Towards Model Checking Stochastic Aspects of the thinkteam User Interface*

Maurice H. ter Beek, Mieke Massink, and Diego Latella

CNR/ISTI – 'A. Faedo', Via G. Moruzzi 1, 56124 Pisa, Italy
{m.terbeek,m.massink,d.latella}@isti.cnr.it

Abstract. Stochastic model checking is a recent extension of traditional model-checking techniques for the integrated analysis of both qualitative and *quantitative* system properties. In this paper we show how stochastic model checking can be conveniently used to address a number of usability concerns that involve quantitative aspects of a user interface for the industrial groupware system thinkteam. thinkteam is a ready-to-use Product Data Management application developed by think3. It allows enterprises to capture, organise, automate, and share engineering product information and it is an example of an asynchronous and dispersed groupware system. Several aspects of the functional correctness, such as concurrency aspects and awareness aspects, of the groupware protocol underlying thinkteam and of its planned publish/subscribe notification service have been addressed in previous work by means of a traditional model-checking approach. In this paper we investigate the trade-off between two different design options for granting users access to files in the database: a retrial approach and a waiting-list approach and show how stochastic model checking can be used for such analyses.

1 Introduction

Computer Supported Cooperative Work (CSCW) is an interdisciplinary research field that deals with the understanding of how people work together, and the ways in which computer technology can assist. This technology mostly consists of multi-user computer systems called groupware [16]. Groupware is often classified according to the time-space taxonomy Ellis [16], *i.e.*. (1) whether its users work together at the same (synchronous) or at different (asynchronous) times and (2) whether they work together in the same (co-located) or in different (dispersed) places. In this paper we deal with thinkteam, which is an asynchronous and dispersed groupware system, as is email.

Recently there has been an increasing interest in using model checking for formal verification of (properties of) groupware [6, 26, 27]. Some properties of interest are related to important groupware design issues like user awareness and concurrency control. In [7, 8] we have used a traditional model-checking approach, using the model checker SPIN [22], to formalise and verify some properties specifically of interest for the correctness of general groupware protocols, *i.e.* not limited to thinkteam's context.

Many interesting properties of groupware protocols and their interfaces can be analysed *a priori*, *i.e.* before implementation, by means of a model-based approach and

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model-checking techniques. There are, however, usability issues that are influenced by the *performance* of the groupware system rather than by its functional behaviour. One such issue was raised by the analysis of thinkteam with a traditional model-checking approach in [7, 8]. It was shown that the system could exclude a user from obtaining a file simply because other users competing for the same file were more 'lucky' in their attempts to obtain the file. Such behaviour was explained by the fact that users were only provided with a file-access mechanism based on a retrial principle. While analysis with traditional model checking can be used to show that such a problem exists, it cannot be used to quantify the effect that it has on the user. In other words, it cannot be used to find out how often, in the average, a user needs to perform a retry in order to get a single file. Of course, the number of retries a user has to perform before obtaining a file is an important ingredient for measuring the usability of the system.

In this paper we address the retrial problem by means of stochastic model checking. This is a relatively new extension of traditional model checking that allows also for the analysis of *quantitative* properties of systems such as those related to performance and dependability issues [10, 20, 24]. Other work on the use of stochastic modelling for usability analysis has been performed in [11], where it has been shown that Markov models and traditional Markov-chain analysis can be used to obtain measures that give an indication of how hard it is for a user to use certain interactive devices. In [14], stochastic modelling has been used to analyse the finger-tracking interface of a whiteboard with augmented reality. The analysis was based on stochastic process algebra models with general (*i.e.* not necessarily exponential) distributions and discrete event simulation. The main purpose of this paper is to show that stochastic model checking can be a convenient model-based analysis technique to address usability issues that involve quantitative measures. We will explain *how* such analysis can be performed in the context of a simple but relevant industrial case study. In a further study we plan to collect more detailed statistical information on typical use of thinkteam in practice in order to calibrate the models for the analysis of specific situations. The current paper shows the formal specification of users and the system and their interactions, the formalisation of relevant quantitative properties and a number of numerical results.

2 thinkteam

In this section we present a brief overview of thinkteam. For more information we refer the reader to [5, 7, 8] and `http://www.think3.com/products/tt.htm`.

thinkteam is think3's Product Data Management (PDM) application catering the document management needs of design processes in the manufacturing industry. Controlled storage and retrieval of documents in PDM applications is called vaulting, the vault being a file-system-like repository. Next to providing a secure and controlled storage environment, vaulting must prevent inconsistent changes to the document base while still allowing maximal access compatible with the business rules. This is implemented in thinkteam's underlying groupware protocol by a standard set of operations:

get – extract a read-only copy of a document from the vault,
import – insert an external document into the vault,
checkOut – extract a copy of a document from the vault with the intent to modify it,

unCheckOut – cancel the effects of a previous checkout,
checkIn – replace an edited document in the vault, and
checkInOut – replace an edited document in the vault, but retaining it checked out.

It is important to note that access to documents (via a *checkOut*) is based on the 'retrial' principle: currently there is no queue or reservation system handling the requests for editing rights on a document. thinkteam typically handles some $100,000$ documents for 20-100 users. A user rarely checks out more than 10 documents a day, but she can keep a document checked out from anywhere between 5 minutes and a few days.

To maximize concurrency, a *checkOut* in thinkteam creates an exclusive lock for write access. An automatic solution of the write access conflict is not easy, as it is critically related to the type, nature, and scope of the changes performed on the document. Moreover, standard but harsh solutions—like maintaining a dependency relation between documents and use it to simply lock all documents depending on the document being checked out—are out of the question for think3, as they would cause these documents to be unavailable for too long periods of time. For thinkteam, the preferred solution is thus to leave it to the users to resolve such conflicts. However, a publish/subscribe notification service would provide the means to supply the clients with adequate information by (1) informing clients checking out a document of existing outstanding copies and (2) notifying the copy holders upon *checkOut* and *checkIn* of the document.

In [7, 8] we studied the addition of a lightweight and easy-to-use publish/subscribe notification service to thinkteam and we verified several correctness properties. These properties addressed issues like concurrency control, awareness, and denial of service. Most properties were found to hold, with the exception of one concurrency-control and a denial-of-service property. The problem with the concurrency-control property arises when a user simply 'forever' forgets to *checkIn* the file it has checked out, which means that the lock on this file is never released. In thinkteam, such a situation is resolved by the intervention of a system administrator.

The problem with the denial-of-service property is that it may be the case that one of the users can never get its turn to, *e.g.*, perform a *checkOut*, because the system is continuously kept busy by the other users, while this user did express its desire to perform a *checkOut*. Such behaviour forms an integral part of the thinkteam protocol. This is because access to documents is based on the 'retrial' principle: thinkteam currently has no queue or reservation system handling simultaneous requests for a document. Before simply extending thinkteam with a reservation system, it would be useful to know (1) how often, in the average, users have to express their requests before they are satisfied and (2) under which system conditions (number of users, file processing time, *etc.*) such a reservation system would really improve usability. We come back to this.

3 Stochastic Analysis

Traditionally, functional analysis of systems (*i.e.* analysis concerning their functional correctness) and performance analysis have been two distinct and separate areas of research and practice. Recent developments in model checking, in particular its extension to address also performance and dependability aspects of systems, have given rise to a renewed interest in the integration of functional and quantitative analysis techniques.

A widely used model-based technique for performance analysis is based on Continuous Time Markov Chains (CTMCs). CTMCs provide a modelling framework, proved to be extremely useful for practical analysis of quantitative aspects of system behaviour. Moreover, in recent years proper stochastic extensions of temporal logics have been proposed and efficient algorithms for checking the satisfiability of formulae of such logics on CTMCs (*i.e.* stochastic model checkers) have been implemented [10, 20, 24].

The basis for the definition of CTMCs are exponential distributions of random variables. The parameter which completely characterises an exponentially distributed random variable is its *rate* λ, which is a positive real number. A real-valued random variable X is exponentially distributed with rate λ—written $EXP(\lambda)$—if the probability of X being at most t, *i.e.* Prob$(X \leq t)$, is $1 - e^{-\lambda t}$ if $t \geq 0$ and is 0 otherwise, where t is a real number. The expected value of X is λ^{-1}. Exponentially distributed random variables enjoy the so called *memoryless property*, *i.e.* Prob$(X > t + t' \mid X > t) =$ Prob$(X > t')$, for $t, t' \geq 0$.

CTMCs have been extensively studied in the literature (a comprehensive treatment can be found in [23]; we suggest [19] for a gentle introduction). For the purposes of the present paper it suffices to recall that a CTMC $\mathcal{M}$ is a pair $(\mathcal{S}, \mathbf{R})$ where $\mathcal{S}$ is a finite set of *states* and $\mathbf{R} : \mathcal{S} \times \mathcal{S} \to \mathbb{R}_{\geq 0}$ is the *rate matrix*. The rate matrix characterises the transitions between the states of $\mathcal{M}$. If $\mathbf{R}(s, s') \neq 0$, then it is possible that a transition from state s to state s' takes place, and the probability of such a transition to take place within time t, is $1 - e^{-\mathbf{R}(s,s') \cdot t}$. If $\mathbf{R}(s, s') = 0$, then no such a transition can take place.[1] We would like to point out that the traditional definition of CTMCs does not include self-loops, *i.e.* transitions from a state to itself. On the other hand, the presence of such self-loops does not alter standard analysis techniques (*e.g.* transient and steady-state analyses) and self-loops moreover turn out to be useful when model checking CTMCs [4]. Therefore we will allow them in this paper.

Usually CTMCs are not obtained in a direct way, due to the increasing complexity of the analysed systems, but instead generated automatically from higher-level specifications given in languages such as *e.g.* stochastic Petri nets, stochastic process algebras or stochastic activity nets [9, 25]. Our approach is no different. We specify our model of thinkteam's underlying groupware protocol in the stochastic process algebra PEPA (Performance Evaluation Process Algebra) [21]. This specification is consequently read into a stochastic model checker, which then automatically builds a CTMC from it.

4 Stochastic Model Checking

In the model-checking approach to performance and dependability analysis a *model* of the system under consideration is required together with a desired *property* or *performance/dependability measure*. In case of stochastic modelling, such models are typically CTMCs or high-level specification languages to generate them, while properties are usually expressed in some form of extended temporal logic. Here we use Continuous Stochastic Logic (CSL) [2, 3], a stochastic variant of the well-known Computational Tree Logic (CTL) [12]. CTL allows to state properties over *states* as well as over *paths*.

[1] This intuitive interpretation is correct only if there is only one transition originating from s. If this is not the case, then a *race condition* arises among all transitions originating from s.

CSL extends CTL by two probabilistic operators that refer to the steady-state and transient behaviour of the system under study. The steady-state operator refers to the probability of residing in a particular state or set of *states* (specified by a state formula) in the long run. The transient operator allows us to refer to the probability mass of the set of *paths* in the CTMC that satisfy a given (path) property. To express the time span of a certain path, the path operators until ($\mathcal{U}$) and next (X) are extended with a parameter that specifies a time interval. Let I be an interval on the real line, p a probability value and $\bowtie$ a comparison operator, *i.e.* $\bowtie \in \{ <, \leq, \geq, > \}$. The syntax of CSL is:

State formulae: $\Phi ::= a \mid \neg \Phi \mid \Phi \vee \Phi \mid \mathcal{S}_{\bowtie p}(\Phi) \mid \mathcal{P}_{\bowtie p}(\varphi)$

$\mathcal{S}_{\bowtie p}(\Phi)$: probability that Φ holds in steady state $\bowtie p$

$\mathcal{P}_{\bowtie p}(\varphi)$: probability that a path fulfills $\varphi \bowtie p$

Path formulae: $\varphi ::= X^I \Phi \mid \Phi \mathcal{U}^I \Phi$

$X^I \Phi$: next state is reached at time $t \in I$ and fulfills Φ

$\Phi \mathcal{U}^I \Psi$: Φ holds along path until Ψ holds at $t \in I$

The meaning of atomic propositions (a), negation ($\neg$) and disjunction ($\vee$) is standard. Using these operators, other boolean operators like conjunction ($\wedge$), implication ($\Rightarrow$), true (TRUE) and false (FALSE), and so forth, can be defined in the usual way. The state formula $\mathcal{S}_{\bowtie p}(\Phi)$ asserts that the steady-state probability for the set of states satisfying Φ, the Φ-states, meets the bound $\bowtie p$. $\mathcal{P}_{\bowtie p}(\varphi)$ asserts that the probability measure of the set of paths satisfying φ meets the bound $\bowtie p$. The operator $\mathcal{P}_{\bowtie p}(.)$ replaces the usual CTL path quantifiers $\exists$ and $\forall$. In CSL, the formula $\mathcal{P}_{\geq 1}(\varphi)$ holds if *almost all* paths satisfy φ. Moreover, clearly $\exists \varphi$ holds whenever $\mathcal{P}_{>0}(\varphi)$ holds.

The formula $\Phi \mathcal{U}^I \Psi$ is satisfied by a path if Ψ holds at time $t \in I$ and at every preceding state on the path, if any, Φ holds. In CSL, temporal operators like $\Diamond$, $\Box$ and their real-time variants $\Diamond^I$ or $\Box^I$ can be derived, *e.g.*, $\mathcal{P}_{\bowtie p}(\Diamond^I \Phi) = \mathcal{P}_{\bowtie p}(\text{TRUE } \mathcal{U}^I \Phi)$ and $\mathcal{P}_{\geq p}(\Box^I \Phi) = \mathcal{P}_{<1-p}(\Diamond^I \neg\Phi)$. The untimed next and until operators are obtained by $X \Phi = X^I \Phi$ and $\Phi_1 \mathcal{U} \Phi_2 = \Phi_1 \mathcal{U}^I \Phi_2$ for $I = [0, \infty)$. In a variant of CSL the probability p can be replaced by '?', denoting that one is looking for the value of the probability rather than verifying whether the obtained probability respects certain bounds.

The model checker PRISM [24] is a prototype tool that supports, among others, the verification of CSL properties over CTMCs. It checks the validity of CSL properties for given states in the model and provides feedback on the calculated probabilities of such states where appropriate. It uses symbolic data structures (*i.e.* variants of Binary Decision Diagrams). PRISM accepts system descriptions in different specification languages, among which the process algebra PEPA and the PRISM language—a simple state-based language based on the Reactive Modules formalism of Alur and Henzinger [1]. An example of an alternative model checker for CSL is ETMCC [20].

5 Stochastic Model of thinkteam—The Retrial Approach

In this section we describe the stochastic model of thinkteam for the retrial approach, after which we perform several analyses on this model. We use the stochastic process

algebra PEPA to specify our model. In PEPA, systems can be described as interactions of *components* that may engage in *activities* in much the same way as in other process algebras. Components reflect the behaviour of relevant parts of the system, while activities capture the actions that the components perform. A component may itself be composed of components. The specification of a PEPA activity consists of a pair *(action type, rate)* in which *action type* symbolically denotes the type of the action, while *rate* characterises the *exponential* distribution of the activity duration. Before explaining our model, we briefly describe the PEPA language constructs that we will use. For a more detailed description of these constructs we refer the reader to [21].

The basic mechanism for constructing behaviour expressions is by means of prefixing. The component $(\alpha, r).P$ carries out activity (α, r), with action type α and duration Δt determined by rate r. The component subsequently behaves as component P.

The component $P + Q$ represents a system which may behave either as component P or as component Q. The continuous nature of the probability distributions ensures that the probability of P and Q both completing an activity at the same time is zero. The choice operator represents a competition (the race condition) between components.

The cooperation operator $P \bowtie_L Q$ defines the set of action types L on which components P and Q must synchronise or *cooperate*. Both components proceed independently with any activities that do not occur in L. In particular, when $L = \varnothing$ then $P \bowtie_L Q$ thus denotes *parallel composition* and the shorthand notation $P \parallel Q$ is used. The expected duration of a cooperation where activities are shared (*i.e.* $L \neq \varnothing$) will be greater than or equal to the expected durations of the corresponding activities in the cooperating components. A special case is the situation in which one component is *passive* (*i.e.* has the special rate $-$) w.r.t the other component. In this case the total rate is determined by that of the *active* component only.

We are now ready to explain our model in detail. In Fig. 1 the models of the User and CheckOut components are drawn as automata for reasons of readability.

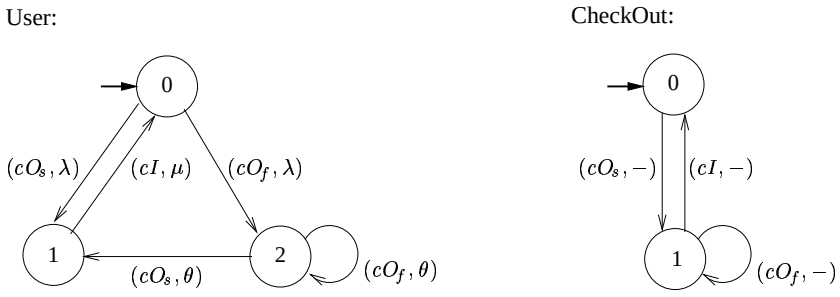


Fig. 1. The retrial approach: automata of the User and the CheckOut components.

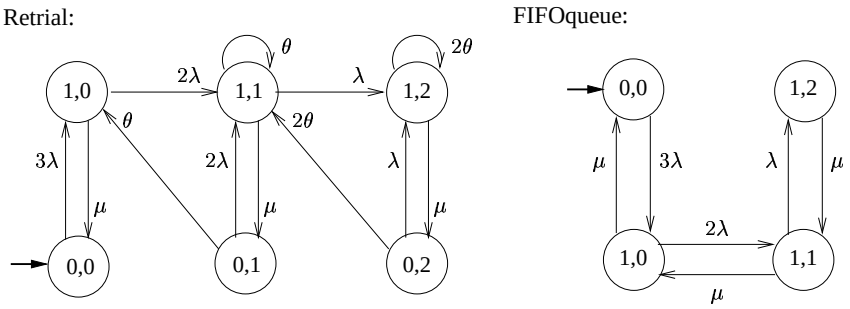
We consider the case that there is only one file, the (exclusive) access to which is handled by the CheckOut component. A user can express interest in checking out the file by performing a *checkOut*. This operation can either result in the user being granted access to the file or in the user being denied access because the file is currently already checked out by another user. In Fig. 1, the *s*uccessful execution of a *checkOut* is modelled by activity (cO_s, λ), while a *f*ailed *checkOut* is modelled by (cO_f, λ). The

exponential rate λ is also called the *request* rate. If the user does not obtain the file, then she may retry to check out the file, modelled by activity (cO_s, θ) in case of a successful retry and by (cO_f, θ) in case the *checkOut failed*. The exponential rate θ is also called the *retrial* rate. The *checkIn* operation, finally, is modelled by activity (cI, μ) and the exponential rate μ is also called the *file processing* rate. The CheckOut component takes care that only one user at a time can have the file in her possession. To this aim, it simply keeps track of whether the file is checked out (state $\langle 1 \rangle$) or not (state $\langle 0 \rangle$). When a User tries to obtain the file via the *checkOut* activity, then she is denied the file if it is currently checked out by another user while she might obtain the file if it is available.

The formal PEPA specifications of the User and the CheckOut component, and the composed model for three User components and the CheckOut component

$$(\text{User} \parallel \text{User} \parallel \text{User}) \bowtie_{\{cO_s, cO_f, cI\}} \text{CheckOut}$$

is given in [5]. These specifications are accepted as input by PRISM and then translated into the PRISM language. The resulting specification is given in [5]. From such a specification PRISM automatically generates a CTMC with 19 states and 54 transitions that can be shown behaviourally equivalent for the purpose of transient and steady-state analysis (strongly equivalent in [21]) to the much simpler CTMC given in Fig. 2(a).[2]



(a) The retrial approach. (b) The waiting-list approach.

Fig. 2. (a)-(b) The CTMCs in case of 3 users for the two approaches of this paper.

The states of this CTMC are tuples $\langle x, y \rangle$ with x denoting whether the file is checked out ($x = 1$) or not ($x = 0$) and $y \in \{0, 1, 2\}$ denoting the number of users currently retrying to perform a *checkOut*. Note, however, that when a user inserts the file she has checked out back into the Vault via a *checkIn* activity, the CheckOut component does allow another user to *checkOut* the file but this need not be a user that has tried before to obtain the file. In fact, a race condition occurs between the request and retrial rates associated to the *checkOut* activity (*cf.* states $\langle 0, 1 \rangle$ and $\langle 0, 2 \rangle$). Note also that once the file is checked in, it is *not* immediately granted to another user, even if there are users that have expressed their interest in obtaining the file. In such a situation, the file will remain unused for a period of time which is exponentially distributed with rate $\theta + \lambda$.

[2] Moreover, the CTMC obtained by removing the self-loops from that of Fig. 2(a) is frequently used in the theory of *retrial queues* [17, 18, 23].

We use the stochastic model and the stochastic logic to formalise and analyse various usability issues concerning the retrial approach used in thinkteam. In this context it is important to fix the time units one considers. We choose hours as our time unit. For instance, if $\mu = 5$ this means that a typical user keeps the file in its possession for $60/5 = 12$ minutes on the average.

5.1 Analyses of Performance Properties

We first analyse the probability that a user that has requested the file and is now in 'retry mode' (state $\langle 2 \rangle$ of the User component), obtains the requested file within the next five hours. This measure can be formalised in CSL as (in a pseudo PRISM notation):[3]

$$\mathcal{P}_{=?}([\ \text{TRUE}\ \mathcal{U}^{\leq 5}\ (\text{User\_STATE} = 1)\ \{\text{User\_STATE} = 2\}\ ]),$$

which must be read as follows: "what is the probability that path formula TRUE $\mathcal{U}^{\leq 5}$ (User_STATE $= 1$) is satisfied for state User_STATE $= 2$?".

The results for this measure are presented in Fig. 3(a) for request rate $\lambda = 1$ (*i.e.* a user requests the file once an hour on average), retrial rate θ taking values 1, 5 and 10 (*i.e.* in one hour a user averagely retries one, five or ten times to obtain the file), file processing rate $\mu = 1$ (*i.e.* a user in the average keeps the file checked out for one hour) and for different numbers of users ranging from 1 to 10.

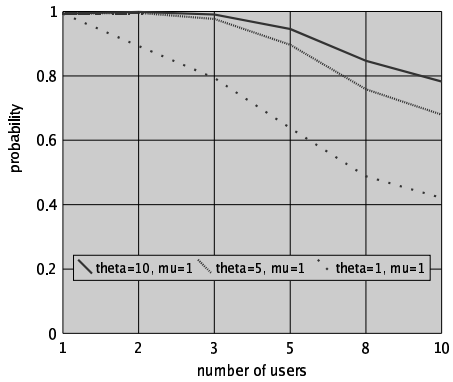
Clearly, with an increasing number of users the probability that a user gets her file within the time interval is decreasing. On the other hand, with an increasing retrial rate and an invaried file processing rate the probability for a user to obtain the requested file within the time interval is increasing. Further results could easily be obtained by model checking for different rate parameters that may characterise different profiles of use of the same system. In particular, this measure could be used to evaluate under which circumstances (*e.g.* when it is known that only a few users will compete for the same file) a retrial approach would give satisfactory results from a usability point of view.

A bit more complicated measure can be obtained with some additional calculations involving steady-state analysis (by means of model checking). Fig. 3(c) shows the average number of retrials per file request for request rate $\lambda = 1$, retrial rate θ taking values 5 and 10, file processing rate μ ranging from 1 to 10 and for 10 users. The measure has been computed as the average number of retries that take place over a certain system observation period of time T divided by the average number of requests during T. To compute the average number of retries (requests, resp.) we proceeded as follows. We first computed the steady-state probability p (q, resp.) of the user being in 'retry mode' ('request mode', resp.), *i.e.* $p \stackrel{\text{def}}{=} \mathcal{S}_{=?}(\text{User\_STATE} = 2)$ ($q \stackrel{\text{def}}{=} \mathcal{S}_{=?}(\text{User\_STATE} = 0)$, resp.). The fraction of time the user is in 'retry mode' ('request mode', resp.) is then given by $T \times p$ ($T \times q$, resp.). The average number of retries (requests, resp.) is then $\theta \times T \times p$ ($\lambda \times T \times q$, resp.). Hence the measure of interest is $(\theta \times p)/(\lambda \times q)$.

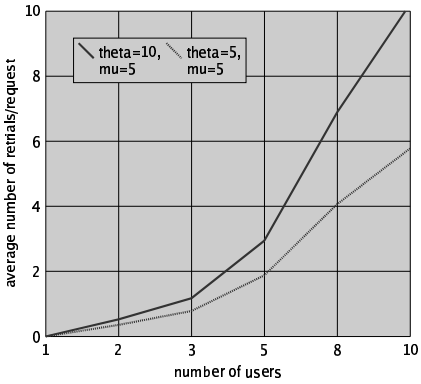
It is easy to observe in Fig. 3(c) that the number of retrials decreases considerably when the file processing rate is increased (*i.e.* when the users restitute, by means of a *checkIn*, the file they had checked out after a shorter time). We also note that a relatively

[3] Here and in the sequel, User_STATE always refers to one specific user.

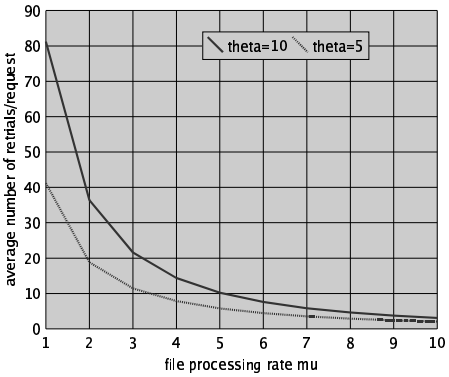
high file processing rate is needed for obtaining an acceptably low number of retrials in the case of 10 users that regularly compete for the same file.



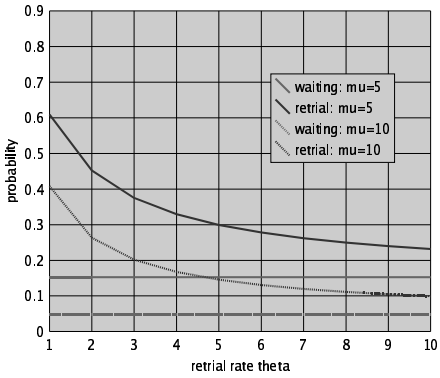
(a) Probability for users in 'retry mode' to *checkOut* requested file within next 5 hrs.



(b) Average number of retrials per file request for a varying number of users.



(c) Average number of retrials per file request in case of 10 users.



(d) The retrial approach *vs.* the waiting-list approach.

Fig. 3. (a)-(d) Results of the analyses performed for this paper.

The effect on the average number of retries is even better illustrated in Fig. 3(b), where with a similar approach as outlined above the average number of retrials per file request is presented for request rate $\lambda = 1$, retrial rate θ taking values 5 and 10, fixed file processing rate $\mu = 5$ and various numbers of users. Clearly, the average number of retrials per file request increases sharply when the number of users increases.

6 Stochastic Model of thinkteam—The Waiting-List Approach

In this section we compare the stochastic model of the previous section to a stochastic model for a waiting-list approach, which we describe next.

In contrast with our model for the retrial approach of Section 5, we now assume that a user's request to *checkOut* the file when it has already been checked out by another user is put in a FIFO queue. The moment in which the file then becomes available, the first user in this FIFO queue obtains the file. This implies the following changes w.r.t. the model of Section 5. Since a user no longer retries to obtain the file after her initial unsuccessful attempt to *checkOut* the file, the new User component has two states only, *viz.* state $\langle 2 \rangle$ is removed from the User component as given in Fig. 1. Moreover, since the CheckOut component now implements a FIFO policy, the new CheckOut component must keep track of the number of users in the FIFO queue. The full specifications of the new User and CheckOut components can be found in [5]. Here we directly use the strongly-equivalent CTMC for three users given in Fig. 2(b).

The state tuples of this CTMC have the same meaning as before, but states $\langle 0, 1 \rangle$ and $\langle 0, 2 \rangle$ no longer occur. This is due to the fact that, once the file is checked in, it is immediately granted to another user, *viz.* the first in the FIFO queue.

The fact that we consider an exponential request rate λ, an exponential file processing rate μ, one file, and three users means that we are dealing with a $\mathrm{M}|\mathrm{M}|1|3$ *queueing system* [19, 23]. The CTMC of Fig. 2(b) is then its underlying CTMC and this type of CTMC is also called a *birth-death process* [19, 23].

We now compare the two models w.r.t. the probability that there are users waiting to obtain the file after a *checkOut* request. To measure this, we compute the probabilities for at least one user not being granted the file after asking for it, *i.e.* the steady-state probability p to be in a state in which at least one user has performed a *checkOut* but did not obtain the file yet. In the retrial approach this concerns states $\langle 0, 1 \rangle$, $\langle 0, 2 \rangle$, $\langle 1, 1 \rangle$ and $\langle 1, 2 \rangle$ of the CTMC Retrial in Fig. 2(a), whereas in the waiting-list approach this concerns states $\langle 1, 1 \rangle$ and $\langle 1, 2 \rangle$ of the CTMC FIFOqueue in Fig. 2(b). Hence this can be expressed (again in a pseudo PRISM notation) as the CSL steady-state formula

$$p \stackrel{\text{def}}{=} \mathcal{S}_{=?}([\ (\text{Retrial\_STATE} = \langle 0,1 \rangle) \mid (\text{Retrial\_STATE} = \langle 0,2 \rangle) \mid (\text{Retrial\_STATE} = \langle 1,1 \rangle) \mid (\text{Retrial\_STATE} = \langle 1,2 \rangle)\ ])$$

in the retrial approach, while in the waiting-list approach the formula is

$$p \stackrel{\text{def}}{=} \mathcal{S}_{=?}([\ (\text{FIFOqueue\_STATE} = \langle 1,1 \rangle) \mid (\text{FIFOqueue\_STATE} = \langle 1,2 \rangle)\ ])$$

The results of our comparison are presented in Fig. 3(d) for request rate $\lambda = 1$, retrial rate θ (only in the retrial approach of course) ranging from 1 to 10, file processing rate μ taking values 5 and 10 and, as said before, 3 users.

It is easy to see that, as expected, the waiting-list approach outperforms the retrial approach in all the cases we considered: The probability to be in one of the states $\langle 1, 1 \rangle$ or $\langle 1, 2 \rangle$ of the CTMC FIFOqueue of the waiting-list approach is always lower than the probability of the CTMC Retrial of the retrial approach to be in one of the states $\langle 0, 1 \rangle$, $\langle 0, 2 \rangle$, $\langle 1, 1 \rangle$ or $\langle 1, 2 \rangle$. Note that for large θ the probability in case of

the retrial approach is asymptotically approaching that of the waiting-list approach, of course given the same values for λ and μ. While we did verify this for values of θ upto 10^9, it is of course extremely unrealistic to assume that a user performs 10^9 retries per hour. We thus conclude that the time that a user has to wait 'in the long run' for the file after it has performed a *checkOut* is always less in the waiting-list approach than in the retrial approach. Furthermore, while increasing the retrial rate (*i.e.* reducing the time inbetween retries) does bring the results for the retrial approach close to those for the waiting-list approach, it takes highly unrealistic retrial rates to reach a difference between the two approaches that is insignificantly small.

7 Conclusions and Further Work

In this paper we have addressed the formal analysis of a number of quantitative usability measures of a small, but relevant industrial case study concerning an existing groupware system for PDM, thinkteam. We have shown how the quantitative aspects of the interaction between users and the system can be modelled in a process-algebraic way by means of the stochastic process algebra PEPA. The model has been used to obtain quantitative information on two different approaches for users to obtain files from a central database; one based on retrial and one based on a reservation system implemented via a FIFO waiting list. The quantitative measures addressed the expected time that users are required to wait before they obtain a requested file and the average number of retries per file, for various assumptions on the parameters of the model. These measures have been formalised as formulae of the stochastic temporal logic CSL and analysed by means of the stochastic model checker PRISM.

The results show that, from a user perspective, the retrial approach is less convenient than the waiting-list approach. Moreover, it can be shown that the situation for the retrial approach rapidly deteriorates with an increasing number of users that compete for the same file. The use of stochastic model checking allowed for a convenient modular and compositional specification of the system and the automatic generation of the underlying CTMCs on which performance analysis is based. Furthermore, the combination of compositional specification of models and logic characterisation of measures of interest provides a promising technique for *a priori formal* model-based usability analysis where quantitative aspects as well as qualitative ones are involved.

We plan to apply the developed models and measures for the analysis of different user profiles of the actual thinkteam system in collaboration with think3. Such *a priori* performance evaluation is addressed also in [25], where stochastic Petri nets are the model that is used to discuss usability aspects of users interacting with a non-groupware system. In a further extension we also plan to deal with the quantitative effects of the addition of a publish/subscribe notification service to thinkteam.

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References

1. R. Alur & T. Henzinger, Reactive modules. *Formal Methods in System Design* 15 (1999), 7-48.
2. A. Aziz, K. Sanwal, V. Singhal & R. Brayton, Model checking continuous time Markov chains. *ACM Transactions on Computational Logic* 1, 1 (2000), 162-170.
3. C. Baier, J.-P. Katoen & H. Hermanns, Approximate symbolic model checking of continuous-time Markov chains. In *Concurrency Theory, LNCS* 1664, 1999, 146-162.
4. C. Baier, B. Haverkort, H. Hermanns & J.-P. Katoen, Automated performance and dependability evaluation using model checking. In *Performance'02, LNCS* 2459, 2002, 261-289.
5. M.H. ter Beek, M. Massink & D. Latella, Towards Model Checking Stochastic Aspects of the thinkteam User Interface—FULL VERSION. Technical Report 2005-TR-18, CNR/ISTI, 2005. URL: `http://fmt.isti.cnr.it/WEBPAPER/TRdsvis.pdf`.
6. M.H. ter Beek, M. Massink, D. Latella & S. Gnesi, Model checking groupware protocols. In *Cooperative Systems Design*, IOS Press, 2004, 179-194.
7. M.H. ter Beek, M. Massink, D. Latella, S. Gnesi, A. Forghieri & M. Sebastianis, Model checking publish/subscribe notification for thinkteam, Technical Report 2004-TR-20, CNR/ISTI, 2004. URL: `http://fmt.isti.cnr.it/WEBPAPER/TRTT.ps`.
8. M.H. ter Beek, M. Massink, D. Latella, S. Gnesi, A. Forghieri & M. Sebastianis, Model checking publish/subscribe notification for thinkteam. In *Proc. FMICS'04*. *ENTCS* 133, 2005, 275-294.
9. E. Brinksma, H. Hermanns & J.-P. Katoen (Eds.), *Lectures on Formal Methods and Performance Analysis, LNCS* 2090, 2001.
10. P. Buchholz, J.-P. Katoen, P. Kemper & C. Tepper, Model-checking large structured Markov chains. *Journal of Logic and Algebraic Programming* 56 (2003), 69-96.
11. P. Cairns, M. Jones & H. Thimbleby, Reusable usability analysis with Markov models. *ACM Transactions on Computer Human Interaction* 8, 2 (2001), 99-132.
12. E. Clarke, E. Emerson & A. Sistla, Automatic verification of finite-state concurrent systems using temporal logic specifications. *ACM Transactions on Programming Languages and Systems* 8 (1986), 244-263.
13. E.M. Clarke Jr., O. Grumberg & D.A. Peled, *Model Checking*. MIT Press, 1999.
14. G. Doherty, M. Massink & G.P. Faconti, Reasoning about interactive systems with stochastic models. In *Revised Papers of DSV-IS'01, LNCS* 2220, 2001, 144-163.
15. P. Dourish & V. Bellotti, Awareness and coordination in shared workspaces. In *Proc. CSCW'92*, ACM Press, 1992, 107-114.
16. C.A. Ellis, S.J. Gibbs & G.L. Rein, Groupware—Some issues and experiences. *Communications of the ACM* 34, 1 (1991), 38-58.
17. G.I. Falin, A survey of retrial queues. *Queueing Systems* 7 (1990), 127-168.
18. G.I. Falin & J.G.C. Templeton, *Retrial Queues*. Chapman & Hall, 1997.
19. B. Haverkort, Markovian models for performance and dependability evaluation. In [9], 38-83.
20. H. Hermanns, J-P. Katoen, J. Meyer-Kayser & M. Siegle, A tool for model-checking Markov chains. *Int. Journal on Software Tools for Technology Transfer* 4 (2003), 153-172.
21. J. Hillston, *A Compositional Approach to Performance Modelling*. CU Press, 1996.
22. G.J. Holzmann, *The SPIN Model Checker*. Addison Wesley, 2003.
23. V. Kulkarni. *Modeling and Analysis of Stochastic Systems*. Chapman & Hall, 1995.
24. M. Kwiatkowska, G. Norman & D. Parker, Probabilistic symbolic model checking with PRISM: A hybrid approach. In *Proc. TACAS'02, LNCS* 2280, 2002, 52-66.
25. X. Lacaze, Ph. Palanque, D. Navarre & R. Bastide, Performance Evaluation as a Tool for Quantitative Assessment of Complexity of Interactive Systems. In *Revised Papers of DSV-IS'02, LNCS* 2545, 2002, 208-222.
26. C. Papadopoulos, An extended temporal logic for CSCW. *Comp. Journal* 45 (2002), 453-472.
27. T. Urnes, *Efficiently Implementing Synchronous Groupware*. Ph.D. thesis, Department of Computer Science, York University, Toronto, 1998.