Report of Dr. Igor V. Tarasyuk on the Russian-German research project "Formal Methods in Design and Analysis of Distributed and Real Time Systems (DARTS)", supported by RFBR (09-01-91334) and DFG (436 RUS 113/1002/01)

1.6. List of the most important publications resulting from this project.

(a) Articles which at the time of proposal submission have been published or officially accepted by publication (two main publications per each year are marked by the symbol '').*

*[Tar09a] Tarasyuk I.V. Performance evaluation in dtsPBC. Proceedings of 18th Workshop on Concurrency, Specification and Programming - 09 (CS& P'09), Krakow-Przegorzaly, Poland, September 28-30, 2009, L. Czaja, M. Szczuka, editors, p. 602-615, Warsaw University, 2009, http://itar.iis.nsk.su/files/itar/pages/dtsshmcsp.pdf.

*[Tar09b] Tarasyuk I.V. Modeling and performance analysis of concurrent processes in the algebra dtsPBC. Vestnik, Quartal Journal of Novosibirsk State University, Series: Mathematics, Mechanics, Informatics 9(4), p. 90-117, Novosibirsk State University, Novosibirsk, 2009 (ISSN 1818-7897, in Russian), http://itar.iis.nsk.su/files/itar/pages/vestnik09.pdf.

*[Tar10a] Tarasyuk I.V. Equivalence relations for behaviour-preserving reduction and modular performance evaluation in dtsPBC. Berichte aus dem Department fuer Informatik 01/10, 75 p., Carl von Ossietzky Universitaet Oldenburg, Germany, April 2010 (ISSN 1867-9218), http://itar.iis.nsk.su/files/itar/pages/dtspbcpeib_cov.pdf.

[TMV10] Tarasyuk I.V., Macia H.S., Valero V.R. Discrete time stochastic Petri box calculus with immediate multiactions. Technical Report DIAB-10-03-1, 25 p., Department of Computer Systems, High School of Computer Science Engineering, University of Castilla-La Mancha, Albacete, Spain, March 2010, http://itar.iis.nsk.su/files/itar/pages/dtsipbc.pdf, http://www.dsi.uclm.es/descargas/thecnicalreports/DIAB-10-03-1/dtsipbc.pdf.

*[Tar10b] Tarasyuk I.V. Performance preserving equivalences for dtsPBC. Bulletin of the Novosibirsk Computing Center, Series Computer Science, IIS Special Issue 31, p. 155-178, NCC Publisher, Novosibirsk, 2010 (ISSN 1680-6972), http://itar.iis.nsk.su/files/itar/pages/dtspencc.pdf.

[Tar11a] Tarasyuk I.V. Performance analysis of the dining philosophers system in dtsPBC. Pre-proceedings of 8th Ershov Informatics Conference - 11 (PSI'11), p. 309-321, Novosibirsk, 2011 (UDK 519.6), http://itar.iis.nsk.su/files/itar/pages/dtsdphpsi.pdf.

*[TMV11] Tarasyuk I.V., Macia H., Valero V. Stochastic equivalence for modular performance evaluation in dtsiPBC. Technical Report DIAB-11-06-2, 50 p., Department of Computer Systems, High School of Computer Science Engineering, University of Castilla-La Mancha, Albacete, Spain, June 2011, http://itar.iis.nsk.su/files/itar/pages/dtsipbceq.pdf, http://www.dsi.uclm.es/descargas/thecnicalreports/DIAB-11-06-2/report_dtsipbdeq.pdf.

[Tar11b] Tarasyuk I.V. Equivalences for modular performance analysis in dtsPBC. Berichte aus dem Department fuer Informatik 04/11, 41 p., Carl von Ossietzky Universitaet Oldenburg, Germany, October 2011 (ISSN 1867-9218), http://itar.iis.nsk.su/files/itar/pages/dtsdphib_cov.pdf.

*[Tar11c] Tarasyuk I.V. Performance evaluation of the generalized shared memory system in dtsPBC. Bulletin of the Novosibirsk Computing Center, Series Computer Science, IIS Special Issue 32, p. 127-155, NCC Publisher, Novosibirsk, 2011 (ISSN 1680-6972), http://itar.iis.nsk.su/files/itar/pages/dtsgsmncc.pdf.

[Tar11d] Tarasyuk I.V. Equivalences of Petri nets with invisible transitions. Proceedings of Russian Conference on Modeling of Informatics Systems - 11 (MSI'11), 18 p., Novosibirsk, 2011 (in Russian), http://itar.iis.nsk.su/files/itar/pages/eqtaumsi.pdf.

*[Tar12] Tarasyuk I.V. Behavioural equivalences of Petri nets with invisible transitions. Vestnik SibSUTI, 25 p., Siberian State University of Telecommunications and Information Sciences, Novosibirsk, 2012 (to be published, in Russian).

2.1. Project's initial questions and objectives.

*** Stochastic Models.**

Defining and investigating stochastic equivalences for fluid SPNs.

We planned to define a variety of behavioral equivalence relations for FSPNs. The resulting fluid stochastic equivalences should respect stochastic timing and quantities of fluid moved with transition firings. The equivalence notions were expected to be extensions of those defined for GSPNs in the literature. We hoped that some of the equivalences could be used for behavior preserving reduction of FSPNs.

*** Stochastic Process Calculi.**

Developing and investigating stochastic equivalences for dtsPBC.

We intended to propose a characterization of algebraic probabilistic bisimulations of dtsPBC, presented by I.V. Tarasyuk in 2005, via new probabilistic modal logics based on PML, introduced by K.G. Larsen and A. Skou in 1991. Two process expressions were assumed to be bisimilar iff they satisfy the same probabilistic logic formulas. As we expected, this would provide one with a possibility for logical reasoning on probabilistic equivalences within dtsPBC. We supposed to construct logics for both interleaving and step probabilistic bisimulations.

We planned to treat the dtsPBC-equivalences to find a congruence relation, i.e. a relation withstanding application of all algebraic operations. The goal expected to be achieved with constructing the congruence was an ability to combine dtsPBC-formulas from equivalent subformulas with algebraic operations and to obtain equivalent expressions as a result. This would be a very useful property while bottom-up designing processes.

We proposed to demonstrate how to compare stochastic processes in their steady states with the use of the relations. We supposed that some bisimulations can guarantee similarity of stationary behavior on the equivalence classes as composite states. We planned to prove that, for any two processes related by step stochastic bisimulation, the overall steady state probabilities to come in the equivalence class coincide. In this case, the mean recurrence time for the equivalence class would be the same for both processes. Moreover, we hoped to demonstrate that for the mentioned processes the steady state probabilities to come in the equivalence class and start a step trace from it are equal.

Also, we intended to explain how the stochastic equivalences can be used to reduce transition systems of expressions and the related formalisms.

*** Case Studies and Tools.**

Examples of specification, modeling, behavioral analysis and performance evaluation within dtsPBC.

We intended to propose some application examples based on process specifications within dtsPBC. We supposed that the examples should demonstrate the specific advantages of the algebra such as multi-way synchronization, step probabilistic semantics and infinite behavior specification. The difficulties we expected here were to find the appropriate application areas where the calculus can be efficiently applied for specification, behavior analysis and performance evaluation. In addition, we had to respect that the examples of realistic systems are normally rather large and complex, and their analysis are usually intricate.

Another point is that we had the only infiniteness construction in dtsPBC, namely, iteration operator. It was nontrivial to build loop constructions needed for infiniteness of the resulted behavior with the iteration only. For this, special stochastic processes were needed like Stop specifying infinite loop with probability 1 and non-termination. The goal pursued with case studies was to demonstrate how theoretical results to be obtained can be used in practice. Constructing application examples allowed one to understand better which advantages and restrictions exist in the formalism used for processes specification, and which is the most appropriate application area for the theory proposed.

2.3. Presentation of results.

*** Stochastic Models. Net Models.**

(a) Construction and investigation of the equivalences for fluid stochastic Petri nets.

A transition labeling has been introduced and a variety of trace and bisimulation behavioral equivalence relations have been defined for fluid stochastic Petri nets (FSPNs). The resulting fluid stochastic equivalences respect stochastic timing and quantities of fluid moved with transition firings. The equivalence notions are the extensions of those defined for GSPNs in the literature. The discrimination ability of all such fluid equivalence relations has been compared and a diagram of their interrelations has been built.

Relevant research situation.

In the literature, no transition labeling or behavioural equivalences for FSPNs, defined in [TK93,CNT97], have been proposed. The equivalences we have presented within the project allow one to compare both qualitative (action-based) and quantitative (timing- and fluid-based) features of FSPNs.

(b) Application of the equivalences for fluid stochastic Petri nets to the reduction and performance evaluation.

A preservation of the stationary behaviour by the fluid bisimulation equivalences has been studied and the relations have been found which allow one to compare and reduce fluid stochastic processes while leaving their performance indices unchanged. It has been demonstrated that the fluid equivalences can be applied to simplify qualitative and quantitative analysis of FSPNs thanks to reduction of the number of considered states, which have been lumped into the equivalence classes interpreted as new aggregated states of the reachability graph quotients.

Relevant research situation.

To analyze FSPNs, simulation and numerical methods are widely used, see [TK93,CNT97], since analytical analysis requires solving large systems of complex equations with first or second order partial differentials. The fluid stochastic equivalences we have defined within the project contribute into simplification of exact solution methods for FSPNs by accommodating modular approach to their transient and stationary analysis.

Perspectives for application.

The results we have obtained for stochastic models can be applied to optimize, simplify and make more effective construction, functional analysis and performance evaluation of many real systems, which are well-suited for modeling by FSPNs. The examples of the systems that can be properly modeled are those with fluid flow (the movement of liquid or dry substances, transportation of energy amounts or information volumes), controlled by discrete logics, such as telecommunication, information, manufacturing and biological systems. The techniques we have developed can be further extended to a wider class of hybrid systems, i.e. those consisting of both discrete and continuous components that communicate by transmitting data types of different nature.

Follow-up research.

Fluid stochastic equivalences will be provided with a logical characterization to be able to change the operational reasoning on the behaviour of fluid stochastic systems by the logical one used while verification. New technique for the analysis of FSPNs will be proposed based on the fluid equivalences which will be used to simplify and optimize the transient and stationary performance evaluation of the modeled fluid systems. A number of case studies will be presented to demonstrate how the mentioned technique can be applied to performance analysis of realistic time- and resource-dependent systems.

(c) Investigation of tau-equivalences for Petri nets with invisible transitions.

In [Tar11d,Tar12], behavioural equivalences of concurrent systems modeled by Petri nets with invisible transitions labeled by silent actions have been investigated. tau-equivalences are relations which abstract from silent actions corresponding to an internal activity of the modeled system. These silent actions are not visible to an external observer who monitors the system behaviour, but, nevertheless they can have an impact on this behaviour. The basic trace, bisimulation and conflict preserving tau-equivalences known from the literature have been transferred from other models to Petri nets with invisible transitions, which are more expressive model. The tau-equivalences have been supplemented by the new notions in the semantics between interleaving and "true concurrency". Interrelations of all the considered basic tau-equivalences have been determined on the whole class of Petri nets and the subclass of sequential Petri nets without concurrent transition firings. The diagrams of interrelations of the mentioned tau-equivalences on the both net classes have been built. The decidability results for basic tau-equivalences have been outlined.

Relevant research situation.

In the literature, a number of tau-equivalences have been defined for different formal models, see [Vog91,PRS92] for the relations on event structures and Petri nets. To choose an appropriate behavioral viewpoint on systems to be modeled, it is very important to have a complete set of equivalence notions in all semantics and understand their interrelations within one model that is expressive enough. This branch of research is called comparative concurrency semantics. To clarify the nature of equivalences and evaluate how they respect internal activity and concurrency, it is actual to consider also correlation of these notions on submodels without silent actions and concurrency-free (sequential) ones. The decidability question is very important for automatic verification of the equivalences. Within the project, we have transferred the most important tau-equivalences into Petri nets with invisible transitions and investigated them according to the mentioned above lines of research.

Perspectives for application.

The results we have got for net models can be applied to enhance qualitative analysis of the large class of concurrent and distributed systems with internal behaviour considered at different levels of abstraction, such as multicore processors, multiprocessor computing systems, computer clusters, distributed computer and communication networks, web and information services. Our approach allows to specify such systems and chose an appropriate semantics to compare, verify and simplify them.

*** Stochastic Process Calculi.**

(a) Logical characterization of stochastic bisimulation equivalences for dtsPBC via probabilistic modal logics.

In [Tar10a], we have presented a characterization of algebraic interleaving and step stochastic bisimulation equivalences of dtsPBC via new probabilistic modal logics iPML and sPML, constructed based on the well-known logic PML. We have proved that two process expressions are bisimulation equivalent iff they satisfy the same formulas of the corresponding probabilistic logic, i.e. iff they are logically equivalent. This has provided one with the possibility for logical reasoning on stochastic equivalences of dtsPBC and has allowed one to apply standard methods of formal verification. On the one hand, such an interpretation has elucidated the nature of the equivalences defined in an operational manner. On the other hand, we have got an operational characterization of logical equivalences, what has made simpler comparing stochastic processes for the equivalences.

Relevant research situation.

In the literature, logical characterization has been proposed for interleaving probabilistic and stochastic equivalences in the framework of untime formal models or those with continuous time, for which interleaving semantics is native, see [LS91] for the probabilistic modal logic (PML) on labeled probabilistic transition systems, and [ASBBSV95] for temporal logic $pCTL^*$ on finite Markov processes. On the other hand, even for discrete-time models, in which step semantics can be naturally incorporated, just interleaving equivalences have been defined and logically characterized, see [BHKW05] for the characterization of interleaving probabilistic bisimulation on discrete time Markov chains (DTMCs) in terms of temporal logic PCTL. Within the project, we have proposed a characterization of step stochastic equivalence of algebraic expressions in the discrete time area. The hard task here consisted in the correct constructing the probability-respecting logic modalities and determining the minimal complete set of them. For the effective satisfiability testing, we had to guarantee a finiteness of the sets of process states by imposing the finite branching condition on the process behaviour.

(b) Preservation of the equivalences by algebraic operations and defining the congruence relation for dtsPBC.

In [Tar10a], we have treated the equivalences of dtsPBC to find a congruence relation for the calculus, i.e. the relation that withstands application of all the algebraic operations. A suitable modification of stochastic isomorphism by adding two extra transitions (step and redo) to the transition systems of expressions has transformed this relation into a congruence. The resulting congruence can be used to combine formulas of dtsPBC from equivalent subformulas with algebraic operations and obtain equivalent expressions again. Being a congruence is a very useful property while bottom-up design of processes, since their behavioural properties should be preserved at all stages of the compilation.

Relevant research situation.

An important question concerning equivalence relations is whether two compound expressions always remain equivalent if they are constructed from pairwise equivalent subexpressions. The equivalence with the property of preservation by the combination operators is called a congruence. In the literature, a congruence relations for stochastic process algebras have been constructed just for the interleaving semantics in the continuous time area, see [Hil96,MVCF08] for the congruences on Performance Evaluation Process Algebra (PEPA) and stochastic Petri box calculus (sPBC). Within the project, we have defined a congruence of stochastic processes for the calculus dtsPBC with step semantics and discrete time. A non-trivial task here was to find a congruence, which would not be too strict equivalence relation. The resulting congruence differentiates only processes with essential distinctions in the behaviour, according to our interpretation of such differences. The relation is also easy to check.

(c) Steady-state analysis and comparison of stationary behaviour with the equivalences of dtsPBC.

In [Tar09b,Tar10a,Tar10b,Tar11b,Tar11c], we have demonstrated how to compare stochastic processes in their steady states with the use of the equivalence relations. We have proved that step stochastic bisimulation equivalence guarantees identity of stationary behaviour of the equivalent processes for all their equivalence classes interpreted as the composite states. In particular, for every two processes related by step stochastic bisimulation equivalence, the overall steady-state probabilities to come in an equivalence class coincide. In this case, the mean recurrence time for an equivalence class is the same for both processes.

Further, it has been proved that for the mentioned processes the steady-state probabilities to come in an equivalence class and start a step trace from it are equal. Since the steady-state distribution is used for performance evaluation via calculation of a number of performance indices, then many indices coincide for equivalent processes, and this guarantees identity of their performance. In addition, we have demonstrated by examples that step stochastic bisimulation equivalence is the weakest equivalence relation we considered that preserves stationary behaviour of processes and, hence, their performance.

Relevant research situation.

In the literature, probabilistic and stochastic equivalences have been proposed, which guarantee a coincidence of the stationary (long-run) probabilities to stay in the states, see [Hil96,BKe01] for the relations on stochastic and probabilistic process algebras. At the same time, no relations have been defined, which additionally ensure identity of traces (sequences of actions) from these states, i.e. equality of both limiting quantitative and qualitative behavioural properties. This equality implies coincidence of different performance indices of the equivalent systems. Moreover, in the publications, only interleaving relations have been discussed, as a rule. During the work over the project, we have proved that step stochastic bisimulation equivalence meets the above requirements. The difficulty here was to find a suitable and easy to check step equivalence, which guarantees similarity of the long-run probabilities. We have demonstrated by examples that no equivalence notion, which is weaker than step stochastic bisimulation one, preserves the stationary behaviour. Constructing examples of such kind has appeared to be a non-trivial problem, since the example processes are rather complex and their analysis is far from being straightforward.

(d) Reduction of processes modulo stochastic bisimulation equivalences of dtsPBC.

In [Tar09b,Tar10a,Tar11b,Tar11c], we have explained how step stochastic bisimulation stochastic equivalence can be used to reduce transition systems of expressions and the related formalisms. The equivalence divides the set of states of an expression by the equivalence classes. The treatment of the equivalence classes as the new "quotient" states allows one to define the minimal reduced by the equivalence transition system and discrete time Markov chain. It is easier to evaluate performance with the use of a Markov chain with less states, since in this case the dimension of the transition probability matrix will be smaller, and we shall solve systems of less equations to calculate steady-state probabilities.

Many performance indices are based on the steady-state probabilities to come in a set of similar states or, after coming in, to start a step trace from this set. The similarity of states is usually captured by an equivalence relation, hence, the sets are often the equivalence classes. Stationary behaviour preservation property for step stochastic bisimulation equivalence guarantees a coincidence of the mentioned indices based on reduced and the initial Markov chain. The method for simplification of behavioural analysis and performance evaluation for stochastic processes based on step stochastic bisimulation stochastic equivalence has been proposed. First, the minimal reduced by the equivalence underlying Markov chain is constructed. Second, the steady-state probabilities and performance indices based on the reduced Markov chain are calculated.

Relevant research situation.

In the literature, the behaviour preserving reduction of stochastic formalisms has been defined by interleaving equivalences, as a rule, see [Hil96,Buc98] for the state space aggregation within PEPA and labeled generalized stochastic Petri nets (GSPNs). The reduction modulo parallel equivalence relations, e.g., by non-interleaving place bisimulation equivalences [AS92], has been considered only in the standard untime models, such as Petri nets. In the project, we have found a step stochastic equivalence that can be used for reduction of the transition systems of the stochastic algebra expressions. This has made easier specification and behavioural analysis of the stochastic processes. The hard point here was to search for the stationary behaviour preserving equivalence relation, which is not too strict and can therefore ensure more sizeable reductions. Additionally, in the general case, the procedure of the expressions reduction could not be trivially transferred from the transition systems level. The reason for that is the following fact: the transition system of the minimal equivalent expression could be not minimal itself, since, in some cases, it can be further reduced resulting in the quotient by the equivalence.

(e) Discrete time stochastic Petri box calculus with immediate multiactions (dtsiPBC).

In [TMV10,TMV11], we have presented an extension of dtsPBC with immediate multiactions, called dtsiPBC. The step operational semantics has been constructed via labeled probabilistic transition systems. The denotational semantics has been defined on the basis of a subclass of labeled discrete time stochastic Petri nets with immediate transitions. A consistency of both semantics has been demonstrated.

To evaluate performance, the corresponding stochastic process, which is the semi-Markov chain, has been analyzed. We have defined step stochastic bisimulation equivalence of expressions and explained how it can be used to reduce their transition systems and underlying semi-Markov chains as well as to compare the stationary behaviour. We have proved that the introduced equivalence guarantees a coincidence of stationary behaviour and performance indices based on stationary probabilities, thus, it can be used for performance analysis simplification.

Relevant research situation.

The semantics of all Markovian calculi known from the literature is interleaving, since their action delays have exponential distribution, which is the only continuous probability distribution with memoryless (Markovian) property. Only a few non-interleaving stochastic process algebras have been proposed among non-Markovian ones, see [KA01] for the review. However, none of such non-interleaving SPAs has the "explicitly" parallel operational semantics, since it has not been explained how to calculate probability of the transitions corresponding to the simultaneous execution of a set consisting of two and more concurrent independent activities. Moreover, in spite of the discrete time approach to constriction of some stochastic calculi, their operational semantics is still (decorated) interleaving. Concurrent execution is often interpreted as synchronization or the asynchronous completion of the activities which have already started. In the latter case, the beginning of the activities execution is accomplished in the interleaving way, i.e. in an arbitrary order, but always sequentially. Hence, any stochastic activities, which could be defined within the non-interleaving stochastic algebras described in the literature will be however interleaving or, according to their differentiating ability, will lie barely between interleaving and step relations.

The new algebra dtsiPBC constructed within the project is a discrete time analog of stochastic Petri box calculus (sPBC) with immediate multiactions proposed earlier in the literature within a continuous time domain, see [MVCR08]. The main advantages of dtsiPBC are the multiaction labels, immediate multiactions and the set of flexible and powerful operations, as well as a step operational and a Petri net denotational semantics allowing for concurrent execution of activities (or transitions). The salient point of dtsiPBC is a combination of immediate multiactions, discrete stochastic time and step semantics in a stochastic process algebra. Semi-Markov chains are used to evaluate performance both in sPBC with immediate multiactions and dtsiPBC, but in the former calculus the residence time in the states is continuous (zero deterministic or exponentially distributed) while in the latter it is discrete (zero deterministic or geometrically distributed). The next unique feature of dtsiPBC in comparison with the mentioned sPBC extension is the step stochastic bisimulation equivalence of expressions that respects zero and stochastic time delays and used to simplify analysis of the modeled systems as demonstrated by application examples.

Perspectives for application.

The results we have obtained for the stochastic process calculi dtsPBC and dtsiPBC can be applied to functional and performance analysis of a wide variety of time-dependent concurrent and distributed systems, which can be naturally specified by the compositional algebraic structures, especially to systems with mass parallelism. The behaviour of the systems is modeled with algebraic processes and can be compared by the algebraic stochastic equivalences. Hence, one can formally verify the systems and simplify them while preserving their qualitative and quantitative behaviour. The class of parallel systems to which our approach is well-suited includes computer, telecommunication systems and networks as well as many different kinds of manufacturing, information and service systems with concurrency and time constraints.

Follow-up research.

Future work will consist in constructing a congruence relation for dtsiPBC, i.e. the equivalence that withstands application of all operations of the algebra. The first possible candidate is a stronger version of step stochastic bisimulation equivalence defined via transition systems equipped with two extra transitions, called skip and redo. We also plan to extend the calculus with deterministically timed multiactions having a fixed time delay (including the zero one, which is the case of immediate multiactions) to enhance expressiveness of the calculus and to extend application area of the associated analysis techniques. Moreover, recursion operation could be added to dtsiPBC to increase further specification power of the algebra.

Contribution of the German side.

As planned, the research on stochastic process algebras has been undertaken by I.V. Tarasyuk in cooperation with his German partner E. Best (University of Oldenburg). He has noticed attention to the problem of stationary behaviour preservation by interleaving stochastic equivalences. He has proposed a net justification of the formula for probability of synchronized activities in dtsPBC and dtsiPBC based on the observation that similar probability functions are used both at the algebraic and net levels. He has initiated application of reduction not just at the level of algebraic expressions or Petri nets, but also on the corresponding transition systems and underlying Markov chains. This approach has led to more significant state space reduction. He has recommended to respect the empty loops (the discrete time steps at which no activities are executed) in the definitions of stochastic equivalences. This method has allowed one to employ the mentioned equivalences for comparison of the performance and simplification of its evaluation. He has given several advices on similarities and differences between dtsPBC and dtsiPBC and other stochastic calculi and on presentation of the originality of our approach in comparison with others.

*** Case Studies and Tools.**

(a) Examples of specification, behavioural analysis and performance evaluation within dtsPBC.

In [Tar09a,Tar09b,Tar10a,Tar11a,Tar11b,Tar11c], we have presented two application examples based on process specifications of dtsPBC that explain how to analyze performance of systems within the calculus ans how to simplify the performance analysis. The examples demonstrate the essential advantages of the algebra: multiway synchronization, step discrete stochastic time semantics and ability for infinite behaviour specification. We have proposed the models of the shared memory system and the dining philosophers one as well as the generalized versions of both systems by setting arbitrary multiaction probability (the probabilistic parameter) in their specifications. For the four systems, the algebraic specifications of the standard and abstract (those abstracting from the concrete names of processors or philosophers) systems have been presented.

Further, we have considered reductions of the abstract systems by step stochastic bisimulation equivalence. Based on the algebraic specifications of the systems, their transition systems and DTMCs have been constructed, and the stationary probabilities have been determined. These steady-state probabilities have been used to calculate a number of performance indices. It has been been shown that the indices coincide for the abstract systems and their reductions. Thus, one can first reduce the systems and then analyze their performance. This simplifies the performance evaluation, especially in the case of major reductions, such as those for the systems with many symmetries and self-similarities.

We have also investigated which effect have quantitative changes of the probabilistic parameter from specifications of the generalized systems upon performance of their quotient abstract variants in the steady states. We have plotted the graphs of the performance indices considered as functions of the probabilistic parameter. Then we have determined analytically at which values of the parameter the performance indices reach their maximums or minimums. This allows one to optimize performance of the systems in a clear, obvious and purely analytical way, just by taking the appropriate parameter values in their algebraic specifications.

(b) Examples of specification, behavioural analysis and performance evaluation within dtsiPBC.

In [TMV10,TMV11], within a case study, a method of modeling, performance evaluation and behaviour preserving reduction of concurrent stochastic systems specified by dtsiPBC expressions has been outlined and applied to the shared memory system and its generalized version with a variable probability of activities. The mentioned probability was then interpreted as a parameter of the performance index functions. The influence of the parameter value to the performance of the shared memory system was analyzed with a goal of optimization by interpreting the graphs of the system's performance indices.

Relevant research situation.

In the literature, the examples of specification and behavioural analysis have been proposed mainly for interleaving stochastic models, see [Bal07,MVCR08] for the case studies in GSPNs and sPBC with immediate multiacions. Within the project, we have constructed several original examples demonstrating specification and verification of behaviour for parallel systems in the stochastic process calculi. These case studies reveal the inherent advantages and restrictions of the process algebras dtsPBC and dtsiPBC featuring step semantics. The difficult task was to find suitable application areas in which the calculi could be efficiently used to specify, analyze behaviour and evaluate probability of the stochastic systems. Therewith, the case studies of realistic systems are normally large and complex. Their analysis is often rather hard, especially when the systems demonstrate non-interleaving behaviour, since, in this case, there are more state transitions, in comparison with interleaving models. On the other hand, many interesting application examples have an infinite behaviour with repeating fragments, as a rule. In the calculi we have considered, there is only one infinite construction, namely, the iteration operator. Building of cyclic constructions required to ensure infiniteness of the resulting behaviour by merely employing the iteration has appeared to be very non-trivial. Therefore, a new special process Stop has been introduced, which never terminates and corresponds to the infinite empty loop with probability 1. Stop has been exploited to model different (mainly, non-empty) infinite loops by taking it as the last argument (termination) of the iteration operation.

Perspectives for application.

The case studies we have presented demonstrate how to use in practice the theoretical results obtained within dtsPBC and dtsiPBC. The practical examples have showed which advantages and restrictions exist in the both stochastic process algebras used for the processes specification, and which is the most appropriate application area for the theory proposed. Thus, the examples that we have constructed and investigated serve as a basis to develop more effective methods and powerful software tools, intended to analyze and evaluate behaviour of time-critical concurrent systems.

Contribution of the German side.

The German partner E. Best (University of Oldenburg) has participated in the improvement and extension of the application examples proposed by I.V. Tarasyuk within dtsPBC and dtsiPBC. E. Best has suggested to use modular approach to performance evaluation of the stochastic processes considered in these case studies.

(c) Examples of specification, behavioural analysis and reduction within Petri nets with invisible transitions.

In [Tar11d,Tar12], an example of equivalence-preserving reduction of a Petri net that models the five dining philosophers system with internal activities has been presented. The reduction has been accomplished by one of the new and most strong tau-equivalence relations called pomset history preserving branching ST-tau-bisimulation equivalence. Thus, the silent actions abstracting behaviour of the initial system and that of reduced one have been shown to coincide at the level of the pointed equivalence.

Relevant research situation.

In the literature, the dining philosophers system has been modeled mainly in the formalisms having interleaving semantics, see [Hoa85] for the corresponding specification in the Communicating Sequential Processes (CSP) algebra. The Petri net specification, where only simultaneous taking forks is allowed, has not been analyzed using the step reachability graph. Silent actions have not been incorporated into the previous models. We have specified and reduced the dining philosophers system by the equivalence abstracting from silent actions in the framework of the expressive formalism of Petri nets with invisible transitions.

Follow-up research.

In the following, we plan to consider examples of more complex and large realistic systems, such as models of web services, communication networks and manufacturing systems. To analyze a non-trivial (as a rule) behaviour of these systems, we need to make a proper choice among existing programming tools, intended to deal with stochastic models, like Markov chains and processes, stochastic and fluid Petri nets, stochastic process algebras. Possibly, in some cases, a suitable modification of the tools will be needed with a goal to accommodate step semantics, instead of interleaving semantics that is standardly implemented there.

List of publications.

(a) Papers of the project participants (published during the DFG grant period).

[Tar09a] Tarasyuk I.V. Performance evaluation in dtsPBC. Proceedings of 18th Workshop on Concurrency, Specification and Programming - 09 (CS& P'09), Krakow-Przegorzaly, Poland, September 28-30, 2009, L. Czaja, M. Szczuka, editors, p. 602-615, Warsaw University, 2009, http://itar.iis.nsk.su/files/itar/pages/dtsshmcsp.pdf.

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3.1. Presentation of the key scientific findings and any potential applications.

*** Stochastic Models. Net Models.**

A transition labeling has been introduced and a variety of behavioral equivalence relations have been defined for fluid stochastic Petri nets (FSPNs). The resulting fluid stochastic equivalences respect stochastic timing and quantities of fluid moved with transition firings. The equivalence notions are the extensions of those defined for GSPNs in the literature. The discrimination ability of all such fluid equivalence relations has been compared and a diagram of their interrelations has been built. A preservation of the stationary behaviour by the given equivalences has been studied and the relations have been found which allow one to compare and reduce fluid stochastic processes while leaving their performance indices unchanged.

Behavioural equivalences of concurrent systems modeled by Petri nets with invisible transitions labeled by silent actions have been investigated. tau-equivalences are relations which abstract from silent actions corresponding to an internal activity of the modeled system. Basic tau-equivalences known from the literature have been transferred to Petri nets with invisible transitions and supplemented by the new notions. Interrelations of all the considered tau-equivalences have been determined on the whole class of Petri nets and the subclass of sequential Petri nets without concurrent transition firings.

*** Stochastic Process Calculi.**

A number of stochastic equivalences of expressions have been defined in the framework of discrete time stochastic Petri box calculus dtsiPBC. A logical characterization via new probabilistic logics has been presented for interleaving and step stochastic bisimulation equivalences. A congruence relation has been defined which is applied while the "down-top" process construction. Step stochastic bisimulation equivalence has been proven to be the most abstract relation that guarantees similarity of the stationary behaviour and allows for the performance-preserving comparison of stochastic processes. It has been demonstrated that the mentioned equivalence can be used for reduction of the transition systems and Markov chains corresponding to the algebraic expressions. A method of modeling, behaviour analysis and performance evaluation for concurrent systems has been proposed that applies the given equivalence. Within the method, their performance indices are calculated on basis of the categorized by the equivalence Markov chains corresponding to algebraic specifications of the systems. Case studies have been presented illustrating application of the method.

A new calculus dtsiPBC which is an extension of dtsPBC with immediate multiactions has been constructed whose step operational semantics is based on labeled probabilistic transition systems while the denotational semantics is based on labeled discrete time stochastic and immediate Petri nets. Step stochastic bisimulation equivalence of expressions has been defined in the framework of dtsiPBC. It has been shown how this equivalence can be used to compare behaviour of stochastic processes as well as to reduce their transition systems and the corresponding semi-Markov chains. The introduced equivalence has been proven to guarantee coincidence of performance indices for stochastic systems with geometrically distributed and zero discrete time delays, hence, it can be applied to simplify performance analysis of that kind of systems. A method of modeling, performance evaluation and behaviour preserving reduction has been proposed that applies step stochastic bisimulation equivalence. The shared memory system example has been treated that illustrates immediate probabilistic choice.

3.2. Any surprises encountered in the course of the project and in the results obtained.

*** Stochastic Process Calculi.**

It has been found that the operational semantics of dtsPBC and dtsiPBC can be improved by moving the empty loop rule (corresponding to one time unit stay in the current process state) from the inaction rules, consuming no time, to the action rules, requiring one time unit to apply. The main idea was that the inaction rules for dynamic expressions must describe their structural transformations which do not change the states of the specified processes. Thus, an application of every inaction rule should not require any discrete time delay, i.e. the dynamic expression transformation described by the rule must be accomplished instantly.

While constructing a congruence relation for dtsPBC, the counterexamples have been found demonstrated that, surprisingly, none of the stochastic trace or bisimulation equivalences defined within the calculus can be accommodated to withstand application of all the algebraic operations. Only the proper modification of the stronger equivalence, stochastic isomorphism, by respecting two extra transitions (step and redo), resulted in the congruence relation.

During determining which equivalences of dtsPBC and dtsiPBC preserve performance of stochastic processes, it has been discovered that one should additionally respect the empty loop transitions in the definitions of these relations. While such new equivalences make not so obvious identifications of processes as previous versions of the relations which have abstracted from empty loops, the new relations have a very important advantage: they preserve both transient and steady-state probabilities and, hence, the performance indices based on them. Interestingly, the equivalences abstracting from empty loops have preserved performance only under the "progress" condition on the behaviour of the compared processes: at least, one activity must be executed at every discrete time moment.

When the stochastic bisimulation equivalences of dtsPBC and dtsiPBC were applied to reduce the process specifications, it has been observed that even more extensive simplifications could be done at the level of their transition systems and underlying Markov chains. The unusual fact about such the reduced semantic objects has consisted in that they themselves cannot in general be interpreted as the transition systems or underlying Markov chains of any algebraic expressions, including some simplified versions of the initial process specifications. As for the Petri net level, for stochastic Petri boxes, the quotients by the equivalences of their reachability graphs and underlying Markov chains often can only be interpreted as those of some non-safe stochastic Petri nets, which are not stochastic Petri boxes, since the latter are safe by definition.

In the case studies within dtsPBC and dtsiPBC, it has been discovered that it is very interesting to investigate the generalized versions of such systems as well. The generalized systems were specified by expressions with variable probabilities of activities interpreted as parameters of the performance indices. The resulting performance index functions have been then analyzed with a goal of performance optimization. We have determined at which values of the parameter the performance indices reach their maximums or minimums, which has allowed us to optimize performance of the system in a clear, obvious and purely analytical way. During observing the plotted graphs of the performance index functions, we have unexpectedly found a number of new useful performance indices which have helped us to understand better some subtle aspects of the systems behaviour.