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MODELING AND PERFORMABILITY EVALUATION OF E-COMMERCE SYSTEMS

EXTENDED ABSTRACT OF A DOCTORAL DISSERTATION

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The newly emerging, so called 'digital economy', is entirely based on the e-Commerce paradigm. Assuring high quality of its Web services, especially regarding the performance, dependability, reliability and availability of e-Commerce systems, unified under the notion of performability, has become an imperative of the contemporary way of doing business on the Internet, and also a fundamental factor for continuous achieving and retaining satisfaction of e-Customers. The complexity of this task is even bigger, knowing the fact that e-Commerce Web services rely on large-scale systems, consisting of thousands of computers, networks, software components, and users. Large systems are inherently complex, whilst the randomness and unpredictability in the way e-Customers demand those Web services, initiate the problem of managing and planning the capacity of their hardware resources. In fact, the true challenge is to achieve an optimal balance among implementation investments and costs needed to continually upgrade and maintain a particular e-Commerce Web site, the performability of the underlying system, and achieved e-Customers' satisfaction, regarding the delivered quality of Web services.

During this research, a single fact becomes evident: besides the existence of relatively big and ever increasing number of e-Commerce systems worldwide, there is a considerably smaller number of research endeavors that are entirely and exclusively dedicated to modeling and evaluation of performability measures of such systems. In most cases, the existing research activities have been focused solely on the performance analysis of e-Commerce systems, while dependability measures, encompassing the reliability and availability measures, have been taken into account either separately and narrowly, or they have not been mentioned at all.

Inspired by previously pointed facts, this research promotes a rather new, holistic approach, concentrated on the development of predictive models usable for evaluating numerous performability measures of generic e-Commerce systems, utilizing the formalism, the syntax and the semantic expressing power of the classes of Deterministic and Stochastic Petri Nets (DSPNs) and Generalized Stochastic Petri Nets (GSPNs), in conjunction with corresponding simulation models, built up for solving the underlying stochastic Petri models. Such an approach has been entirely based on the analysis of the dynamic and stochastic behavior of e-Customers during their online shopping sessions. As a direct consequence of this hybrid approach, the realization of more systematic, more complex and more computationally efficient analyses has been made possible, covering all crucial aspects of the performability evaluation of present-day e-Commerce systems, in a unique and consistent way.

The originally proposed methodology, along with the obtained results, as well as the conclusions that have been drawn from, set up new frontiers in the sphere of capacity planning, and also give a considerable contribution in the field of performability evaluation of e-Commerce systems. As being a first attempt of this kind, this approach opens many new possibilities and raises many new unanswered questions which impose the need for further and long-term exploration of not only e-Commerce systems and e-Customers' online shopping behavior, but also the tools and techniques for addressing the wide spectrum of issues related to performability modeling and evaluation of systems an e-Commerce paradigm relies on.

1 PUBLISHED PAPERS RELATED TO THE RESEARCH

Book chapters:

[1] Mitrevski, P., **Hristoski, I.**, "e-Consumer Online Behavior: A Basis for Obtaining e-Commerce Performance Metrics", in *ICT Innovations 2010*, Gušev, M. and Mitrevski, P. (Eds.), Communications in Computer and Information Science (CCIS), Vol. 83, ISBN 978-3-642-19324-8, pp. 142-151, Springer Berlin Heidelberg, **2011**

Journal papers:

[2] **Hristoski, I.**, Mitrevski, P., "Performability Modeling and Evaluation of e-Commerce Systems", *Computer Science and Information Systems Journal (ComSIS)*, ISSN: 1820-0214, **2013** (JCR 2011 **Impact Factor: 0,625**) (submitted for publication)

[3] **Hristoski, I.**, Mitrevski, P., "Simulating e-Commerce Client-Server Interaction for Capacity Planning", *e-Society Journal: Research and Applications,* Vol. 3, No. 2, pp. 85-94, ISSN: 2217-3269, **2012**

Conference papers:

[4] Mitrevski, P., **Hristoski, I.**, "Acquiring Performability Metrics of e-Commerce Systems", *Proc. of the XLVIII International Scientific Conference on Information, Communication and Energy Systems and Technologies (ICEST 2013)*, Ohrid, Macedonia, **2013** (to be published)

[5] **Hristoski, I.**, Mitrevski, P., "Obtaining Business-Specific Performance Metrics in e-Commerce", *Proc. of the International Economics, Management & Finance Doctoral Students Conference*, Tirana, Albania, **2012**

[6] **Hristoski, I.**, Mitrevski, P., "Simulating e-Commerce Client-Server Interaction for Capacity Planning", *Proc. of the International Conference on Applied Internet and Information Technologies (AIIT 2012)*, pp. 41-46, Zrenjanin, Serbia, **2012 (best selected papers)**

[7] **Hristoski, I.**, Mitrevski, P., "On Stochastic Modeling and Performance Analysis of E-Customer's Online Behavior", *Proc. of the 9th CiiT Conference on Informatics and Information Technology*, pp. 74-78, Bitola / Skopje, Macedonia, **2012**

[8] **Hristoski, I.**, Mitrevski, P., "The Challenges of Web Services' Quality of Service (QoS) Management", *Proc. of the 6th May Conference on Strategic Management (MCSM 2010)*, pp. 304-315, Kladovo, Serbia, **2010**

[9] **Hristoski, I.**, "e-Commerce security aspects", *Session of scientific communications with international participation "The society of knowledge and the progress of democracy"*, Târgu – Jiu, Romania, **2008**

[10] Mitrevski, P., **Hristoski, I.**, "Customer Behavior Modeling in e-Commerce", *Proc. of the International Conference: "Business and Globalization"*, Vol. 1, pp. 395-401, Ohrid, Macedonia, **2007**

Annual publications:

[11] Mitrevski, P., **Hristoski, I.**, "Taxonomies of e-Customers, Operating Profiles, and Performability of e-Commerce Systems", *Proceedings of the Faculty of Technical Sciences*, St. Clement of Ohrid University - Bitola, Bitola, Macedonia, **2012** (to be published)

2 MOTIVATION AND OBJECTIVE

The existing research activities in this field originate barely 10-15 years ago. They focus, mainly, on particular, isolated segments and do not belong to an overall, systematic approach. Besides the on-going, high dynamics in development and exceptional attractiveness of this substance, a very few research endeavors have been dedicated to modeling and evaluation of performability measures of general-purpose computer systems. These are based, generally, on the development and appliance of deterministic models, whilst the stochastic processes, e.g. Markov processes, have been used seldom, due to their mathematical complexity. Even lesser number of research activities has been dedicated to performability modeling and evaluation of e-Commerce systems. These systems are, in fact, computer systems, but they possess many unique characteristics, due to the interaction with the e-Customers. In most cases, the up-to-date research has been focused solely on the analysis of performances of e-Commerce systems, whereas the dependability measures have been taken into account either very narrowly, or they have not been mentioned at all. Nonetheless, there are also few research endeavors that address completely the performability measures, but they take into account particular and specific e-Commerce systems, so they are limited in their widespread applicability.

All of these presented facts have been quite a sufficient motivation and an immense impetus that have naturally imposed the necessity to undertake a comprehensive research, such that the key aspects of performability of contemporary e-Commerce systems would be addressed, taking into account e-Customers' online behavior during their shopping sessions via Internet. Having this on mind, the basic motivation to carry out this research can be specified as follows: *to define a methodological framework for evaluation and analysis of both the performance and performability metrics of a conceptual, generic e-Commerce system, based on stochastic modeling of e-Customers' dynamic behavior during online shopping sessions in virtual stores*. The motivation for realization of such research work comes out from the impression that the field of performability analysis of e-Commerce systems, which is, by the way, an exceptionally significant topic, has not been studied and investigated quite well, not only in the country, but also worldwide.

The subject of this doctoral dissertation can be defined as follows: *investigation of the possibilities to apply different classes of stochastic Petri nets as tools for building predictive stochastic models of Web-based e-Commerce systems in order to evaluate various performability measures, along with the employment of DES software programming environment to build up corresponding simulation models for solving the stochastic Petri models*, a hybrid approach which is both novel and unique enough to present a considerable contribution in this field.

The basic objective of the doctoral dissertation can be defined both theoretically and practically, as follows: *i) a theoretical objective: to build a new theoretical framework (a new methodology) for performability analysis of e-Commerce systems, based on stochastic modeling of the e-Customers online behavior during their shopping sessions via Internet and workload characterization, in the context of capacity planning; ii) a practical objective: to conduct an analysis and evaluation of numerous performability measures of a conceptual e-Commerce system through the development of series of stochastic Petri models, at which enormous and always variable number of online sessions have been simultaneously initiated, processed and completed, at various arrival rates of e-Customers of different classes, comprising various mixtures within various operating profiles.* The analysis and evaluation of performability measures is based on development of series of stochastic models, suitable for defining, analyzing, evaluating and predicting a wide range of performance, reliability and availability measures, as a function of a plethora of input parameters, which are known *a priori*.

An essential component and a premise, that all of these stochastic models have been built upon, is the stochastic modeling of the dynamic online shopping behavior of e-Customers, who, due to their intrinsically different mind-sets, always exhibit heterogeneous, but still predictable navigational patterns throughout the e-Commerce Web sites. Capturing those navigational patterns and defining them quantitatively, in accordance with a relevant taxonomy of e-Customers' behaviors, is a basic premise to performing both modeling and evaluation of a wide gamut of performability measures.

3 MAIN CONTRIBUTIONS

Throughout all segments within this research, the basic, underlying idea is that the dynamic and stochastic online behavior of e-Customers during their shopping sessions via Internet is the main reason for overloading e-Commerce systems, which results in series of phenomena, including the unexpectedly prolonged response time, as being one of the most prominent performance measures. This is the exact cause for e-Customers' frustration and dissatisfaction, which yields a sequence of negative effects, e.g. premature abandoning of e-Commerce Web sites, disloyalty, decreased reputation and bad image of the Internet company, increased loss of e-Customers, etc. All of these effects directly and negatively affect company's revenues, as well as all major e-Commerce business indicators. Therefore, the DSPN Petri model of the online shopping behavior, originally proposed by Mitrevski *et al.* (2002), has been recognized and utilized as a fundamental building block during construction of the series of stochastic Petri models for evaluation of plentiful performability measures. This stochastic model, which is based on the decision-making process during online sessions, depicts the complexity of the interaction between a typical e-Customer and the e-Commerce Web site in a rather simplified way. For simplicity reasons, it has been supposed that, during online shopping sessions, an e-Customer can visit just two states (i.e. invoke just two e-Commerce functions), *Search* and *Checkout*, where he/she stays for a certain time, exponentially distributed with rates λ and μ, respectively. While the e-Customer stays in any of these two states, the timeout mechanism can be activated due to his/her inactivity, meaning that a deterministic time τ has run out and the session has been terminated forcibly and prematurely by the e-Commerce system. Otherwise, the session terminates regularly, with two possible endings: either successfully (with order placed), or unsuccessfully (without order placed). However, in the later case, two outcomes are possible, including the following ones: i) the e-Customer has previously put one or more products into the shopping cart, but he/she has not buy any of them; ii) the e-Customer has left the virtual store with an empty shopping cart.

Based on this stochastic model, a qualitative analysis of e-Customers' typical behaviors has been carried out for the first time, regardless of their socio-economic, demographic, ethnic and other characteristics, their innate and gained habits to go for shopping, as well as regardless their immediate motivation to shop online. As a result of such analysis, specific *classes of e-Customers* have been defined, as well. It should be pointed out that based on this qualitative, narrative description, a quantitative definition of these identified classes of e-Customers has been made, too, using the parameters of the previously mentioned DSPN Petri model (i.e. the firing rates of the exponential transitions and the weights of the immediate transitions).

Further on, the *operational environment* has been modeled, as well, through the definition of specific *operating profiles* (working scenarios). In fact, each operating profile specifies, in percentages, the participation of each defined class of e-Customers within the mix that represents the workload, presented to a specific e-Commerce system. Indeed, the *workload characterization* is the key aspect that defines the service demand, i.e. the demand for various hardware resources (CPU, HDD, RAM …) at the e-Commerce system (Menascé & Almeida, 2000a). Namely, within each specific operating profile, e-Customers, belonging to specific classes, participate in various proportions, whilst each particular class is characterized by a specific frequency (intensity) and a specific sequence of invoked specific e-Commerce functions (Login/Register, Search, Add-to-Cart, Checkout …). Each invocation of any of these functions results in generating and sending a corresponding HTTP message from the e-Customer's browser towards the servers of the e-Commerce system. The system has to accept and process all of these HTTP messages, and each of them has to be answered by sending a corresponding HTML code backwards, to the client's computer. The conclusion is obvious: each operating profile poses a characteristic and different workload to the e-Commerce system.

Besides the specification of various operation profiles, the process of workload characterization also includes the rates at which particular shopping sessions have been initiated at the e-Commerce Web site (e-Customer arrival rate). The process of e-Customers' arrival is the Poisson process, i.e. a stochastic process where the time elapsed between two consecutive arrivals is exponentially distributed, with a mean of $1/\lambda$, where λ denotes the intensity of arrivals of e-Customers in the system. As a matter of fact, λ is the arrival rate in a general context. If there are K classes of e-Customers being defined in total, and p_1, p_2, ..., p_K are the probabilities that correspond to the participation of each class within a specific operating profile, where $p_1 + p_2 + ... + p_K = 1$, then e-Customers belonging to *class 1* arrive in the system with an intensity of $\lambda_1 = p_1 * \lambda$, e-Customers belonging to *class 2* arrive in the system with an intensity of $\lambda_2 = p_2 * \lambda$, whilst e-Customers belonging to *class K* arrive in the system with an intensity of $\lambda_K = p_K * \lambda$.

Based on these assumptions, a simulation model in a SimPy/Python programming environment has been built up, taking into account the two basic subjects being involved in the client/server interaction via Internet, i.e. the e-Customers and the e-Commerce system. The client-side entirely reflects the semantics of the DSPN model of e-Customer's online shopping behavior, whilst the values of the working parameters within the model dynamically change, corresponding to those being defined for each particular class of e-Customers. To satisfy the needs of this simulation, three classes of e-Customers have been defined, including the Rare, the Ordinary, and the Frequent classes of e-Shoppers. This taxonomy has been defined based on the buying intensity during online shopping sessions. Three operating profiles (i.e. working scenarios) have been defined as well, consisting of the following ones: S_1(10%, 30%, 60%), S_2(33%, 34%, 33%) and S_3(50%, 30% и 20%). The e-Commerce system has been modeled on a system level, rather than on a component level (CPU, HDD, RAM ...), where each system represents a particular server with an infinite queue length. The server-side is modeled as a two-tier architecture, which is usual for moderately large e-Commerce systems, consisting of the following types of servers: a Front-End Server (FES), a Web Server (WS), a Database Server (DbS), an Application Server (ApS), and an Authentication Server (AuS), distributed into two LAN segments. For each particular server, it has been assumed that the processing time of a single HTTP message follows the Normal distribution $N(\mu$ [ms]; σ [ms]). In addition, for each particular type of HTTP message (Search, Browse, Checkout, ...), the sequence of back-end servers that is referenced during its processing, has been defined and modeled, in accordance with its corresponding Client/Server Interaction Diagram (*CSID*) (Menascé & Almeida, 2000b). The modeling of the propagation time via Internet, both for a particular HTTP message being directed from the e-Customer's browser towards the e-Commerce Web site, and for each particular HTML response, being directed from the e-Commerce Web site back to the client's computer, has been done by sampling from the Normal distribution $N(\mu = 0.200$ [s]; $\sigma = 0.033$ [s]), so 99.73% of the values within the interval ($\mu \pm 3\sigma$) belong to the interval [0.100, ..., 0.300] [s]. The transmission delays of the messages among various servers have been neglected in the simulation model, due to the usage of high-speed LAN segments.

Based on these premises, a plethora of simulation runs have been carried out, for all three working scenarios. The values of numerous performance measures have been evaluated as a function of the e-Customers' arrival rate, including the *mean response time*, a performance measure of a vital interest to e-Customers (Fig. 1). As expected, Fig. 1 shows that the working scenario S_1 generates such a workload that induces and poses the biggest service demand to the hardware infrastructure of the e-Commerce Web site, since the Frequent e-Customers have been presented by 60% within the mix. Since they invoke the *Add-to-Cart* and the *Checkout* e-Commerce functions more frequently, the number of the generated HTTP messages will be noticeably increased. As a result, the number of the hits of the Web server (WS) will be raised to such an extent, that its queue length will exceed 800 HTTP messages, at some points of time. All of this lead to a significant increase of delays and prolongation of the total time needed to process each queued HTTP message, which causes the decrease of the *throughput* and the *utilization* of the servers, especially of the Web server (WS), as presented on Fig. 2 and Fig. 3.

The Web server (WS), which accepts the biggest service demand, becomes the 'bottleneck' of the whole system. In order to eliminate such a harmful condition, corresponding techniques of horizontal/vertical or diagonal scaling of the Web server have to be applied.

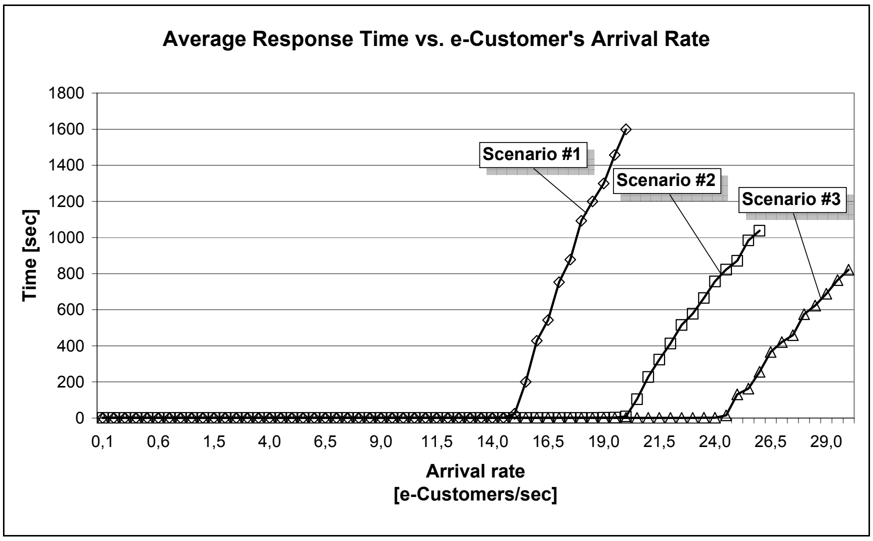


Figure 1: Mean response time, as a function of the e-Customers' arrival rate ($0.1 \leq \lambda \leq 30.0$ [s^{-1}])

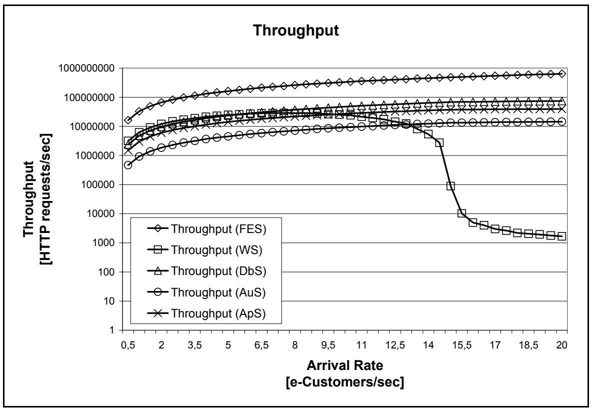


Figure 2: Servers' throughput (Scenario S_1; λ_{S1} = 14.78 [s^{-1}])

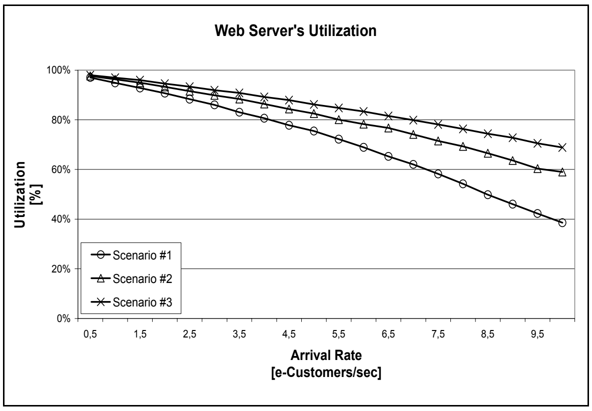


Figure 3: Utilization of the Web server (Scenario S_1; λ_{S1} = 14.78 [s^{-1}])

The estimated critical values of e-Customer's arrival rates, i.e. the points when the mean response time reaches the 'psychological' threshold of 4.0 [s], have been computed by appliance of the linear interpolation method. Their values are as follows: λ_{S1} = 14.78 [e-Customers/s]; λ_{S2} = 19.81 [e-Customers/s]; λ_{S3} = 24.28 [e-Customers/s], for the three working scenarios, respectively. The percentage of the group of unsatisfied e-Customers, i.e. e-Customers who have experienced a response time longer than 4.0 [s], increases as the arrival rate raise, regardless of the underlying working scenario. For instance, for a fixed value of the arrival rate of λ = 20.00 [e-Customers/s], the percentage of unsatisfied e-Customers is: 98.69% (for the working scenario S_1), 67.66% (for the working scenario S_2), and 0.00% (for the working scenario S_3), as depicted on Fig. 4. On the other hand, Fig. 5 shows that the number of clients who belong to the group of moderately satisfied e-Customers, i.e. e-Customers who experience a response time between 2.0 [s] and 4.0 [s], raises from 0 reaching its maximum at the point when the arrival rate reaches its critical value (for the working scenario S_3, λ_{S3} = 24.28 [e-Customers/s]), and then, as the arrival rate increases, the number of clients who belong to this group decreases back to 0.

During simulations, in addition to the evaluation of the mean response time, many other performance metrics have been assessed and evaluated, as well. In that context, it is worthy to mention the *mean processing time* of HTTP messages on the server-side, both by the various types of back-end servers, and by various types of HTTP requests, for all three working scenarios. It depends not only on the e-Customer's arrival rate, but also on the types of servers involved in processing of HTTP requests. All types of servers, except the Web server (WS), exhibit a linear and gradually increasing trend of the mean processing time against the e-Customer's arrival rate (Fig. 6). The exception is made with the Web server (WS), which demonstrates a non-linear and drastically increasing function of the mean processing time, since it is overloaded by HTTP requests and is a 'bottleneck' in the whole system. In that context, at the Web server, the mean processing time of a single HTTP request goes beyond 1.0 [s] at λ_{S1} = 14.78 [s^{-1}], 10.0 [s] at λ = 15.00 [s^{-1}], 100.0 [s] at λ = 15.50 [s^{-1}], and outreaches 200.0 [s] at almost λ = 16.00 [s^{-1}].

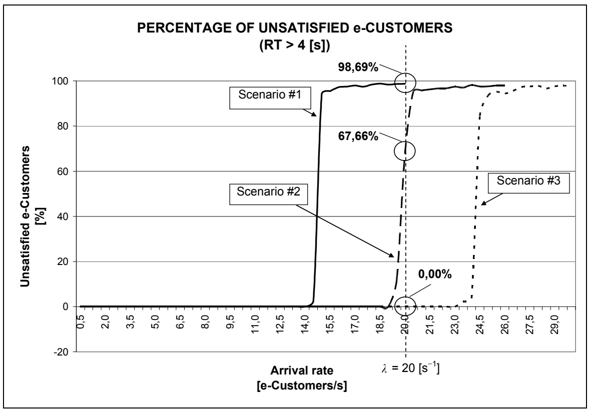


Figure 4: Observed response time, greater than 4.0 [s], for all three working scenarios ($0.5 \le \lambda \le 30.0$ [s^{-1}])

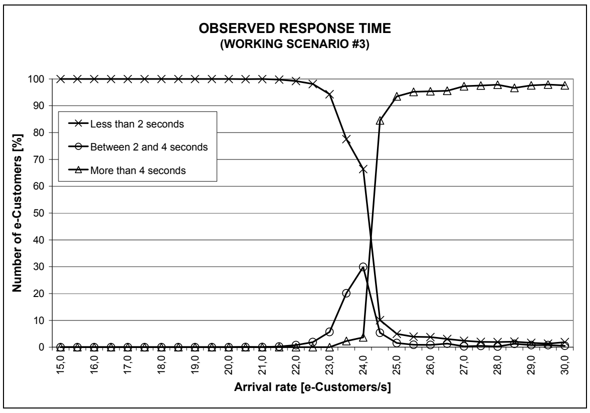


Figure 5: Observed response time for the working scenario S_3 ($0.5 \le \lambda \le 30.0$ [s^{-1}])

Fig. 7 portrays the reliance of the mean processing time on the e-Customer's arrival rate, by particular types of HTTP requests (*Browse*, *Search*, *Checkout* and *Add-to-Cart*), for the working scenario S_1. It is obvious that for all types of HTTP requests, the function has got an identical shape. A very small dissimilarity among the particular functions is evident for arrival rates that are smaller than the critical one, λ_{S1} = 14.78 [e-Customers/s]. For arrival rates higher than the critical one, the mean processing times for various HTTP requests become identical.

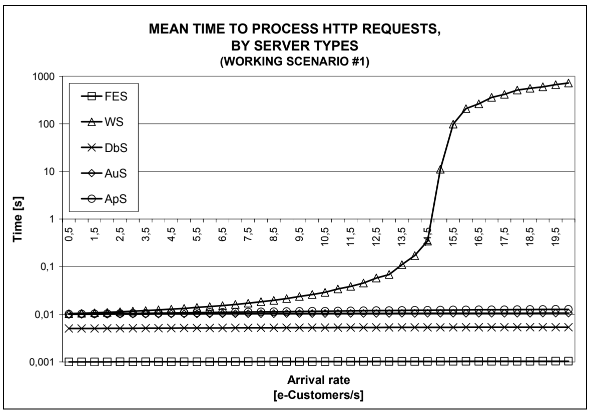


Figure 6: Mean time to process HTTP requests, at various servers, for the working scenario S_1 ($0.5 \le \lambda \le 20.0$ [s^{-1}])

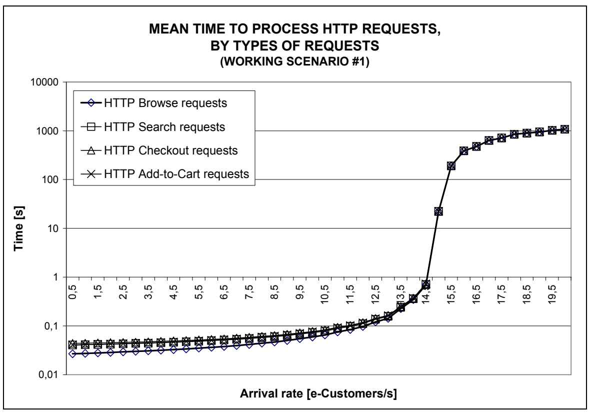
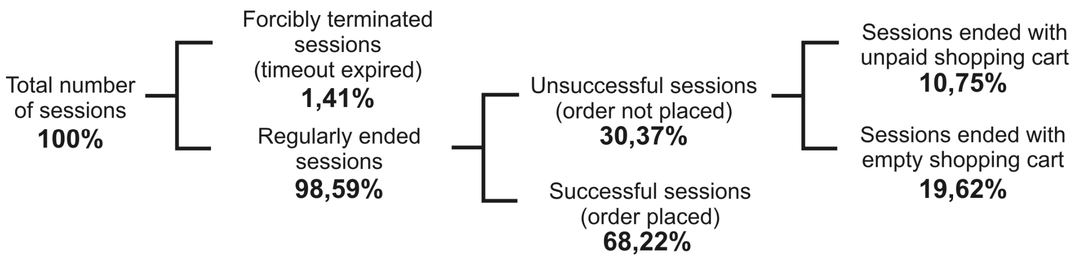


Figure 7: Mean time to process various types of HTTP requests, for the working scenario S_1 ($0.5 \le \lambda \le 20.0$ [s^{-1}])

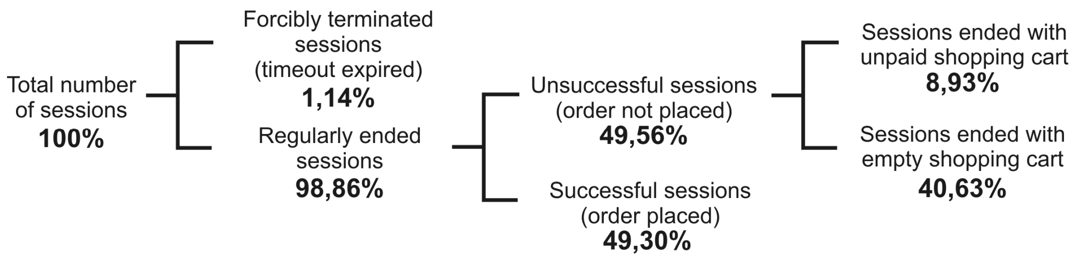
On the client-side, many performance measures have been evaluated, too. The following ones can be also obtained analytically, by solving the corresponding Customer Behavior Model Graph (*CBMG*) (Menascé & Almeida, 2000a; Menascé & Almeida, 2002): *mean number of visits to each state* in the CBMG; *steady-state probabilities* of being in any of the *Search* or *Checkout* states; *percentage of e-Customers that have left the e-Commerce Web site* with a non-empty shopping cart; *average session length* [s]; and *Buy-to-Visit ratio* [%], which shows how many sessions out of the total number of sessions, have ended successfully (with an order placed).

Besides assessing the previous ones, the DES simulation has allowed the following performance measures to be obtained, as well: *mean sojourn time* [s] in each of the *Search* and *Checkout* states; *percentage of sessions that have ended with an empty cart*; *mean number of HTTP requests* been generated per session; *percentage of sessions that have terminated regularly* (i.e. sessions that have not been forcibly terminated by the e-Commerce system due to expiration of the timeout limit); *average number of products that have been put into the shopping cart and have been paid*; *average number of products that have been put into the shopping cart, but have not been paid*. The last two performance measures can be used for evaluation of the specific and innovative, so called *business-oriented performance metrics*, including the *revenue throughput* [€/s] and the *potential loss throughput* [€/s] (Menascé & Almeida, 2000a).

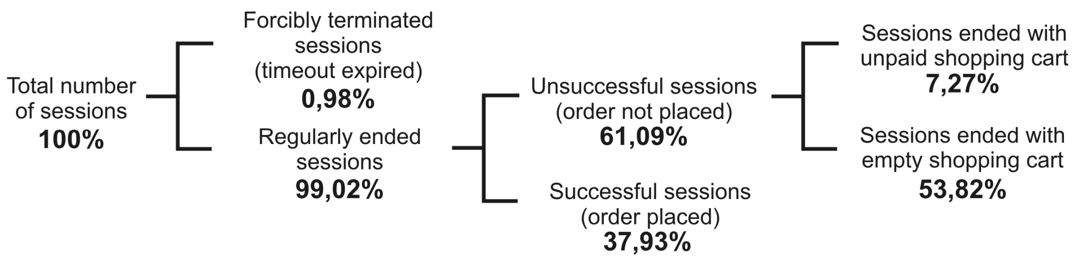
On the client-side, it was also very important to perform an analysis of the shopping sessions, by various working scenarios (Fig. 8). Such an analysis allows one to get a clear and concise picture of session performances, by various working scenarios, which can be effectively utilized for forecasting purposes and carrying out various 'what-if' analyses.



(a) Working scenario S_1



(b) Working scenario S_2



(c) Working scenario S_3

Figure 8: An analysis of online shopping sessions, according to different working scenarios

Based on some previously evaluated performance measures that have been obtained by simulations, it has been shown for the first time, both methodologically and on an example, the methodology of how to obtain the innovative business-oriented performance measures. This is exceptionally important, since they are very closely related to the financial effects and indicators of Internet companies that sell online. The *Buy-to-Visit ratio* [%] (*BV*), which measures the average number of sessions that have ended successfully during an observed period of time, can be computed according to the expression (1), where $S_{Success}$ is the total number of successful sessions (i.e. sessions during which e-Customers have bought something); $S_{Unsuccess}$ is the total number of unsuccessful sessions (i.e. sessions during which e-Customers have not bought anything); $S_{Completed}$ is the total number of sessions that have terminated regularly; and $S_{Expired}$ is the total number of sessions that have been forcibly terminated by the e-Commerce system, due to e-Customer's inactivity.

$$BV = \frac{S_{Success}}{S_{Total}} = \frac{S_{Success}}{S_{Completed} + S_{Expired}} = \frac{S_{Success}}{S_{Success} + S_{Unsuccess} + S_{Expired}} \quad (1)$$

The *Revenue Throughput* (*RT*) [€/s] can be estimated in accordance with the expression (2), whilst the *Potential Loss Throughput* (*PLT*) [€/s] can be evaluated using the expression (3), where t is the observed interval of time [s]; K is the total number of product types being sold online, C_i is the price per unit of the product's type i, i = 1, 2, ..., K; p_i is the probability of buying an item of the product's type i, i = 1, 2, ..., K; $I_{Put\text{-}and\text{-}Paid}(i)$ is the estimated number of sold items of the product's type i, i = 1, 2, ..., K; $I_{Put\text{-}and\text{-}Not\text{-}Paid}(i)$ is the estimated number of items of the product's type i, i = 1, 2, ..., K, that have been put into the shopping carts, but have not been paid/bought.

$$RT = \frac{1}{t} \cdot \sum_{i=1}^{K} C_i \cdot I_{Put-and-Paid}(i) \cdot p_i \quad (2)$$

$$PLT = \frac{1}{t} \cdot \sum_{i=1}^{K} C_i \cdot I_{Put-and-Not-Paid}(i) \cdot p_i \quad (3)$$

Assuming the values of the parameters K, C_i, and p_i, i = 1, 2, ..., K;, as well as taking into account the values of the parameters $I_{Put\text{-}and\text{-}Not\text{-}Paid}$, $I_{Put\text{-}and\text{-}Not\text{-}Paid}$, $S_{Success}$, $S_{Unsuccess}$, and $S_{Expired}$, which were previously evaluated by simulations, an estimation of the values of business-oriented performance metrics has been made, for the three working scenarios, for specific e-Customer's arrival rates, during the observed time period t (Table 1).

The simulations have also showed that, for various arrival rates of e-Customers, the estimated values of the *Revenue Throughput* and the *Potential Loss Throughput* are functionally dependent on the e-Customer's arrival rates, i.e. their values linearly increase as the arrival rate increase (Fig. 9). Contrary to this behavior, the value of the *Buy-to-Visit ratio*, for a given working scenario, does not depend on the e-Customer's arrival rate increase, but it varies around its own mean value (Fig. 10).

In order to encompass, in a simultaneous and a consistent way, all the components of e-Commerce system's performability, including its performances, reliability, and availability, a hybrid approach has been promoted for the first time. It consists of the following aspects: i) Due to the complexity of the concept of performability, the *hierarchical composition approach* has been applied; as a result, the problems of *largeness* and *stiffness*, that are inherent to monolithic models, have been elegantly bypassed; ii) Due to the complexity of modeling by usage of Markov processes straightforwardly, some classes of stochastic Petri nets have been applied, and the discrete-event simulation (*DES*) approach has been utilized for obtaining their solution. In such a way, instead of building a single, monolithic model, three separate, yet mutually interconnected stochastic sub-models have been developed. There is a substantial exchange of information among them, in the following manner: the output results, obtained from the Petri model of reliability and from the Petri model of performances, have been presented as input parameters into the hierarchical Petri model of performability, whilst the reliability measures can be obtained by integration of the information that comes out from the stochastic Petri model of e-Customer's online behavior during a single session and the information that comes out from the stochastic Petri model of the operational environment.

Table 1: Estimated values of the business-oriented performance measures, for three possible working scenarios ($\lambda = 10$ [s^{-1}], $t = 7200$ [s])

Business-oriented performance measures	**Scenario #1:** Rare = 10% Ordinary = 30% Frequent = 60%	**Scenario #2:** Rare = 33% Ordinary = 34% Frequent = 33%	**Scenario #3:** Rare = 50% Ordinary = 30% Frequent = 20%
Buy-to-Visit ratio	0.68204	0.49442	0.37709
Revenue Throughput	586.69 [€/s]	339.60 [€/s]	219.05 [€/s]
Potential Loss Throughput	107.51 [€/s]	82.07 [€/s]	64.48 [€/s]

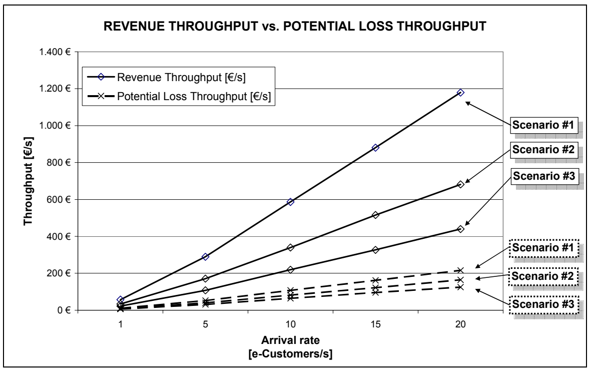


Figure 9: Revenue throughput and potential loss throughput, for various arrival rates, for three working scenarios ($1.0 \leq \lambda \leq 20.0$ [s^{-1}])

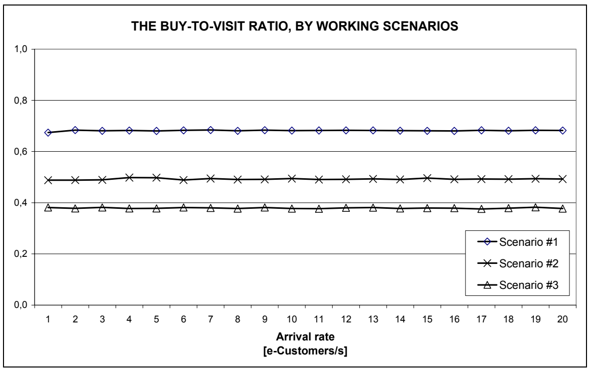


Figure 10: The Buy-to-Visit ratio, for three working scenarios ($1.0 \leq \lambda \leq 20.0$ [s^{-1}])

As in previous cases, the *stochastic Petri model of a single e-Customer's online shopping behavior* during his/her session with the e-Commerce Web site, comprises the foundation for all research activities (Fig. 11). In fact, it is a Generalized Stochastic Petri Net (*GSPN*), derived directly from the DSPN model, being proposed by Mitrevski *et al.* (2002).

The analytical solution of the GSPN model includes finding out both the steady-state solution and the transient (time-dependent) solution, by using its infinitesimal generator matrix Q. Therefore, the dissertation contains the construction of the *extended reachability graph* (*ERG*) of the GSPN model, as well as the *reduced reachability graph* (*RRG*), deduced from the ERG. Based on the RRG, the *Continuous-Time Markov Chain* (*CTMC*) of the underlying GSPN Petri model has been obtained, and the matrix Q has been derived, as well. However, since its derivation requires a substantial computational effort and is a time-consuming operation, and having on mind the fact that not just one, but many GSPN models have to be constructed and solved, the approach to obtain an analytical solution of such models is highly unfeasible and practically unacceptable. Even more, some of the stochastic Petri models, which have been constructed later on, belong to the class of Deterministic and Stochastic Petri Nets (*DSPNs*), which are even more complex to be solved analytically (Ciardo & Lindemann, 1993). Therefore, in order to obtain a solution of such stochastic models, the approach of discrete-event simulation (*DES*) has been chosen instead, which yields a numerical, rather than an analytical solution.

In order to carry out the performability analysis, five different classes of e-Customers have been defined, both qualitatively and quantitatively, using the parameters of the GSPN model, depicted on Fig. 11. These include: the Passionate, the Focused, the Reluctant, the Curious, and the Selective e-Shoppers, arranged in a descending order regarding the corresponding *conditional probability* for a successful outcome of sessions, being estimated by simulations, too. The Bowman-Shelton test of normality has shown undoubtedly that the conditional probability for a successful outcome of sessions follows the Normal probability distribution, for each particular class of e-Customers. It has been also concluded that the highest *average successful rate* (0.85264 [s^{-1}]) is evident for the class of the Passionate e-Customers, followed by the classes of the Focused (0.56816 [s^{-1}]) and the Reluctant (0.19756 [s^{-1}]) e-Shoppers. Contrary to all expectations, the class of the Curious e-Shoppers (0.09893 [s^{-1}]) exhibits an insignificant, yet a higher average successful rate than the Selective e-Shoppers' one (0.02451 [s^{-1}]), a fact that confirms the previously listed arrangement of e-Customers' classes in a descending order.

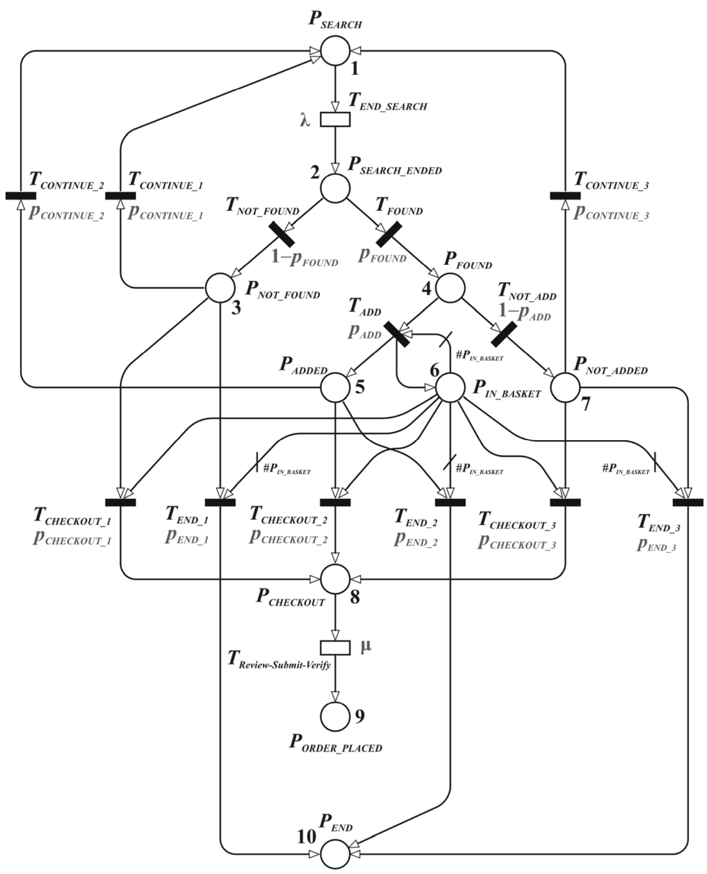


Figure 11: The GSPN Petri model of a single e-Customer's online shopping session

The analysis of the partial coefficients of elasticity, obtained by series of simulation runs in which the conditional probability for a successful outcome of sessions (dependent variable) has been evaluated against the values of the weights of immediate transitions (independent variables) within the GSPN Petri model (Fig. 11), has shown that the successfulness of sessions is a result of the complex process of decision-making, and is least dependent on the probability of putting a product into the shopping cart (p_{ADD}), and the probabilities of initiating an order ($p_{CHECKOUT\_1}$, $p_{CHECKOUT\_2}$, $p_{CHECKOUT\_3}$) representing the weights of immediate transitions within the GSPN Petri model (Fig. 11), contrary to the expectations.

Eight characteristic operating profiles have been defined on the basis of the *stochastic GSPN Petri model of the operational environment*, including the following ones: OP#1(100%; 0%; 0%; 0%; 0%), OP#5(20%; 20%; 20%; 20%; 20%), whilst the rest six of them can be represented by the vector (80%; *a*%; *b*%; *c*%; *d*%), where *abcd* are combinations of the values 0 and 10, of class 4, given $a + b + c + d = 20$. The underlying idea is to carry out various evaluations for operating profiles in which the percentage of the most desirable class of e-Customers (the class of Passionate e-Customers) is 20% less than in the OP#1, and also to investigate the impact of the equal distribution of the classes within the workload mix.

Based on these assumptions, an evaluation of the *total probability for a successful outcome of sessions* has been performed, by different operating profiles, as a measure of reliability. Again, as in the case of conditional probability, the appliance of the Bowman-Shelton test of normality has shown that the distribution of the total probability follows the Normal distribution. As expected, the OP#1, which is 100% comprised by the class of the Passionate e-Customers, has resulted with the highest total probability ($\bar{P}_{SUCCESS}$ = 98,27%) for a successful outcome of sessions, whilst the OP#5, which defines a mix of uniformly distributed classes of e-Customers, has resulted with the lowest total probability ($\bar{P}_{SUCCESS}$ = 50,48%) for a successful outcome of sessions. Within operating profiles where the participation of the Passionate e-Customers' is 20% less than OP#1, the average value of the total probability for a successful outcome of sessions varies between 84.45% and 91.97%, i.e. $84.45\% \leq \bar{P}_{SUCCESS} \leq 91.97\%$.

A propos the performance measures, an evaluation of the *mean session length* has been carried out, for various operating profiles. Simulations have shown that the mean session length is shortest with operating profiles OP#4 (254.30 [s]) and OP#8 (254.87 [s]), whilst OP#5 exhibits the longest mean session length (324.00 [s]). Further on, an evaluation of the *mean time to timing failure* has been accomplished. It is highest with OP#5 (311.80 [min]), whilst OP#1 (122.07 [min]) and OP#2 (124.55 [min]) exhibit lowest mean time to timing failure. Finally, the *mean number of sessions to timing failure* has been evaluated, too. It is highest with OP#5 (77.92), which is almost as twice as bigger value than with other operating profiles (33.40 - 40.40).

The analysis of performability measures has been done in two specific cases: i) When the e-Commerce system is comprised of a single module (a standard configuration); ii) When, besides the main module, there is an additional, redundant, spare, and non-active module, waiting to be activated in the case of failure of the main module (a cold standby configuration).

The evaluation of performability measures has been carried out taking into account the following parameters: the *mean time to failure* (*MTTF*) and the *mean time to repair* (*MTTR*). In the case of the cold standby configuration, besides the previously mentioned ones, one of the key parameters is also the *mean activation time* (*MAT*) of the spare module. The values of all of these parameters correspond to the specification of a 'well managed system' (Araújo *et al.*, 2011).

The hierarchical composition approach requires the input parameters for the both GSPN Petri models of performability that correspond to the two considered configurations, be the total probability for a successful outcome of sessions, obtained by solving the reliability sub-model, as well as the mean session length, obtained by solving the performance sub-model. The following performability measures of the e-Commerce system have been evaluated for its two configurations, including: i) *mean time to an unsuccessful session*; ii) *mean number of successful sessions to an unsuccessful session*; iii) *availability* of the e-Commerce system's configuration.

Fig. 12 shows that the *mean time to an unsuccessful session* is inversely proportional to e-Customers' arrival rate, for all operating profiles. Its function decreases monotonously from ∞ (for $\lambda = 0$ [e-Customers/s]), and asymptotically approaches a limit value, which is different and characteristic for each operating profile (for $\lambda \to \infty$ [e-Customers/s]). The operating profile OP#1, comprised of 100% Passionate e-Customers, exhibits the smallest, whilst the operating profile OP#5, where all classes of e-Customers are being included equally, exhibits the largest value of the mean time to an unsuccessful session.

In order to detect the existence of a statistically significant correlation among the dependent variable (i.e. the mean time to an unsuccessful session) and the dependent variables (i.e. the total probability for a successful outcome of sessions and the mean session length), a correlation analysis has been performed and the value of the Pearson's correlation coefficient has been evaluated, for each pair of variables. It has been found out that there is a statistically significant correlation only between the mean time to unsuccessful session and the total probability for a successful outcome of sessions (Pearson Correlation = –0,987). The repetition of the same simulations for the cold standby configuration, performed under the same operational conditions as with the standard configuration, has shown that there is no significant change of the mean time to an unsuccessful session.

The functional reliance of the *mean number of successful sessions to an unsuccessful session* on the e-Customers' arrival rate is graphically presented on Fig. 13, for all operating profiles. It can be described by a logarithmic function, for each particular operating profile. For a given arrival rate λ, the operating profile OP#1, including 100% of Passionate e-Customers, demonstrates the biggest value, whilst the operating profile OP#5, where e-Customers' classes have been equally distributed, shows the smallest value of this measure. The simulations have also shown that there is no statistically significant variation of the values of this measure in the case of the cold standby configuration, compared to the standard configuration's one.

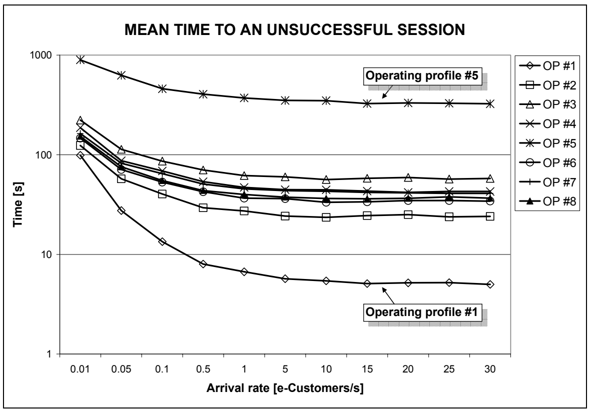


Figure 12: Mean time to an unsuccessful session, for various operating profiles and e-Customers' arrival rates
($0.01 \leq \lambda \leq 30.0$ [s^{-1}])

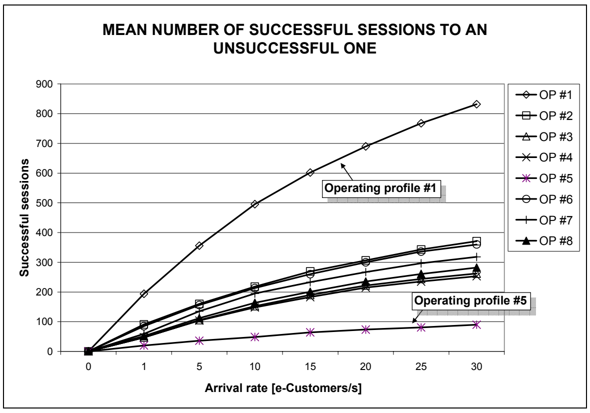


Figure 13: Mean number of successful sessions to an unsuccessful session, for various operating profiles and e-Customers' arrival rates
($0.00 \leq \lambda \leq 30.0$ [s^{-1}])

Table 2 depicts the descriptive statistics of the availability for both configurations being investigated. According to the value of the *average availability*, the cold standby configuration results with about 1% bigger availability compared to the standard configuration's one.

The obtained parameters are based on a series of simulation runs of a 30 days' period of time. If one makes an assumption that these estimated average values of availability are annual, than the absolute increase of 0.010178789% means additional 3.715257985 days, or 89.16619164 hours, or 5,349.9714984 minutes, or 320,998.289904 seconds additional working time of the e-Commerce system, per year.

Now, using this information, it is trivial to estimate the number of additional sessions per annum due to increased availability, at various arrival rates of e-Customers. Knowing the total probability for a successful outcome of sessions, and assuming the percentage of participation of various operating profiles per annum, it is easy to estimate the gain in number of successful sessions for each operating profile, per annum, given a specific arrival rate, λ (Fig. 14).

Table 2: A comparative review of the descriptive statistics underlying the probability distributions of availability of e-Commerce systems (standard vs. cold standby configuration), based on 16,000 simulation runs of 30 days simulated time period (MTTF_main = 360 [h], MTTR_main = 8 [h], MTTF_spare = 140 [h], MTTR_spare = 10 [h], MAT = 0.125 [h])

Parameters of the descriptive statistics	Standard configuration	Cold standby configuration
Number of observations	16,000	16,000
Arithmetic mean	0.959879230	0.970058019
Standard deviation	0.060544984	0.032126560
Minimum	0.016454920	0.181019047
First quartile	0.947964442	0.967546120
Median	0.973953407	0.976388847
Third quartile	0.991752107	0.983050361
Maximum	1.000000000	1.000000000

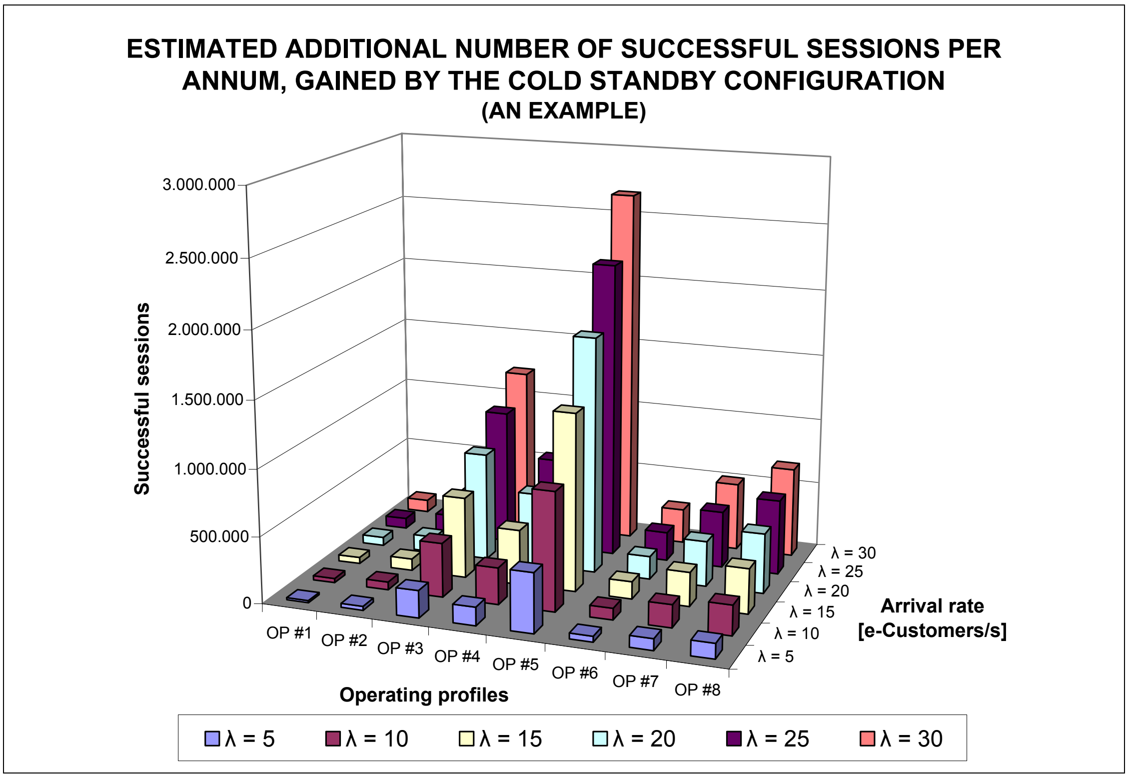


Figure 14: Evaluation of the number of successful sessions when the availability of the e-Commerce system has been increased by 1% (cold standby configuration) (an example)

Finally, if one supposes that each successful session will yield a profit of just 1 €, the total extra profit per year can be easily estimated, at various arrival rates, λ. In that context, the analyses show that if the availability of the system increases by 1% per annum, than the Internet company will make an additional profit of more than 1 million euros per annum, at an arrival rate of just 5 [s^{-1}], under the conditions being previously introduced.

The main contributions of this research can be summarized as follows:

1. Compared to all existing approaches, which treat the problem of performability evaluation of e-Commerce systems in a partial and heterogeneous way, a new, original, holistic, integrated and homogeneous approach has been promoted within this dissertation for the first time, based on building and evaluation of stochastic predictive models, through the usage of corresponding graphical and mathematical formalisms, and their solving by using computer simulations with discrete events. This brand new and unique approach, which is entirely and solely focused on the e-Commerce systems, is robust, unified and general by virtue;

2. The applied concepts and methodologies rely entirely on the dynamic and stochastic behavior of e-Customers during their online shopping sessions, since: i) a stochastic model of e-Customer's online shopping behavior has been used, for the first time; ii) a qualitative and a quantitative classification of e-Customers have been carried out for the first time, taking into account their similar patterns of online shopping behavior; iii) a workload characterization of an arbitrary generic e-Commerce system has been defined for the first time, through the specification of characteristic operating profiles, that define the participation of various classes of e-Customers in the mix, in various proportions;

3. For the first time, the hierarchical composition approach has been promoted in studying the complex concept of performability of e-Commerce systems, for developing stochastic models that implement its particular components, including the performances and dependability (reliability and availability);

4. This research is the first attempt that promotes a hybrid approach to evaluation of performability measures of e-Commerce systems, relying on the usage of the classes of Deterministic and Stochastic Petri Nets (DSPNs) and Generalized Stochastic Petri Nets (GSPNs) for modeling various key aspects of the extremely complex e-Commerce systems, as well as the promotion of the new approach to solving those classes of stochastic Petri nets using a programming language for discrete-event simulation, based on active processes (SimPy/Python);

5. For the first time, a monolithic simulation model of the client/server interaction between e-Customers and e-Commerce system via Internet has been built up, to evaluate numerous performance measures inherent to the e-Commerce paradigm, both on the client- and the server-side. A special attention has been given to derivation and evaluation of business-oriented performance measures.

4 THESIS ORGANIZATION

The doctoral dissertation consists of seven chapters altogether.

In the second chapter, the reader becomes familiar with the basic terminology and the fundamental aspects that the research presented in this dissertation is based upon. In that sense, the problem of capacity planning has been elaborated first, as being a basic cause and a driver, a *spiritus movens*, of the existence of this and similar research works. Its genesis, essence, meaning and gains have been covered in detail. Next, the focus has been put on the analysis of e-Customers' online shopping behavior, and the necessity not only to achieve, but also to retain continuously their satisfaction regarding the delivered Web services has been pointed out, as being a basic premise to successfully running businesses on the Internet. Referring to those findings related to e-Customers' online shopping behavior, the lifecycle of a typical e-Commerce Web application has been described, as well. The logical order of activities involved in the interaction between an typical e-Customer and the e-Commerce system's interface has been presented by a corresponding flowchart diagram. At the end of the chapter, the notion of workload characterization has been both defined and elaborated, since it is a crucial aspect of any e-Commerce system's performability analysis.

The third chapter introduces the existing research endeavors and models. The focus has been put on modeling the e-Customers' online behavior during shopping sessions with virtual stores, since this type of interaction is the core of the e-Commerce paradigm. Besides reviewing many different models that are closely related to the concept of 'e-Customer's behavior', but which have interpreted it in a rather broader manner, several other models, that are predictive by nature, have been observed and described, including the *State-Transition diagram*, the *Customer Behavior Model Graph* (*CBMG*), the *Client-Server Interaction Diagram* (*CSID*), and the *Customer Visit Model* (*CVM*), all being introduced by Menascé & Almeida (2000a; 2002). The *referential model of e-Business* (Menascé & Almeida, 2000a) has been also described, due to its universal meaning and comprehensiveness, and since it is a basis of the general approach in the development of predictive models within this research. At the end, the motives for introducing a brand new approach in treating this complex substance have been identified and elaborated, through a critical review of the advantages and disadvantages of current models.

The fourth chapter is entirely devoted to the stochastic and dynamic behavior of e-Customers during their online shopping sessions, as being a basis for obtaining many performance measures. At the beginning, it is shown, in a formal way, that the e-Customers' online shopping behavior is a stochastic process, or, more precisely, a Markov Regenerative Process (*MRGP*). Next, the focus has been put on modeling e-Customers' online shopping behavior using stochastic Petri nets. The stochastic Petri model, based on the class of Deterministic and Stochastic Petri Nets (*DSPNs*), which has been originally proposed by Mitrevski *et al.* (2002), has been taken as a basis for all other models that have been derived and introduced within the dissertation. This stochastic model, besides inclusion of both timed transitions with exponentially distributed times and immediate transitions that fire instantly, also includes a timeout mechanism, that models the expiration of a deterministic time due to e-Customer's inactivity while invoking a specific e-Commerce function (Search, Checkout …).

Next, specialized software tools for obtaining a numerical solution of DSPN Petri models have been reviewed, including TimeNET and DSPNexpress. In addition, the approach of discrete-event simulation (*DES*) and the SimPy/Python software programming environment, suitable for development and execution of simulation models that correspond to stochastic Petri models, have been introduced, as well. The core of this chapter is, in fact, the DES model that simulates the interaction between e-Customers and an e-Commerce system, for evaluation of numerous performance measures. The model itself encompasses modeling the client-side (i.e. the dynamic and stochastic e-Customers' online shopping behavior), modeling the server-side (i.e. the hardware configuration of e-Commerce Web site on a system level, CSIDs for each particular e-Commerce function), modeling the workload characterization (classes of e-Customers, working scenarios, e-Customers' arrival rates), as well as modeling the propagation time via Internet. Subsequently, the simulation results have been presented, along with the obtained values of numerous performance measures, being evaluated for capacity planning purposes. As an important constitutional part of this simulation series, a methodology for evaluating innovative, business-oriented performance measures has been both proposed and demonstrated on an example, based on particular performance metrics that have been previously obtained by DES.

The fifth chapter is committed to modeling and evaluation of performability measures of e-Commerce systems, through evaluation of specific metrics that are unique and applicable for computer systems of this particular type. During the development of this suite of stochastic models, the hierarchical composition approach has been applied, which results in simplified structure of Petri net based models and DES simulation programming code, as well as in faster prototyping and execution of simulations. First, the stochastic Petri model of a single online buying session has been presented, which is suitable for evaluating *the conditional probability for a successful outcome of a session*. This Petri model can be derived directly from the previously mentioned DSPN model of e-Customers' online shopping behavior, by removing the deterministic transition which models the timeout mechanism. As a result, a Generalized Stochastic Petri Net (*GSPN*), is derived, whose underlying stochastic process is Continuous-Time Markov Chain (*CTMC*). Despite the fact that the stochastic models which were developed afterwards include the usage of this GSPN model, and since the hybrid approach presented throughout the dissertation does not rely on their analytical solution, but rather on their numerical solution by DES simulation, only the *extended reachability graph (ERG)* and the corresponding *reduced reachability graph* (*RRG*) of the GSPN model have been presented, along with its characteristic *infinitesimal generator matrix*, Q (*CTMC generator matrix*). This is a basis for obtaining an analytical solution of the model, i.e. for performing both a steady-state and a transient analysis, which is out of the scope of this work.

Further on, the *operational environment* has been modeled, too. It includes both modeling various *classes of e-Customers* and defining *characteristic operating profiles*, where each class is presented with a rather different probability. Next, the *stochastic Petri model of reliability* has been introduced, which can be used to obtain the *total probability for a successful outcome of online shopping sessions*, for each operating profile. In addition, the *stochastic Petri model of performances* has been introduced next, which, compared to the previous one, includes the timeout mechanism. It can be activated whenever the e-Customer is inactive for a specific period of time while invoking a specific e-Commerce function (Search, Checkout …). This model is suitable for evaluating the *mean session length* for each operating profile, regardless of the shopping result. Besides this, the model can be also used for evaluation of two other performance measures, including the *mean time to a timing 'failure'*, as well as the *mean number of regularly terminated sessions* (without a timing 'failure'). Finally, the *stochastic Petri model of performability* has been built using the hierarchical composition approach. This approach itself is based on information exchange among various sub-models, i.e. the total probability for a successful outcome of a session, obtained from the reliability model, along with the mean session length, obtained from the performance model, constitute an input into the performability model. The evaluation of performability measures has been carried out during concurrent online shopping sessions. Two sub-models of *availability* have been taken into account: i) the case when the e-Commerce system can be either operational or non-operational (a standard configuration with a single module); ii) the case when it becomes a fault-tolerant system, by adding a redundant, spare module in a cold standby. In both cases, the *mean time to an unsuccessful session*, as well as the *mean number of successful sessions to an unsuccessful one*, have been evaluated.

The sixth chapter deals with the analysis of the reliability, performance and performability measures, by presenting the simulation results of the execution of stochastic Petri models, previously described within the fifth chapter.

Within the last chapter, the concluding remarks have been presented regarding the substance in focus, and several main results and conclusions have been outlined, as well. At the very end, the dissertation is concluded with a brief discussion about projected future research.

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