Urban Air Mobility

Optimisation of Skyport Locations and Fleet Sizes

analytical. quantitative. tech.

2020

Leveraging advancements in technology, the deployment of urban air mobility services presents a promising new mode of transportation. In this insight, a quantitative approach to optimise infrastructure and fleets for urban air mobility services is presented – from estimating demand over applying combinatorial optimisation models to interpreting them for planning and operations.

The presented approach and results were obtained in collaboration with Julian Berzborn, in the context of his master thesis at the Chair of Operations Research at RWTH Aachen. We would like to thank Julian for the excellent work on urban air mobility and his contributions to the d-fine team.

Furthermore, Janina Erb and Till Seifert were key contributors to the content creation of the insight.

Content

Management Summary
Urban Air Mobility - Optimisation of Skyport Locations and Fleet Sizes

100+

UAM pilot projects

250+

VTOL concepts

60%

Population living in cities (2030)

Use cases for UAM – Passenger and goods transportation

- Intra-city services
- Airport shuttle services
- Inter-city flights
- Last-mile parcel delivery
- Transport of medicine and organs

Optimal infrastructure location and fleet size for UAM
A data-driven and mathematical approach

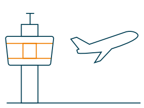
1. Determine demand
2. Design optimisation model
3. Interpret and visualise results

The case Chicago – Applied optimisation of UAM infrastructure

The City of Chicago serves as a prime example to analyse infrastructure requirements for deploying UAM through a data-driven approach. The generic methodology is easily transferable to other cities and can take local requirements and needs into account.

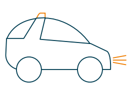
1 Determine demand

Model demand for intra-city and airport services leveraging taxi data



2 airports

Large downtown area



Historic taxi data

TOP 5% quantile UAM demand

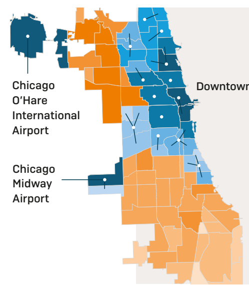
2 Design optimisation model

Develop optimisation models increasing in complexity

Models	Input
Aggregated Facility Location Model	■ demand at origin
Facility Location Model	■ demand at origin ■ per connection
Aggregated Routing Model	■ demand at origin ■ per connection ■ per time

3 Interpret and visualise results

Given limited resources not all demand can be satisfied



Limited Resources

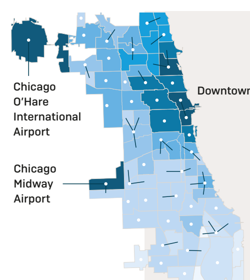
15

skyports

100

air taxis

Increasing skyport location investment allows to satisfy demand



Limited Customer Relocation

52

skyports

76

air taxis

01

Urban Air Mobility – A new mobility service on the horizon

Currently, there are more than 100 start-ups and projects related to urban air mobility. To successfully launch within the next years, questions surrounding safety, regulation, technology, economics as well as infrastructure integration need to be answered.

The concept of urban air mobility leverages the advancements in drone and vertical take-off and landing (VTOL) technology, to provide an alternative means of passenger or goods transportation and enable a faster point-to-point connection. Passenger transport includes air taxi services as on-demand intra-city services, airport shuttle services with scheduled short-range operations and inter-city flights with medium- to long-range operations. Typical use cases in goods transportation are the shipment of parcels or special services such as the transport of organs and medicine as well as applications in agriculture.

The Special Condition for small-category VTOL aircraft has paved the way for the launch of Urban Air Mobility services

Driven by advancements in electric engines and autonomous flight, a continuous extension of existing passenger drone concepts is taking place. These concepts range from multicopters and the related quadcopters to fixed wing air shuttle concepts. Depending on the respective use case of urban air mobility some of these concepts are more adequate than others.

The variety of concepts that already exist in the form of tested copters or prototypes proves the great development that is made towards the deployment of air taxi services. This is supported by the Special Condition for VTOL, published by the EASA in July 2019, which acknowledges the 250+ concepts in the market and establishes the VTOL aircraft class. The paper forms the regulatory framework for the certification of piloted air taxis, with the potential and expectation to include autonomous air taxis in the future.

Use cases for UAM

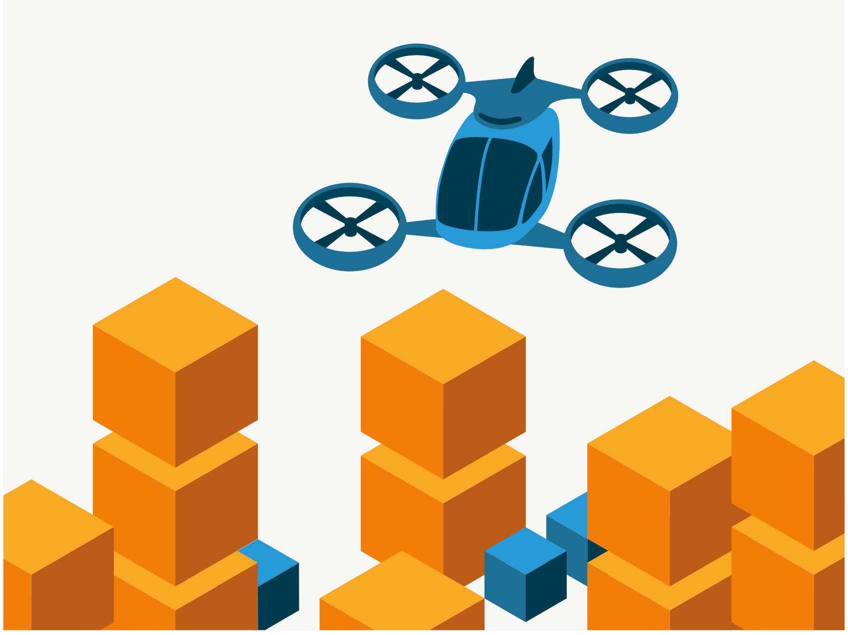
Airport shuttle | Inter-city flights | Intra-city air taxi | Logistics | Ambulance transports

Integration of UAM use cases into the urban mobility landscape is the key to attract customers

Regardless of the aircraft type, an efficient infrastructure is needed to offer an air taxi service. Within its "Smart Cities and Communities Programme" the European Union provides support for cities and regions that strive to find answers to the question how urban air mobility services can be integrated into the urban mobility landscape.

In order to provide the right infrastructure for a future service, in terms of skyports, charging infrastructure, maintenance facilities or fleets, the following questions arise for cities and operators:

- How high is the expected city-specific demand for urban air mobility?
- How many skyports are needed to efficiently meet the expected demand and demand growth?
- Where should skyports optimally be located to increase coverage and customer value?



Using mathematical modelling and optimisation approaches, the expected demand and optimal infrastructure can be determined for an intra-city urban air mobility service

In the following, a methodology to address the above coined questions for a potential intra-city urban air mobility service is proposed. More specifically, the City of Chicago is used as a prime example of application: Using historic taxi-trip data, the expected demand for an urban air mobility service in Chicago is analysed. Afterwards, the developed optimisation models are applied in order to find answers to the questions of optimal VTOL infrastructure positioning and required fleet size for an UAM service in Chicago.

02

Systematic approach to optimal UAM infrastructure

The optimal infrastructure for intra-city air taxi services can be determined by applying combinatorial optimisation models of varying complexity on the expected demand derived from forecasting models.

In order to optimise the infrastructure for air taxi services, an understanding of the expected demand is fundamental. Accordingly, the optimisation process is conducted by applying the optimisation models on the expected demand and analysing the results in a step-wise approach:

1. **Demand forecasting:** Modelling of expected passenger demand for an urban air mobility service in a given region
2. **Optimisation model design:** Development of optimisation models to determine optimal skyport locations and fleet size
3. **Analysis of results:** Interpreting and visualising the results of the models and leveraging them for planning and operations

The expected demand builds the foundation for optimising UAM infrastructure
Previous to deploying UAM services, operators need to analyse the market potential for their services by taking into account demand, their individual business concept and further specific local constraints and needs such as the customers willingness to pay. Due to the innovative nature of intra-city air traffic, demographic data or data from other existing private or public mobility solutions can be relevant sources to estimate demand for a potential future UAM service. Hence, historic intra-city taxi trips – openly available for selected cities – can be an interesting data source. By identifying trips that have a high likelihood of being replaced by urban air mobility, a good estimation of UAM demand can be obtained. As soon as first UAM services are deployed, demand data from those cities might be transferable in the future when scaled properly.

Optimisation models of increasing complexity process local demand, demand per route and time-dependent demand
A well-known challenge in mathematical optimisation is the trade-off between the closeness to reality of the model and the associated computational complexity – resulting from the increased amount of variables and degrees of freedom. Accordingly, the application of three optimisation models, increasing in complexity and level of detail, considers this trade-off by processing different aggregations of demand:

1. **Aggregated Facility Location model (AFL):** aggregates demand per area independent of time and connections between areas;
2. **Facility Location model (FL):** aggregates demand per connection independent of time;
3. **Aggregated Routing model (AR):** considers demand per connection and time slice.

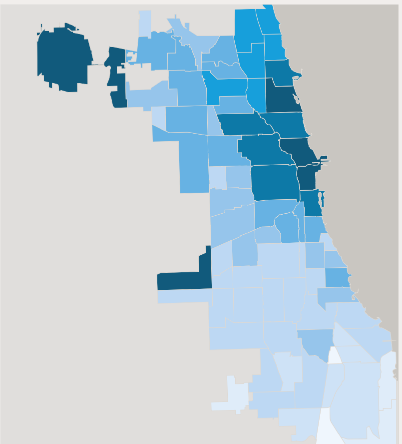
In a very simplistic view, the AFL model reduces the extent of information to be considered and only focuses on the aggregated demand per area. The approach does not include any time or connections details of trip routes. This saves a lot of complexity, while the results can still serve as a foundation for further analyses by providing a first indication of optimal locations and number of skyports per area. By no longer only aggregating demand based on trip origins, but rather time-independent origin-destination pairs, the FL model uses the demand per route as input and enables to map flights more efficiently to those routes. Finally, in the AR model the level of detail is increased even further by including time-dependecy. By including the time-dependency per route, hourly and daily fluctuations in demand are respected by the optimisation model. Furthermore, adding the time component allows to quantify the required fleet size and enables further analyses of time-related questions such as peak shaving, or required charging infrastructure and enhances estimations compared to the previously presented models.

Concluding, each of the models has certain benefits and may be extended in order to model reality even more closely or answer specific questions. In some cases, the selection of a model can also depend on the granularity of the available data. Further model details regarding the design and application are provided in the next chapter.

Schematic representation of the cascading approach of the models AFL, FL and AR

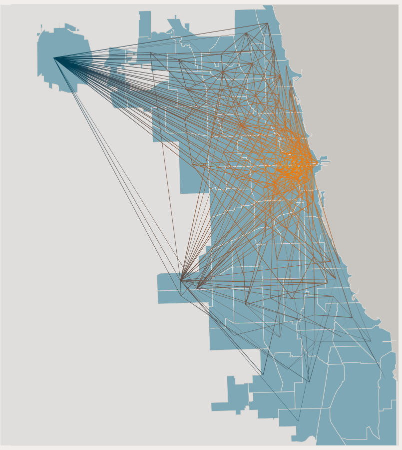
Visualisations are key to support the interpretation of results in order to leverage them for infrastructure planning
In order to build a solid decision basis for infrastructure planning in UAM projects and create value for cities, service providers and regulatory authorities, it is crucial to present the results of the optimisation models to the stakeholders in detail. This includes analysing the results individually, visualising them with appropriate methods for a better understanding and taking into account the constraints, purposes and objectives of each model.

Aggregated Facility Location model (AFL)



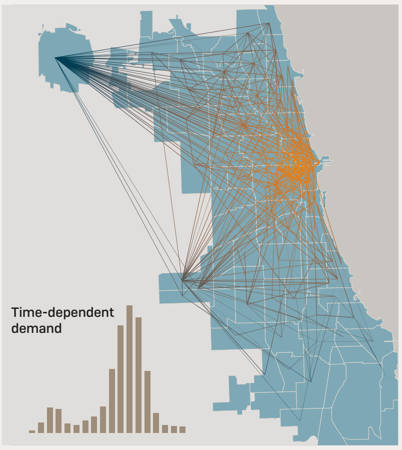
Source: Own illustration of data from the Chicago Data Portal

Facility Location model (FL)



Source: Own illustration of data from the Chicago Data Portal

Aggregated Routing model (AR)



Source: Own illustration of data from the Chicago Data Portal

03

The case Chicago – Applied optimisation of UAM infrastructure

Available historic taxi data allows to model the demand for an UAM service in the City of Chicago, and the optimisation models are applied to optimise the required infrastructure and fleet sizes.

Chicago, situated in the state of Illinois, is the third most populous city in the United States. With its two airports of different size it serves as a prime example for analysing the urban air mobility use case of intra-city air taxi services in combination with airport shuttle services. In addition to the interesting size and features of the city, the City of Chicago operates an open data portal that provides an extensive amount of data on individual taxi traffic within the city. For each taxi-trip, going back to 2013, the start and end time, the length in both time and distance, the starting and ending city areas and trip costs are reported. In order to protect personal information, the start and end time are given in 15 minute intervals and the starting and ending location in low demand areas are, if at all, only provided on a more aggregated level.

Systematic approach to determine the optimal infrastructure for a potential air taxi service in Chicago

Data source
- Public taxi trip and traffic data of the City of Chicago

Preprocessing of raw data
- Analysis of raw data and filtering of demand for air taxi services

Mathematical Modelling
- Design of combinatorial optimisation models increasing in complexity

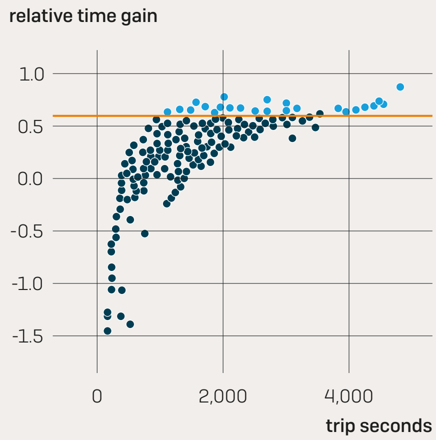
Implementation
- Interaction with the Gurobi mathematical optimisation solver
- Performing computations on a calculation cluster

Solutions
- Discussion of the solutions to the different optimisation models

Determining the expected demand of urban air mobility services based on historic taxi data

In order to estimate the demand for air taxi services in the City of Chicago, each historic taxi trip is compared to a hypothetical air taxi flight. As a result, trips are extracted based on relevance, i.e. those trips that generate a certain level of potential time gain for customers. More precisely, in a first step trips with missing location information are removed from the set. These trips anyway occur in low demand areas or are out-of-city trips and do not provide any essential information to the analysis. Second, the trip data is enriched by calculating the commuting time of a comparable air taxi flight, also including the additional travel time to and from the skyports. Lastly, the trips with the largest reduction of relative travel time are filtered out to be used in the optimisation models (see figure below).

Demand estimation based on historic taxi trips



Historic taxi trip duration and calculated relative time saving by switching to an air taxi. Negative values indicate an increase in travel time. The data points above the orange line represent the assumed demand for air taxis.

Source: Own illustration of data from the Chicago Data Portal

In a first approach, the top 5% quantile of relative time savings is taken as a basis to model the expected UAM demand for the City of Chicago. However, this parameter allows to take into account city-specific conditions and might be adjusted accordingly. In this approach, the willingness of the customers to pay is assumed, considering the expected competitive pricing. Nevertheless, it can be relevant in future analysis to include price-dependent demand modelling.

Application of the optimisation models to derive an optimal UAM infrastructure in Chicago

To consider the trade-off between the closeness to reality and the associated computational complexity the three optimisation models introduced above are applied in ascending order of complexity to the City of Chicago. The different level of detail of the models is produced by processing different aggregations of demand.

Optimising UAM infrastructure reveals a trade-off between costs and the level of customer value
When defining optimisation objectives for UAM infrastructure, a trade-off between costs and customer value needs to be considered. In order to quantify this problem, costs such as the infrastructure costs for skyports and, in case of time-dependent modelling, fixed and variable fleet operating costs as well as charging station costs of each solution are calculated. Additionally, the effective value for customers is expressed by the weighted total ground commuting time. Correspondingly, the optimisation problem is split into two parts:

- First, customer value is maximised given a restricted number of installable skyports, by finding optimal skyport locations. More precisely, given a limited number of skyports (and air taxis) the sum of the distances passengers need to travel to their assigned skyport is minimised.

- Second, costs are minimised while guaranteeing a predetermined level of customer value, again by determining an optimal number of skyports and their locations. Accordingly, an upper bound for the distance passengers will travel to their assigned skyport is defined, and the optimisation model minimises the overall costs.

The least complex AFL model aggregates demand over all time slices and connections between areas

First results and an initial overview are achieved by applying the least complex AFL model. Since the model utilises a high level of aggregation, it is not possible to consider traffic patterns and peak times or obtain insights on required fleet sizes. Nevertheless, the model provides answers to the main questions of where to install skyports, and how many. As input parameters the Community Areas as defined for the City of Chicago and the corresponding demand per area are used. Further, the commuting time between areas is provided to calculate ground travel time in case skyports cannot be installed in all areas with positive demand due to restrictions in the number of installations, in which case customers need to be redirected to a skyport in another area. Within the optimisation the model obeys operational constraints in each area and at each skyport as well as further constraints for performing the relocation of demand to nearby skyports. Given these inputs and constraints, the AFL model optimises the number and location of skyports. The resulting travel time and distance of ground trips are calculated, and for areas without skyports it is further specified to which nearby skyport customers are redirected. Although applying a high level of aggregation, the solutions provide a good first assessment and are obtained with low computational costs.

Representation of the AFL-model

Input data:

- Set of areas
- Demand per area
- Travel times between areas

Constraints:

- Maximum number of skyports per area
- Maximum number of flights per skyport
- Maximum commuting distance to skyport

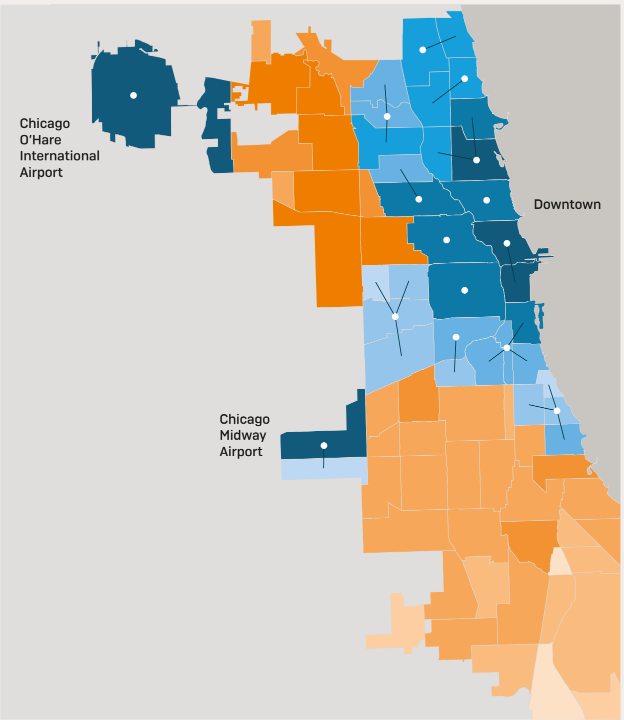
Optimise:

- Location of skyports
- Number of skyports
- Allocation of customers to skyports

Applying the AFL model to the City of Chicago leads to promising results
The application of the AFL model leads to first results for the City of Chicago, considering both optimisation perspectives: limited resources and limited customer relocation.

To support the analysis, the results are visualised in a map. The colouring of the areas depicts the respective demand on a logarithmic scale, and the proposed number of installations of skyports within a community area are illustrated by white dots. In addition, allocations of customers to skyports are visualised by blue lines that connect adjacent areas. In orange areas the demand is neglected, and a feasible connection to a skyport is not possible.

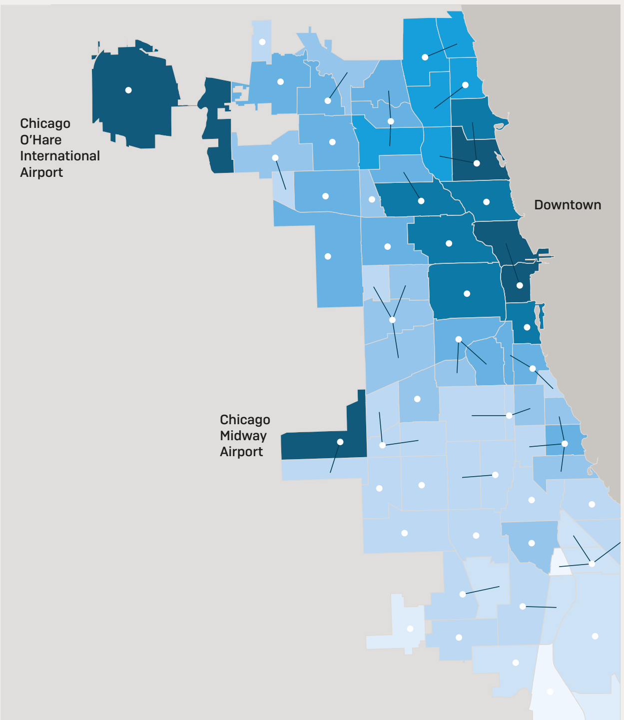
AFL model – limited resources



Optimal location and allocation of skyports in the City of Chicago assuming limited ressources.

Source: Own illustration of data from the Chicago Data Portal

AFL model – limited customer relocation



Optimal location and allocation of skyports in the City of Chicago ensuring a certain level of customer value.

Source: Own illustration of data from the Chicago Data Portal

Limited resources: In this scenario it is assumed that not more than 15 skyports can be deployed due to financial or infrastructural constraints. As anticipated, the findings show that this limited number of facilities cannot provide a satisfactory air taxi service for the whole city area. Quite the contrary, in the solution of the AFL model even areas with medium demand are not served. The allocation of skyports is centred on downtown and Chicago's two airports. Surrounding areas are grouped together such that they can be served most efficiently by the same skyport.

Limited customer relocation: In order to provide a minimum level of customer value, the distance of each customer to a skyport is fixed to be less than 1.2 miles. In addition, the total ground travel distance is constrained to be less than 2 miles. Minimising the costs given these constraints suggests an installation of 46 skyports in Chicago. Customers are redirected to nearby areas only in very low demand areas, in those areas with high infrastructure costs. In the south-east of the city a rather cost-intensive allocation of infrastructure with respect to the low customer demand is proposed. However, due to the large span of these areas, they cannot share skyports while ensuring the upper bound of maximum distance for passenger ground travel.

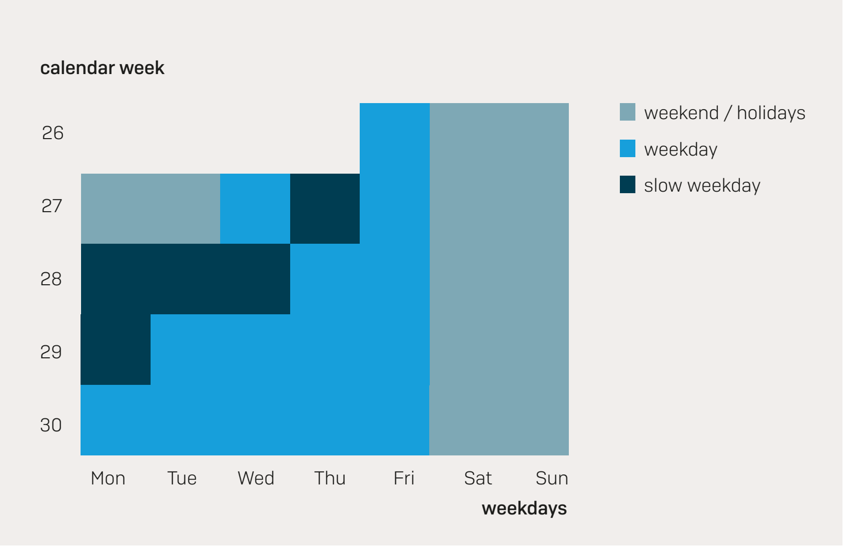
Applying the Aggregated Routing Model reveals further information on the actual operation of an UAM service

It can be seen that in the case of Chicago, extending the AFL model to the FL model and considering demand per route instead of only demand per area does not substantially impact the optimisation results. This indicates a certain symmetry in the data, or in other words is motivated through the fact that areas with high demand are also attractive destination areas (e.g. downtown and airports). Instead, considering demand per time is essential to model the reality more closely. This, for the first time, allows to model single flights and thus enables to quantify fleet sizes and conduct further analyses such as peaks in demand, the number of excess flights that need to be operated to serve customers and optimal charging schedules. Therefore, in the Aggregated Routing model the demand per connection and time slice is considered in order to extend the achieved results. Since the model allows for further time-dependent analyses, additional information such as operational costs of charging stations per area, variable air taxi operating costs, maximum travel distance per full charge as well as constraints for areas and air taxis are further provided to model capacity and safety restrictions more closely.

The time horizon is reduced to decrease computational time to an acceptable level

The inclusion of the time component within the model adds a further dimension to the variables within the optimisation problem and thus increases the degrees of freedom drastically. Hence, this comes with an immense increase in computational complexity. Therefore, a reduction of the time horizon to representative days is conducted. In a first step, an aggregation of demand per connection in hourly time steps results in a vectorised representation of the demand per day. Applying a statistical cluster analysis on the vectorised demand leads to three representative type of days in a year: weekend / holidays as well as two types of weekdays, varying mainly in traffic volume (referred to as weekday and slow weekday). The representative clusters and the demand per hour profiles, with typical weekday rush hour peaks, are illustrated in the following.

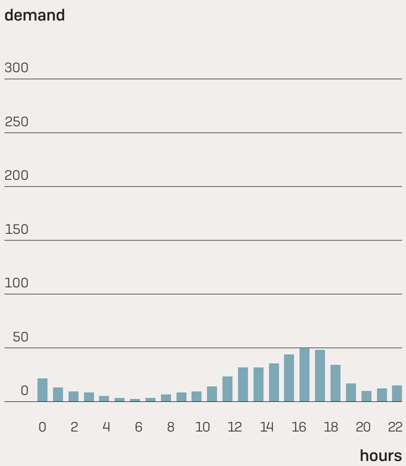
Three clusters of representative days for the month of July



Source: Own illustration of data from the Chicago Data Portal

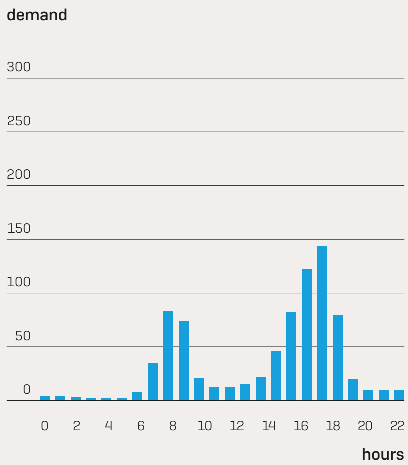
The demand per hour profiles show the expected traffic fluctuations of the three representative days: weekend / holidays, weekday and slow weekday.

weekend / holidays



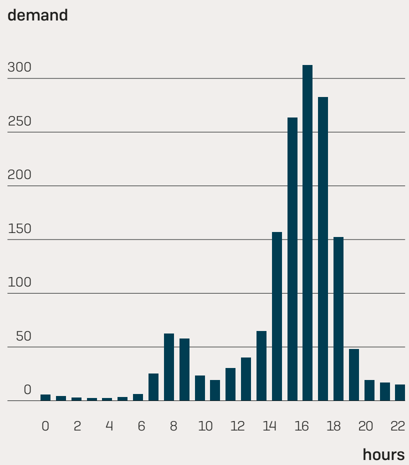
Source: Own illustration of data from the Chicago Data Portal

slow weekday



Source: Own illustration of data from the Chicago Data Portal

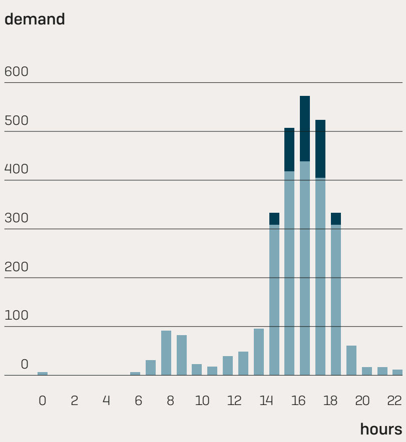
weekday



Source: Own illustration of data from the Chicago Data Portal

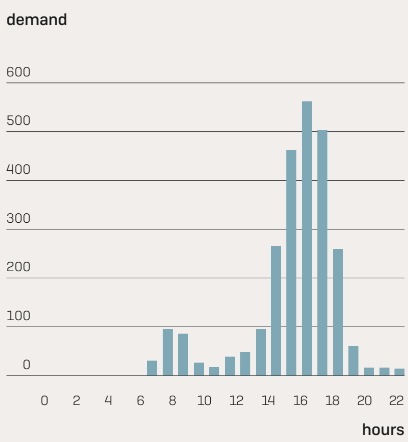
Given limited resources, it can be observed that especially during rush hour peak times the demand cannot be completely satisfied (dark blue, top). When ensuring a minimum level of customer value (right), even peak times are fully covered.

Limited resources



Source: Own illustration of data from the Chicago Data Portal

Limited customer relocation



Source: Own illustration of data from the Chicago Data Portal

The results of the Aggregated Routing Model provide valuable insights into the actual operation

Limited resources: By considering demand per connection and time slice the AR model allows to determine optimal fleet sizes in addition to skyport allocations. Accordingly, in addition to the 15 skyports, a maximum of 100 air taxis is included as a resource constraint. At first sight, it can be observed that the location of skyports in the Aggregated Routing model does not vary much from solutions obtained by the simpler AFL model. Nevertheless, by incorporating the time component valuable insights into demand peaks, excess flights and charging schedules are provided. It can be observed that especially during the busier representative weekday, demand during peak times cannot be completely satisfied given the restricted resources. The limitation of resources further leads to restricted fleet routing and an increased number of excess flights. Regarding fleet charging, the solution considers operation at its capacity limits, but in order to account for safety restrictions, such as a minimum required charging state, further constraints would need to be included in the model.

Limited customer relocation: In contrast to the case of limited resources, the solution of the Aggregated Routing model in regards to ensuring a minimum level of customer value differs significantly from previous findings. By nature of the objective function, the demand at all representative days, even at peak times, is completely satisfied. This is achieved by installing skyports, 52 in total, in almost every area and even multiple ones in areas of high demand. The more significant result of the optimisation though is that the fleet size is held at 76 air taxis. This is possible as the number of excess flights is reduced drastically due to the dense network of connections.

Comparison of solutions and leveraging results for planning and operations

Comparing the solutions of the AR model it can be seen that in the case of limited resources up to 100 air taxis need to be deployed, while in the second scenario only 76 air taxis are required. Even more, in the latter scenario more demand, especially during peak hours, is satisfied. An explanation for this behaviour is that the capacity of 100 vehicles cannot be fully utilised with only 15 skyports being available. This reveals that a certain number of skyports is required to efficiently cover demand and insufficient installation of skyports cannot be compensated by utilising a higher number of air taxis. Ultimately, for further model development, it can be interesting to allow for a combined optimisation approach, e.g. giving upper bounds to the number of installable skyports, available air taxis and commuting time of the customers.

Slight deviations in demand for air taxi services do not affect the optimal location of UAM infrastructure significantly

In the future, it is a probable scenario that demand for air taxi services will start at a low level and then gradually increase over time, e.g. when safety is proven and service charges become more competitive. To model the effect of growing demand, the AR model is applied for the City of Chicago, using both the upper most 2% quantile and the upper most 5% quantile of the taxi trips with respect to relative time gain. Through the comparison, it can be observed that in both scenarios (limited resources and limited customer relocation) the optimal solutions for skyport locations do not vary significantly – at least for the initial growth of the market.

04

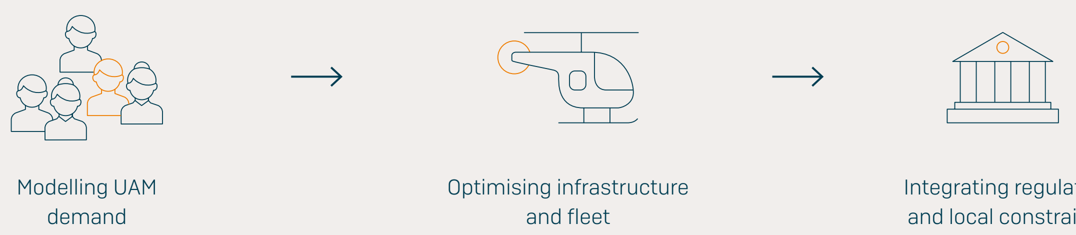
The future of UAM and further steps

UAM offers a promising concept for future urban mobility. Applying mathematical approaches allows to set the foundation by optimising infrastructure and fleet sizes of air taxi services. The results found for the City of Chicago can be extended and transferred to other cities.

Although being ahead of the time when air taxis will commute in every large city, this paper provides a first approach to understand the driving forces that influence the optimal infrastructure for urban air taxi services. It is essential to understand and prepare the deployment of such a service in advance, and data-driven and mathematical approaches have shown to provide relevant insights. Even more so, the infrastructure for future services can already be developed today, especially considering that piloted air taxi services are already being established.

In a bottom-up approach demand forecasting and optimisation models, increasing in complexity, were developed in order to provide answers to main questions regarding expected demand and skyport infrastructure. By applying more complex models, further insights into the operation of an UAM service such as optimal fleet sizes and covered demand can be obtained.

The application of demand forecasting and optimisation modelling is easily transferable to other cities, taking lokal and regulatory constraints into account.



Based on the current implementation, a combined optimisation approach might be considered and the models can also be extended in the future to include flight zone restriction, air space congestion or noise emissions. Thus, it can be considered and ensured that safety and noise emission restrictions imposed by cities are met. Even more, the models can be used to improve the public perception of urban air mobility. Furthermore, price-dependent demand modelling can be included in the future in order to reflect the effect of pricing on demand and to calculate expected return-on-investments (ROIs).

As a first step, the above approach has been shown for the City of Chicago, serving as a prime example for analysing the urban air mobility use case of airport shuttle services in combination with intra-city air taxi services. Due to the methodical approach to the modelling, the presented optimisation methodologies are transferable to other cities. This allows cities, operators or regulatory authorities to analyse the deployment of an UAM service, taking specific local constraints and needs into account, and supports the successful deployment of urban air mobility services in the near future.

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Our service offerings

Air taxi services is one way (cable cars and ropeways are another) of extending the concept of multimodal urban mobility to the third dimension. Therein, the successful deployment of air taxis as well as the systematic integration into an urban mobility context pose technological, processual, and methodological challenges. We combine our analytical, quantitative and technological expertise in the fields of urban mobility and public transport as well as digital aviation to support you in:

- Infrastructure positioning, demand-driven network optimisation, as well as integration of resilient scheduling concepts;

- predictive air traffic routing and ETA and ETD calculations, dynamic pricing for revenue management as well as smart charging strategies;

- development of intermodal mobility platforms and data analytics modules for data-driven and collaborative decision-making;

- analysis of regulations, reporting requirements, and impact on your business models.

Whether it is a business case analysis, proof-of-concept or full integration into operations: we support your project from the first workshop to the technical design and implementation.

Get in touch with our experts!

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