.e., BSC), $J \subset I=\{s_1, s_2,\ldots, s_p\}$. The coverage matrix assumes that the preferred coverage of any BSC also includes the cells adjacent to above, below, left, and right. For instance, the BSC located in the cell 123 can respond to the service demands originated in the cells 122, 123, 124, 105, and 140 (see Fig. 3). The corresponding maximum coverage distance is $S = 5.5$ km.

The service coverage can now be maximized by optimizing the locations of $p=\{12, 24, 36, 48\}$ BSCs. The results are summarized in Fig. 3. The resulting demand coverage rates, which are defined as the absolute covering normalized by the total service demand, are equal to 69.4%, 95.95%, 99.97%, and 100%, respectively. Thus, nearly complete demand coverage can be already achieved for $p = 36$ BSCs. In practice, it is likely that some areas may tolerate larger maximum service distances, so the total number of BSCs required for providing the baggage distribution service in Greater London would be less than 36. However, the number of BSCs to be actually created is fundamentally limited by the capital and operational costs.

It is informative to compare the BSC locations provided by solving the MCLP problem to the locations obtained from solving the p-median problem. The p-median problem aims to provide high service accessibility by minimizing the average or the overall weighted travel distances to the nearest BSC for all users. As shown in Fig. 4, the more BSCs are deployed, the more accessible the service becomes for both the demand-weighted total distance and the demand-weighted average distance. These metrics reveal how the distances to the service facilities decrease with the number of these facilities.

The results in Figs. 3 and 4 capture the trade-off between the required investments and the potential service accessibility when designing the ground baggage distribution networks. Furthermore, it is obvious that the aims of these two location problems are different. The MCLP problem leads to more even allocations of BSCs across the whole area, whereas the p-median problem allocates more BSCs in densely

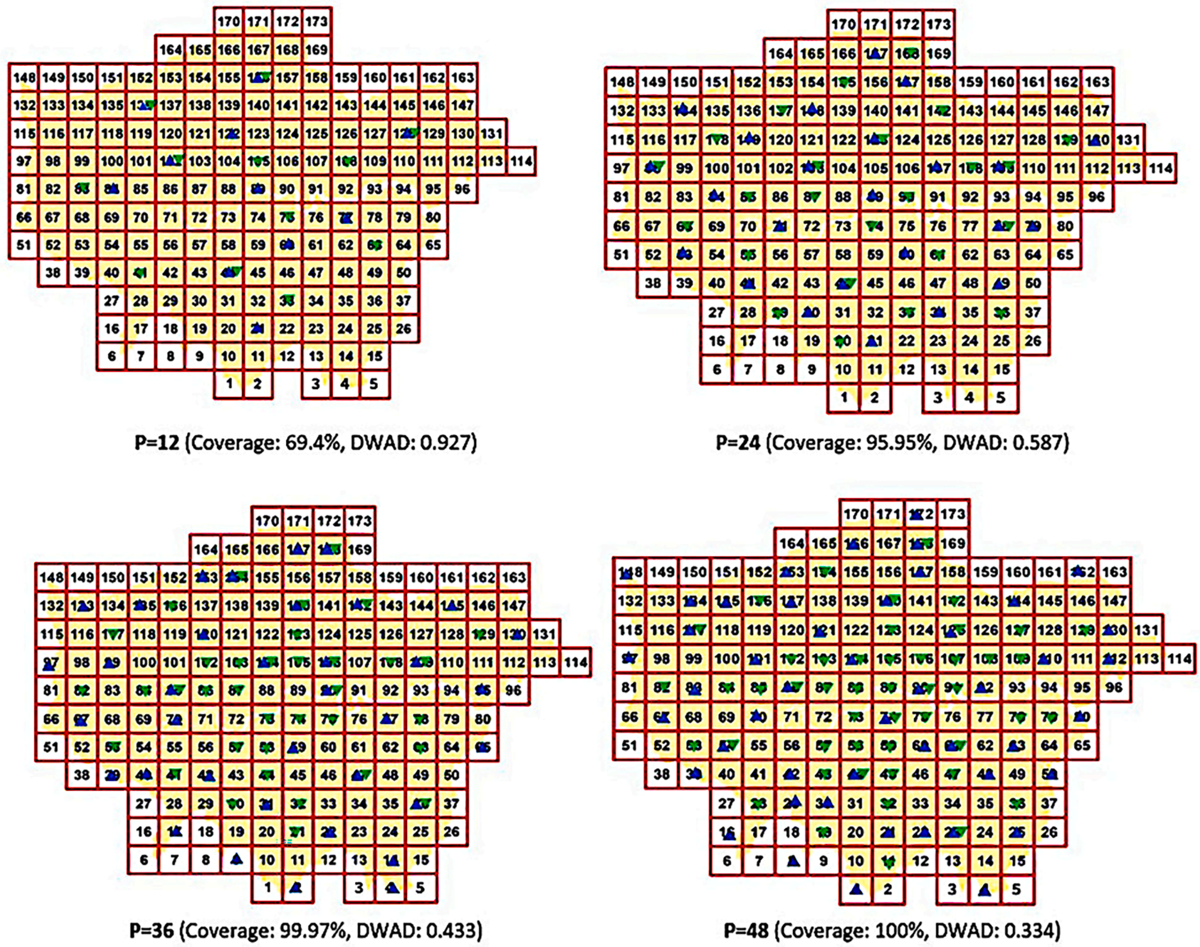

Fig. 3. The optimum BSC locations obtained by both the MCLP and *p*-median models in the four scenarios.

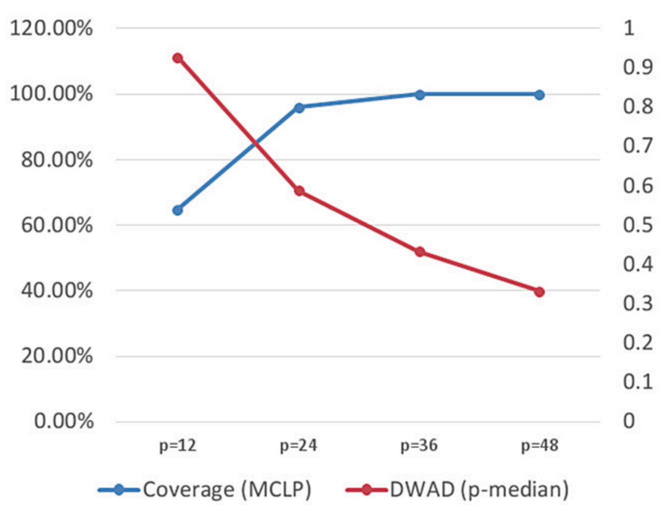

Fig. 4. The results of optimization when the number of BSCs is increased from 12 to 48. The demand-weighted average distance (DWAD) reflects the service accessibility. It is computed as the ratio of the demand-weighted total distance (DWTD) to the total demand.

populated areas in order to minimize the total travel distance for all users. Furthermore, by comparing the solutions from both models, we can identify the cells which simultaneously provide both high coverage rate and small travel distances. For instance, for case of $p = 36$ and $p = 48$ BSCs, there are 11 possible such BSC locations, which are shared in the solutions of MCLP and *p*-media problems as shown in Table 1. Among these 11 shared BSC locations, there are 4 BSC locations (the cells 90, 104, 140 and 168) that appear in the solutions for all *p* values considered. We can conclude that these 4 cells are crucial for establishing the baggage distribution network. The population data used and the detailed computations are provided in Supplementary Material.

Scenario 2: Major civilian airports in the UK

The UK is considered to be among the most interconnected countries in the world. It has a diverse and competitive system of airports that offer many destinations in the UK as well as internationally. The challenge is that many large airport hubs operate very close to their capacity, so outsourcing baggage processing outside the airports would alleviate some capacity pressures on their infrastructure.

In our study, the area of the whole UK was partitioned into 310 cells with equal sizes of 36 × 36 km, as shown in Fig. 5. The population

Table 1
The shared BSC locations in the grid from the solution of MCLP and p-median optimization problems for p = 36 and p = 48 BSCs, respectively.

Scenario	Shared BSC locations	Demand Coverage	Demand-weighted average distance
p = 36	36, 47, 85, 90, 104, 106, 109, 140, 142, 154, 168	99.97%	0.433
p = 48	23, 44, 54, 61, 74, 86, 90, 104, 125, 140, 168	100%	0.334

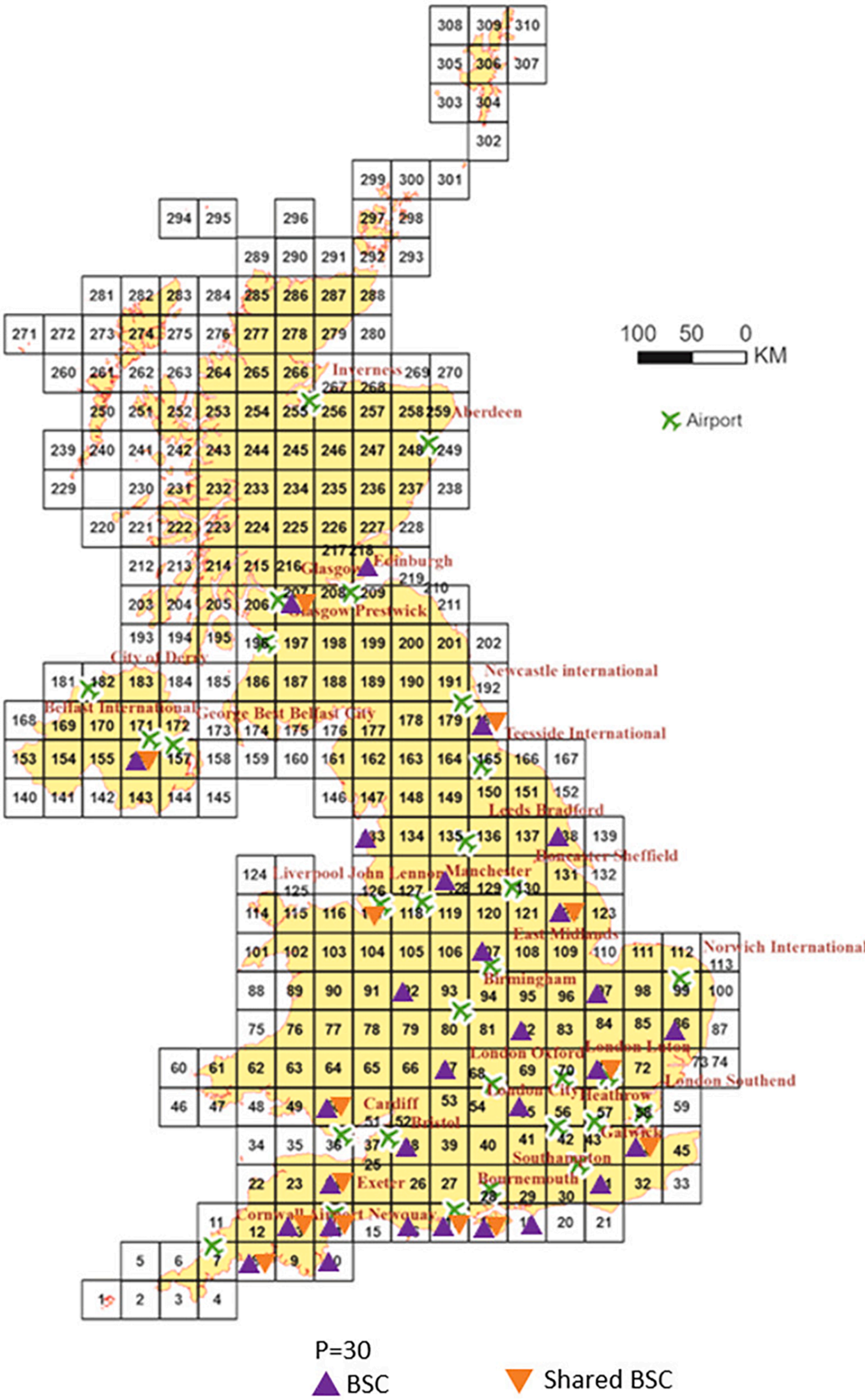

Fig. 5. The ground baggage delivery network with 30 optimally placed BSCs.

density of the UK was obtained from the government portal (UK Data Service, 2011). The population in each cell was calculated using the ArcGIS. The maximum coverage distance was set to $S = 36$ km. Moreover, the BSCs can serve more than one airport, since many airports in the UK are relatively close to each other.

Different configurations of the baggage ground distribution network across the whole UK were evaluated assuming the number of BSCs, $p = \{10,15,20,25,30,40,50,60\}$, in order to maximize the demand coverage. The optimal BSC locations, the population size covered, and the corresponding coverage rate for each configuration are summarized in Table 2. We can observe that, for $p = 35$ BSCs, the coverage is guaranteed to be at least 90%. In practice, it is likely that the coverage distance of some BSCs can be assumed larger, so 100% coverage of the whole UK could be obtained by about 30 BSCs. Fig. 5 shows the optimum locations for $p = 30$ BSCs.

Solving the MCLP is numerically demanding. However, the initial locations of BSCs serving a given airport can be quickly determined by assuming that these BSCs should be within the maximum coverage distance. Such locations for the selected UK airports are summarized in Table 3. They can be compared with the locations obtained from solving

Table 2
The population covered and the corresponding covering rate with *p* optimally located BSCs obtained from the MCLP model.

Scenario	BSC locations	Population covered	Demand coverage rate
p = 10	29,44,52,81,106,117,129,134,208	41,386,908	57%
p = 15	18, 30, 39, 44, 51, 55, 71, 80, 95, 105, 120, 126, 135, 180, 208	49,497,848	69%
p = 20	13, 17, 18, 30, 37, 44, 50, 55, 71, 80, 86, 95, 105, 120, 126, 131, 135, 156, 180, 208	54,657,351	76%
p = 25	10, 13, 16, 17, 18, 124, 30, 39, 44, 50, 55, 66, 71, 81, 87, 96, 106, 117, 129, 134, 138, 156, 180, 207, 218	58,796,331	82%
p = 30	8, 10, 13, 14, 16, 17, 18, 19, 24, 31, 38, 44, 50, 55, 67, 71, 82, 86, 92, 97, 107, 117, 122, 128, 133, 138, 156, 180, 207, 218	62,232,462	86%
p = 40	7, 8, 9, 10, 13, 14, 15, 16, 17, 18, 19, 20, 21, 24, 27, 29, 39, 44, 51, 56, 63, 68, 72, 79, 84, 95, 99, 106, 117, 122, 129, 134, 138, 156, 162, 165, 191, 207, 218, 248	67,214,824	93%
p = 50	4, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 27, 28, 29, 31, 36, 45, 52, 56, 63, 68, 72, 78, 83, 93, 99, 108, 110, 117, 118, 129, 134, 156, 162, 165, 171, 191, 198, 206, 218, 248	70,187,381	97%
p = 60	3, 4, 6, 7, 8, 9, 10, 11, 12, 17, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 27, 28, 29, 30, 31, 36, 45, 52, 56, 63, 68, 72, 78, 83, 93, 99, 102, 108, 110, 117, 118, 129, 131, 134, 151, 156, 162, 165, 169, 184, 191, 196, 198, 210, 216, 227, 248, 256	71,993,661	100%

the MCLP problem. The overlapping BSC sites are more critical in providing the baggage delivery service coverage. These sites are listed in the last column of Table 3. More aggressive sharing of BSCs can exploit the relatively proximity of many UK airports. For example, the BSC in the cell 13 can be shared by both the Newquay Cornwall Airport and the Exeter International Airport, whereas the cell 44 is the best location for the BSC to serve all six London airports. Overall, among 30 BSCs required to achieve the service coverage of the whole UK, approximately 50% of those will very likely be shared by different airports.

Discussion

The optimization models used in our study are obviously simplified. The models could be made more realistic by incorporating other factors and data. For example, the service demands can be estimated much more accurately by using actual flight data. Unfortunately, such data are normally confidential. The solution can be to dimension the baggage distribution networks for the worst-case scenarios. It is also important to consider the road congestion at different times of day, and the models can account for service allocation equity (Xu et al. 2023) and transportation alternatives (Campbell & O'Kelly, 2012).

More detailed models may require commercial solvers that better scale with the model size and complexity (Church & Wang, 2020). Moreover, deterministic modeling can be supported by stochastic simulations (Andoh & Yu, 2022; Yu et al. 2021). The simulations allow exploring the network design at defined levels of model granularity, and also studying unpredictable events potentially leading to service disruptions. The ultimate goal would be a comprehensive simulator which integrates arriving and departing flights with baggage distribution over the ground network.

However, the model assumed in our case studies appears to be good enough to provide initial estimates of the number of BSCs required to cover the geographical areas of interest. This can be used in further studies, for example, to assess how to actually implement the baggage flows to and from the airports as well as to obtain estimates of the operational costs.

Table 3
The un-optimized off-airport BSC candidate locations and the shared BSC locations determined by solving the MCLP for selected UK airports.

Airport	Candidate BSC locations	Shared BSC locations obtained by MCLP
Newquay Cornwall Airport	6, 7, 8, 11, 14	8, 14
Exeter International Airport	13, 14, 15, 10, 24	13
Bournemouth Airport	16, 17, 18, 27	17, 18
Southampton Airport	27, 28, 29, 18, 40	27, 18
Gatwick Airport	29, 30, 31, 20, 42	29, 20
Cardiff Airport	35, 36, 37, 50, 24	50, 24
Bristol Airport	36, 37, 38, 25, 51	36, 51
Heathrow Airport	41, 42, 43, 30, 56	56
London City Airport	42, 43, 44, 31, 57	44
London Southend Airport	57, 58, 59, 44, 72	44, 72
Luton Airport	69, 70, 71, 56, 70	56
Stansted Airport	70, 71, 72, 57, 84	71, 72
Birmingham International Airport	93, 94, 95, 81, 107	93
East Midlands Airport	116, 117, 118, 104, 126	117
Liverpool John Lennon Airport	117, 118, 119, 127, 105	117
Manchester Airport	121, 120, 122, 130, 108	122
Doncaster Sheffield Airport	134, 135, 136, 128, 149	134
Leeds Bradford International Airport	164, 165, 166, 180, 150	165, 180
Durham Tees Valley Airport	178, 179, 180, 164, 191	180, 191
Newcastle Airport	155, 156, 157, 143, 171	156
Belfast International Airport	156, 157, 158, 144, 172	156
George Best Belfast City Airport	195, 196, 197, 206, 186	206
Glasgow Prestwick Airport	206, 207, 208, 197, 216	207
Glasgow International Airport	207, 208, 209, 217, 198	198
Aberdeen Airport	247, 248, 249, 237, 258	248
Inverness Airport	254, 255, 256, 266, 245	256

The dissociation of passenger travel and baggage delivery is being seriously considered by the main stakeholders in air transport industry including the Baggage Working Group at the IATA. It suggests that passenger and baggage dissociation will eventually become the default option in all future travel. However, there are many logistical, technological, business, safety, and security challenges that have to be resolved first. At present, the key IATA regulation stipulates that luggage must be on the same flight with passengers unless a few exactly defined exceptions. Any modification to this rule will likely only be possible when the processes and infrastructure have been substantially adopted.

The evolution of processes and infrastructure in air transport is usually governed by the IATA through their resolutions and short to medium-term innovation programs. Some of these developments set the stage for eventual more radical changes including baggage dissociation. For instance, since June 2018, the IATA resolution 753 mandates that the airlines and airports record all baggage events and track baggage ownership at all times. This means that, in case of the baggage dissociation, the baggage ownership would be passed from the traveller to a baggage courier to deliver it to the departing airport, where the ownership is passed onto the airport baggage handlers or to the airline. The baggage owner is responsible that there is no unauthorized access to baggage contents, that the baggage does not get displaced, and that it is delivered in time. These issues directly affect the insurance policies.

New baggage dissociation services will require extra transport capacity. At present, it is unclear, if the benefits provided by baggage dissociation can outweigh the need for extra capacity as well as the added complexity. Moreover, it is likely that separate baggage delivery will be more costly due to additional parties and infrastructure involved. The baggage reconciliation at the end of the passenger journey is a very difficult problem to solve. However, one cannot dismiss the concept of baggage dissociation without first performing thorough investigations and feasibility studies, which can in turn suggest new and not so obvious innovative solutions that have not been yet considered. The design of baggage ground distribution network investigated in this paper offers one step towards this goal. Moreover, it is likely that, at least initially, the baggage distribution networks would be piloted in the areas surrounding large airports to generate sufficient service demand.

The key findings that can be deduced from our study are as follows. The baggage ground distribution network is a necessary enabler for the complete end-to-end dissociation. The ground distribution networks for baggage can be designed akin to the parcel distribution networks. However, building and operating the ground distribution network is most likely beyond the economical capabilities of many airlines and airports, so the substantial support from the governments will likely be necessary. The airlines and airports can instead focus on better utilizing the capacity of the existing infrastructure, and otherwise outsource the baggage delivery services to third party companies. Alternatively, airports or airlines can establish shared BSCs, and reuse the existing infrastructure and multi-modal transport options in order to make the new baggage services cost-effective and economically viable.

Baggage dissociation will very likely become the default style of future travel not only in air transport. This concept can be particularly beneficial for other modes of transportation where the storage space for luggage may be severely limited, or where it complicates passenger boarding and disembarking in vehicles such as buses and trains. Since these transport modes have only one ground segment with many stops and stations on the way to the destination, the design of baggage distribution networks for these transport modes is likely to be different, but it can be a subject of our future research.

Conclusion

The seemingly simple concept of baggage dissociation, which allows baggage delivery independently from passenger travel, faces many daunting challenges. Some of these challenges were outlined in this paper. However, these challenges provide many research opportunities to explore how to radically change future travel not only in air transport. The main drivers behind baggage dissociation are the enhanced travel experience and substantially improved utilization of the infrastructure and other resources.

The problem of designing baggage ground delivery networks was investigated as one of the many challenges, since it is crucial for enabling the eventual end-to-end dissociation. The standard location optimization models with population density used for estimating the service demands were solved numerically to assess the number and locations of BSCs required in Greater London, and also to provide sufficient service coverage across the whole UK. These results provide insights for the policy makers and innovation planners in air transport.

CRediT authorship contribution statement

Sarah Al-Hilfi: Software, Validation, Investigation, Data curation, Visualization, Writing – original draft. **Hao Yu:** Methodology, Validation, Investigation, Visualization, Writing – review & editing. **Pavel Loskot:** Conceptualization, Resources, Investigation, Writing – review & editing, Supervision, Project administration.

Declaration of Competing Interest

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

Data availability

The data will be made publicly available upon acceptance.

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Appendix A. Supplementary data

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