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Real options and flexibility analysis in design and management of one-way mobility on-demand systems using decision rules ☆

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ABSTRACT

This study explores the concepts of real options and flexibility analysis as an approach to address uncertain demand growth in mobility on-demand (MoD) vehicle-sharing systems, with the goal of improving expected lifecycle performance. As MoD systems are gaining popularity worldwide, they inevitably face significant uncertainty in terms of needs and customer demands. Designing, planning capacity deployment, and operating such system can be challenging, and require significant capital investments for companies and cities. Two distinct real options analysis (ROA) models are developed to evaluate and optimize flexible strategies for these systems, relying on a novel methodological approach to value flexibility based on decision rules. The decision-rule-based approach differs from standard ROA approaches used to quantify the value of flexibility in irreversible investment projects, typically based on dynamic programming. It emulates the decision-making process by capturing mathematically a triggering mechanism that determines when it is best to exercise the flexibilities embedded in the system design. Two prevalent types of MoD systems are studied in this paper as demonstration of the methodological framework: a station-based system where customers must pick up and return the vehicle at specific locations, and a free-floating system, where customers may pick up and drop the car anywhere within a certain area. A simulation-based approach is used to analyze the station-based system, which models the rebalancing operations from a micro-level perspective. The approach consists of a discrete event simulator for performance estimation, and an optimization algorithm for design space exploration that integrates a population-based search algorithm with Optimal Computing Budget Allocation (OCBA). For the free-floating system, an analytical model is developed where the decision rule is formulated into and solved using stochastic mixed integer programming (MIP). The study provides guidance to system operators on potential strategies for deploying MoD systems, considering explicitly uncertainty and flexibility as a value enhancing mechanism.

1. Introduction

An important yet challenging question in urban planning is how to easily and quickly enable short distance travel. Mobility on-Demand (MoD) vehicle-sharing systems are considered a convenient and comfortable means of urban transportation. Well-designed and managed, MoD systems should be able to offer more attractive combinations of costs and latencies than

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alternative systems such as private automobiles, taxis and transit systems (Mitchell, 2008). MoD systems not only extend choices available for travel and ease traffic pressure, they also reduce pollutions since most MoD companies use clean energy vehicles. Substantial evidence suggest that encouraging people to use MoD systems is effective to alleviate people's reliance on private vehicles: a previous study showed that 26% of participants sold their personal vehicles after using car-sharing services, and 53% of participants were able to avoid an intended purchase (Katzev, 2003).

Because of the associated social benefits of MoD systems, many companies founded in recent years have begun implementing MoD systems, though under different operating models. The earlier models of MoD systems were based on two-way traveling, which means users must return the vehicle to the same point where it was picked up (e.g. Zipcar®). Such systems are generally intended for relatively long distance travel. Most recently, a different type of MoD system operated under a one-way sharing model has gained popularity (e.g. Car2Go®). Users can return the vehicle to any parking area rented by the company (in station-based systems) or have the freedom to drop off the vehicle anywhere within a certain area (in free-floating systems). The characteristics of one-way sharing systems make them a more promising solution to urban mobility and short distance travel.

Efficiently designing, planning capacity deployment, and managing operations for one-way MoD systems, however, remains a challenge. Imbalanced traffic flows require real time rebalancing operations (Boyacı et al., 2015; Cepolina and Farina, 2012). Accurate estimates of the demand for such systems are difficult to make, and are rarely reliable. Given the emergence of new transportation models (e.g., Uber®) as well as shifting demographics and customer preferences, the future of MoD systems remains uncertain, despite the fact that many MoD operators have experienced exponential growth in the past few years (Shaheen and Cohen, 2014).

Many studies have shown that designing a flexible system is a viable approach for improving the performance of engineering systems like MoD systems under uncertainty (De Lessio et al., 2015). Flexibility – also referred to as real options – provides the "right, but not the obligation to change a project or system in the face of uncertainty" (Trigeorgis, 1996). Systems designed with such attributes are able to extract as much value as possible from uncertainty by reducing exposure to downside risks (like an insurance policy) while positioning the system to capture upside opportunities (like a call option on a stock). The net effect is typically to improve the expected economic performance of the system. The work on MoD systems typically focuses on finding stochastically optimal solutions with a set of fixed design parameters. This approach, however, may not enable the decision makers to adapt to changing conditions in a dynamic environment (Fassi et al., 2012).

One challenge to analyzing flexibility in MoD system is to determine the value of flexibility, as compared to the cost of enabling it in the system (e.g. providing for additional parking spots). Real options analysis (ROA) is an approach developed by economists to quantify the value of flexibility in large-scale irreversible investment projects. The form of the solution obtained using standard ROA, however, may not be intuitive for decision-makers to use in practice. Based on dynamic programming, it requires finding the current state of the system in a binomial lattice, projecting future uncertainty realizations, and conducting a backward induction to find the optimal strategy at each point in time (or stage). This may prove difficult to use in practice, unless the user is accustomed to such analytical approach. Another challenge is that many assumptions underlying standard ROA do not hold well in an engineering setting. For instance the performance of engineering systems is path dependent since decisions on capacity deployment ultimately affect the value of the system. The structure of binomial lattices used in standard ROA, however, inherently assumes path independence, which does not capture all of the complexities of real-world systems (Wang and de Neufville, 2005).

To address these issues, this study proposes two new ROA models to analyze flexibility in MoD systems. The studies are unified methodologically by their reliance on a novel approach to ROA based on decision rules. Decision rules can be described as triggering mechanisms that determine when it is appropriate to exercise the flexibility embedded in the system during operations. The solutions lead to performance enhancing design and management strategies in an environment where user demand may be uncertain, and the prospects of commercial success is unclear. Two studies capture the essential elements of the main types of MoD systems currently in operations worldwide, namely station-based systems and free-floating systems.

The organization of this paper is as follows: Section 2 provides a literature review that illustrates the concept of flexibility in engineering design and summarizes the simulation-based and analytic-model-based methods for analyzing complex systems. Section 3 describes the methodology used in this paper. Section 4 studies a station-based system using a simulation-based method, followed by Section 5, which studies a free-floating system using an analytic-model-based method. Section 6 concludes with the major discoveries and future work.

2. Literature review and motivation

2.1. Mobility on-Demand (MoD) transportation systems

Most of the literature on MoD systems addresses planning issues – i.e. where to install stations from where vehicles can be picked up/returned and maintained, and how to distribute vehicles across the stations – independently of operational decisions. On the one hand, studies focusing on operational level decisions mostly assume demand to be stochastic, but with the configuration of the system already being determined. On the other hand, the majority of studies investigating MoD system planning strategies are based on the assumption of deterministic demand and no operational level decisions. This sub-