Decisions in Mobility Service Networks

Coordinating Demand and Supply Using a Mechanism Design Approach

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Abstract

Passenger transportation has become more diverse in the recent past. New providers and transportation services are reeling up markets around the world. Together with the rise of the sharing economy, substantial ramifications for the transportation sector emerge. As a result of an increasing number of mobility options, the traveler can choose from a richer mobility menu. The difficulty of selecting the most appropriate mobility alternative, however, grows in the number of mobility options. Hence, without appropriate decision support, the full potential of mobility alternatives may remain locked from utilization. We leverage structurally similar observations from the domains of IT service management and cloud computing to address this issue. In particular, we introduce a formal model for matching supply and demand on graphs via a market platform. This platform allows for efficient matching and orchestration of a set of individual means of transportation with demand featuring heterogeneous user preferences. Our specific contribution comprises the formalization of complex mobility services and the corresponding optimization problem as well as the development of an incentive-compatible auction mechanism, the complex mobility service auction. A stylized example demonstrates the efficacy of our approach.

Keywords

intermodal passenger transportation, mobility services, service networks, mechanism design

1. Introduction

Real-time ridesharing is at a height of popularity. In a 2012 study conducted by UC Berkley already 20% of participants were willing to use real-time ridesharing once a week [1]. Services like Uber¹ and Lyft² were far from well-established in 2012, but are now continuously gaining ground and are transforming taxi markets and public transportation around the world. Given the simplicity and attractiveness to customers it is not far-fetched to expect further growth. Additionally, car rentals by the hour like Zipcar³ and private peer-to-peer car sharing like RelayRides⁴ change the way we think about car rentals and enable the idea of carsharing. Moreover bike sharing schemes have been offered for decades and are increasingly becoming a part of the cityscape of metropolitan areas in the last five years (e.g. Vélib’ in Paris⁵, and Citi Bike in New York City⁶).

While the companies scrimmaging in these markets range from public-private partnerships over traditional companies emerging into new markets to start-up companies, it can be said that transportation options are growing for customers. With options increasing, decisions can become bothersome. This facilitates a breeding ground for platforms like Moovel⁷ owned by German automotive manufacturer Daimler AG that combines the offers of the German railway with taxi services, bike sharing and Daimler’s care sharing service Car2Go⁸. Customers can state their desired destination and the service returns the transportation possibilities of reaching that destination. These platforms are becoming more popular and help customers in finding their preferred way on their intermodal journey. However, as of now they are commonly administered by providers offering only their own set of mobility services or services specific to a certain geographic region. So far, it is thus not possible for customers to solve all their individual mobility demand on a single platform that allows for decision support and the booking of the physical transportation itself.

In line with service research priorities – in particular the development of service networks and systems, and the understanding of value creation [2] – we leverage the extensive research on service value networks (SVNs). To this end, a service network offers a single point of access for customers and the co-creation of value [3], irrespective of the domain under consideration. The objective in this work lies in maximizing consumer welfare (aggregate utility) based on consumers heterogeneous preferences regarding the set of

1. https://www.uber.com/
2. https://www.lyft.com/
7. https://www.moovel.com/
8. https://www.car2go.com
feasible transportation combinations in intermodal transport networks. This utility maximization is pursued according to the preferences of the customer, ranging from "the fastest", over "the greenest" to "the cheapest" way of reaching a destination given a feasible combination of mobility services. Regarding technical aspects, we incorporate network-based optimization concepts (decision support) from the field of intermodal freight transportation to the domain of passenger transportation. On the side of market and incentive design, the complex service auction introduced in [4] ensures incentive compatibility for all participants, rendering it an interesting mechanism candidate for passenger transportation networks.

This research is conducted in accordance to the design science paradigm [5]. The objectives are to: (1) adopt the concept of service value networks for intermodal passenger transportation networks, (2) develop a mechanism suitable for assignment of users to routes in these networks (model artifact) and (3) evaluate this artifact in a stylized example to demonstrate its usefulness and efficacy. The contribution of this research is a formal definition of complex mobility services in passenger transportation systems assembled by a mobility service network. We formalize the corresponding optimization problem and develop and implement an incentive-compatible auction mechanism. Its goal comprises satisfaction of heterogeneous demand via efficient and incentive-compatible integration of a wide range of mobility services.

The structure of the work at hand is as follows: In section 2 we analyse related work. Section 3 describes employed research methods. In section 4 we introduce the research artifact comprising the formalization of our model and the compilation of the corresponding optimization problem. A numerical example in section 5 displays the efficacy of our approach. We close with a discussion of our results and a conclusion in sections 6 and 7.

2. Literature Review

In this section we provide a review of related work. First, quality aspects in the area of mobility is covered. Second, research on intermodal routing in transportation services is examined. Lastly, we look at coordination mechanisms in networks.

2.1. Quality in mobility

Human demands are the driver for any human behavior. The perception of individual demands, however, is unique to each individual [6]. In the case of mobility humans strive for the satisfaction of complex personal demands that comprise functional and non-functional dimensions [7], [8].

According to [9] (perceived) quality can be described as the extent up to which customers’ expectations regarding quality are met or exceeded. The perceived quality is therefore a crucial factor for the usage of mobility offers [10].

The demand of individual users for different kinds of mobility may depend on both situational influences, e.g., time pressure or weather [11], [12], [13], and user characteristics, e.g., openness or attitude towards risk [14], [8]. The extent to which these factors affect individual users’ decision making so far remains unexplored: Most works studying these factors affecting decision making are of qualitative nature and restrict their attention to the differentiation between functional [15], [16] and non-functional [17] requirements of mobility demand.

2.2. Intermodal routing in transportation services

In many cases passenger transportation relies on more than one mode of transportation. Derived from supply chain management and logistics the terms intermodal passenger transport and mixed-mode commuting have found general acceptance when discussing two or more modes of transportation in a passenger journey [18]. The combination of different transportation modes with their individual strengths is the focus of research in this area [19]. For freight transportation this problem is widely discussed [20], with an emphasis on improving economic outcomes [21].

Most current approaches solving intermodal transportation problems focus on the solution of a shortest path problem [22]; or the formulation of constraint-satisfaction-problems [23]. In both cases functional factors such as time and cost are considered, while non-functional attributes are neglected. For instance, formal definitions of specific networks and their services are commonly represented with description languages like WSDL 9. However, as mere description languages these do not allow for automated compositions and require additional coordination mechanisms.

A principled approach to apply inter-modality in the area of passenger transportation with its functional and non-functional constraints and dynamic changes remains missing by now [21]. One reason is that solution concepts for this problem with its critical operational setting response time and complexity have still not been extensively developed [24].

2.3. Coordination mechanisms in networks

Mechanism design focuses on the problem of coordinating self-interested participants in pursuing an overall goal [25]. Mechanisms for standard optimization problems in the area of task scheduling and routing have already been designed by different authors [4]. For the context of mobility services path auctions - as a subset of combinatorial auctions - are of special interest. They reduce complexity through predefining

9. Web Services Description Language as recommended by the W3C.
all feasible service combinations in an underlying graph topology and are investigated in [26], [27]. Therein path auctions are used to set prices in and routes through a network. Application-related issues of auctions to optimal routing are examined by [28], [29].

3. Method

This research is conducted according to the design science research (DSR) paradigm following [5]. Primarily to ensure the rigour and procedure model of the conducted research, with this work following the structure recommended in [30]. The DSR paradigm – based on engineering and the sciences of the artificial [31] – is a problem-solving paradigm. Its aim is to "create things that serve human purposes" [32]. Specifically the construction and evaluation of IT artifacts enable organizations to address information-related tasks [5], [33], [34]. DSR artifacts are defined as constructs (vocabulary and symbols), models (abstractions and representations), methods (algorithms and practices), and instantiations (implemented and prototype systems). With the intent of applying and standardizing conceptual structures derived from game theory, mechanism design is the eminent theory when implementing a social choice [35]. As a subfield of game theory, it is concerned with the establishment of rules for the agents taking part in the game.

The goal of designing the mechanism is to derive a set of rules that implements a certain social choice function, i.e., a specific kind of allocation of goods that satisfies certain economic desiderata. Common goals in classic mechanism design are efficiency (or profit maximization), budget balance, and individual rationality. In scenarios relevant to the domain of information systems, computational complexity is additionally of particular importance. Often, trade-offs between economic desiderata and computational tractability arise.

The method artifact proposed in this research is a construct to provide optimal allocation and combination of mobility services to meet heterogeneous customer needs in an intermodal mobility context. DSR relies upon the application of rigorous methods in both the construction and evaluation of the design artifact.

The utility, quality, and efficacy of a design artifact must be rigorously demonstrated via well-executed evaluation methods [5], [30]. We provide an extensive numerical example do demonstrate its efficacy and assumption–based argumentation to demonstrate quality and utility of the proposed artifact [36], [37].

4. Artifact Description

In this section we define the basic concepts and parameters required to evaluate mobility services. First, we introduce the mobility service network, followed by the demand model to account for heterogeneous quality perception. Then, we describe the benchmark problem of allocating users to routes under perfect information and ignoring incentive issues. Finally, the complex mobility service auction, preserving incentives on the user side, is presented.

4.1. Mobility Service Network

We begin by defining the basic concepts and parameters of a mobility service network (MSN) required to analyze mobility services within a network. Our definition is based on a simplified state diagram model described by [38]. State diagrams are graphs that allow for simple serialization leveraging standardized formalisms. They are in prominent use by industry standards (e.g. WS-BPEL). More specifically, we leverage and adapt the service value network formalization introduced in [39] and further refined in [4].

A MSN consists of a set of mobility services \( V \). Each mobility service \( v_i \) is characterized by a set of quality attributes \( A \) (e.g., travel convenience, greenhouse-gas emissions, etc.) commonly referred to as quality of service (QoS) attributes. Additionally, the cost of transportation \( C \) and capacity \( c \) is assigned to each (mobility) service (e.g., a bus will only seat a certain number of travelers). The mobility services are offered by a set of mobility service providers \( p \in P \) and classified as a means of transportation \( m \in M \). A single provider \( p \) can offer more than a single mobility service. Providers can either be professional entities (e.g., national rail company) or users providing a certain transportation-relevant activity themselves (e.g., personal car sharing or ride sharing). Whether a mobility service is provided by a certain provider \( p \) is facilitated by the ownership relation

\[
\sigma : V \rightarrow P. \tag{1}
\]

Mutually compatible mobility services \( (v_i, v_j) \in V \) are connected by edges \( e_{ij} \in E \), i.e., drop-off of the initial means of transportation \( v_i \) and the departure point of \( v_j \) are within walking distance, and departure of \( v_j \) takes place after arrival of \( v_i \). The edge label denotes the distance between two distinct means of transportation, which may be of the same mode, i.e., transferring from one train to another.

Mobility service offers and the edges connecting them form a \( k \)-partite, directed and acyclic graph with a source and sink node denoted as the \( v_O \) and \( v_D \).

As a mobility platform, a MSN facilitates economic coordination between transportation providers and clients (passengers) via a single point of access. From the customer’s point of view, the MSN can be formalized as \( G = (V, E, M) \). The providers \( P \) are implicitly modeled via the ownership relation (1). An illustration of a MSN with the introduced concepts is depicted in Figure 1.
The preferences $\lambda^{cat}$ describe the perceived importance of a user for a certain quality category $cat$. The set $\Lambda^k = \{\lambda^1, \ldots, \lambda^{cat}\}$ represents the individual distribution of weights for each user $k \in K$ over all aggregated quality attributes of a complex service.

In order to account for relevant situation variables like weather or time pressure that influence the perceived importance and hence user utility, we introduce the variable $z \in Z$. This allows to express a users attribute weighting (i.e., his preferences) in a situation-dependent way: $(\Lambda|z) = \{\lambda^1, \ldots, \lambda^{cat}|z\}$.

The scoring function comprises user preferences and quality attributes of the complex services. It is given by the function $S(A_i, \Lambda|z) = \sum_{v \in \text{cat}} \lambda^{cat} \cdot A^{cat}(a_i)$ mapped on the interval $[0, 1]$.

When requesting a complex service in a MSN platform $G$, each user must reveal (potentially manipulated) information about his destination $D$, willingness to pay $\alpha$, individual situation dependent preferences $\Lambda|z$, and the quality attributes boundaries $\Gamma$. Thus, a request $\xi$ is represented by the vector $\xi = (G, D, \alpha, \Lambda|z, \Gamma)$.

The cost for a complex service is denoted by the sum of all transfer payments the requester has to pay to service providers $P_i$ along the path to $D$ through the MSN that comprises of the attribute combination $A_D$. The cost $C$ to reach the destination $D$ is the sum of costs of individual services required to travel along the path of the specified complex service $i$, i.e., $C_i = \sum_{v \in \text{cat}} C_v$.

From the set of feasible services offered by the MSN, with attribute combinations $A_i$, a user $k$ will choose the one with the utility-maximizing service $U^*_k = \max_i U_i$. We represent utility as a function of a user’s willingness to pay $\alpha$, his individual situation dependent preferences $\Lambda|z$, the service $A_i$, and all payments $C$. Formally, utility is defined as

$$U(\alpha, \Lambda|z, A_i, C) = \alpha \cdot S(A_i) - C_i. \quad (2)$$

Note that, for the sake of notational simplification, we drop the user index $k$.

4.3. Benchmark: Allocation under perfect information

For benchmarking purposes, we assume perfect information regarding users’ preferences and total cost. Based on perfect information, a welfare-maximizing social choice function can be implemented. This social choice function maps individual user preferences and problem constraints into a specific assignment decision. In the case of the MSN and assuming the demand model introduced before, the network operator’s decision variable concerns the assignment of users’ requests $k \in K$ to routes $r \in R$. An assignment $x$ is thus a mapping

$$x: (K, R) \rightarrow \{0, 1\}. \quad (3)$$

Figure 1. Graphical representation of a MSN synthesized from [39], [4].
Social welfare $W$ is defined as the sum of individual valuations of served mobility requests reduced by the cost of the corresponding allocation. For simplicity, we assume the marginal cost of transportation (for an additional traveler) to equal zero. While this assumption may be far-fetched in the long run, it reasonably resembles reality in the short run, i.e., when capacities cannot be adjusted. Formally, social welfare is then defined as follows:

$$W = \sum_{k \in K} \sum_{r \in R} U_k(r)x_{kr} - C(x)$$

(4)

$$= \sum_{k \in K} \sum_{r \in R} U_k(r)x_{kr}$$

(5)

A social planner is interested in finding efficient assignments via appropriately deciding over assignments. Accordingly, the objective function reads as follows:

$$\max_x W$$

(6)

In order to ensure solution validity, the (auxiliary) decision variables need to be appropriately constrained. First, a route only renders utility to the user, if this route connects origin $O$ to destination $D$. This is equivalent to assigning the user to a route only, if she is assigned to each of the edges in that route. To model this, we introduce an auxiliary decision variable $\phi$ that assigns users $K$ to mobility services $V$ with $\phi : (K, V) \rightarrow \{0, 1\}$. This decision variable is in turn constrained by the previously introduced decision variable $x$ as follows:

$$\phi_{k,v} \leq x_{k,r} \quad \forall v \in \{v | v \in r\}, \forall k \in K$$

(7)

After constraining the assignment decision of users to mobility services and routes, we allow a user to only be assigned to a single route, or be left without service.

$$\sum_{r \in R} x_{k,r} \leq 1 \quad \forall k \in K$$

(8)

To complete the formulation of the optimization model, we ensure that the total number of users assigned to routes does not exceed available capacity on any of the means of transportation.

$$\sum_{k \in K} x_{k,r} \leq \bar{c}_v \quad \forall v \in V$$

(9)

We are searching for an assignment of users to routes that maximizes welfare, given the network capacities and further domain-specific constraints. What renders the problem more difficult than the classic maximum flow problem is that user utility depends not only on the binary allocation decision, but on the specific assignment (a train ride may yield greater utility to some user than a coach ride). Accordingly, the problem structure corresponds to the generalized assignment problem [44]. For sake of tractability, however, we ignore effects of potential externalities between users.

Formulating a centralized optimization model often ignores incentives to individual users. Users may find it therefore beneficial not to truthfully reveal their preferences: Misrepresenting one’s preferences may result in more favorable allocation decisions by the central planner. This general shortcoming of central optimization approaches can be tackled by means of mechanism design, introducing additional incentive-preserving constraints into the original optimization problem.

### 4.4. The Complex Mobility Service Auction

To account for individual incentives, we present a mechanism that implements the desired social choice function through appropriate allocation and payment rules. By virtue of these rules, truthful revelation of private information becomes the dominant strategy for users.

In more detail, the distributed activities in a mobility service network can be coordinated by a modified complex service auction (CSA) introduced in [4]. The CSA is a scalable, multidimensional auction mechanism originally designed for the allocation and pricing of complex IT services. In this line of research complex services are compositions of generic IT services with a series of QoS parameters. Similar to the quality of IT services, different means of transportation offer heterogeneous service quality. Additionally, complex services are composed of simpler services. Multimodal trips, similarly, require the composition of complex mobility services from a pool of mobility providers and their offerings.

Accordingly, the SVNs with the CSA on-top can be adapted from the IT service domain to mobility services. Interestingly in this context, the CSA features the property of incentive compatibility (IC), rendering the revelation of private valuations and attribute weights a weakly dominant strategies. This property is an important prerequisite to determining efficient service allocations.

We now present the two core parts of the complex mobility service auction.

#### 4.4.1. Allocation rule

The allocation procedure comprises three steps, as outlined in Algorithm 1. Monotonicity in the allocation decisions is a necessary prerequisite to ensure incentive compatibility. To this end, the first of the allocation rule’s three steps comprises of ordering users’ requests $\xi \in \Xi$ greedily in descending order of their net utility. While computation of net utility requires the details of the transfer rule introduced below, we abstract from these details for a moment. Subsequently, based on the network structure and capacities, as well as the user’s preferences, the utility maximizing path through the network is computed based on Dijkstra’s algorithm for determining shortest paths in graphs [45]. Note that this computation is performed for each user individually. As a result of this greedy procedure,
Algorithm 1: The mechanics of the allocation rule of complex mobility service auction (CMSA).

1  Algorithm: CMSA(Ξ, V)
2  c ← COMPUTECAPACITY(V)
3  x = ∅
4  for ξ ∈ SORT(Ξ) do
5      if c > 0 ∧ Ξ ≠ ∅ then
6          v' ← ALLOCATEUTILMAX(ξ, V)
7          c ← REDUCECAPACITY(v', c)
8      x ← x ∪ (v', ξ)
9  return x

Algorithm 1: The mechanics of the allocation rule of complex mobility service auction (CMSA).

the resulting assignment may not be globally optimal. If the
determined assignment yields positive utility to the corre-
sponding user, this assignment is fixed and the capacities of
the employed v ∈ V is reduced by one unit. This process is
repeated until either all users have been taken into account,
or there is no feasible route, i.e., a route with positive
capacity connecting O and D, left.

4.4.2. Transfer rule. If users could manipulate allocation
decisions without paying for the eventual allocation, strateg-
ic users would choose to do so – with possibly highly
detrimental effects on system welfare. Therefore, to ensure
that users report their private type information truthfully and
do not inflate their willingness to pay, the allocation rule
is augmented with an appropriate transfer (payment) rule
that relies on critical value pricing [46]: Allocated users
are guaranteed to pay an amount less (or at most equal)
to the declared utility of the allocation, which may differ
from their true utility. In particular, critical value payments
are equivalent to the infimum over possible bids that would
have been necessary to ensure the same allocation.

Clearly, in situations with excessive supply, the critical
value pricing rule may translate into zero payments, reflect-
ing a supply glut. Under heavy demand, in contrast, prices
close to the actual utility of the user may arise, yielding only
small net utility.

Augmenting the greedy allocation rule with critical value
payments yields a dominant strategy incentive compatible
(DSIC) mechanism, the strongest solution concept available
in mechanism design: Irrespective of what the other agents
are declaring, it is the best strategy to truthfully reveal (i)
the willingness to pay and (ii) the parameters of the cor-
responding scoring function, such as preferences regarding
travel duration and comfort.

5. Evaluation

To demonstrate the applicability of the introduced con-
cepts and mechanisms, we provide a numerical example.
Due to space limitations and in order to keep the example
tractable, we describe a reduced scenario of three users

Table 1. User characteristics.

<table>
<thead>
<tr>
<th>symbol</th>
<th>user 1</th>
<th>user 2</th>
<th>user 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>willing to pay</td>
<td>α</td>
<td>100</td>
<td>75</td>
</tr>
<tr>
<td>duration preference</td>
<td>λdur</td>
<td>0.1</td>
<td>0.5</td>
</tr>
<tr>
<td>comfort preference</td>
<td>λcmf</td>
<td>0.5</td>
<td>0.2</td>
</tr>
</tbody>
</table>

Table 2. Available mobility services.

<table>
<thead>
<tr>
<th>j</th>
<th>mobility service</th>
<th>a^dur</th>
<th>a^cmf</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>coach</td>
<td>0.6</td>
<td>0.5</td>
</tr>
<tr>
<td>2</td>
<td>train</td>
<td>0.3</td>
<td>1.0</td>
</tr>
<tr>
<td>3</td>
<td>train</td>
<td>0.7</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Figure 2. Example MSN.

As we assume capacity of one passenger for each means
of transportation, we forgo the tabulation of more detailed
capacity information. Moreover, for reasons of clarity we
ignore the walking times necessary to change between
mobility services.

Each service is characterized by a duration and comfort
attribute as displayed in Table 2. The necessary aggregation
functions for these attributes are defined as as the sum of
individual durations, i.e.,

A^dur = \sum_{v_i \in A_D} a^dur |_{v_i}.

(10)

To aggregate the comfort of multiple mobility services
quantitatively, we employ the minimum relative comfort
value of a participating service:

A^cmf = \min_{v_i \in A_D} a^cmf |_{v_i}

(11)

Utility for the top path (trains with changeover), for user
1, i.e., \{v_2, v_3\} and the bottom path (\{v_1\}) is defined as
follows.
\begin{align*}
U_{1}^{top} &= 100 \cdot \left( \alpha_{1} \cdot \frac{\text{duration}}{\lambda_{1}^{dur}} \cdot (0.7 + 0.3) + 0.5 \cdot \min\{1, 1\} \frac{\text{comfort}}{\lambda_{1}^{cmf}} \right) \\
&= 100 \\
U_{1}^{bottom} &= 100 \cdot \left( \alpha_{1} \cdot \frac{\text{duration}}{\lambda_{1}^{dur}} \cdot (0.6) + 0.5 \cdot \min\{0.5\} \frac{\text{comfort}}{\lambda_{1}^{cmf}} \right) \\
&= 55
\end{align*}

Accordingly, user 1 gains more utility from a train trip with transfers than a direct coach connection. The corresponding utility values for all passengers and both complex mobility services are documented in Table 3.

<table>
<thead>
<tr>
<th>Table 3. Passenger utility.</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>( U_{1}^{top} )</td>
<td>100</td>
<td>70.5</td>
<td>50</td>
</tr>
<tr>
<td>( U_{1}^{bottom} )</td>
<td>55</td>
<td>40.5</td>
<td>45</td>
</tr>
</tbody>
</table>

Based on these utilities, which are computed for each user, assignment decisions are made and, correspondingly, the critical value payments are computed. In the allocation step, the users are sorted in decreasing order of their net utility from allocation. User 1 is assigned to the top path (train) in the MSN (Fig. 2), and capacity of all services involved with this path is reduced by one. As we assume initial capacity to equal unity, the top path is no longer available for other users, and we can focus on the utility of the bottom path in Table 3. User 3 gains most utility from allocation (\( U_{3}^{bottom} = 45 \)), hence the decision to assign him to the bottom path (coach trip). User 2 is left without service, as capacity is scarce.

We now turn towards computation of critical value (CV) payments as indicated in Table 4: The minimal admissible bid (through a combination of willingness to pay and quality preferences) for user 1 to ensure allocation would have been the utility of user 2 for the top path, plus an infinitesimal increment. Accordingly, user 1 pays 70.5. User 2 is not allocated, hence his payment equals zero. User 3 is competing with user 2 for allocation, and hence must pay the latter’s bid (i.e., 40.5).

Although left without allocation, user 2 is central to payment computation in our stylized example; excluding him would yield zero payments.

### 6. Discussion

Having identified the similarities between decisions for complex service compositions and passenger transportation services, we have successfully adapted the concept of service value networks to intermodal passenger transportation networks. Therefore, we have extended the extant body of knowledge about SVN by developing and integrating concepts that are crucial in the domain of passenger transportation services. Accounting for decision critical attributes like individual user characteristics and situation related influences in our mechanism’s formulation legitimates its application in the mobility context.

However, a deeper understanding about the set of quality categories and their corresponding aggregation functions is essential to increase our mechanism’s validity, see [47]. Qualitative and quantitative empirical studies about customer needs in behaviour will expedite the required insights in that area.

In our stylized example we illustrate that the mechanism is capable of efficiently coordinating demand and supply in the mobility domain. It also accounts for a heterogeneous set of customer needs. However, our example exhibits preliminary character. In order to demonstrate its full capabilities, the evaluation should be augmented to include more realistic and complex sets of customer requirements, situational restrictions and service offers. To further the evaluation of the proposed mechanism’s properties, numerical validation via simulation, ideally employing realistic data from sources such as existing time tables and service portfolios, would provide more detailed insights. Both the mechanism’s economic as well as computational performance in realistic settings should be further evaluated.

### 7. Conclusion

We have shown that diverse mobility services can be abstracted along multiple quality dimensions and integrated into mobility service networks. Conceptually, we provide a benchmark problem formulation to determine social welfare assuming non-strategic demand agents. For the case of strategic agents we reformulate the complex service auction concept and adapt it to the domain of mobility service networks. Our numerical example provides further insights into the mechanics of allocation and payment determination.

Critically, our approach combines optimization and incentive design to form a robust solution to the integration of highly heterogeneous mobility services on one common market platform. Our work should thus be understood to provide a cornerstone into solving the challenges associated with ad-hoc intermodal passenger transportation in the digital era.
A number of challenges remain: User preferences regarding different modes of transport may not be stable over time, but feature highly context-specific components. It would be interesting to see, how, empirically, (user-specific) attribute weights change depending on meteorological circumstances or users’ demographics. Furthermore, while travel duration and comfort are key aspects of travel planning, issues related to reliability, required walking distances, etc. may significantly alter usage decisions and should be taken into account in future model extensions. We aim to refine and validate the proposed utility function through quantitative empirical studies.

On the supplier side, extensions of the CMSA regarding capacity and investment planning may be fruitful and provide further industry-relevant insights. In particular, the trade-off between system efficiency, supplier participation and payment distribution warrants further examination. To this end, modification and application of established concepts from cooperative game theory may provide interesting insights.

References


