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Parking space occupancy as an example of a shared resource modelling problem

Zajmowanie miejsc parkingowych jako przykład problemu modelowania zasobów współdzielonych

Abstract. City logistics is at the forefront of mainstream logistics. In the literature, definitions of this logistics include, among others, the issues of traffic flow and parking space availability in cities. There is a steady increase in the number of wheeled vehicles in cities of all sizes. This generates the problem of parking space availability. The limited amount of available parking resources, which will always be insufficient, especially with increasing vehicular traffic, causes the need for their rational use. In this paper, we analyse the problem of occupancy and demand for free parking spaces. A discrete simulation method was used. A stochastic model was developed in a computer environment, taking into account such parameters as: (a) density of traffic streams; (b) demand of vehicles for free space; (c) vehicle parking times; (d) actual parking space utilisation in examples. Simulations using the developed model were carried out for three car parks. These showed that only car park B maintained traffic flow, as it had enough spaces to handle the traffic flow. Car parks A, and B are inefficient and allow for a smooth parking period of 2 to 3 hours from a neutral state. However, this is impossible in practice as these car parks are never empty as there are always vehicles parked there. The simulation gives reliable results within a 90% confidence interval.

Key words: logistics, parking spaces, modelling, parking utilisation analysis

Synopsis. Logistyka miejska znajduje się w czołówce logistyki głównego nurtu. W literaturze definicje tej logistyki obejmują m.in. kwestie płynności ruchu i dostępności miejsc parkingowych w miastach. Obserwuje się stały wzrost liczby pojazdów kołowych w miastach każdej wielkości. Powoduje to problem dostępności miejsc parkingowych. Ograniczona ilość dostępnych zasobów parkingowych, która zawsze będzie niewystarczająca, zwłaszcza przy rosnącym ruchu kołowym, powoduje potrzebę ich racjonalnego wykorzystania. W artykule analizujemy problem obłożenia i zapotrzebowania na wolne miejsca parkingowe. Zastosowano dyskretną metodę symulacji. Model stochastyczny został opraco-

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wany w środowisku komputerowym, biorąc pod uwagę takie parametry, jak: (a) gęstość strumieni ruchu; (b) zapotrzebowanie pojazdów na wolną przestrzeń; (c) czas parkowania pojazdów; (d) rzeczywiste wykorzystanie miejsca parkingowego w przykładach. Symulacje z wykorzystaniem opracowanego modelu przeprowadzono dla trzech parkingów. Wykazały one, że tylko parking B utrzymywał płynność ruchu, ponieważ miał wystarczająco dużo miejsc do obsługi przepływu ruchu. Parkingi A i B są nieefektywne i pozwalają na płynny okres parkowania od 2 do 3 godzin od stanu neutralnego. Jest to jednak niemożliwe w praktyce, ponieważ parkingi te nigdy nie są puste, ponieważ zawsze są tam zaparkowane pojazdy. Symulacja daje wiarygodne wyniki w 90-procentowym przedziale ufności.

Słowa kluczowe: logistyka, miejsca parkingowe, modelowanie, analiza wykorzystania parkingów

JEL codes: L91, R40, R41, M20

Introduction

Logistics is a relatively young and quite capacious field of knowledge, and its importance in the economy and business is growing in parallel with the increase in com-petition on the market. It affects not only large concerns but also a medium, small, and micro-enterprises. The tasks posed to logistics in enterprises vary depending on the organisation of the company, its size, and structure, as well as the multiplicity and range of tasks that it can cover [Brzeziński 2006].

A completely different category of problems is tackled by city logistics, which has a prominent place in mainstream logistics. In the literature there are many definitions of city logistics [Würdemann 1992, Stabenau 1993, Sołtysik 2001, Taniguchi et. al 2001, Krawczyk 2004, Crainic 2009] in which one of the most important priorities to improve is the fluidity of communication and availability of parking spaces in cities. Hence the idea for the topic in this paper. As the number of wheeled vehicles is con-stantly increasing in cities of all sizes, the same problem occurs – the limited amount of available parking resources, which will always be insufficient, especially with in-creasing vehicular traffic.

This study aims to show a new method and possibilities of computer modelling of resource occupancy, using the example of the use of parking spaces – as a resource shared with other road users. As a consequence of simulations, it will be possible to estimate the demand for parking spaces, taking into account local conditions such as traffic flow density and average packing times in a given area. In a broader context, the presented solution may find application in many fields, among others:

- investigation of the occupancy of car parks, post boxes, parcel machines, etc;
- survey on the occupancy of borrowed resources, library, bicycle rental, etc;
- testing the occupancy of toilets, vending machines, or other public facilities;
- testing the occupancy of any buffer zones in urban traffic or industry.

State of the art review

For a better understanding of the problem, previously applicable approaches for the analysis of the use of already existing car parks will be shown, as well as methods for estimating the required number of parking spaces for new developments. In construction projects, it is assumed that the number of parking spaces is determined by accepted standards. Using these global benchmarks ignores the existing variation in local traffic behaviour. This paper [Stienstra 2014] describes a calculation method that takes into account local conditions. The essential elements in the calculation are:

- the number of arrivals,
- parking period,
- the permissible level of car park occupancy.

In the proposed approach, the number of parking spaces needed for the development can be calculated using equation (1).

$$P = \frac{A*D}{B*T} \tag{1}$$

where:

P – number of parking spaces required,
A – number of vehicle arrivals during the survey period (e.g. working day or Saturday),
D – average dwell time,
B – average permissible occupancy level,
T – test period, number of hours (minutes) for the test period.

The variables *D* (mean parking time) and *T* (test period) shall be expressed in the same units (e.g. hours or minutes). The average idle time (*D*) of the cars is calculated using formula (2).

$$D = \frac{\sum d_i}{A} \tag{2}$$

To calculate the value of (*D*), an additional variable d_i is introduced in formula (2), which denotes the parking time of a single car in the car park. However, if the adopted unit of time measurement is the minute, then the total number of parking minutes used will be expressed by formula (3).

$$\mathrm{A} \cdot \frac{\sum d_i}{A} = A \cdot D \tag{3}$$

An incremental method for determining the demand for free parking spaces at MOPs along motorways and expressways is presented in the paper (Stawowy et al. 2017). The use of video monitoring for computer counting of vehicles entering and leaving the service area was used. Based on the computer processing of discrete data, the demand for parking spaces in a given period is calculated. Aggregation of events to designated periods will enable the presentation of the number of vehicles as a function of time. The number of cars entering the MOP in the period from $t_1$to t_2 is determined using formula (4). The number of cars leaving the MOP in the period from $t_1$to t_2, formula (5).

$$n_{1(t_1;\, t_2)} = \sum_{t_2}^{t_1} e_{1\,(t_1;t_2)} \tag{4}$$

$$n_{2(t_1;\, t_2)} = \sum_{t_1}^{t_2} e_{2\,(t_1;t_2)} \tag{5}$$

$$n_z = \sum_{t_3}^{t_4} \left(\sum_{t_1}^{t_2} e_{1(t_1;t_2)} - \sum_{t_1}^{t_2} e_{2(t_1;t_2)} \right)_{(t_3;t_4)} \tag{6}$$

where:

– e_1 and e_2 are vehicle registration events at the entrance and exit of the MOP respectively,
– t_1 and t_2 are the initial and final times (moments), respectively, for determining the value of n.

The authors calculate the parking demand in a given period using formula (6), where the period from t_3 to t_4 is the time for determining the parking demand of the car park n_z.

Slightly different but important indicators were considered when analyzing the use of parking spaces in the Krakow Paid Parking Zone [Pietruch 2017]. In addition to the typical counting of vehicles and occupancy, parking turnover was measured, the basic measure of which was the parking turnover ratio W_r according to formula (7), as well as the parking space utilization ratio W_p according to formula (8).

$$W_r = \frac{P_{pn}}{M_p} [P/\text{stanowisko}] \tag{7}$$

$$W_p = \frac{P_p}{M_p} \cdot 100[\%] \tag{8}$$

where:

– P_{pn} is the total number of vehicles using the parking spaces during the study period,
– M_p is the total supply of parking spaces,
– P_p is the number of parked vehicles in a given period (defined as the percentage of parking spaces occupied by parked vehicles in a given period).

A very interesting, but different approach to estimating the need for parking spaces is presented in another paper [Hampshire 2018]. In this case, the authors focused on studying the traffic stream in order to estimate the number of parking spaces needed based on its intensity. An observation was made of an empty parking space in the vicinity of the traffic stream. They then counted how many vehicles are willing to occupy this empty space. On this basis, formula (9) was developed to calculate the parking demand.

$$\hat{p} = \frac{n}{\sum_{i=1}^{n} x_i} \tag{9}$$

The method is very easy and practical to apply because it answers the question of what part of the traffic stream wants to park. Each car in motion creates a traffic stream. In order to use this method in practice, it is necessary to make *(n)* observations, to check how many cars drive past a free parking space and how many want to park there. One vehicle trip is one observation, i.e. an attempt to park in the free space. Each attempt can end in two ways:

- success – the car is parked,
- failure – the car passes a vacant parking space and drives on.

The estimation is performed based on a geometric probability distribution. For each observation, we count the number of attempts needed to achieve success, i.e. to park the vehicle. The probability of observing success (p), forms the share of drivers in the traffic looking for free parking. We assume that $X_1, X_2, \ldots, X_n$ corresponds to a sequence of n-independent observations at a newly vacated parking space, where X_i is the number of passing cars before the first success. Based on equation (9), it is possible to estimate the probability of the share of cars in traffic. And the estimated share of cars in traffic is the inverse of the average number of cars that want to park. Of course, such an estimation is always subject to statistical error and should be expressed in terms of a confidence interval, giving the standard deviation or variance.

The computational example given by the authors is as follows. Suppose that 20 observations have been made of how many cars pass a vacant parking space before occupying it. Consider the following distribution of the distribution:

- in 10 attempts, parks the first oncoming car that sees a clear space.
- in 5 attempts, parks the second passing car that sees a clear space.
- in the remaining 5 five trials, park the third car that sees the open space.

The calculation for all trials for success is as follows:

$$\sum_{i=1}^{20} X_i = 10 \cdot 1 + 5 \cdot 2 + 5 \cdot 3 = 35$$

The estimated amount of parking space required will be according to formula (9):

$$\hat{p} = \frac{20}{35} = 0{,}57.$$

The reported result of 0.57 falls within the standard 95% confidence interval of $0.41 \leq \hat{p} \leq 0.73$, according to the authors' assumptions the number of observations above 300 already gives very precise estimates suitable for practical applications.

In the following paper [Spławińska and Solecka 2017], a review of existing methodologies for estimating parking spaces at MOP facilities in various countries, including Poland, the United Kingdom, the USA, and Germany, is presented. As a result of comparing the existing methodologies used in these countries, the characteristics on which the number of needed places at MOPs may depend were singled out and taken into account in the proposal of a new national methodology formula (10).

$$P_T = N_T \cdot SDR_T \cdot WS_T [\text{liczba miejsc/15km}] \tag{10}$$

where:

T – type of vehicle (light, heavy),

P_T – number of parking spaces required,

N_T – conversion ratio (taking into account peak parking demand, average parking time, percentage of vehicles stopping at the ILO, ILO facilities, spatial linkage),

SDR_T – average daily traffic per year in the analysed traffic direction,

WS_T – index of seasonal variation (taking into account the peak month and day of the week of the year).

The most important change in the proposed solution is the consideration of the seasonal variability of traffic (the highest average traffic volume per year instead of the average daily traffic per year) and the directions of traffic. Furthermore, it is possible to clearly define the length of the road section for which the number of parking spaces will be determined (for example the minimum required for motorways i.e. 15 km) as well as the attractiveness of the MOP. On the other hand, the methodology is universal (it allows determining the number of spaces needed for light and heavy vehicles) and simple (tabulated volumes).

In addition to demand planning and parking space location, an important new class of problems arises with parking management systems. Today, city logistics and so-called *smart city* solutions use intelligent systems to manage parking vacancies, space reservations and driver guidance. Smart parking systems receive parking requests one by one, which have to be processed in real-time and operate online. Examples of such solutions can be found in the extensive literature on the subject, including works [Zhao et al. 2014, Amato et al. 2016, Litman 2016] and others.

Materials and methods

A discrete simulation method will be used to analyse the occupancy and demand for available parking spaces. A stochastic model will be developed in the computer environment to take into account parameters such as:

- the density of traffic flows;
- vehicle requests for space;
- vehicle parking times,
- the actual development of parking spaces in examples.

Based on the input variables, statistical distributions will be developed for the generation of events in the simulation model. A well estimated statistical distribution is able to accurately represent the real events using a random number generator. The input events, i.e. parking requests, will be described by an exponential distribution, widely described in the literature [Matuszak 2011, Grishkevich 2015][1]. This distribution is widely used in many fields, such as traffic modelling, customer service, handling incoming requests, etc. It is the so-called "memoryless" distribution, the best for generating randomness, described by the function $f{:}R \rightarrow R$, formula (11), where λ > 0 is the probability density of the event. On the other hand, the expected value of the arrival of an event (in the literature can be found under the name of the scale parameter), is described by formula (12).

$$f(x) = \begin{cases} 0 & dla\ x<0 \\ \lambda e^{-\lambda x} & dla\ x\geq 0, \end{cases} \tag{11}$$

$$E(X) = \frac{1}{\lambda}, D^2(X) = \frac{1}{\lambda^2} \tag{12}$$

Vehicle traffic and driver behaviour observations will be carried out at three randomly selected car parks in Przemyśl (Figures 1, 2, 3):
Specification of individual car parks:

- **A** city-center car park on the surface, payable, 89 parking spaces + 5 disabled parking spaces (Figure 1) – mainly tourist services, shopping, offices, offices;
- **B** parking at the shopping centre, underground, free of charge, 800 parking spaces including handicap spaces (Figure 2) – shopping, entertainment;
- **C** parking at the municipal office, parking along a one-way road, 20 spaces + space for a disabled person (Figure 3) – administrative matters.

[1] https://wazniak.mimuw.edu.pl/index.php?title=Rachunek_prawdopodobienstwa_i_statystyka [accessed: 14.12. 2021]

Disabled parking spaces will not be included in the simulation model as their existence is regulated by separate legislation.

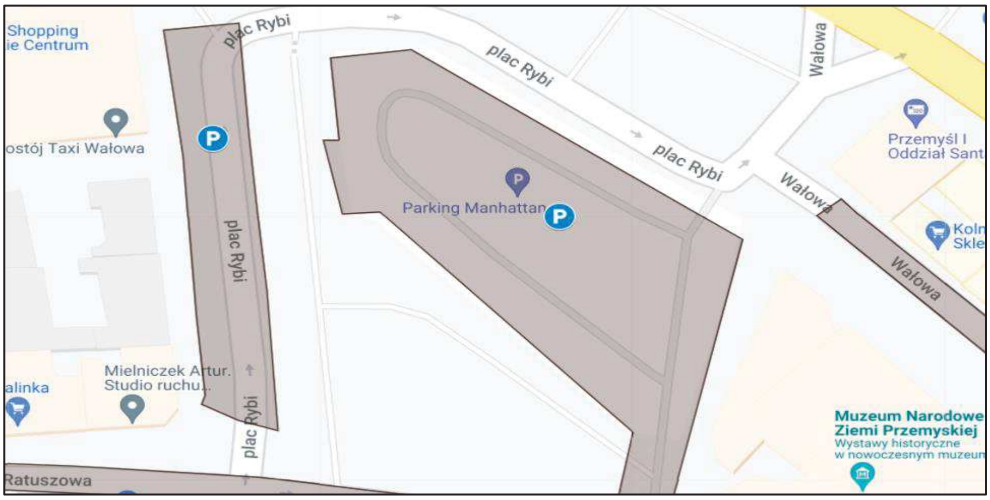

Figure 2. Car park A – Manhattan
Rysunek 1. Parking A – Manhattan

Source: Google Maps.

Figure 2. Car park B – shopping centre
Rysunek 2. Parking B – centrum handlowe

Source: authors' photo.

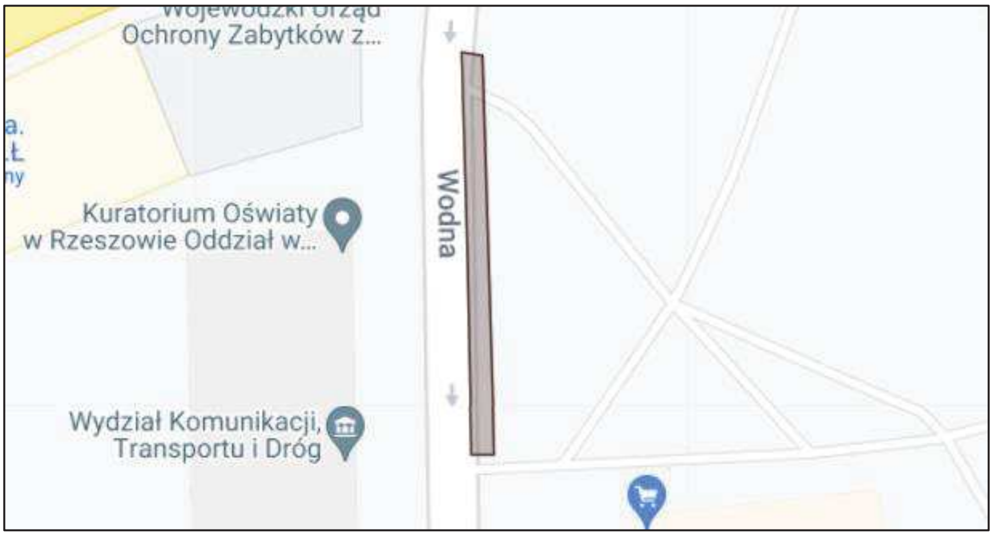

Figure 3. Parking area C – parking spaces along Water street in Przemyśl
Rysunek 3. Parking C – miejsca parkingowe wzdłuż ulicy Wodnej w Przemyślu
Source: Google Maps.

Quantitative measurements in traffic conditions were carried out at car parks A, B, C, the visualisations of which are presented in Figurs 1, 2, 3. Input data for the model were estimated based on empirical observations during the daily traffic rush hours between 3 p.m. and 5 p.m. on working days. The following parameters were assumed for the statistical distribution:

- the frequency of accesses to car park A averages 1 vehicle per minute;
- parking time at car park A is 90 minutes on average;
- frequency of accesses to parking area B average of 1 vehicle every 20 seconds;
- parking time at car park B on average 120 minutes;
- frequency of accesses to car park C average of 1 vehicle every 125 seconds;
- Parking time at car park C is 60 minutes on average;

It is worth reminding that these are not values for simple arithmetic mean, but estimated intervals of events in the Poisson process, which in a short period of time are very random, only in a long period of observation they tend to the mean values recorded in the model. This way of an event description is the best for modelling randomness in traffic. The second advantage of such a description of data is the possibility to realise many scenarios for conducting a series of simulation experiments with variable input parameters.

Figure 4 shows a block diagram of the computer model for investigating parking space occupancy. The necessary computational algorithms have been developed and the input parameters have been entered, i.e. entry frequencies, parking times, and available parking space resources. In the following section, the results obtained from the simulations carried out will be discussed.

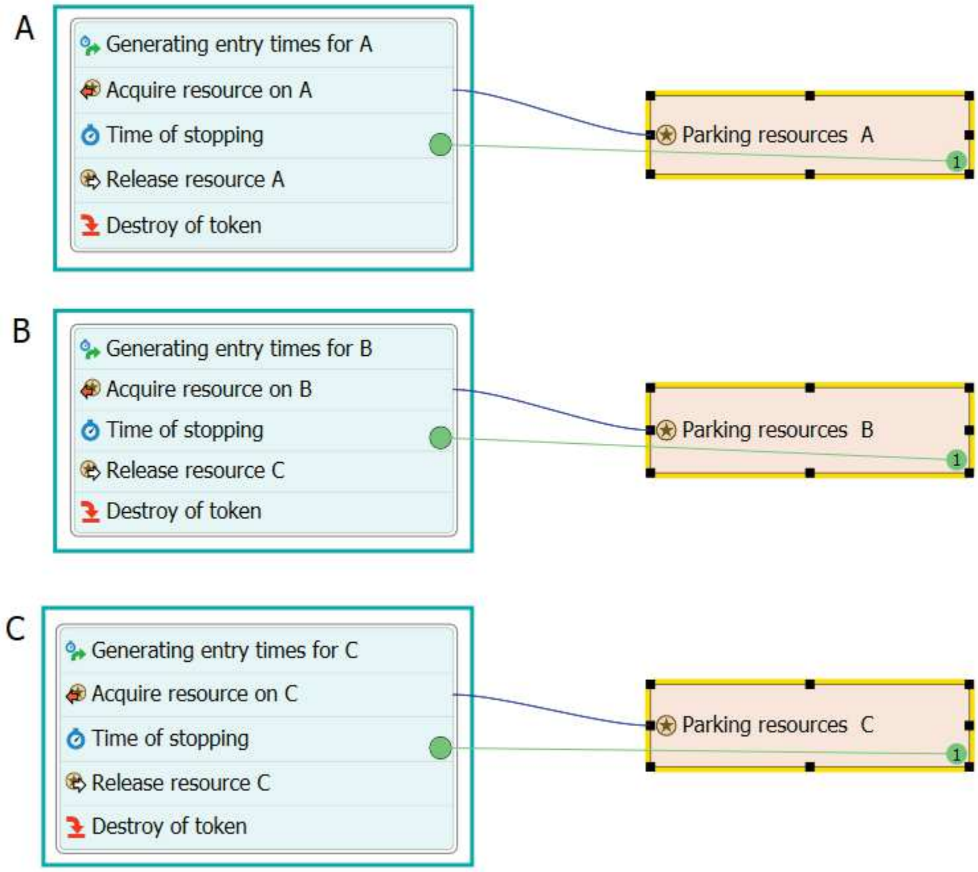

Figure 4. Block diagram of the computer model for the implementation of events in car parks A, B, C
Rysunek 4. Schemat blokowy modelu komputerowego do realizacji zdarzeń na parkingach A, B, C
Source: own studies.

Results and Discussion

The results of the analysis for car park A are presented graphically in Figure 5, which consists of three diagrams. Assumed time unit 1 second, simulation period 8-hour shift from 8.00 a.m. to 4.00 p.m..

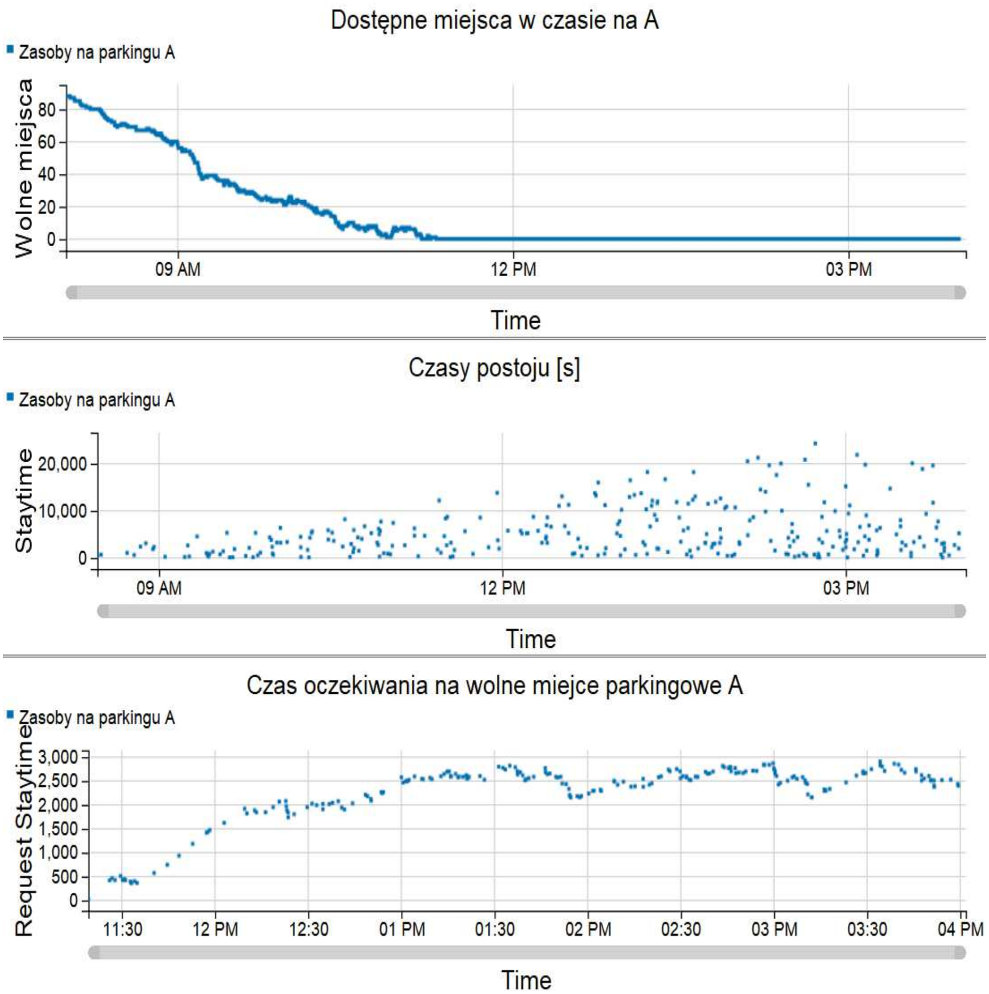

Figure 5. Test results for car park A

Rysunek 5. Wyniki badań dla parkingu A

Source: own studies

Figure 5 is in three parts, going from the top it can be seen that free parking spaces are exhausted already around 11.15 a.m., the size of the stock from this point on is zero. After this hour, the next arriving cars have to wait for free space or they give up parking. Then going down the figure one can read the next operational parameters:

- dwell time: min.: 10.71, max: 23327.71, mean: 5027.48;
- parking requests: 487
- vehicles serviced: 372
- unserviced vehicles: 115
- theoretical average waiting time for free space when the entire car park is full: 1844.89 seconds.

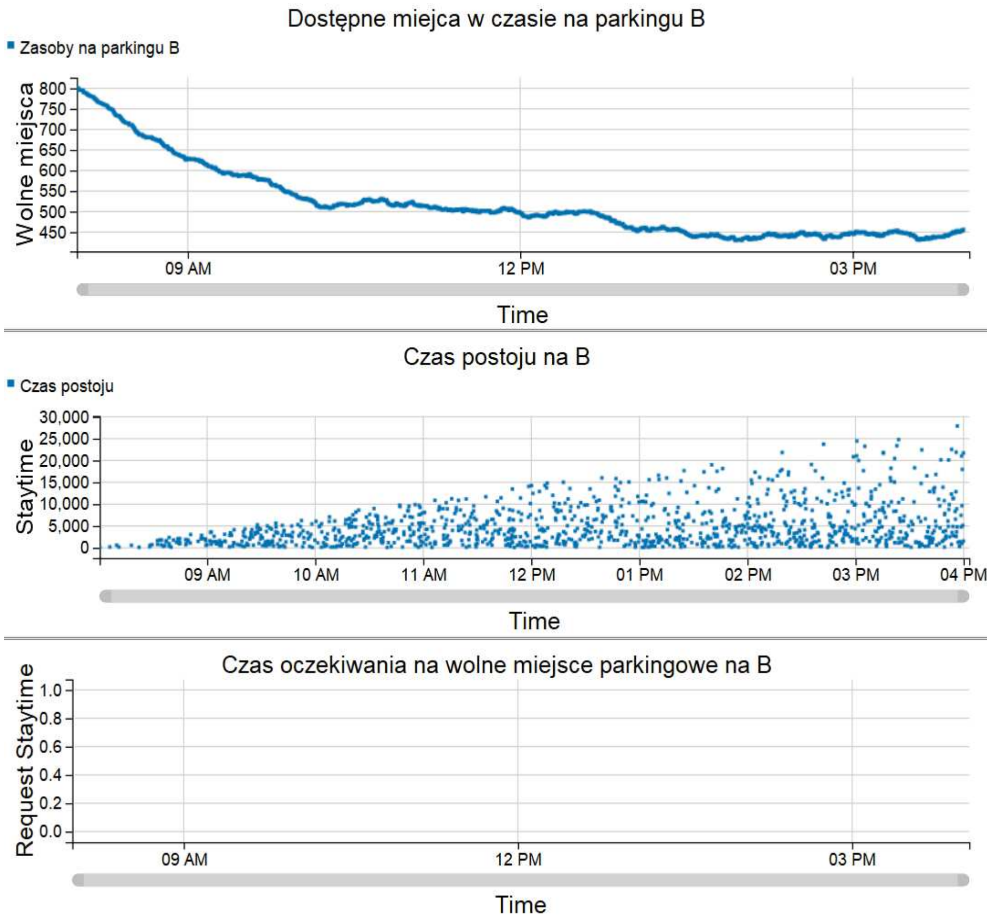

Figure 6. Test results for car park B
Rysunek 6. Wyniki badań dla parkingu B
Source: own studies

Simulation results for car park B are shown in Figure 6, which also consists of three diagrams. Assumed time unit 1 second, simulation period 8-hour shift from 8.00 a.m. to 4.00 p.m. In this case, the free parking spaces are not exhausted, the average number of free resources is maintained at about 517 spaces. As there are no problems in this car park and free spaces are available the waiting time is zero, the bottom diagram in Figure 6 is empty. Key performance parameters estimated by the model:

- dwell time: min: 22.20, max: 27821.87, mean: 4892.49;
- parking requests: 1534;
- vehicles serviced: 1534;
- vehicles not serviced: 0;

• theoretical average waiting time for free space when the entire car park is full: 0 seconds.

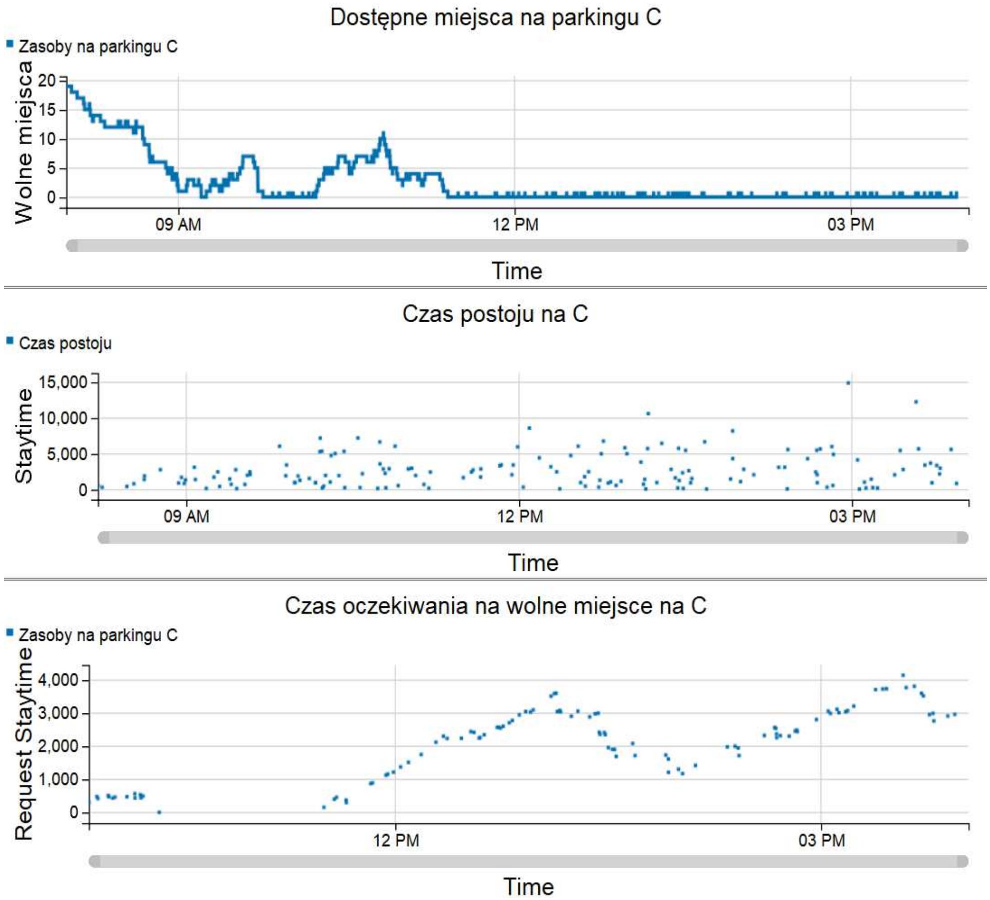

Figure 7. Test results for car park C
Rysunek 6. Wyniki badań dla parkingu C
Source: own studies

The simulation results for car park C are shown in Figures 7, which also consists of three diagrams. The time unit used is 1 second, the simulation period is an 8-hour shift from 8.00 a.m. to 4.00 p.m. In the first diagram (Figure 7), it can be seen that free parking spaces are exhausted already around 11 a.m., the volume of resources from then on is zero until the parking space previously occupied is released. After this hour, theoretically, the next arriving cars can wait for a free space, but practically they give up parking and drive on because of the obstruction of traffic. Other operating parameters can then be read out:

• Estimated stopping time: min.: 58.04, max: 14856.06, mean: 2710.78;
• parking requests: 204;
• vehicles served: 179;

- unserviced vehicles: 25;

theoretical average waiting time for free space when the entire car park is full: 1286.74 seconds.

Conclusion

As the simulations showed, only car park B kept traffic flowing as it had enough spaces to handle the traffic flow. Car parks A and B are inefficient and allow smooth parking from zero, i.e. from full capacity, within 2 to 3 hours. However, this is impos-sible in practice as these car parks are never empty because there are always vehicles parked there. The simulation carried out gave reliable results within a 90% con-fidence interval. In order to obtain more precise results, it would be necessary to make longer empirical observations (and not only during peak hours), as traffic volume changes quite dynamically during the day. In the simulations carried out for A and C, the maximum intensities were assumed. However, for car park B (shopping centre) the empirical studies based on which the model parameters were estimated concerned the average working day. Exceptional situations can be pre-holidays or special events, which can lead to all spaces being occupied.

Management in the area of city logistics is a multifaceted issue and modern simula-tion methods work well in this field. Often in city centres it is not possible to expand parking spaces due to various restrictions and lack of space. The only way to keep traffic flowing is through integrated management of available resources.

References

Amato G., Carrara F., Falchi F., Gennaro C., Vairo C., 2016: Car parking occupancy detection using smart camera networks and deep learning, IEEE Symposium on Computers and Communication (ISCC), 27–30 June, Messina, Italy.

Brzeziński M., 2006: Logistyka w przedsiębiorstwie, Bellona, Warszawa.

Crainic T.G., 2009: Simulating the impact of New Australian Bi-Moda urban freight terminals, trends, challenges and perspectives in city logistics, Buletin AGIR 4, 45–51.

Grishkevich A., 2015: Distributed simulation models to estimate structural reliability indices of power systems, Electrical Review 91.12, 106–109.

Hampshire R.C., Shoup D., 2018: What share of traffic is cruising for parking? Journal of Transport Economics and Policy 52.3, 184–201.

Krawczyk S., 2004: Logistics in city management, International School of Logistics and Transport, Academy of Economics, Wrocław.

Litman T., 2016: Parking management: strategies, evaluation, and planning, Victoria Transport Policy Institute, Victoria, BC.

Matuszak Z., 2011: Przykłady opisu kompozycjami rozkładów czasów zdatności uszkodzeń urządzeń i systemów technicznych, Automatyka 15, 335–344.

Opracowanie programów nauczania na odległość na kierunku studiów wyższych – Informatyka, [electronic source] www. wazniak.mimuw.edu.pl/index.php?title=Rachunek_probability_and_statistics [access: 14.12.2021].

Pietruch M., 2017: Analiza wykorzystania miejsc parkingowych w strefie płatnego parkowania w Krakowie, Transport Miejski i Regionalny 2, 10–15.

Sołtysik M., 2001: Teoretyczno-metodologiczne problemy współczesnej logistyki, Gospodarka Materiałowa i Logistyka 11, 4-17.

Spławińska M., Solecka K., 2017: Metody obliczania zapotrzebowania na miejsca postoju na obiektach MOP, Autobusy 12, 423–427.

Stienstra S., 2014: Obliczanie popytu na miejsca parkingowe, Zeszyty Naukowo-Techniczne SITK RP, Oddział w Krakowie 1(103), 371–177.

Stabenau H., 1993: Bedarfsgerechte Gestaltung einer Leistungsfähigkeiten City-Logistik, Traffic Networks 93, Vortragband des Kongress am 22/23 Juni 1993 in Bremem, KPS Messe- und Ausstellungs GmbH, Bremen.

Stawowy M., Perlicki K., Czarnecki T., 2017: Przyrostowa metoda wyznaczania zapotrzebowania na wolne miejsca na parkingach przy autostradzie, Prace Naukowe Politechniki Warszawskiej. Transport 119, 445–453.

Taniguchi E., Thompson R.G., Yamada T., van Duin R., 2001: City logistics – network modelling and intelligent transport systems, Pergamon, Oxford.

Würdemann G., 1992: ExWoSt-Informationen zum Forschungsfeld, Städtebau und Verkehr 3, Bundesanstalt für Landeskunde und Raumordnung, Bonn.

Xuejian Z., Zhao K., Hai F., 2015: An algorithm of parking planning for smart parking system, Proceeding of the 11th World Congress on Intelligent Control and Automation, 29 June – 04 July, IEEE, Shenyang, China.