Modelling: Quantitative Modelling
Second Year Report

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AMETIST DELIVERABLE 1.3

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1 Introduction

This is the AMETIST second year's deliverable of Task 1.3 on Quantitative Modelling. The purpose of this task is to study and develop extensions of the basic model of timed automata emphasising their specification and composition. As indicated in the Description of Work this Task is more specifically aimed at stochastic extensions of real-time models to capture soft real-time concerns, related to modelling uncertainty and performance of timed systems. Part of the reported work has been funded from other sources than the AMETIST project, but all of the reported work is strongly related to AMETIST in terms of application area or techniques and tools used, as well as the involved researchers.

The contributions of the consortium to this task so far can be classified into four areas:

- **Process algebra-based modelling.** A substantial amount of work inside and outside the AMETIST project has been done on studying compositional aspects of stochastic timed behaviour in the framework of stochastic process algebra (SPA). This deliverable incorporates three surveys: a general overview of SPA [4], an overview of Markovian process algebra [6], i.e. only involving memoryless stochastic distributions, and an overview of stochastic process algebra involving general distributions [3]. A fourth contribution [5] discusses an abstraction technique that maps stochastic behaviour to timed automata with deadlines, making the analytical theory of the latter model class available to study properties of timed behaviour with non-zero probability.

- **General modelling languages.** A wider trend that the AMETIST project is contributing to is the development of wide-spectrum modelling languages. This Task, more specifically, is concerned with the inclusion of stochastic features for the specification of alternative and soft real-time behaviour. This deliverable contains two such contributions, viz. [7] on the stochastic extension of UML statecharts, which has been received well by OMG experts, and [2] that proposes support for the stochastic features of the general modelling language MoDeST.

- **Modelling for scheduling.** Since scheduling is one of the main applications of the AMETIST approach to timed systems, this deliverable also contains specific extensions to models for scheduling in the context of stochastic phenomena. A foundational contribution is provided [1], which discusses the use of timed automata modelling for a whole range real-time scheduling problems including scheduling under uncertainty. Contribution [11] discusses the risk conscious scheduling of batch processes, and [10] proposes stochastic integer programming for the modelling and analysis of real-time scheduling problems.

- **Modelling for hybrid control.** Closely related to scheduling synthesis, but more complicated, is the issue of controller synthesis for real-time systems. Here, also uncontrolled behaviour by the environment of a system must be taken into account. Techniques studied in AMETIST can also be applied successfully here. This section contains one contribution so far, viz. [9], which proposes a model for taking computational performance into account for hybrid controller synthesis.

As a final contribution relevant for this Task we mention the proceedings of the AMETIST -funded FORMATS Workshop *Formal Modelling and Analysis of Timed Systems*, edited by Kim G. Larsen

and Pieter Niebert [8].

The following sections contain short abstracts of each of the contributions mentioned above. The presented material realizes the anticipated milestone for this Task after 24 months amply: a good understanding of the extensions of the timed automaton model to stochastic timing is well-documented. Moreover, the incorporation of this theoretical development in the applied setting of general modelling formalisms, such as UML and MoDeST, is also being realized. This work within AMETIST is at the forefront of international research in this area.

In the third and final year we anticipate work in two directions, viz. the further application of these models and tools to practical modelling and case studies, and the study of further extensions that involve the combination of stochastic timing and non-determinism (as in, e.g. Markov decision processes). The latter models are of great significance for the study of (optimal) scheduling.

2 Process algebra based modelling

2.1 Compositional Theories of Qualitative and Quantitative Behaviour

The integrated modelling and analysis of functional and non-functional aspects of system behaviour is one of the important challenges in the field of formal methods today. Our ever-increasing dependence upon of all sorts of critical applications of networked and/or embedded systems, often including sophisticated multi-media features, lends this intellectual challenge also great practical relevance. The survey [4] reports on work in this area in the past decade or so on the use of techniques from so-called formal methods in the area of performance modelling and analysis, and in particular on the theory of stochastic process algebra (SPA) and its application.

2.2 Process algebra for performance evaluation

This paper [6] surveys the theoretical developments in the field of stochastic process algebras, process algebras where action occurrences may be subject to a delay that is determined by a random variable. A huge class of resource-sharing systems - like large-scale computers, client-server architectures, networks - can accurately be described using such stochastic specification formalisms. The main emphasis of this paper is the treatment of operational semantics, notions of equivalence, and (sound and complete) axiomatisations of these equivalences for different types of Markovian process algebras, where delays are governed by exponential distributions. Starting from a simple actionless algebra for describing time-homogeneous continuous-time Markov chains, actions and random delays are integrated both as a single entity (like in known Markovian process algebras like TIPP, PEPA and EMPA) and as separate entities (like in the timed process algebras timed CSP and TCCS). In total, four related calculi are considered and their relationship to existing Markovian process algebras is investigated. It is also briefly indicated how one can profit from the separation of time and actions when incorporating more general, non-Markovian distributions.

2.3 Tutte le algebre insieme: Concepts, Discussions and Relations of Stochastic Process Algebras with General Distributions

The survey [3] reports on the state of the art in the formal specification and analysis of concurrent systems whose activity duration depends on general probability distributions. First of all the basic notions and results introduced in the literature are explained and, on this basis, a conceptual classification of the different approaches is presented. Most of the approaches agree on the fact that the specification of systems with general distributions has a three level structure: the process algebra level, the level of symbolic semantics and the level of concrete semantics. Based on such observations, a new very expressive model is introduced for representing timed systems with general distributions. It is shown that many of the approaches in the literature can be mapped into this model establishing therefore a formal framework to compare these approaches.

2.4 From Stochastic Automata to Timed Automata: Abstracting probability in a compositional manner

An abstraction from stochastic automata into timed automata with deadlines is presented in [5]. The translation abstracts probabilities and preserves trace behaviour. Moreover, it is compositional in the sense that the translation of the parallel composition of two stochastic automata is equivalent to the parallel composition of the timed automata resulting from the translation of each component.

3 General modelling languages

3.1 Stochastic extension of UML statecharts

Performance, dependability and quality of service (QoS) are prime aspects of the UML modeling domain. To capture these aspects effectively in a modeling language requires easy-to-use support for the specification and analysis of randomly varying behaviors. [7] introduces an extension of UML statecharts with randomly varying durations, by enriching a specific syntactic construct: The "after" operator is equipped with (discrete or continuous) probability distributions, determining the duration of the delay caused by this operator. The semantics of this extension is given in terms of a variant of stochastic automata. It is shown how existing model-checking tools can be used to calculate model-inherent QoS characteristics automatically. A UML model of an automatic teller machine scenario is studied using this approach.

3.2 The MoDeST modelling tool and its implementation

The tool-suite Motor supports the modeling and analysis of MoDeST specifications. The tool architecture, and the implementation details of the tool components that do already exist, in particular, the parser, the SOS implementation, an interactive simulator, and a state-space generator, are presented in [2]. As the expressiveness of MoDeST goes beyond existing notations for real-time as well as probabilistic systems, the implementation of these tool components has a non-trivial intrinsic complexity.

4 Modelling for scheduling

4.1 Scheduling with Timed Automata

This thesis [1] develops a new methodology for posing and solving scheduling problems. The essence of this approach is to model the system as a timed automaton where schedules correspond to paths in the automaton and optimal schedules correspond to shortest paths. A model of the classical job-shop problem, is extended to treat preemption, partially-ordered tasks and scheduling problems with temporal uncertainty. For all these problems, algorithms are developed, implemented, and their performance tested on benchmark examples. The thesis is a contribution both to the theory and practice of scheduling and to the analysis of timed automata.

4.2 Risk Conscious Scheduling of Batch Processes

Real-time scheduling problems of flexible batch processes under the special consideration of uncertainties are addressed in [11]. Here, any decision has to be made subject to a certain risk since it affects the future evolution of the process, which is not precisely predictable. This difficulty can be faced by a moving horizon approach with frequent re-optimisations. The use of a model framework from stochastic programming is proposed to reflect the uncertainty and the potential of recourses realistically. The framework is applied to a real-world process from the polymer industries, a decomposition algorithm is sketched and numerical results are given.

4.3 Modelling and Solving Real-Time Scheduling Problems by Stochastic Integer Programming

This contribution deals with scheduling problems of flexible chemical batch processes with a special emphasis on their real-time character [10]. This implies not only the need for sufficiently short response times, but in particular the burden of incomplete knowledge about the future. To solve such problems, the application of two-stage stochastic integer programming techniques on moving horizons is proposed. They reflect the need for immediately applicable decisions and the potential of later recourse actions to cope with realized uncertainties. In addition to the classical expected value objective, simple measures of risk can be included. Motivated by an example process, some essential modelling prerequisites are discussed. As an important first step, the master scheduling problem is studied and a number of master scheduling models are presented. Large mixed-integer linear problems arise, which are well-suited for a dual decomposition approach. Numerical experiments with a problem-specific solution algorithm demonstrate the applicability of the method to real-world problems.

5 Modelling for hybrid control

5.1 On Control with Bounded Computational Resources

This contribution [9] proposes models that capture the influence of computation on the performance of computer-controlled systems, and which allow to employ computational considerations in early stages of the design process of such systems. The problem of whether it is possible to meet performance requirements given resource constraints is phrased as a problem of synthesizing switching controllers for hybrid automata, for which algorithms that in some cases are guaranteed to converge, and in others can be solved in an approximate manner, are given.

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