NETWORKS OF QUEUES FOR THE SIMULATION OF URBAN FLOW SYSTEMS: AN INTERMODAL TRAFFIC SYSTEM

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Abstract: In this paper we introduce a queueing network model, which can be used to simulate the behaviour of specific traffic systems in an urban context. The frame of the work is that of road automation and traffic system control by queue based models simulation.

1. Introduction

This investigation has been carried out in the context of studies concerning a computer simulation of urban and metropolitan flow systems. Methodologies of simulating network-of-queues models are based on languages and procedures of evaluating the performances of computer systems elaborated in the United States since the 1970s and later in France. In our context, we have simulated systems of vehicular traffic [1] and systems of pedestrian flow [2].

The main aspect of these investigations is the possibility to represent a system of urban flow through an appropriate and detailed network of queues with controlled customers' flows that reproduces, in its functioning, the evolution of the actual system under consideration. Queues are therefore used to represent this particular typology of flow systems.

The problem concerning methodologies of representing vehicular traffic systems was set out in the literature in [3], where some possible prospects are listed to solve this open problem, including the hypothesis of networks of queues. To date, the only literature studies of this issue concern analytical solutions relating to traffic systems that are subject to very specific conditions and, therefore, cannot be used to analyse systems which are commonly taken into account in an urban or metropolitan context (*e.g.* [4]).

Actually, network-of-queues models used to represent urban flow systems have proven to be complex, analytically insolvable and only to simulate the transitory evolution of the specific system under consideration.

In this work a specific networks-of-queues model is presented that allows one to simulate the evolution of a system of urban mobility characterized by an interaction of the following elements:

- a collective passengers transport system: train, subway, bus;
- a generic station, where public transport stops and a flow of outgoing passengers is generated;
- a system of moving staircases for mechanized transfer of pedestrians.

This model is therefore used to study issues that are frequently noticed in the planning of an intermodal urban traffic system. Intermodal traffic systems are one of the main elements of the rules to set and implement in Plans of Urban Traffic [5].

The model allows us to measure, through simulation, the exact impact of a project implying the use, at a given station, of moving staircases for mechanized transfer of pedestrians on customer flow. In the project, each moving staircase is characterised by its specific width and speed, determined by an estimate of user flows based on incoming collective transport.

QNAP2 was used to implement the model and create the simulator. QNAP2 is an object-oriented programming language for computer system analysis developed in France by INRIA. QNAP2 includes a queue object and a consumer object, among other types of default data, and it implies two levels made up of a control language and an algorithmic language. In the present investigation, this model is applied to an analysis of a system being the main pedestrian approach to a city in Central Italy. The system is made up of a bus terminal connected to a moving staircase system linking it with the upper town.

In this context, the analysis concerns the system's functioning in peak time and allows one to confirm direct observations.

2. The model

Let us now define the network-of-queues model shown in Figure 1 and describe its components. This model is a multiple-class network of queues made up of the following devices.

Station A – it is a source queue generating the incoming flow of public transport. This device is a single server queue with "infinite" customers belonging to the customer class that represents the public collective transport in the system under consideration, *e.g.*: train, subway, bus. When the service of a customer in A is finished, that customer is routed to the B queue and the following A queue customer starts its service. Therefore, service time at A represents the time between two incoming means of collective transport at station B.

Station B – it is a multiple server queue and represents the public transport arrival terminal. The number M of servers of this queue is the number of arrival platforms taken as crucial for the evaluation of the system under consideration. When executing the service algorithms of B queue servers, pedestrian flows are generated and are routed to station C. These pedestrian flows are marked according to
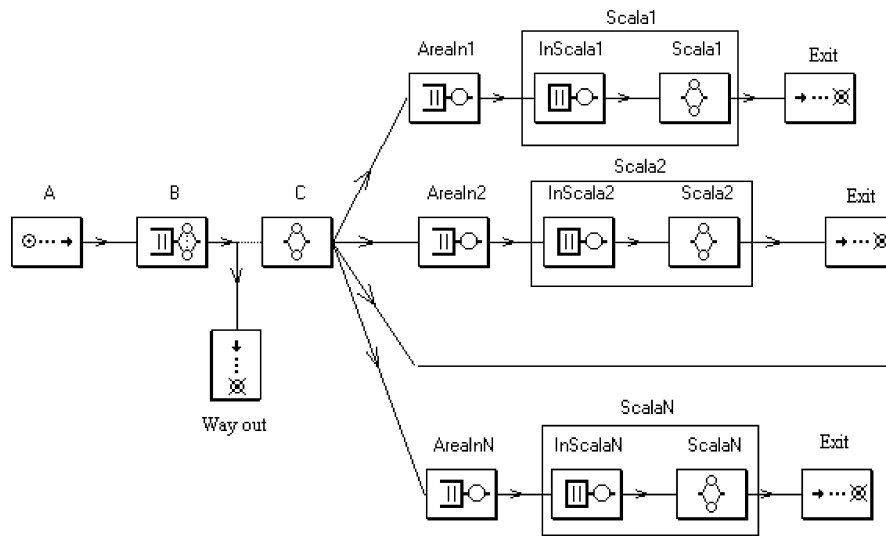
Figure 1. A scheme of the considered network of queues

customer classes. A passenger who steps off is routed to the C queue as a customer of a specific class. Passenger assignment to a customer class is done through a probability distribution, which the model is given as an input datum. In this context, a customer class represents a possible route a pedestrian follows to go from the arrival platform to the entrance of the moving staircase he chooses to use. When its service in the B queue is finished, each coach is routed to a way out.

Station C – it is an infinite servers' queue for the pedestrian type customers. All customers are served in C according to the class they belong to. Service time of a customer at this station represents the time a pedestrian needs to move from the arrival platform to the entrance of the moving staircase he is going to use. Therefore, a customer's service time in C is a random variable subject to a probability distribution that is specific for each customer class and is given to the model as input data.

Area stations – they are single server queues. This type of devices represents the area before the access to a mobile staircase. This is the area where a queue of customers waiting to get on the mobile staircase can form. Actually, the model can detect if pedestrian flow towards some of the N mechanized facilities exceeds the maximum flow the relevant mobile staircase's access area is able to absorb. Then, Area stations act as access queues for the staircase sectors of entrance to the staircase. We will see that these sectors are single server devices with no waiting space, equipped with a status indicator for the Area station just behind. A customer's service algorithm in an Area queue server monitors the status of the entrance sectors. When the entrance is free, the pedestrian is transferred to the first step of the staircase in no time; otherwise he is kept in the server, holding up the following customers.

Staircase (scala) stations – they represent the mobile staircase mechanized facilities for pedestrian transfer. The model of these devices, as shown in the figure, consists of two queues set in a line. A staircase queue InScala is the pedestrian access point to a mobile staircase. This component can be a bottleneck in the pedestrian flow

system. It consists of a server with no waiting space. Customers' mean service time, t, in a staircase is the mean time a customer takes to climb and slide on the access step of the escalator. It follows that $1/t$ is the mean frequency of pedestrians climbing a mobile staircase. This parameter depends on the staircase's width, L_s, and slide speed, V_s. Increasing L_s or V_s we increase the mean access frequency of a staircase, F. Given L_s and V_s, our model is implemented to work with two possible mean values of F: under normal conditions and under congestion conditions. Therefore, given the structural physical staircase characteristics L_s and V_s, $F_{\max}$ represents the mean access frequency that occurs under congestion conditions when pedestrians climb "crowding" on the staircase occupying the whole available access section.

Having left the InScala station, pedestrians enter the Scala station. This is an infinite servers' queue. The pedestrian service time, t_s, in this device is the transfer time from the access position to the exit position of the mobile staircase. In this model, t_s is a constant value that depends on the length of the staircase, L_s, and its slide speed, V_s. The $n_s(t_0)$ number of customers that, at a given instant t_0, stand in this service device represents the number of pedestrians that simultaneously stand at t_0 in a mobile staircase, properly positioned along the staircase according to their access instant.

3. An exemplary application

In this paragraph we describe an application of the previously defined networks-of-queues model in a simulation investigation of a specific intermodal urban transport system. The system under consideration is made up of the following components:

- a bus public transport system,
- a bus terminal station, for the arrival of incoming passengers,
- an upwards escalator for pedestrians transfer from the bus terminal to the upper town.

This system is one of the main points of access to the city of Chieti, a medium-sized city of Central Italy (see Figure 2). In the subsequent subsections we describe the details of the model as applied to our example (Section 3.1) and present exemplary results (Section 3.2).

3.1. System specification

In Figure 3, the configuration of the model simulating the considered exemplary system is shown. In the figure, components of the system are described as follows:

A – the source of buses' arrival flow,
B – the bus terminal, with 20 arrival platforms,
C – the queue that simulates the pedestrian routes from the arrival platforms to the mobile staircase,
D – the pedestrian area just before the mobile staircase going to the upper town,
E – an upwards escalator, with the following characteristics:

- the time to climb the staircase is 2.44267 minutes,
- the time to move from step to step is 0.012 minutes,
- the staircase's width is 100 centimetres.

Mobile staircase view   Mobile staircase: indoor view

Parking area   Approach to a mobile staircase

Staircase access   Car parking access

Figure 2. Photos of the principal elements of the considered communication system
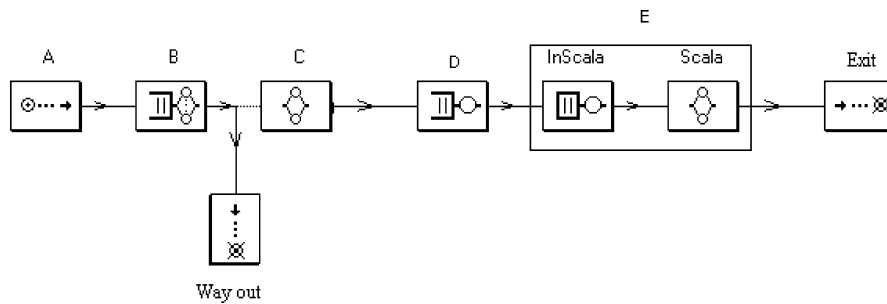

Figure 3. Schematic representation of the studied communication track

The implementation of a simulator based on the networks-of-queues model shown in Figure 2 was realized using the QNAP2 programming language developed by INRIA in France. This is an object-oriented language whose types can be determined by the user. The language has, among its base types, a `QUEUE` object and a `CUSTOMER` object, and a `FLAG` type for synchronizations. QNAP2 implements an algorithmic language that is similar to Pascal and a command-based language that separates the

source program's compilation and execution phases in different sections. The following are a few sections of the QNAP2 program implementing the networks-of-queues model described in Figure 3.

The /DECLARE/ command introduces a section that defines variables whose type has been previously described.

```
/DECLARE/
    QUEUE A, B, C, D, INSCALA, SCALA;
    FLAG FERMO;
    REF CUSTOMER RC;
    INTEGER N;
```

The /STATION/ command introduces a section that defines a service station based on a queue-type variable.

```
/STATION/
    NAME=A;
    TYPE=SOURCE;
    SERVICE=IF (TIME>=T1) AND (TIME<T2)
        THEN EXP(0.32)
        ELSE EXP(2.037);
    TRANSIT=B;
/STATION/
    NAME=B;
    TYPE=SERVER,MULTIPLE(20);
    SERVICE=BEGIN
            FOR N:=1 STEP 1 UNTIL 50
            DO BEGIN
                RC:=NEW(CUSTOMER); EXP(0.1);
                TRANSIT(RC,C);
            END;
        END;
    TRANSIT=OUT;
......
/STATION/
    NAME=D;
    TYPE=SERVER,SINGLE;
    SERVICE=IF INSCALA.VALUE <= 1 THEN
            BEGIN
                UNSET(FERMO);
                TRANSIT (INSCALA);
            END
        ELSE
            BEGIN
                WAIT(FERMO);
                TRANSIT (INSCALA);
            END;
/STATION/
    NAME=INSCALA;
    TYPE=SERVER,SINGLE;
    SERVICE=BEGIN
        UNSET(FERMO);
        IF (D.NB)>=50
            THEN CST(0.0084444444)
            ELSE CST(0.0120666666);
        SET(FERMO);
        END;
```

```
        TRANSIT=SCALA;
/STATION/
        NAME=SCALA;
        TYPE=SERVER,INFINITE;
        SERVICE=CST(1.7963);
        TRANSIT=OUT;
......
```

The service algorithm of station B, representing the bus terminal, includes the execution of a for loop containing the `RC:=NEW(CUSTOMER)` statement. Customer is a QNAP2 variable base type and represents a network user. In the same loop, the `TRANSIT(RC,C)` statement sends the customer pointed by `RC` to station C. Thus, we have pedestrian flows of passengers getting off the buses and going towards the mobile staircases.

The `SET()` and `UNSET()` procedures are used to assign the "open" or "closed" value to the `FLAG` variable, while the `WAIT()` procedure forces the present customer to wait for the `FLAG` opening, stopping its service in the device.

The InScala station has a service time that depends on the overcrowding in the D queue, representing the access to the mobile staircase. Checking the number of customers at station D during the simulation, we can distinguish two different service times for a pedestrian's passage from the access position to the position on the staircase. These are service times that account either for congested conditions (maximum load time) or for normal conditions (standard load time). Maximum load time is defined as the ratio between the time to move from the first to the second step and the maximum step load (in our case $0.012/1.5 = 0.00844$). The standard load time is defined as the ratio between the time to move from the first to the second step and the standard load step (in our case $0.012/1.0 = 0.012$).

The staircase station is an infinite server and represents the residual component of the mobile staircase. Please note that the access to this device takes place serially from the first step. This device is used to evaluate the number of presences on the mobile staircase over time. Service time is invariable for all customers and corresponds to the time necessary to move from the first step up to the exit from the staircase.

3.2. Exemplary simulation results

The system analysis presented herein concerns the conditions of maximum congestion.

We have fixed one minute as the unit of simulation time, and 60 minutes as the simulation's duration. The A queue is the source of flow of buses arriving at the terminal. Two different generation frequencies are distinguished in its service algorithm, as the buses' inflow in the 7.55–8.00 time interval is higher. If the variable "time" (*viz.* the current time of the simulation) assumes values between instant 15 and instant 20, the mean time between the arrival of two buses is 0.32 minutes; otherwise it is 2.037 minutes.

The B queue – representing the bus terminal with 20 arrival and departure platforms – is a multiple server and, according to our records, it requires a mean service time of about 5 minutes per one arrival (the customers getting off and the bus departuring). The probability of congestion at this station has turned out to be negligible. Actually, the probability for all the servers to be busy is approximately

Table 1. Simulation standard results

Name	Service	Busy pct	Customer no.	Response	Served no.
A	1.283	1.000	1.000	1.283	43
B	0.1775	$0.6360 \cdot 10^{-2}$	0.1272	0.1775	43
D	$0.987 \cdot 10^{-2}$	0.3538	40.15	1.120	2150
InScala	$0.1005 \cdot 10^{-1}$	0.3602	0.7173	$0.2002 \cdot 10^{-1}$	2150
Scala	1.796	0.3202	67.90	1.895	2150

$1.3894929 \cdot e^{-9}$. In order to obtain the latter value we can refer to a single bus station component and (making some exemplifying hypotheses) consider the well-known M/M/20/20 finite memory system. Knowing that 43 buses arrive in the period of maximum congestion and taking into account one hour of real time, we can develop the following calculations: $\lambda = 43/60$ buses per minute, $\mu = 1/5$ buses per minute, $P_k = P_0(\lambda/\mu)^k/k!$, so that $P_{20} \approx 1.3894929 \cdot e^{-9}$. Such an evaluation is possible because, in this model, station B is the access entry of customers in the network and the functioning of this component is independent – as very rarely happens when dealing with urban flow – of other components of the system.

Table 1 illustrates some results of the simulation. Times are given in minutes and some of the system queues are shown with relevant data concerning mean service time, busy percentage of the station, average number of customers, the system's response time and number of served users (buses, persons).

Figures 4–6 illustrate, respectively, the time evolution of the following variables: the number of customers produced by station A, the length of the access queue to the mobile staircase, and the number of customers on the mobile staircase. The following conclusions can be drawn from these data. At peak time, around minutes 15–20, we have a heavier inflow to the system; this heavy inflow can lead to a temporary congestion we are able to measure. It should be observed that the A-B subsystem, that is the bus terminal, does not exhibit any congestion problems, in agreement with the analytical calculation above. We can be even more precise and point out that we get
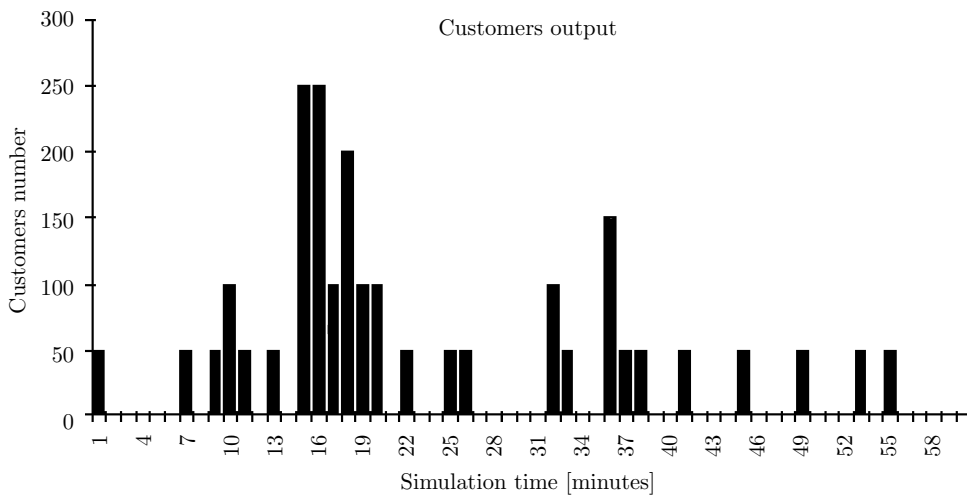
Figure 4. The number of customers produced by station A versus time
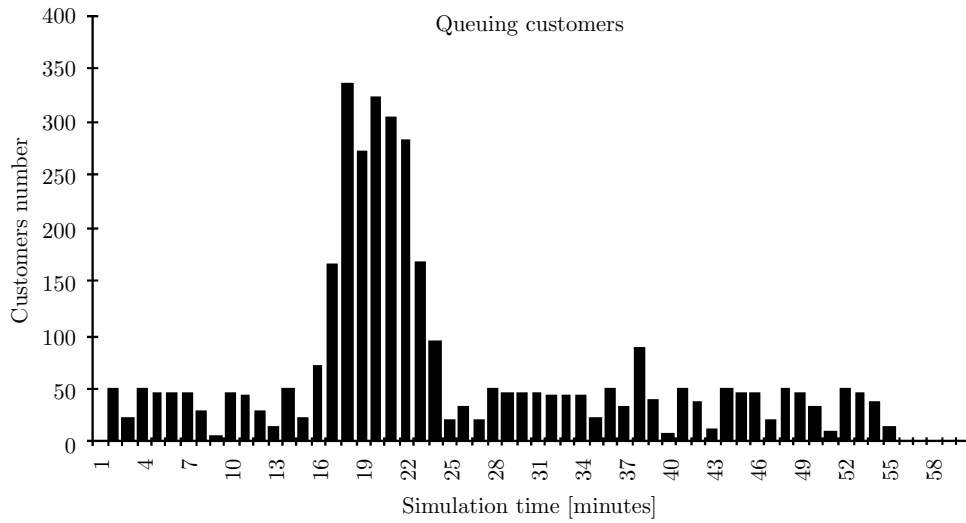(proportional to the number of arriving buses)

Figure 5. The length of the access queue to the mobile staircase versus time
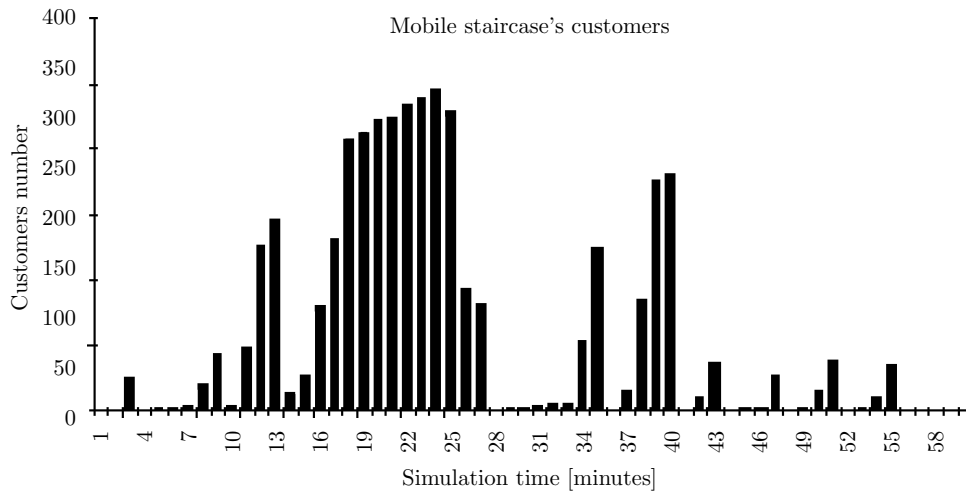

Figure 6. The number of customers on the mobile staircase versus time

the heaviest inflow of 12 buses at minute 20 and minute 21, due to the peak of arrivals in the interval [15–20]. As far as the pedestrian flow is concerned, we observe that when the peak of arrivals occurs, with a maximum of 250 people between minute 15 and minute 20, a queue forms between minute 15 and minute 23, cleared up by the escalator within minute 26.

4. Conclusions

In the present investigation we have analysed customer flow in a node of a specific intermodal urban transport system, applying a simulation with networks-of-queues models. The concerned node is a bus terminal acting as a junction to a moving staircase system in the city of Chieti.

The technologies used in this work have been developed by some research centres of the French INRIA we work with. These are procedures to simulate dis-

crete flow systems using synchronization and service centres' networks. To better understand how customer flow works in the system under consideration, we usually integrate such methodologies with spatial interaction models.

The analysis concerns the system in the maximum congestion timeframe. The functioning of the mobile staircase is also reproduced in the simulation. The analysis implies that the parking area of the bus terminal is over-dimensioned. On the other hand, the pedestrian access area to the mobile staircase is adequate to the incoming customers, who – when the peak inflow takes place – fill a surface that rounds a maximum of 100 square metres while waiting to climb the mobile staircase.

References

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