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Military Queueing Systems in Saturation Regime and Some Practical Consequences

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Military queueing systems, in combat conditions above all, could be exposed to heavy-traffic conditions. An extreme or boundary case of heavy traffic is saturation. Saturation of queueing systems assumes that intensity of demands for servicing is equal to the nominal capacity of the service channel. A possibility for theoretical modeling and analysis of such systems is very limited due to mathematical complexity, so that researchers turn to other methodological approaches. This paper presents the results of modeling and analysis of a queueing system in saturation, by the use of a novel method of Monte Carlo simulation modeling, marked as "Automated Independent Replications with Gathering Statistics of Stochastic Process". The main problem which has to be solved is a problem of accuracy of simulation results. It will be also demonstrated that a queueing system under saturation conditions and for finite time of engagement may operate mainly in the initial transient regime.

Key words: **mass servicing system, military system, logistics, system saturation, Monte Carlo Method.**

Introduction

THIS paper presents the results of modeling and analyzing a queueing system under the conditions of saturation. Saturation is a boundary case of heavy traffic, characterized by fullness of server capacity. In [1], there is an indirect confirmation of the importance of this case: "The ability to model the heavy traffic regime accurately is therefore crucial for the designer or operator of a queueing system". The phenomenon of saturation is discussed in Section 2. Successful dealing with saturation leads to another phenomenon, the initial transient problem, discussed in Section 3.

One novel simulation method was applied for modeling and analysis in a concrete example. It is known as "Automated Independent Replications with Gathering Statistics of Stochastic Processes", or shortly: AIRGSSP, [2]. We have exploited a suitability of this method to support modeling and analysis of a queueing system characterized by "five Any", [1]: "Any time of engagement; Any traffic intensity; Any type of input and output of client's flows; Any complexity; and Any size". In this paper, we are focused on "any traffic intensity" and "any time of engagement". Section 4 points out the importance and purpose of the time-dependent states probabilities of a queueing system. These probabilities are obtained by the use of the AIRGSSP method.

A concrete example in Section 5 relates to the military logistics: a model of vehicle maintenance process in a military unit in a hypothetical United Nations (UN) mission. Besides this is only an example, its importance lies in a fact that "participation in peace building and peacekeeping in the region and the world" is the second mission of the national military forces declared in Serbian strategic documents, [3]. However, more significance comes from conceptual generality of queueing systems. Almost the same Queueing models could present a very different reality in different branches (engineering, military, logistics, traffic, etc). The same conclusion is valid for methods of modeling and analyses of queueing systems.

In order to demonstrate how this endeavor helps to the logistics and military management, we carried out an Operational Readiness Evaluation (ORE, [4]) of a vehicle fleet in a military unit engaged in an UN mission. Section 6 demonstrates the use of the simulation results in evaluating the Operational Readiness of the unit for the case of a vehicle fleet.

Case of saturation

Saturation is a case when the intensity of a client's input stream (a stream of demands for service) is equal to the intensity of an output client's stream (nominal capacity of the service channel to process demands for service). Both streams of clients (input and output) are characterized by randomness. Client's demands for servicing and servicing itself are both of a stochastic nature. In other words, saturation is a case when the frequency of input demands for service is equal to the frequency of servicing. In this sense, we can compare saturation of queueing systems with the phenomenon of resonance in some technical systems.

Classical, mostly used queueing theory results are related to the steady-state regime, Fig.1. In a case of saturation, it is not appropriate to use any of these – steady-state related results. The only suitable theoretical results acceptable for application in a case of saturation are known under the name: transient solutions. An indirect confirmation for this kind of reasoning and actuality of the problem is found in one novel paper [1], where Hlynka, Hurajt and Cylwa used a theoretical (analytical) approach to the problem while a simulation approach is preferred in this paper.

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In their essence, transient solutions are complete solutions valid for any traffic intensity and for both regimes: initial (transient, warm-up, start-up, relaxation) and steady-state (equilibrium). Transient solutions assume time-dependent variables.

The division of the queueing system behavior to a transient regime and a steady-state one is artificial in a sense. Practically, there is no clear and definite “switch moment” from the transient to the steady-state regime, at least for the models with unlimited queues. Instead, that is a continual change across time, more or less long. Queueing system states probabilities displayed as time-dependent variables could confirm this observation, as we will see latter in Fig.2.

Application and perception of queueing systems usually place artificial limitations on traffic intensity, such as: “the intensity of the input client stream has to be smaller than the intensity of servicing”. However, reality can be different from this artificial boundary. If we ignore reality in model building, then that model will not have enough fidelity and will not be able to serve its purpose accordingly.

The problem arises when an analyst is faced with a need to study a queueing system which operates inside a finite portion of time, and without any limits to traffic intensity, [6]. Such demands appear in various military studies. Wars, battles and missions are all planned and executed during a finite period. Military resources are often heavy loaded and even overloaded from time to time. If we want a high fidelity queueing model as a military reality [7], then we have to face the initial transient problem [1].

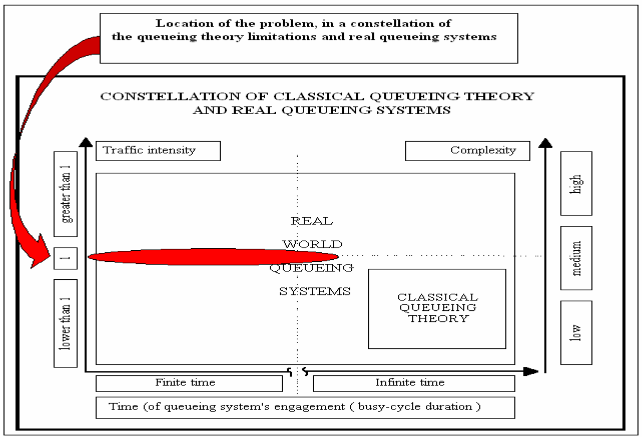

Figure 1. Location of the saturation problem in constellation with the limitations of the theory

Initial transient problem

The initial transient phenomenon indicates the behavior of a queueing system in a period which precedes the steady-state regime. Due to the mathematical complexity of theoretical transient solutions we do not have practical capacity to calculate transient response of the queueing system. On the other hand, a steady-state regime is well documented, but it is hard to determine when it actually begins. Answering to this question involves the initial transient problem which is considered as one of the fundamental problems in the queueing simulation field.

Transient and stationary regimes are complementary. The transient working regime occurs in the meantime, while we wait for the steady state. When the steady-state regime begins, and how long the transient period is are also complementary questions. Strictly speaking, the answer to any of those questions is a precondition for the correct use of steady-state solutions. Our belief that the queueing system under study works mainly or exclusively in a steady-state regime, and that the transient regime is of relatively short duration, is only a hypothesis.

Practical consequences of the transient regime are values of performance measures different from their steady-state values. This is particularly important in situations when the time interval characterized by the transient regime is a respective part of the whole period of engagement (working time) of queueing systems.

The initial transient phenomenon is well known in simulation of queueing systems. There are some other terms and phrases used for this phenomenon: warm-up or start-up problem, non-stationary regime, relaxation time, etc. One view [8] on the dynamic nature of the initial transient problem in simulation offers a possible explanation for this variety of terms.

In order to get insight into this phenomenon, we need to have transient solutions. However, this is a hard task: solution procedures are mathematically demanding and solutions alone are very complex. Transient solutions were determined only for a limited set of queueing models of simple structures. This long-standing problem has attracted much research particularly from the simulation field through decades: from the time of Gafarian, Ancker and Morisaku (1978) [9], across the eighties (Odoni and Ruth 1983) [10], and the nineties (Pawlikowski 1990) [11], to the modern times (Glynn 2005, Robinson 2005) [12]. Although this phenomenon deserves a long list of related references, we will point out only a few of them:

- Gross and Harris (1974) on page 75 said [14]: “The transient derivation for M/M/1 is quite a complicated procedure. The solution of this problem post-dated that of the basic Erlang work by nearly half a century, with the first known solution published by Lederman and Reuter (1956), in which they used spectral analysis for the general birth-death process. In the same year, two additional papers appeared on the solution of this problem, by Bailey (1956) and Champernowne (1956)”.
- Bhat (1984) on page 360 wrote that [15]: “In many real situations, transient solutions are more appropriate, but they require better tools and techniques then we have now”.
- Rothkopf and Oren (1979) observed [16]: “The general transient solution for the stationary single server queue is known. Unfortunately, it involves infinite sum of Bessel function and would not normally be used for numerical computation”.
- Kleinrock (1975) on page 78 [17] made a remark about the analytical solution for states probabilities for the M/M/1 model: “This last expression is most disheartening. What it has to say is that an appropriate model for the simplest interesting queueing system leads to an ugly expression for the time-depended behavior of its state probabilities. As a consequence, we can only hope for greater complexity and obscurity in attempting to find time-dependent behavior of more general queueing systems”.

The queueing theory as an older and more formally established discipline made influence on the simulation modeling. Relations between these two disciplines, together with some fundamental problems, are known to the simulation community. Schmeiser and Schruben (2005) said in [18]: “Discrete-event simulation analysis methodology inherited much of its context from queueing theory. Simulation analysis methodology had to demonstrate that, at least from practical point of view, simulation models, when subjected to a rigorous analysis, can produce system-performance estimators that are as good as those obtained from queueing theory. It is embarrassingly hard to find explicit statements of fundamental simulation research question: *the initialization bias problem, the run duration problem,* or *the input modeling problem.* The literature has little to offer concerning systems that are never in steady state".

Perception of the initial transient problem in the Monte Carlo simulation of queueing systems is quite different than in a pure theoretical approach. A simulated queueing system cannot jump into its steady-state regime, as it is easy in the theoretical queueing theory approach. For example, state equations for the M/M/n queueing model are first order differential equations and with a stroke of the pen one can let the argument time tend to infinity. By doing so, one skip the initial transient period immediately, and reach the steady-state regime, while state equations become algebraic instead of differential ones. A simulated queueing model, on the other hand, really travels through its transient regime. The problem is, that a simulationist (a human that comes from a finite world), cannot wait for infinite time. He has to specify that infinity- to some reasonable extent, even when it is a large number- is still finite.

Simulation of state probabilities

In the steady-state regime of the queueing system, all state probabilities become constant. In the initial (transient, non-stationary) regime, state probabilities of the queueing system are time-dependent. If we could obtain, somehow, state probabilities as time-dependent variables, then it would be of great help to make clear insight into the behavior of the queueing system in both regimes: transient and steady-state one.

In fact, state probabilities are primary measures of performances of queueing systems. The mathematical description of queueing systems starts with the system of differential equations: every possible state of the queueing system is presented with one differential equation (Erlang's equations, or Kolmogorov-Chapman equations). Those are next differential equations of first order (1):

$$\dot{p}_0(t) = -\lambda p_0(t) + \mu p_1(t)$$

$$\dot{p}_1(t) = \lambda p_0(t) - (\lambda+\mu) p_1(t) + \mu p_2(t)$$

$$\ldots \tag{1}$$

$$\dot{p}_{n-1}(t) = \lambda p_{n-2}(t) - (\lambda+\mu) p_{n-1}(t) + \mu p_n(t)$$

$$\dot{p}_n(t) = \lambda p_{n-1}(t) - \mu p_n(t)$$

Also, these are the normalization condition (2) and the initial conditions (3):

$$\sum_{i=0}^{n} p_i(t) = 1 \tag{2}$$

$$p_0(0)=1,\; p_1(0)=p_2(0)=p_3(0)=\ldots=p_n(0)=0 \tag{3}$$

The variables $p_i(t)$ present time-dependent probabilities of the queueing system states. The index i presents the number of clients in a system. The independent variable is time (t). The intensity of input client's stream is λ. The intensity of output client's stream (servicing) is μ.

The complete solution of this system of differential equation assumes obtaining state probabilities as time-dependent variables. However, this task is very hard to perform, as we point out in Section 3.

Instead of a purely theoretical approach and "deep analytical water" (Kleinrock), we can use numerical methods to solve a system of differential equations. However, numerical method approach becomes cumbersome in case of queueing systems with many possible states. In the following example with 400 hundred vehicles, we would have to solve a system of 401 differential equations.

Nevertheless, this is not the only problem with the application of numerical methods. In case of other types of queueing systems (non-exponential distributions, queueing networks, etc.) it is hard even to establish a system of differential equations. In short, irrespective of having or not a system of differential equations as an analytical description of the queueing system behavior, we want to get solutions: time-dependent probabilities of possible states of the queueing system under study.

Complexity of a purely analytical approach or numerical method application to this task could be avoided using the Monte Carlo simulation modeling methodology. In [2], we propose a concrete simulation method for simulating state probabilities as time-dependent variables. Practically, we got numerical solutions for time-dependent state probabilities by the use of the Monte Carlo simulation modeling and without dealing with the system of differential equations itself.

The basic statistics postulates were used in order to establish control over the accuracy of simulation results. This approach was thus termed "Statistical integration of differential equations", or, which is already known in literature, "Monte Carlo integration". We mark this specific simulation method as "Automated Independent Replications with Gathering Statistics of Stochastic Processes", shortened as: AIRGSSP. The essence of the method is in his name.

The next formula (4) gives the connections among: number of Independent Replications (n, sample size); probability (proportion) which is estimated (p) and its complement (q=1-p); maximal error of estimation in percents (ε); and confidence coefficient for Normal distribution (Z_c). This formula comes from a well-known interval estimation for probability.

$$n = \frac{q}{p}\left(\frac{100}{\varepsilon}\right)^2 z_c^2 \tag{4}$$

In [9], we demonstrate how to achieve control over discrepancy of the simulation results with increasing a number of Independent Replications (IR) of the simulation experiment. For example, ten thousands Independent Replications of the simulation experiment obtain maximally 7.7% of discrepancy of estimation, for a probability level of 0.1, and with the level of statistical confidence at 0.99 (Z_c (0.99) = 2.58). This number of IR is used in the example in the next section.

One example of saturation

Here we will elaborate one military logistics situation. It is a model of vehicle maintenance process in a military unit in a UN mission. Some modifications are related only to numerical values.

Duration of the mission is six months, which corresponds to 18,000 arbitrary chosen time units in the simulation model (that is: one day corresponds to 100 time units). Demands for vehicle maintenance appear every 50 time units on average. Demands are stochastic according to the exponential distribution function. The average service time is also 50 time units, having a stochastic pattern in agreement with the Exponential distribution function.

This military unit covers a huge area of responsibility with everyday tasks on patrolling, escorting, etc. Vehicles are among the most important items for this kind of a job. There are 400 vehicles. The road network in the mission area is poor. The military unit is far away from national and UN logistics bases, so supply routes are long.

According to the UN mandate, there is a strictly limited number of soldiers and a possible increase of logistics personnel automatically means a decrease in the number of mission core soldiers. Therefore, logistics resources are very limited and there could be only one mobile maintenance team.

The maintenance officer got several tasks. The unit commander ordered him to make the operational readiness evaluation (to estimate probability that defined percentage of vehicles would be operationally available, i.e. “not in failure”). The main logistics officer asked for an estimate of average number of vehicles in the state of “failure”, as well as for an average time of waiting for maintenance. Finally, his subordinates from the mobile maintenance team asked for information whether they would work all the time, or there would be some free time.

When summarizing all this, the maintenance officer found the following: this is a queueing model M/M/1 in saturation. Time of mission is finite and that is valid for the queueing model too. The main hypothesis is as follows: in finite operating time, the queueing system may not reach the steady state.

In the case of saturated conditions, the steady state practically means a disaster: probably all vehicles will be in state of failure! Therefore, the use of steady-state solutions could be inappropriate (because of finite time, not because of a disaster). He decided to make a simulation model for the described maintenance situation and to find: average queue length, average waiting time in queue, and level of utilization of the service channel.

Above all, as a professional officer, he wants to carry out the order of the unit commander. For that purpose, he will simulate state probabilities as time dependent variables: $p_0(t)$ and $p_1(t)$; and grouped (clustered) states probabilities: $p_{2\text{-}11}(t)$, $p_{12\text{-}21}(t)$, $p_{22\text{-}31}(t)$, $p_{32\text{-}41}(t)$, $p_{42\text{-}51}(t)$, $p_{52\text{-}101}(t)$, and $p_{i>101}(t)$. Clustered states probabilities present groups of states: 1 to 10 clients in queue; 11 to 20 clients in queue; 40 to 50 clients to queue; 50 to 100 clients in queue; and more than 100 clients in queue. This approach allowed him to produce a quick and useable support for operational readiness evaluation.

He made a simulation model using the AIRGSSP method and got a time-dependent response for the desired states probabilities. Then he displayed them as in Fig.2.

It is obvious from the shape of the curves in Fig.1 that this queueing system works mainly in the transient regime. Simply because none of the state probabilities has a constant value, instead, they have dynamic characters.

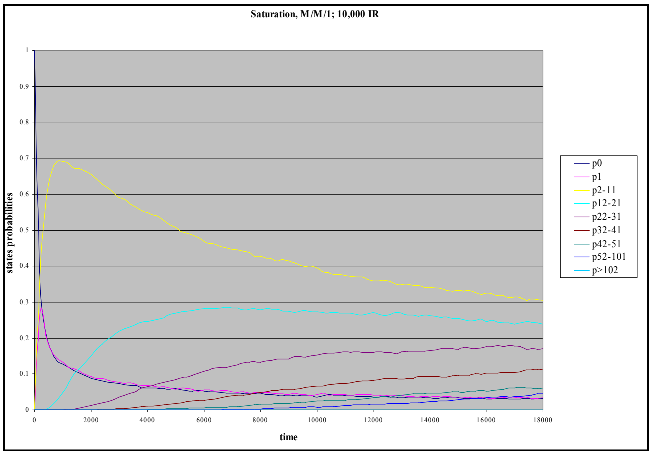

Figure 2. Time-dependent states probabilities of the queueing system in saturation.

Two state probabilities are presented as single ones: $p_0(t)$ and $p_1(t)$. Other state probabilities are clustered: 10 to 20; 21 to 30; 31 to 40; 41 to 50; 50 to 100; and, more than 100 vehicles in the state of failure, i.e. in queue waiting for maintenance (Series p_0, to $p_{>102}$, respectively, Fig.2).

Evaluation of operational readiness

Some indicative numerical values for state probabilities are presented in Table 1. Fig.3 shows two cases for time-dependent Operational Readiness Evaluation: probability that 95% (and 90% in the other case) of vehicles will be ready for use during six months of the mission (Series 1 and 2 respectively, Fig.3).

Operational readiness evaluation assumes the estimation of probability that the defined percentage of vehicles would be operationally available.

Thanks to simulation data, we can make this evaluation across the time span for any point on the time axis (using data presented in Fig.3), or also make some general conclusions for the end of the mission, as well as deal with some average values for the entire mission (Table 1).

Table 1. Numerical values of state probabilities: at the end of the mission, and on average for the entire mission

<table>
<tr><th></th><th>p_0</th><th>p_1</th><th>$p_{2\text{-}11}$</th><th>$p_{12\text{-}21}$</th><th>$p_{22\text{-}31}$</th><th>$p_{32\text{-}41}$</th><th>$p_{42\text{-}51}$</th><th>$p_{52\text{-}101}$</th><th>$p_{>101}$</th></tr>
<tr><td>At the end</td><td>0.0314</td><td>0.033</td><td>0.30678</td><td>0.242851</td><td>0.169516</td><td>0.112677</td><td>0.0589</td><td>0.04434</td><td>0.004</td></tr>
<tr><td>Onaverage</td><td>0.06637</td><td>0.05815</td><td>0.434563</td><td>0.23497</td><td>0.117019</td><td>0.053812</td><td>0.02344</td><td>0.011658</td><td>1.7E-05</td></tr>
<tr><td>Operational readiness</td><td colspan="6">On average, for the whole mission period, we can claim with probability of 0.965 that Operational readiness of the military vehicles will be 90%.
NOTE: we summarized probabilities of all states where the queue length is less than or equal to 40 vehicles, (Military unit has 400 vehicles, so 40 vehicles represent 10 %).</td><td></td><td></td><td>Probability of “disaster” is very small.</td></tr>
</table>

The average utilization of the service channel is 0.937. Therefore, the personnel from the mobile maintenance team will have more than 6% of time in mission for free activities.

The average waiting time is 608 time units. Thequeue length on average is 12.3 clients. The average number of satisfied demands for maintenance for the entire mission is 340.2.

To conclude, the assumed situation of saturation for the queueing model presenting operations of mobile maintenance team will not be a disaster. It is true that the service channel will be occupied almost all the time. It is also true, however, that the unit will be able to perform its UN mission with reasonably high operational readiness. On average, from 400 hundred vehicles, fewer than 14 will be in state of failure: waiting for repair (in queue fewer than 13), or being in the service channel (1).

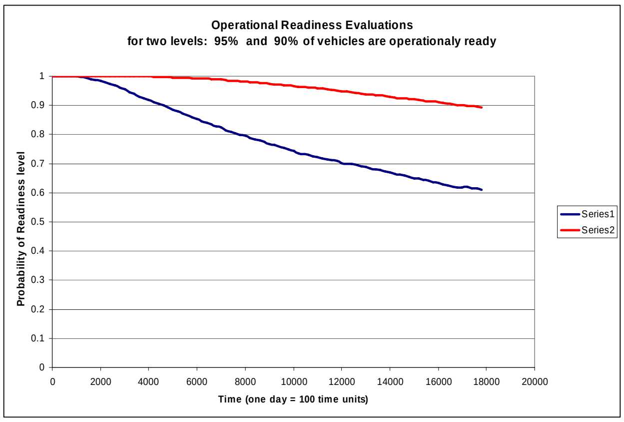

Figure 3. Time-dependent Operational Readiness Evaluation for two cases

In the end, it could be said that a dramatic situation of saturation (similar conclusion could be drawn for the case of heavy traffic and some cases of overloading) in a queueing model which operates for finite time has been softened owing to the influence of the initial transient phenomenon.

Conclusion

A careful investigation of conditions under which the theory is valid, in correlation with fidelity in modeling of reality, can lead to potentially new insights into the problem. The queueing theory has some important limitations related to the heavy-traffic operating conditions. A case of saturation is one of them.

The simulation results confirm that the initial transient period could have a respective duration. Therefore, in the case of military queueing systems engaged for a finite time, it is possible to sustain Operational Readiness dynamic at an acceptable level.

Future research could be dedicated to the next interesting case: overloading of queueing systems. Overloading is a case when the intensity of input client streams is greater than the intensity of servicing in service channels.

Queueing models and corresponding methods are general in their essence. So, results and achievements in one scientific discipline (like military logistic, in this case) could be used in other disciplines (like purely engineering disciplines).

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Vojni sistemi masovnog opsluživanja u režimu zasićenja i neke praktične posledice

Vojni sistemi masovnog opsluživanja mogu biti izloženi visokom nivou opterećenosti, što naročito važi za borbene uslove. Granični slučaj visoko-opterećenog režima, u tom smislu je režim zasićenosti. Režim zasićenosti sistema masovnog opsluživanja podrazumeva da je intenzitet pojave zahteva za opsluživanjem jednak nominalnom kapacitetu kanala opsluživanja. Mogućnosti teorijskog modelovanja ovih slučajeva su vrlo ograničene zbog

matematičke složenosti postuupka kao i samog rešenja, pa se izlaz traži u drugim metodološkim pristupima. U radu su prikazani rezultati modelovanja i analize rada sistema masovnog opsluživanja u zasićenom režimu, primenom metode Monte Karlo simulacionog modelovanja, označene kao "Automatizovana Nezavisna Ponavljanja sa Prikupljanjem Statistike Slučajnih Procesa". Osnovni problem koji treba rešiti jeste problem tačnosti simulacionih rezultata. Takođe, pokazaće se da u konačnom vremenu funkcionisanja sistem masovnog opsluživanja u režimu zasićenja značajno vreme provodi u takozvanom prelaznom režimu rada.

Ključne reči: **sistem masovnog opsluživanja, vojni sistem, logistika, zasićenost sistema, metoda Monte Karlo.**

Военные системы массового обслуживания в режиме насыщенности и некоторние практические последствие

Военные системы массового обслуживания могут быть подвергнуты высокому уровню нагрузки, что особенно относится к боевым условиям. Предельный случай режима высокой нагрузки в этом смысле представляет режим насыщенности. Режим насыщенности системы массового обслуживания подразумевает, что интенсивность явления требования за обслуживанием равна номинальной ёмкости канала обслуживания. Возможности теоретического моделирования этих случаев очень ограничены из-за математической сложности поступка, а в том роде и самого решения, и из-за этого выход пришлось искать в других методических подходах. В настоящей работе показаны результаты моделирования и анализа работы системы массового обслуживания в режиме насыщенности, при применении метода Монте Карло симуляционного моделирования, обозначенного как «Автоматизированные Самостоятельные Повторения со Скоплением Статистики Случайных Процессов». Главной проблемой, которую надо решить, является проблема точности симуляционных результатов. Тоже проявиться, что в конечном времени функционирования система массового обслуживания в режиме насыщенности значительную долю времени проводит в так называемом переходном режиме работы.

Kly~evwe slova: **система массового обслуживания, военная система, тыл и снабжение, насыщенность системы, метод Монте Карло.**

Les systèmes militaires de file d'attente dans le régime de saturation et certaines conséquences pratiques

Les systèmes militaires de file d'attente peuvent être exposés à un niveau de dense circulation, ce qui est surtout évident dans les conditions de combat. Le cas limite du régime de la dense circulation est, dans ce sens, le régime de la saturation. Ce régime de la saturation du système suppose que l'intensité des demandes de service est égale à la capacité nominale de la chaîne de service. Les possibilité de la modélisation théorique de ces cas sont très limitées à cause de la complexité mathématique du procédé et de la solution même ; pour tout cela la solution est recherchée parmi les autres procédés méthodologiques. Dans ce papier on a exposé les résultats de la modélisation et l'analyse du fonctionnement du système de la file d'attente dans le régime de saturation, à l'aide de la méthode Monté Carlo de la modélisation simulée qui est désignée comme »les répétitions automatiques indépendantes avec rassemblement statistique des procédés stochastiques ». Le problème basique à résoudre consiste dans la précision des résultats de la simulation. On démontrera aussi que dans le temps final du fonctionnement le système de la file d'attente sous le régime de saturation passe un temps considérable dans le régime transitoire d'engagement.

Mots clés: **système de la file d'attente, système militaire, logistique, saturation du système, méthode Monté Carlo.**