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MODELLING OF THE OPERATION OF THE MULTI-STOREY AUTOMATED GARAGE WITH A BIG CAPACITY

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ABSTRACT. Background: The paper presents the issues of parking in the cities. The idea of multi-storey, overground garage with the capacity of 400 cars per hour has been proposed in the paper. The main focus is on analyzing loading and unloading as well as trans-shipment of the cars on the storeys of the garage.

Methods: The queuing theory has been used in the modelling process of the vehicles operation. The theory may enable to draw up general methods which let us indicate basic factors describing the process of the operation and the evaluation of the quality of work of the queuing theory system.

Aims: The subject of the paper is to check the influence of stochastic effects on the effectiveness of the parking operation in multi-storey garage.

Conclusions: The garage could be a solution to parking problems in the city centres, in the vicinity of factories, office buildings, academic centres and the like. Furthermore the research method may support and speed up a decisional process while choosing the optimal structure, organization and first of all the construction of the parking.

Key words: overground automated garage, queuing theory, modelling of transportation processes.

INTRODUCTION

The increasing need for supplying the necessary amount of parking spaces for motorized vehicles is the reason for the development of different parking structures. Analyzing the situation [Michalak 2006] we can say that parking structures enable the growth and disperse of the urban building development. The need to provide a sufficient number of stopping and parking places in the immediate vicinity of newly-erected buildings, offices, bureaux, shopping centres, large, industrial plants, academic centres, stadiums and airports, results from regulations and is one of the elements of city spatial development politics. It is important to have knowledge about real needs of travelling persons. It will help to construct better transportation system because if a constructed system of sustainable urban transportation is adapted to the transportation-related needs of the inhabitants, then the system will be truly implementable and effective operationally [Sierpiński 2011, 2012, Sierpiński, Celiński 2012]. The choice of the most favourable solution in order to meet the parking space needs, depends on numerous factors, of which particularly important, in the urban conditions because of high costs of land, is the absorption of land area to create one stopping space. The right decision about the car park and garage issue is of a vital importance for the proper functioning of the city or otherwise the wrong decision may become an obstacle in its development. [Biedrońska et al. 2010, Michalak 2006]. The subject of the study report is the multi-storey, aboveground, automated garage built on the base of the rectangle and of the huge capacity

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of 400 cars an hour, both ways [Pypno 2008]. In currently, rarely built aboveground, fully automated garages, mechanical parking systems enable, depending on the storey, parking and retrieving of the car within 40-120 seconds, which means 90-30 cars an hour. Presumably the average is 60 cars an hour. This cycle starts the moment the driver drives his/her car onto the pallet and gets out of it and the system takes the car into the lift, the lift transports it to a given storey, there the car is moved to a proper box and the lift returns to the ground floor for the next car (Fig. 1). However, automated FATA Skyparks parking system has an efficiency of only 24 cars per hour with the capacity of 3000 cars! (Fig. 1b). In the description of the American patent referring to this issue, you can find remarks about problems connected with cars` slow storage and retrieval in automated garages. The being designed garage is not likely to have these inconveniences, and thanks to the advanced mechanical-automatic system, it will be able to store coming cars straightaway.

At present, in European countries, especially in Germany, they created the database with current filling of city garages. The driver who wants to park his/her car, equipped with the onboard computer with the suitable navigation software is directed to the nearest garage with available, vacant places [Bogenstattet 2006].

Source: www.wired.com/science/discoveries/news/2007/12/dayintech_1205#;
www.fataic.com/gallerymain.php 14.11.2008

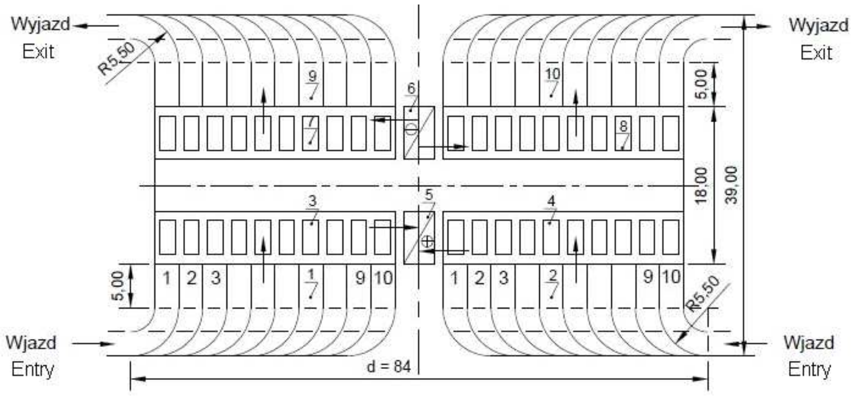
Fig. 1. The automated multi-storey garage - a) circle view ,b) rectangular view
Rys. 1. Garaż zautomatyzowany wielokondygnacyjny; a) na rzucie koła, b) na rzucie prostokąta

THE IDEA OF THE AUTOMATED GARAGE WITH THE CAPACITY OF 400 CARS PER HOUR

It is assumed that the garage built on the rectangle projection will have 17 storeys with 60 cars on each storey what gives a total capacity of 1020 cars (Fig. 3). The area demand for the being designed garage considering the access and exit roads. Designing this area a convenient access to the garage was assumed and right before the entering the garage cars stop at road lights (red/ green) placed in front of the building. The surface occupied by the garage equals 39m x 84m = 3276m^2.

An urban parking with the capacity of 1016 cars occupies the area of 21 375m^2 (Fig. 2).

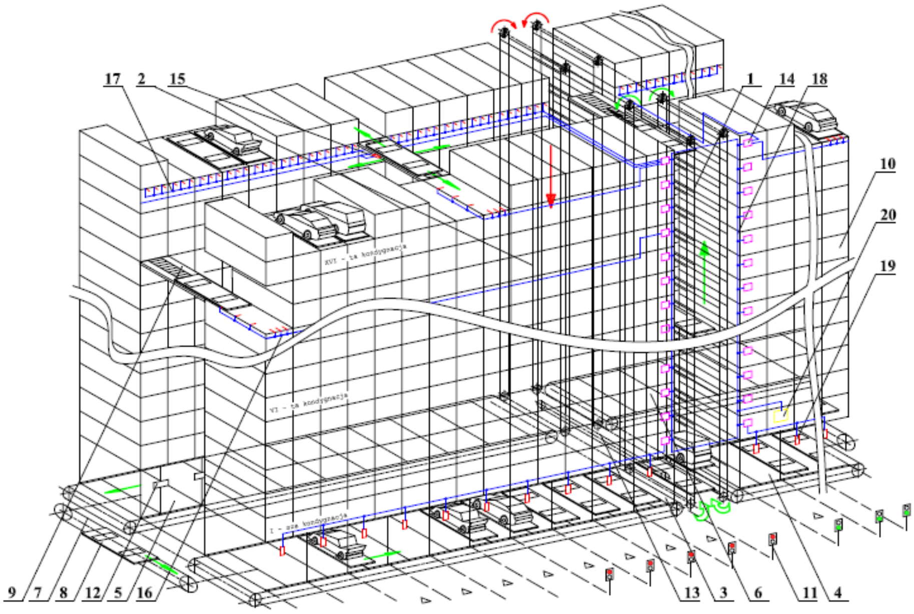
In the mechanical section on the ground floor there are, among other things, pallet conveyors for taking and returning vehicles. First, from the loading zone, vehicles are transported on pallets, onto particular storeys by the first electrical lift. On the level of every storey, vehicles are transferred from the lift by storey platforms to the parking spaces in boxes. Vehicles are transported downstairs to their owners by the other electrical lift (Fig. 3).



Source: own research

Fig. 2. Total demand for the area of the garage: 1,2 - the entrance zone, 3,4 - cars on take-in conveyors, 5 - electrical lift for transport of cars upwards, 6 - electrical lift for transport of cars downwards, 7,8 - cars on give-out conveyors, 9,10 - the exit zone.

Rys. 2. Całkowite zapotrzebowanie na powierzchnię dla prezentowanego garażu: 1, 2 - strefa oczekiwania na wjazd, 3, 4 - samochody na przenośnikach odbierających, 5 - dźwig elektryczny transportujący samochody do góry, 6 - dźwig elektryczny transportujący samochody w dół, 7, 8 - samochody na przenośnikach wydających, 9, 10 - strefa wyjazdu dla samochodów z garażu.



Source: own research

Fig. 3. The diagram of automated garage; 1- chain hoisting lift, 2- chain lowering lift, 3 - taking conveyor left, 4 - taking conveyor right, 5 - returning conveyor left, 6 - returning conveyor right, 7 - reserving conveyor, 8 - pallet, 9 - storey platform, 10 - boxes, 11 - lights red/green, 12 - electronic display, 13 - emergency conveyor, 14 - local S1 drive controlling half of the storey, 15 - controlling of the storey platform, 16 - positioning system with a vehicle in the box, 17- local network of ultrasound/magnetic sensors positioning storey platforms, 18 - annular network of the exchange of data between drivers S1, 19 - network of the system controlling the process of taking and returning vehicles, 20 - central controlling system S2.

Rys. 3. Schemat zautomatyzowanego garażu; 1- dźwig łańcuchowy podnoszący, 2- dźwig łańcuchowy opuszczający, 3- przenośnik przyjmujący lewy, 4- przenośnik przyjmujący prawy, 5- przenośnik wydający lewy, 6- przenośnik wydający prawy, 7- przenośnik odwodowy, 8- paleta, 9- platforma kondygnacyjna, 10- boksy składowania, 11- światła czerwone/ /zielone, 12- wyświetlacz elektroniczny, 13- przenośnik awaryjny, 14- lokalny sterownik S1 sterujący połową piętra, 15- sterowanie platformy kondygnacyjnej, 16- system pozycjonujący paletę z pojazdem w boksie, 17- lokalna sieć czujników ultradźwiękowych/ magnetycznych pozycjonujących platformy kondygnacyjne, 18- pierścieniowa sieć wymiany danych pomiędzy sterownikami S1, 19- siec systemu sterującego przyjmowanie i wydawanie pojazdów, 20- centralny system sterujący S2.

Taking vehicles from the owners of the cars to the garage

We assume that in the first stage of the analysed case there are no vehicles in the garage. On the ground floor there are 2 x 10 vehicle taking conveyor, left (3) and right (4), entrances, where drivers leave their cars. Maximum and safe, drive in and admission time of 10 vehicles onto receiving conveyors, e. g left one, takes 90 seconds. After that time, during the subsequent 90 seconds the lift (1) carries vehicles upstairs, where on storeys, they are successively transported on platforms (9) to the boxes. At the same time, during the same 90 seconds of the garage work, next 10 vehicles go onto the right (4) receiving conveyor, then they are transported upstairs by the same lift during the subsequent 90 seconds and at the same time, 10 further vehicles will get onto the conveyor (3) and will be transported by the lift upstairs within the time of subsequent 90 seconds of the garage work etc.

It can be seen here that on "zero level" in the take-in zone the work of the conveyors (3,4) is alternating, only the lift works continuously.

Trans-shipment from the lift and storing cars on the storeys of the garage

The lift hoisting the cars upwards works for three seconds and moves by the distance of one storey h = 2.032m, then it stops for three seconds. During this time a harpoon pulls out the car onto the platform and the platform transports the car into the empty box. Cars can be pulled out onto the platform simultaneously on many storeys of the garage.

Returning vehicles to their owners

Car owners come to the garage passageway and declare to retrieve their cars using e.g. magnetic cards or introducing their car registration number onto the proper panel.

The steering system works in this way that first a storey platform comes to a proper box, next the car is pulled by the harpoon from the box onto the platform and now the platform transports the car to the lift and the car is placed onto the lift. All transport and trans-shipment actions into the boxes on the storey take place independently of the work of the lift. The cars places on the lift are transported downwards in the cycle as previously namely the lift moves down for three seconds and then it stops for six seconds. This time is necessary for moving subsequent cars from platforms onto the lift. On the " zero level" during the lift stop cars are unloaded from its shaft onto the returning conveyor (5) or (6).

There are 10 entrances for each returning conveyor in the passageway. Over each entrance you can see lighting notice boards showing the registration numbers of retrieved cars.

Simultaneous taking and returning of the cars

Theoretically, the actions described here can take place at the same time, and in this way working, computer-operated garage is able to take and return 400 vehicles, nonetheless, it is hardly possible to occur.

MODELLING THE PROCESSES OF ENTERING AND EXITING SERVICE IN A GARAGE

Basic assumptions

The proposed model is supposed to describe the process of entering and exiting service in an automatic multilevel garage. The basic assumptions of the model are as follows:

1. A garage treated as a complex system of mass service (a queuing system).
2. Particular queue systems of a complex system of mass service is the process of entering and leaving the vehicle at rest and the process of moving the vehicle from the "box", placing the vehicle in a lift and exiting. These processes are considered separately.
   In defining the queuing system three ideas should be characterized: the stream of

applications, the way of servicing and the number of servicing channels. Another two assumptions stem from this:

3. The exponential shifted schedule of intervals between the applications was adopted.
4. Times of service have got a free shifted schedule.
5. In the proposed garage there is one basic channel of service, a lift with elements which assist the vertical and horizontal translocations.

The description of the process of entering and exiting using the queuing theory

Time intervals between the notifications of other vehicles are fate variables. Assuming the full fate of the occurrence - Poisson's schedule is restricted due to necessity of having a minimum space between the vehicles - vehicles have a finite length. Assuming the above, the exponential shifted schedule of intervals between the notified vehicles was used and it is often used in reflecting the models of vehicle traffic (as e.g. in [Krystek 1980, Tracz 1990, Kuwahara et al. 2002]):

$$F(t_{ij}) = 1 - e^{-\frac{(t_{ij} - t_{\min})}{(\bar{t} - t_{\min})}} \qquad (1)$$

where:

t_{ij} - time interval between given vehicles *i j* (when j = i +1 is the interval between another vehicles) [s]

t_{min}- the minimum time interval between the vehicles in one lane [s]

t - average time interval between the vehicles [s]

The minimal interval makes a constant shift of the exponential schedule. So the given time interval is the sum of the fate variable t_{los} and the minimal interval t_{min} (fig. 4):

$$t_{ij} = t_{los} + t_{\min} \qquad (2)$$

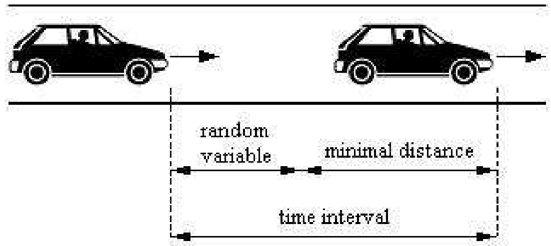


Fig. 4. Time interval between appearances of vehicles
Rys. 4. Odstęp czasowy między kolejnymi zgłoszeniami pojazdów

Because the concept assumed vehicles standing on independent positions waiting for entering, the possibility to change the position from the moment of appearance of the vehicle was omitted.

A traditional queuing model described in the Kendall's classification by symbols M/G/1 is characterized by Poisson's process of appearances (3), exponential intervals between the appearances (4) and one service channel; times of service have got a free schedule.

$$p_n(t) = \frac{(\lambda t)^n}{n!} e^{-\lambda t}, \; n = 0,1,2,... ; \qquad (3)$$

$$f(t) = \lambda e^{-\lambda t}, \; t \geq 0 ; \qquad (4)$$

Service time schedule is described by two quantities:

– the expected value (average) - m

$$m = E(X) = \sum x_i \cdot P(x_i) ; \qquad (5)$$

where:

x_i - observed values of the occurrence

$P_{(x\ i)}$ - probability of a given value of the occurrence

– variance □□^{2}

$$\sigma^2 = V(X) = E(X^2) - (E(X))^2 = \sum x_i^2 \cdot P(x_i) - m^2 \qquad (6)$$

M/G/1 does not belong to Markow's systems what makes the analysis more difficult. Not Markow's processes are usually studied with the approximation through the Markow's model. In this case the method of Markow's build in chains was used (among others in [Kleinrock 1975, Rajski and Tyszer 1986, Adan and Resing 2001]). In order to achieve this, the system was to be observed in chosen discreet moments - at times when other vehicles finish servicing (and are moved to the place of "rest"). If one assumes that is the number of vehicles in the system in the moment of finishing servicing by vehicle "k" and X k is the number of vehicles which came in the time of servicing the vehicle "k" two things can be seen (7):

- in the moment of finishing the service of the vehicle k-1 there was no queue (no waiting vehicles) $L_{k-1} = 0$,
- in the moment of finishing the service of the previous vehicle k-1 there was a queue $L_{k-1} > 0$.

$$L_k = \begin{cases} X_k & ;\ L_{k-1} = 0 \\ L_{k-1} + X_k - 1 & ;\ L_{k-1} > 0 \end{cases} \tag{7}$$

Defining additional random variable $U(L_{k-1})$, which takes 0 when $L_{k-1} = 0$, and in the case when U = 1 was replaced by the formula (7):

$$L_k = L_{k-1} - U(L_{k-1}) + X_k \tag{8}$$

In this way a built in Maslow's chain was created. Next making a series of changes a Pollaczek-Khintchina's formula is obtained [Kleinrock 1975]:

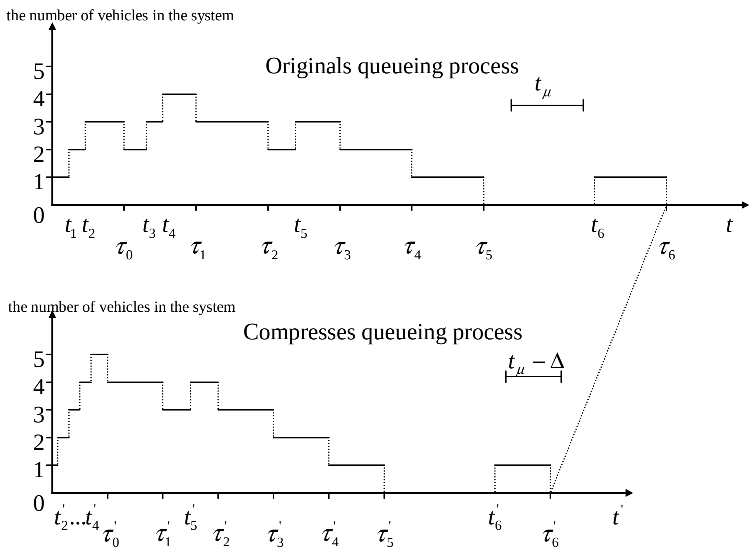
$$\overline{L} = \rho + \frac{\lambda^2 \cdot \sigma_\mu^2 + \rho^2}{2 \cdot (1-\rho)} \tag{9}$$

However, one should remember about the necessity of taking into account a finite length of a vehicle which means shifts in the intervals between the appearances and the times of service. Joining processes of Woch's queues were used for that matter and adopted to the model $M_{+\Delta}/G_{+\Delta}/1$.

If $\frac{1}{\mu}$ is the average operation time. And *Δ* is the minimal time distance between the vehicles. Then $\frac{1}{\mu'}$ will be the equivalent of the average factor after the separation of the constant part in the form of *Δ*, namely:

$$\frac{1}{\mu'} = \frac{1}{\mu} - \Delta \tag{10}$$

Figure 5 presents the graphic interpretation of the joining process.



Source: Woch 1998

Fig. 5. Exemplary accomplishment of original and joining processes
Rys. 5. Przykładowe realizacje procesów oryginalnego i zlepionego

The average interval between the appearance of vehicles in the system, that is the inverse of intensiveness of appearances λ may be the sum of a random and constant element (the minimal time interval):

$$\frac{1}{\lambda} = \frac{1}{\lambda'} + \Delta \qquad (11)$$

which can be shown differently:

$$\lambda' = \frac{\lambda}{1 - \lambda \cdot \Delta} \qquad (12)$$

If the system is stable (the only one to be considered), according to the queuing theory intensiveness of appearance must be less frequent than the operation performance.

$$\rho' = \frac{\lambda'}{\mu'} < 1 \qquad (13)$$

and the following relation occurs:

$$0 < \Delta < \frac{1}{\mu} < \frac{1}{\lambda}$$
(14)

From the above-mentioned formulae we can get the dependence ρ' presented in the following quantities:

$$\rho' = \frac{\lambda \cdot \left(\frac{1}{\mu} - \Delta\right)}{1 - \lambda \cdot \Delta} < 1 \qquad (15)$$

Having applied appropriate transformations we can obtain a formula for the average queuing time for the queuing system M/G/1:

$$\overline{W_q}' = \frac{\lambda'^2 \cdot \sigma_\mu^2 + \left(\frac{\lambda'}{\mu'}\right)^2}{2 \cdot \lambda' \cdot \left(1 - \lambda' \cdot \overline{t_\mu}'\right)} = \frac{\lambda' \cdot \left(\sigma_\mu^2 + (\mu')^{-2}\right)}{2 \cdot \left(1 - \lambda' \cdot \overline{t_\mu}'\right)} \qquad (16)$$

Whereas the appropriate formula for the original system $M_{+\Delta}/G_{+\Delta}/1$ is:

$$\overline{W_q} = \frac{\lambda \cdot \sigma_\mu^2 + \lambda \cdot \left(\frac{1}{\mu} - \Delta\right)^2}{2 \cdot (1 - \rho)} \cdot (1 - \mu \cdot \Delta) \qquad (17)$$

In the above-mentioned formula factor $(1 - \mu \cdot \Delta)$ has been added in comparison with the previous formulae. This factor shows the value of operation time variability, $\mu \cdot \Delta$ namely, it is a quotient of the constant time operation to the expected value of time operation while elevator moving ($\Delta / \overline{t_\mu}$).

Another explanation is the fact that in the described process another vehicle does not have to wait till the previous one has been serviced. For a single vehicle the minimal time after which its driving in begins equals $\frac{1}{\mu} - \Delta$. Generally this value is multiplied by the intensiveness of operation μ, which equals $(1 - \mu \cdot \Delta)$. This assumption is applied for reallocated layout of probability [99].

With the following formula (17) and formulae:

$$\overline{L} = \lambda \cdot \overline{W};$$

$$\overline{L} = \overline{L_q} + \frac{\lambda}{\mu};$$

$$\overline{L_q} = \lambda \cdot \overline{W_q};$$

$$\overline{W} = \overline{W_q} + \frac{1}{\mu} \qquad (18)$$

one can achieve four main basic dimensions of productivity and efficiency for a chosen queuing model :

L - an average number of clients in a system,
L_q - an average number of clients in a queue,
W - an average time of waiting in the system and
W_q - an average time of waiting in a queue.

The process of exiting the automatic multilevel garage can be described using similar model conditions. The service runs in the same way, but in the opposite direction. Notifications show schedule of applications of people coming to collect a vehicle. Naturally depending on the character of a garage and its purpose the full chance of notifications can change. It can happen in the case of a garage ,servicing vehicles of a given company, with regular times of work. The process of notifications of both vehicles as well as people coming to collect a vehicle may in certain times have a similar form to a deterministic arrangement. In other instances the use of model $G+_{\Delta}/G+_{\Delta}/1$ can be considered. However, it goes beyond the topic of this article.

DISCUSSION AND CONCLUSIONS

Present transport systems focus on problems with being overcrowded. It is especially visible in the centres of towns. At the same time attention should be paid to the fact that transport absorbs space. Parking in street lanes takes additional space, which can be used in a different way, more friendly to the inhabitants. The proposed construction makes it possible to limit the space taken by cars in a town (at the moment of parking).

The automatic garage, described in the article, can be one of the solutions to the problem with fast parking in the centres of towns, next to factories, large buildings, universities etc. It is worth noticing that a garage of this type can be part of a transfer junction of the type Park and Ride and in this way help the activities of sustainable transport development [White Papers, Bruntland Report]. The research method showed in the article through the description of the process using the queuing theory can on one hand help in defining the efficiency of that solution and on the other assist the decision about the choice of the structure and organization of the service, but most of all about the choice of the parking construction.

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MODELOWANIE OBSŁUGI ZAUTOMATYZOWANEGO GARAŻU WIELOKONDYGNACYJNEGO O DUŻEJ PRZEPUSTOWOŚCI

STRESZCZENIE. **Wstęp:** Artykuł dotyczy problematyki parkowania w miastach. Zaproponowano koncepcję projektu wielokondygnacyjnego nadziemnego garażu o przepustowości 400 samochodów na godzinę. Skupiono się na analizie systemu załadunku, rozładunku oraz na analizie systemów przeładunku samochodów na kondygnacjach garażu.
Metody: Do modelowania procesów obsługi pojazdów zaproponowano użycie teorii kolejek, która może pozwolić na opracowanie ogólnych metod umożliwiających wyznaczenie podstawowych wskaźników charakteryzujących proces obsługi i ocenę jakości pracy systemu kolejkowego.
Cele: Celem artykułu było zbadanie zjawisk stochastycznych na efektywność obsługi garażu wielokondycyjnego.
Wnioski: Opisany garaż byłby rozwiązaniem problemów z szybkim parkowaniem samochodów w centrach miast, obok fabryk, dużych biurowców, uczelni itp. W dalszej pracy wskazana metoda badawcza może wspomagać proces decyzyjny dotyczący wyboru optymalnej struktury i organizacji obsługi, a przede wszystkim wybór konstrukcji parkingu.

Słowa kluczowe: zautomatyzowany garaż wielokondygnacyjny, teoria kolejek, modelowanie procesów transportowych.

STEUERUNGSMODELLIERUNG DER AUTOMATISIERTEN MEHR-GESCHOSSIGEN GARAGE VON HOHER UMSCHLAGSKAPAZITÄT

ZUSAMMENFASSUNG. Einleitung: Der Artikel betrifft die Parkplatzproblematik in den Städten. Es wurde ein Entwurfskonzept einer mehrgeschossigen oberirdischen Garage vom Umschlagsgrad von 400 Autos/Stunde vorgeschlagen. Man hat sich auf eine Analyse sowohl des Verladungs- und Ausladungssystems als auch der Umladungssysteme von Autos in den Garagengeschossen konzentriert.
Methoden: Zur Modellierung der Prozesse der Fahrzeugsteuerung wurde die Theorie der Warteschlangen vorgeschlagen, die erlauben kann, allgemeine Methoden auszuarbeiten. Sie ermöglichen folglich, die den Bedienungsprozess charakterisierenden Grundrichtwerte zu bestimmen und die Qualität der Arbeit des Warteschlangensystems zu beurteilen.
Ziele: Das Ziel der Arbeit war es, den Einfluss der stochastischen Erscheinungen auf die Effektivität der Bedienung eines mehrgeschossigen Garage zu erforschen.
Ergebnisse und Fazit: Die beschriebene Garage wäre eine Lösung der Probleme mit schnellem Parken in Stadtzentren, in der Nähe von Fabriken, von gro?en Bürohäusern, von Universitäten usw. Die in anderen Arbeiten gezeigten Untersuchungsmethoden können den Entscheidungsprozess, der die Auswahl der optimalen Struktur und Organisation der Steuerung und vor allem die Auswahl einer geeigneten Garagenkonstruktion anbetrifft, weitgehend unterstützen.

Codewörter: Automatisierte oberirdische Garage, Theorie der Warteschlangen, Modellierung von Verkehrsprozessen.

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