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Performance evaluation using closed queueing network in Bike Sharing Systems

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Abstract – The overpopulated cities complain about the congestion and the pollution made by conventional transport system. The Vehicle Sharing Systems come as a great solution for these problems. The vehicles can be Electrical Cars, Electrical Scooters, Electrical Bikes or conventional Bikes. Vélib' one of the biggest Bike Sharing System (BSS) with 18000 bikes, is operational in Paris since 2007. An Electrical Scooter Sharing System is in a testing phase in Paris (Cityscoot) and is planned to be fully operational in the middle of 2016. Already many cities, having such operational system, need tools to manage it and make it more efficient. The performance evaluation is needed to get insights and make strategic and operational decisions. We model the bike sharing system using the queueing theory, precisely the Closed Queueing Networks (CQN). For the derived class of network, the steady-state probability of the states of the network model has a product form solution. This allows us to use the Mean Value Analysis (MVA) to derive the mean performances in steady state. The mean number of bikes in the different stations is calculated as well as the availability of free bikes in a station. The utilisation rate of bikes is also deduced. Finally some strategic insights were deduced to get better performance of the system.

Key words: Bike Sharing System / Steady-State Performance / Queueing Networks / Mean Value Analysis

1 Introduction

The principle of the BSS is simple; a user looks for a bike in a station of departure, then he travels to a destination station where he deposits the bike in a free dock.
The performance evaluation of these systems is important for the stakeholders and will be the subject of this paper. In part 2, we present a state of the art of. Then, in part 3, a model of the system is exposed and we show the MVA method in part 4. Finally we present the results of a simple example studied.

2 State of the art

In [1] a framework of the BSS problems has been presented in three dimensions: strategic, tactical and operational. The strategic dimension concerns the design of the network as the number of stations their capacity and the fleet sizing. The tactic dimension deals with incentives for customer based distribution of bikes. And the distribution of bikes by the service provider is considered as the operational control of the system. A survey in [2] presented some algorithm to tackle the main problems of the BSS. Several authors have defined specific performance indicators and use them to evaluate some different control policies. In [3] the 'proportion of problematic stations' was used to evaluate the redistribution and incentives in the BSS.

3 The underlying model

A closed queueing network from the vehicles' perspective was exploited to model the BSS system in [4]. Our work is built on the framework model in [4]. In this network, we will consider two types of nodes (N): infinite servers' node (I) and single server node (S). The number of bikes T in the system is constant.
In figure 2 we show an example of system of two stations. The single server node (nodes 1 and 2) presents the physical station: the buffer is the amount of free bikes in the station. The service time (noted $1/\lambda_i$ for a single node i) is a virtual service on the bikes and is taken as the inter-arrival time of the demands for bikes.
An infinite server node presents (nodes 3, 4, 5 and 6) the time trip (with rate noted μ_i for infinite server i) between two several stations.
A routing matrix $P=[p_{ij}, 1 \le i,j \le card(N)]$ is defined for the routes pattern of the bikes.
Considering this class of networks: the service time of the single and infinite nodes are considered to be exponentially distributed, this model falls into the class of BCMP networks [4], which has a product form solution.
For a network of T bikes, the continuous-time Markov process underlying the queueing network model has state space:

$$K = \left\{ (n_1, n_2, ..., n_N) / \sum_{i=1}^{N} n_i = T, n_i \ge 0 \right\} \quad (1)$$

The N-tuple elements designate the number of bikes in every node of the network. The product form expression of the steady-state probability can be defined as:

$$P(n_1, n_2, ..., n_N) = \frac{1}{G(T)} \prod_{j=1}^{N} \phi_j(n_j) \quad (2)$$

with

$$\phi_i(m) = \left(\frac{\pi_i}{\lambda_i} \right)^m \cdot \frac{1}{m!}, \forall i \in I \quad (3)$$

$$\phi_i(m) = \left(\frac{\pi_i}{\lambda_i} \right)^m, \forall i \in S$$

G is referred as the normalization constant.
We define the balance equation where π_i is referred as the relative throughput of node i.

$$\pi_i = \sum_{j=1}^{N} \pi_j p_{ji} \quad (4)$$

These flow balance equations are linearly dependent, and thus do not have a unique solution. So we solve it using a predetermined reference node r. We define then the visit ratio.

$$\upsilon_i = \frac{\pi_i}{\pi_r}. \quad (5)$$

4 The MVA method

For this class of network admitting a closed form solution, the Mean Value Analysis method can be established. This method is effective since no obligation is made going through extensive calculations of product terms or normalization constant to calculate performances. The MVA recursively (equations 6, 7 and 8) obtain the mean steady state performances (throughput, cycle time, queue length) of the nodes of the network.

$$R_i(t) = \frac{1}{\mu_i(1)}, \forall i \in I \quad (6)$$

$$R_i(t) = \frac{1}{\lambda_i}(1 + L_i(t-1)), \forall i \in S \quad (7)$$

$$L_i(t) = t \cdot \frac{\upsilon_i R_i(t)}{\sum_{j=1}^{N} \upsilon_j R_j(t)}, \forall i \in N \quad (8)$$

$R_i(t)$ is the expected response time and $L_i(t)$ the expected queue length of node i in a network of t bikes.
Iteratively from t=0 to t=T, we obtain $R_i(T)$ and $L_i(T)$ for a closed network of T bike.

5 Numeric results

We apply the MVA to evaluate some performance criteria: the mean bikes in stations, the availability of bikes in stations and the utilisation rate of bikes. The system under study, presented in figure 2, is composed by two stations. The rate of the inter-arrival of users is $\lambda_1=\lambda_2=15$ and the time period of travel is 2 hours ($\mu_3=\mu_4=\mu_5=\mu_6=0.5$). The routing is showed in the figure 2.

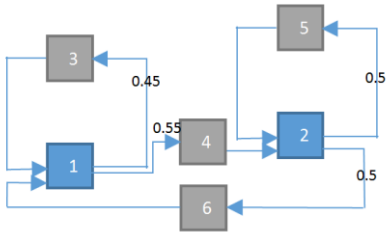

Figure 2. A system composed by 2 stations

Some performances can be derived from the MVA results. As follows, the availability in a station is defined as the throughput (L_i/R_i) divided by the service rate (λ_i), and the utilization rate of bikes is the sum of mean number of bikes in travel in all the system divided by the fleet size T. We depict the evolution of the mean number of bikes in a station as a function of the fleet size in figure 3. We can see that the mean number of bikes in the first station remain constant as the fleet size get larger. In figure 4, the availabilities of bikes in the first station are shown as a function of the fleet size. The curve shows an asymptotic behaviour. The utilization rate of the bikes is evaluated in figure 5.

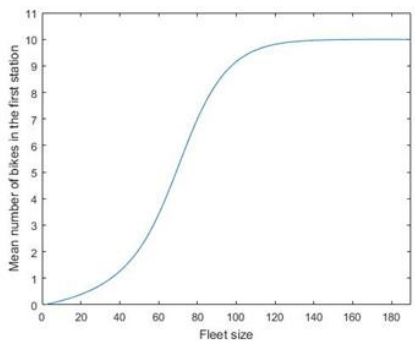

Figure 3. Mean number of bikes in the first station

From the performance figures, we can deduce some strategic decisions of the BSS. From the evolution of the mean number of bikes, we can decide what capacity we would make for a certain station.

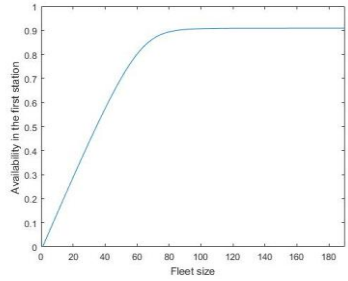

Figure 4. Availability in the first station

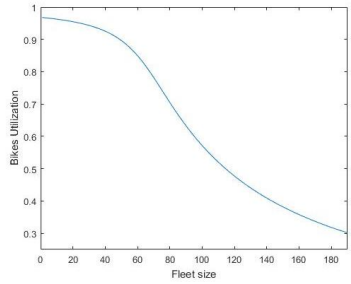

Figure 5. Bike utilization

An optimal fleet size can be obtained from the evolution of the availabilities in stations. For the example studied, the optimal fleet size for better availability, in the first station, would be between 70 and 80 bikes. For this fleet size the utilization rate of the bikes is between 78 % and 70 %.

6 Perspectives

The design parameters (fleet size) can be injected in other models of BSS dealing with operational control, like the redistribution of bikes for example. The stations capacities are known, they can be integrated in a closed networks model with limited capacities, and then we obtain more realistic results of performances.

7 References

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