PROJECT FINAL REPORT

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Name of the scientific representative of the project's co-ordinator[1], Title and Organisation:

Professor Kim G. Larsen, Aalborg University, Denmark

Tel: +45 99 40 88 93

Fax: +45 99 40 97 98

E-mail: kgl@cs.aau.dk

Associate Professor Brian Nielsen, Aalborg University, Denmark

Tel: +45 99 40 88 83

Fax: +45 99 40 97 98

E-mail: bnielsen@cs.aau.dk

Project website address: http://www.quasimodo.aau.dk/

[1] Usually the contact person of the coordinator as specified in Art. 8.1. of the Grant Agreement.

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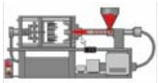
1.1 Executive Summary

Embedded systems are a modern technology that is rapidly changing society as we know it. Intelligence, in the form of software and hardware, is introduced into all kinds of products and objects with the objective of enhancing their functionality.

A key characteristic of **embedded systems** is that they are constrained by the amount of resources (computation resources, power consumption, memory usage, communication bandwidth, costs, etc.) they are allowed to consume, and yet have to satisfy high functional and performance guarantees (timing constraints, quality-of-service, availability, fault tolerance, etc.). Moreover, a system may operate in a multitude of different environments that are not exactly known (different arrival rates of external events and variation in discrete and continuous signals). Such resource amounts, performance guarantees, and system loads are ***quantitative system properties*** whose values and limits must be determined during system development. The treatment of quantitative properties in existing ***model-driven tools*** is still very limited, and hence cannot address these critical design problems. *Quasimodo has developed theory, methods and tools for model-driven system design that can increase system development productivity while achieving predictable system safety, real-time, performance and dependability properties.*

Quasimodo has extended modelling-, analysis-, synthesis-, and testing-techniques with multiple quantitative properties. Quasimodo has dramatically **advanced analysis techniques**, both in term of the richness of the models and properties being analyzed and in the performance of the analysis techniques. The frontier of analyzable problems has thus been significantly advanced; in more cases, performance have been improved by orders of magnitude, enabling industrial systems that before were out of reach to be analyzable now. Quasimodo goes beyond analysis, but also considers implementability, algorithmic **controller synthesis**, and **testing**. The techniques have been implemented in an extensive collection of unique **powerful tool components**, which in specific instances are linked to - and integrated with - industrial tool chains like Matlab/Simulink, STATEMATE, and tools for the Architecture Analysis and Design Language (AADL).

Case study	Problems	Results
Hydraulic pump Ctrl. 	– Synthesis of Controllers – Software Testing	– Application of our tool suite for automated controller synthesis resulted in a safe controller with 33% improved energy efficiency – Model-based testing revealed significant defects in an existing implementation.
MAC protocols in Wireless Sensor Networks	– Timing analysis – Performance analysis – Software Testing	– Real-time model-checking identified a design-flaw in the studied MAC protocol (demonstrated that clocks may become de-synchronized in certain topologies). – Message collision rates and effectiveness of collision detection were analysed using stochastic models and discrete event simulation – Real-time model-based testing identified unexpected behaviour during start-up and re-synchronization
Satellite attitude and control software	– Schedulability Analysis	– A framework was developed for model-based schedulability analysis that may be more optimistic that classical response time analysis

The techniques has been successfully applied to and evaluated on a wide variety of 6 larger industrial case studies and numerous smaller ones. We have identified important and potentially expensive defects in both proposed designs and implementations, see table. In the Hydac case-study, our approach far outperforms the existing controllers. This **intensive work on case studies** clearly demonstrates that Quasimodo techniques can have practical impact on industrial development. We hope that our Industrial Handbook may play an important role in the training and education of engineers. *In conclusion, the Quasimodo results are promising and may thus help Europe maintain and advance its competitive edge in complex systems design.*

1.2 Context and Objectives

Embedded systems are a modern technology that is rapidly changing society as we know it. Intelligence, in the form of software and hardware, is introduced into all kinds of products and objects with the objective of enhancing their functionality. To meet this goal, their design must face a complex array of constraints related to hardware, software, and the specific needs of the application of the overall product. The reliable design of embedded systems, therefore, poses a great challenge.

It is the objective of Quasimodo to research and develop methods and tools that can be used to design reliable embedded systems that meet their requirements in a controlled and resource-efficient way using a model-based approach. This means that design decisions, analysis, simulation, testing, code generation, etc. are always based upon models that reflect the relevant aspects of the design. This requires methods to maintain, manipulate, analyse and transform models in a coherent and meaningful way.

A key characteristic of embedded systems is that they are constrained by the amount of resources (computation resources, power consumption, memory usage, communication bandwidth, costs, etc.) they are allowed to consume, and yet have to satisfy high functional and performance guarantees (timing constraints, quality-of-service, availability, fault tolerance, etc.). Moreover, a system may operate in a multitude of different environments that are not exactly known (different arrival rates of external events and variation in discrete and continuous signals). Such resource amounts, performance guarantees, and system loads are quantitative system properties whose values and limits must be determined during system development.

Model-Driven Development (MDD) is a new software development technique in which the primary software artefact is a model, which is a collection of views. Ideally, the technique allows engineers to (graphically) model the requirements, behaviour and functionality of computer-based systems. The design is iteratively analysed, validated, and tested throughout the development process while automatically generated production quality code can be output in a variety of languages.

MDD is a drastic approach where models are the product of each step in the development. More modest approaches that use models only at some critical points in the development cycle will also benefit from the outcomes of the project.

Existing MDD tools for real-time embedded systems are rather sophisticated in handling functional requirements but their treatment of quantitative properties is still very limited. There is little to no support for high-level modelling and analysis of real-time, probabilistic and hybrid aspects of system behaviour, and for ensuring that quantitative properties that have been established for some model are preserved when this model is further refined and/or implemented. Hence MDD will not realise its full potential in the embedded systems area unless the ability to handle quantitative properties is drastically improved.

The objective of Quasimodo is to develop theory and techniques for handling quantitative properties in the model-driven development of real-time embedded systems. To this end, the project will use timed, hybrid and probabilistic automata as a preferred formalism. More specifically, the Quasimodo project aims at:

1. Improving the modelling of (possibly diverse) quantitative aspects of embedded systems in a sound, coherent and effective manner. For instance, there is currently no satisfactory formalism to specify and analyse stochastic aspects together with real-time constraints.

2. Providing a wide range of powerful techniques for analysing models with quantitative information and for establishing abstraction relations between such models. The ability to model and analyse quantitative aspects will make it possible to represent important features of the final execution platform at early design stages, and enable early assessment of resource consumption and performance (quality-of-service) of particular designs.

3. Providing effective implementation mappings (code generation) from abstract quantitative models onto concrete (often small) platforms with guarantees that correctness and performance properties established of the models also hold (maybe in slightly weakened form) of the running implementation. This is a challenge, as models often lack various aspects only introduced at the translation step (e.g. knowledge of operating system, manipulation and representation of data variables, abstract actions of the model may correspond to executable C-code at the implementation level, indirect interaction with environment via various device drivers, arbitrary precision of clocks in the model).

4. Improving the overall quality of testing by using suitable quantitative models as the basis for generating sound and correct test cases. Test generation for models with e.g. stochastic aspects is still mainly an open issue: test cases that expose the more representative scenarios in term of probability mass is a research challenge.

In order to demonstrate the usefulness of our techniques, we will apply them to several complex industrial case studies. The consortium will provide unique tool components to be used as plugins in industrial tools or tool chains in order to create first prototypes of a tool environment that supports —in an integrated fashion— quantitative modelling, analysis, implementation and testing of embedded systems. These tool environments will provide a starting point for further industrial development.

This project addresses the Objective ICT-2007.3.3: Embedded Systems Design. The descriptive text for target outcome (a) of this Objective says:

> *Theory and methods for system design: Methods that can increase system development productivity while achieving predictable system properties, including dependability and security. This will require a formal framework for systems design in addition to holistic and adaptive component based design and verification methods. Key issues encompass heterogeneity (building embedded systems from components with different characteristics); composability; predictability of extra-functional properties such as performance and robustness (e.g. safety, security, timing and resources); concepts and tools for specifying and evaluating security properties; adaptivity for coping with uncertainty; and unification of approaches from computer science, electronic engineering and control. International cooperation should address foundational research challenges and provide mutual benefits; cooperation activities with the US National Science Foundation (NSF) will continue and extend to other countries.*

1.3 Main S&T Results

1.3.1 WP1: Modelling and Specification

WP1 aims at improving modelling and specification of quantitative properties of embedded systems. Our main results are described below; further details are provided in technical deliverables D1.1-D1.4.

Task 1.1 - Model Process improvement

Our work in this task aims at developing methods for obtaining adequate and faithful models of embedded systems. The current approach can be characterized as "model-hacking" and very ad-hoc. We identified 7 properties that a "good" formal model should have (it has a clearly specified object of modelling; it has a clearly specified purpose and (ideally) contributes to the realization of that purpose; it is traceable such that model elements relate to requirements, assumptions, domain knowledge or system components; it is truthful such that relevant properties of the model carries over to (holds for) the object of modelling; it is simple - but not too simple; it is extensible and reusable; it has been designed to evolve and be used beyond its original purpose; and finally, it has been designed and encoded for interoperability and sharing of semantics). These properties have emerged from our and others extensive experience in applying formal modelling and analysis. To gain further experience with these properties, we reviewed our modelling effort on the Quasimodo case studies, and identified a number of situations where satisfaction of these properties lead to good models, and where their violation resulted in less usable models. It is our belief that a systematic and explicit check of these properties will lead to better and more usable models. Interestingly, this review also identified a number of notation and tool limitations that hindered a smooth modelling process. As tangible results a new Uppaal tutorial has been written with special emphasis on guidance of the modelling process.

Task 1.2 - Modelling of Quantitative System Aspects

We have mainly worked on four different behavioural aspects of quantities and combinations thereof: stochastic component-based modelling, probabilistic timed modelling, stochastic hybrid modelling, and resources modelling, and how these may be captured precisely and conveniently in different formalisms enabling subsequent analysis and synthesis. The most significant results are:

1. We propose the **Arcade**[2] **approach for Architectural Dependability Evaluation**. This work links existing ideas from concurrency theory and probabilistic systems to the area of dependability evaluation, opening up a new rich class of potential applications. We have established a link between **AADL**[3] (the Architecture Analysis and Design Language of the Society of Automotive Engineers) and the world of probabilistic automata and model checking.
2. We have shown that using an integral semantics, probabilistic and expected reachability properties are preserved for **Probabilistic Timed Automata** with closed, diagonal-free clock constraints. This allows checking a considerable set of interesting properties by first applying the integer semantics, resulting in a purely probabilistic model, and then using existing and proven probabilistic model checkers. We have developed a tool that automatically translates MoDeST-models (Modelling and

[2] Boudali, H.; Crouzen, P.; Haverkort, B.R.; Kuntz, M.; Stoelinga, M.I.A.; Architectural dependability evaluation with Arcade. IEEE International Conference on Dependable Systems and Networks, 2008.

[3] http://www.aadl.info

Description Language for Stochastic and Timed Systems) – if corresponding to probabilistic timed automaton – to input models for the PRISM[4] Probabilistic Symbolic Model-checker (and other tools) using the integral representation of time.

3. To enable modelling and exploration of variations of systems it is very useful to use parameters explicitly, rather than using fixed values. The solution to an analysis problem becomes a function of these parameters, whose ranges can then be explored and optimized. We have proposed **Parametric DTMC (Discrete Time Markov Chains)**, and developed practical techniques for computing the parametric unbounded reachability probability for Parametric DTMCs (with reward extensions and initial results for non-deterministic models).
4. Further, we have identified **Interactive Markov Chains** as an elegant and effective vehicle for developing compositional reasoning and abstraction techniques for probabilistic models for performance analysis, and have based on this developed promising simulation preserving abstraction techniques. We also introduce **Constraint Markov Chains** as a foundation for compositional component-based design of probabilistic systems.
5. We have extended probabilistic automata with continuous behaviour and safety verification of such **probabilistic hybrid automata**
6. We have studied and settled (decidability) for a number of problems for **Priced Timed Automata** including optimal infinite runs using mean pay-off or discounting metrics, model-checking as well as Pareto-optimal reachability for priced timed automata with multiple costs. Inspired by the Hydac case, a new line of natural decision and optimization problems have been identified with both negative and positive cost(-rates) on locations and transitions. (Un)decidability has been settled in certain settings but a large number of problems remain open. We have developed an alternative semantics of Priced Timed Automata where the accumulated cost (energy) must be kept within a lower and upper bound, and studied how algorithms can be developed. In particular we studied untimed lower bound problem, the timed (1 clock) lower bound problem, and extended the setting with exponential rate prices.
7. For the *combined* model of **Priced and Probabilistic Timed Automata (PPTA)** we provide an algorithm for cost-bounded probabilistic reachability analysis for PPTA, and define the conditions on which the problem is (un)decidable.
8. To enable compositional verification of large timed systems we have developed a complete **interface theory for timed input/output automata**. This framework supports constructs for refinement checking, consistency checking, logical and structural composition, and quotienting. Tool support is implemented on top of Uppaal-Tiga.

Task 1.3 - Design Notations and Tools

Our work on design notations and tools aims at describing quantitative aspects syntactically in design notations for embedded systems with accompanying tool support. Developing a quantitative notation that is intuitive to use for designers, that has a precise semantics, that allows it to be preserved when transformed into the formalisms supported by current analysis tools is a quite challenging task.

The nuances of the mentioned underlying mathematical models (e.g. semi Markov chains, Markov decision processes, or probabilistic timed automata) for combined probabilistic, real-time and cost features that are manipulated by Quasimodo tools, are too fine-grained to be directly used as specification means by an embedded systems designer. Hence, we also seek to make them accessible as back-end notations.

[4] www.prismmodelchecker.org

Important results are:

1. We have developed a stochastic extension of **Statecharts "StoCharts"**. This extension adds a probabilistic choice operator, random delays, and decoration with costs. The extension is accompanied by a clean and compositional semantics. A prototype tools allows this notation to be translated into the MoDeSt formalism and analysed using the Quasimodo tools. Further we have developed a translator for a subset of state charts into Uppaal timed automata. In particular, **UML** comments are translated into Uppaal declarations enabling simple but effective way of modelling analyzable timed systems using UML Statecharts.
2. We have developed a Markov decision process extension for STATEMATE[5]. This is implemented as a **plugin for STATEMATE** for design time evaluation of dependability properties through a compositional augmentation with probabilistic timing information.
3. We have worked extensively with the **Architecture Analysis and Design Language (AADL)** and formalized a significant subset of AADL, incorporating its recent Error Model Annex for modelling faults and repairs, enabling a component based and precise description of nominal hardware and software operations, hybrid (and timing) aspects, as well as probabilistic faults and their propagation and recovery. The underlying probabilistic extension is based on interactive Markov chains. This gives a solid basis for the tools for dependability and performance analysis that have been and will be developed. Specifically, we have added support for automated analysis of these aspects via our MRCM tool.
4. We have used Quasimodo tools and notations as background tools for (domain specific) industrial notations and tools suites. Also a domain specific language for design-space exploration of large parameter sets has been mapped to Uppaal.
5. We have indicated **a tool chain for Simulink**[6] for controller synthesis based on Uppaal-TiGa models, and have enabled co-simulation with Simulink and Uppaal-TRON.
6. We have proposed **Live Sequence Charts** as an easier means for industrial engineers to specify systems and real-time properties to be checked in Uppaal.
7. Our experience indicate that the more **mature QUASIMODO notations** and tools, like Uppaal-timed automata, can be applied in industrial practice, and has potential to become accepted as an industrial notation.

Conclusions:

Whilst a single overarching notation and tool has not fully materialized, we have demonstrated several links to industrial notations and tools that shows the practical applicability of the underlying Quasimodo notations and tools. Hence, Quasimodo has much to offer to future developments of general purpose and domain specific notations.

1.3.2 WP2: Analysis

The overall ambition of WP2 is to provide a wide range of powerful techniques for analyzing models with (possibly multiple) quantitative information. WP2 has produced a large collection of significant results on model-checking, abstraction/refinement, and approximate analysis far beyond what was originally planned.

Selected significant results (in arbitrary order of relevance):

[5] http://www.ibm.com/software/awdtools/statemate/

[6] http://www.mathworks.se/products/simulink/index.html

1. Decidability and efficient data-structures supporting Pareto-optimal reachability for multi-priced timed automata.
2. Heuristic guided search engines for exploration of timed automata using the Russian Dolls principle.
3. Counter-examples: efficient generation algorithms, compact representations, and counter-example-guided abstraction refinement of MDPs (Markov Decision Processes).
4. Advances in three-valued abstraction of CTMDPs (Continuous-Time MDPs) resulting in the transient analysis of the largest tree-based queuing network ever.
5. Application of SMT-solving (Satisfiability-Modulo-Theory) to discrete-time probabilistic hybrid systems.
6. Discrete-event simulation of CSL (continuous-time stochastic logic) model checking on CTMCs (Continuous Time Markov Chains).
7. Advances on Segala's probabilistic automata, e.g., syntactic reduction techniques, extension with exponential distributions and compositional abstraction.
8. A complete specification framework for probabilistic automata, timed systems, and weighted systems.
9. Statistical model checking for networks of priced timed automata.
10. Approximate algorithms for time-bounded reachability in CTMDPs.
11. Approximate parameter synthesis algorithms for MDP, DTMC and CTMC verification.

The results are further described below; we refer to the deliverables D2.1-D2.5 for details.

Task 2.1 - State space representation and model checking

The main focus has been to consider a model with multiple quantitative aspects, viz. continuous time (as in timed automata), costs, and probabilities. For improvements to the analysis of pure timed automata new heuristic search algorithms have been implemented in the tool Uppaal.

Substantial effort has been invested into extending **timed automata with resource information**. In particular we have developed efficient techniques for priced timed automata for computing optimal infinite schedules, and have designed a multi-priced zone data structure supporting optimal reachability for multi-priced timed automata. Several contributions have been made to the verification of energy constraints: the accumulated cost during any execution must stay between a given upper and lower bound. A connection to mean pay-off games has been established, and exponential prices have been considered (where cost grows exponentially rather than linear with elapsed time).

We have also extended **timed automata with probabilistic** information. Support for probabilistic reachability analysis for probabilistic timed automata using a symbolic abstraction/refinement partitioning algorithm has been designed and implemented as a branch (Uppaal-Prob) of the tool Uppaal.

A **combined probabilistic and priced extension of timed automata** (PPTA: probabilistic priced timed automata) has been considered and promises to be an important model for representing real-time systems with resource constraints where e.g., resources are subject to failures, and where timed systems are subject to random phenomena. The central question has been to consider decidability of the so-called cost-bounded probabilistic reachability (CBPR) question, i.e., is the probability to reach a set of goal states (within a deadline) with cost at most *c*, higher than probability *p*? Classes of PPTA are identified for which this problem is undecidable and classes for which it is decidable. A prototypical tool (named Fortuna) has been realized which involves several improvements to the underlying data structures of priced timed automata model checking.

Continuous-time Markov chains (CTMC) model checking has been enriched with the first algorithm for the verification of CTMCs against linear real-time specifications that are given as deterministic timed automata. The main technical achievement has been a reduction of this model-checking problem to the computation of probabilistic reachability properties in a (simple variant of) piecewise deterministic Markov process. For **the non-deterministic variant of** CTMCs (CTMDPs) model checking, an investigation and classification of timed schedulers have been made. In this setting, time-abstract schedulers that are used for MDPs are insufficient, and the main question is which time information is important for timed schedulers to yield maximal (and minimal) reachability probabilities. It has been established that total time-positional schedulers suffice. Such oracles need the current state together with the total time that has elapsed so far to steer their decisions. In addition, major progress has made towards the approximate verification of time-bounded reachability probabilities in CTMDPs. This is a long-standing open problem in probabilistic model checking. Two approaches have been developed that yield promising results.

The variant of Segala's probabilistic automata, baptized **Markov automata,** incorporates labelled transitions that yield a probability distribution over states, as well as transitions labelled with parameters of exponential distributions (i.e., randomly timed transitions) that yield states as their target. The central question has not been to define the model, but instead to come up with a notion of weak bi-simulation that fulfils a number of criteria such as: (a) congruence property with respect to parallel composition, enabling component-wise reduction, (b) backward compatibility with weak bi-simulation on IMCs and probabilistic automata both sub-models of Markov automata, and (c) an equivalence satisfying some natural laws.

The reduction techniques for **Markov Decision Processes with data** are focused on syntactic transformations that are aimed at reducing the state space before generating it while preserving their functional and quantitative properties. We have defined an intermediate format and efficient transformations that map parallel processes to such format. The format allows for several optimisations that may yield state space optimisations of up to 95%. This has been complemented by confluence reduction techniques, an approach akin to partial-order reduction, which preserves (branching) probabilistic bi-simulation. Reductions obtained in this manner exceed those by partial-order reduction. In addition, bi-simulations have been linked to compositional proof systems for a general class of continuous-time continuous-space models.

Task 2.2 - Abstraction, Refinement, and Compositionality

Task 2.2 is concerned with analyzing very complex models — either due to their size or the type of quantitative aspects considered — where efficient techniques are needed for transforming the models into manageable abstract models allowing for the analysis in question to be settled at least partially. To obtain truly scalable techniques we have exploited compositionality and abstraction. Here, the idea is to exploit abstraction in a component-wise manner, thus avoiding the generation of the state space of the entire model. This principle has been successfully applied to timed automata, as well as interactive Markov chains, basically CTMCs equipped with separate action transitions.

Counter-example generation algorithms have been developed, realized, and integrated into the predicate abstraction approach, yielding a CEGAR **(Counter Example Guided Abstraction-Refinement)** setting for probabilistic programs, i.e., programs with random assignments. This allows for the automated verification of parameterized systems. Besides, compact representations of counter-examples have been developed using regular expressions. Further results that are relevant to abstraction are the development of efficient algorithms for checking probabilistic simulation. The worst-case time complexity of these new algorithms is quadratically faster than the algorithms known so far. The key to this result is the use of parametric network flows. For monolithic abstraction, it has been shown that game-based abstraction is optimal (in the sense of an abstract-interpretation setting), and that abstraction of infinite CTMCs is practically feasible.

The base for abstraction is a formal notion of equivalence or pre-order between processes. In that respect, we have achieved **quantitative versions of trace inclusion, trace equivalence, and (bi)simulation** in a setting in which propositions are interpreted quantitatively. Further, polynomial-time algorithms have been developed for checking language equivalence of labelled Markov chains, and it is shown that this problem for labelled MDPs requires schedulers with infinite memory. Support for various refinement relations between timed automata models has been obtained using reductions to timed games, allowing the branch Uppaal-Tiga to be used.

Complementary abstraction techniques have been fully developed using **predicate abstraction**, an approach that has been proven quite successful for software model checking, and the framework of three-valued abstraction in traditional model checking has been combined with that of modal transition systems and successfully applied to Segala's probabilistic automata. The latter resulted in a complete specification framework for probabilistic automata. Similar work has been done for timed systems, which is combined with new on-the-fly algorithms for checking Büchi objectives of two-player timed games using zones as symbolic representation. Modal transitions systems have also been used for weighted systems, resulting in a completed specification framework for weighted transition systems.

The theoretical framework of **three-valued abstraction of continuous-time Markov chains** has been realised in a prototypical tool, and used for experimentations on case studies from classical queuing theory. In particular, it has been shown that by adequate abstraction of the state space, transient probabilities in so-called tree-based quasi birth-death processes (a continuous variant of probabilistic pushdown automata) can be obtained for extremely large state spaces, up to 10^{300} states by accurate abstraction of about 500,000 states. Such results clearly show the potential of this approach.

Finally, progress has been made on the verification of safety properties of probabilistic hybrid automata using aggressive abstraction techniques, and very useful results have been obtained for parametric model checking of CTMCs, DTMCs, and MDPs, where the focus is on which parameter ranges ensure the validity of a given desired quantitative property.

Task 2.3 - Approximate Analysis Techniques

In this task fruitful results have been established for model checking probabilistic models using **discrete-event simulation** rather than with numerical analysis techniques. Theoretical results have been achieved together with algorithms, and experiments have carried out to compare the results with model checking based on hypothesis checking, another variant of simulation. By means of extensive experiments, the drawbacks and benefits of discrete event simulation compared to hypothesis testing have been investigated, and reported. The discrete-event simulation techniques have also been realized in the model checker MRMC. These results are complemented by a minimization algorithm for acyclic phase-type distributions. Such minimization is important to minimize the state-space representation of non-exponential distributions that are approximated by phase-types.

Approximate parameter synthesis techniques have been developed for parametric MDPs and PCTL (Probabilistic Computation Tree Logic) formulas. By means of this technique, a hyper-rectangle is approximated such that all MDPs obtained by instantiating with parameter values inside this shape satisfy a given PCTL formula. Secondly, major progress has made towards the approximate verification of time-bounded reachability probabilities in CTMDPs, a continuous-time version of MDPs. This is a long-standing open problem in probabilistic model checking. Two approaches have been developed that yield promising results.

In addition, **statistical model checking** algorithms have been developed and implemented for networks of stochastic timed networks, an automata-based algorithm for CSL model checking has been designed, and PCTL model checking of discrete-time stochastic hybrid systems is tackled by an approximation yielding DTMCs, such that error bounds on the satisfaction of reachability probabilities can be given.

Conclusions. All the main objectives of WP2 that were planned in the Description of Work have been successfully fulfilled and surpassed.

1.3.3 WP3: Implementation

WP3 have been organized according to two main tasks: Task 3.1 - Controller Synthesis and Scheduling and task T3.2 - Implementability and Code Generation. We highlight below the main scientific contributions that have been obtained in those two tasks.

Task 3.1 - Controller Synthesis and Scheduling

Games with mean-payoff and energy constraints. When modelling control problems for embedded systems, we need to take into account a variety of quantitative aspects like energy consumption, memory consumption, etc. As a consequence, we need to consider games with quantitative objectives (and not only Boolean objectives). We have in particular provided new more efficient algorithms for mean-payoff games, and we have shown reduction from mean-payoff games to energy games and vice versa. We have studied timed automata games extended with energy constraints, multi-dimension extensions of mean-payoff and energy games. Those results have been summarized in the deliverables D3.4 and D3.7.

Timed games for solving scheduling problems. We have shown how timed automata and timed game automata can be used to model and solve rich scheduling problems. Timed automata allow us to model scheduling problems that are out of reach of more classical scheduling theory methods, e.g. we can model precisely the use of shared resources, we can handle nondeterministic arrival time of tasks, preemption, etc. We have shown that our automata-based techniques can be used successfully to show that complex systems can be correctly scheduled while they were declared non-schedulable by classical techniques. In particular, we have applied that on large case studies provided to us by Terma (from the spatial application domain). General modelling patterns for scheduling problems have been defined to easy the modelling task. Those contributions are summarized in deliverable D3.5.

Games with imperfect information. When modelling embedded controllers, we need to take into account the view that the controller has on the system or the environment to control. Usually, controllers acquire information about the system and its environment using sensors with finite precision. As a consequence, to faithfully model control problems in that context, we need to consider game with “imperfect information”. Indeed, we are looking for control strategies that use only the information available to the controller, i.e.

that the controller can acquire with its sensors. Games with imperfect information are usually computationally more expensive to solve. We have studied several classes of models with imperfect information and studied the decidability frontier for those models. We have also defined tailored data-structures and symbolic algorithms for solving them. The contributions about games with imperfect information have been summarized in deliverables D3.3 and D3.4.

ATL with strategy context and bounded memory strategy. The logic ATL has been introduced as a general temporal logic to express control objectives. We have obtained new results on the expressiveness of the logic and we have proposed alternative semantics for that logic. We have also studied the problem of synthesizing winning strategy that use bounded memory. Those results are summarized in deliverable D3.4 and D3.7.

The Hydac case study. This case study is based on a product which has been developed by HYDAC, but is not yet available on the market. The problems and tasks for this concrete product are also easy transferable to other products, so the HYDAC has a great interest in the knowledge transfer provided by this EU-project. The product is an accumulator-charge controller (ACC) which optimizes the energy and the wear of the used components, especially the pump. For this case, we managed to enforce safety properties in an efficient way, such that the controller consumes nearly the least possible amount of energy. This is obtained in a systematic way using a chain of automatic tools for the synthesis (Uppaal-Tiga), verification (PhaVer[7]) and simulation (Matlab/Simulink). With this case study, we have been able to show the applicability of the controller synthesis methods that we have developed in WP3 and it has also allowed us to formulate new relevant research questions. The case-study has been described in deliverable D3.7, and also in deliverables D5.2, D5.5 and D5.7 (see also the summary of WP5 for additional details).

Task 3.2 - Implementability and Code Generation

Robustness analysis of timed automata Several notions of robust semantics for timed automata and their relation with implementability have been studied. In particular, we have shown that the classical semantics for timed automata is not robust. This implies that when a timed automata model has been shown correct for this fragile semantics, it may not be implementable because the slightest deviation in timing can introduce new incorrect behaviours. As slight deviations cannot be avoided when implementing a timed model, correctness results cannot be transferred from the model to the implementation with the classical semantics. To avoid this problem, several robust semantics have been proposed and it has been shown that correctness properties established on models with those robust semantics can be transferred to implementations in a systematic way. Verification algorithms have been adapted to the robust semantics. Efficient data-structure and symbolic algorithms have been defined and implemented in the tool Uppaal. Those results have been published in a large number of papers and have already had a large influence on the scientific community working with timed automata; see also deliverable D3.1 and D3.2.

From models to code for real-time controllers Methods for generating real-time code from automatically synthesized winning strategies have been defined, implemented, and applied to a demonstrator. This

[7] http://www-verimag.imag.fr/~frehse/phaver_web/

demonstrator shows that automatic code generation from high-level abstract models of a control problem using Uppaal-Tiga, Simulink and Real-time Workshop[8] can be realized; see also deliverable D3.6 and D3.7.

Conclusions.

All the main objectives of WP3 that were planned in the Description of Work have been successfully fulfilled.

1.3.4 WP4 Testing

Testing is the system quality control mechanism that is dominant in practice. It is estimated that 30-70% of all project resources are spent in the testing phase. Model-based testing (MBT) is an innovative testing technique that is able to drastically reduce these costs, by providing methods to automatically generate, execute and evaluate test cases. A well-developed and rich theory for model-based testing exists for control-dominated systems.

The goal of WP4 is to study the possibilities and challenges of extending the existing control-dominated testing techniques towards quantitative models, leading to a quantitative model-based testing theory, methods, and tools, which allow generating, selecting, executing and analysing tests from models which combine control with real-time, continuous data, and stochastic requirements. The aim is to improve the overall quality and effectiveness of testing by using suitable quantitative models as the basis for generating sound and correct test cases.

Indeed, the Quasimodo project has enriched existing, control-dominated MBT techniques and extended them with a rich palette of quantitative system aspects. This led to an efficient and effective testing framework for testing quantitative embedded system aspects, which is provably sound and complete. Below we summarize these results; see delivables D4.1 to D4.6 for details. The techniques have been integrated into the model-based testing tools Uppaal-Tron, JTorX, and TorXakis, see work package 5. Extensive case studies (see WP 5 as well) with industrial partners within and outside the project have convincingly shown the practical applicability of these methods, and the advantage of model-based testing over traditional testing techniques. Finally, the ESI/UT Spinoff Axini uses several project results at a daily basis with its customers.

Task 4.1 - Test Generation

The task on test generation is concerned with algorithms to derive test suites from quantitative system models. In particular, the following activities were identified. (i) the definition of suitable notions of correctness (conformance) for quantitative models; (ii) the development test generation algorithms that are formally sound and complete wrt. these notions of correctness; (iii) extension of existing coverage metrics and test selection techniques; (iv) the development of efficient test generation tools and components; (v) the study of the relation between stochastic model-based testing and other techniques like traditional performance testing, and statistical model checking.

Achievements with respect to these activities have been centered around the various quantitative models.

[8] http://www.mathworks.se/products/simulink-coder/index.html

Timed testing. Groundbreaking progress has been made in the area of timed testing. First, a family of timed conformance relations (timed input/output conformance, t-ioco) have been defined, which mathematically pin down what it means for a timed system under test (SUT) to conform to its specification. Based on these conformance relations, novel online and offline algorithms for test case evaluation have been defined, leveraging the enormous success of real-time model checkers to real-time testing. Particularly fruitful is the innovative use of timed games here, which provide a natural and efficient way to obtain test cases with certain purposes (test a certain feature, or part of the system) or with certain optimality criteria (fastest, lowest costs) etc. This approach has been explored both for cooperative games (where the tester and the SUT work together to achieve a certain goal), as well as for competitive games (where the tester and the SUT obstruct each other). Also, timed testing under partial observability has been explored in depth.

Symbolic testing. Important progress has been made with respect to symbolic treatment of (potentially infinite) data domains. Several symbolic methods have been developed to efficiently represent and manipulate data domains. In particular the use of Symbolic Transition Systems has been viable solution here, leading to drastic gains in time and memory consumption during the test generation and execution phase.

Hybrid testing. Uppaal has recently been extended with so-called stopwatches. These are continuous clock variables that can be stopped (by setting its derivative to zero) and resumed (setting its derivative back to one), thus providing a means for integration over time. Uppaal is able to perform an (over-approximate) reachability analysis for such timed automata with stopwatches. Earlier work has shown that reachability analysis of linear hybrid automata can be reduced (via a translation) to reachability analysis of timed automata with stop watches. Since, we have incorporated stopwatches in the testing tool Uppaal-Tron, (resulting in a slightly over approximated state-set). This gives a path to testing linear hybrid automata with the existing tool.

Other interesting and relevant results have been obtained by using Uppaal-Tron for hybrid testing. Uppaal-Tron does not support continuous variables, but integer variables can be updated at certain time intervals defined by the clock variables. In this way, continuous variables can be emulated. These techniques turn out to work well in many cases.

Probabilistic Testing. A probabilistic model contains information that expresses with what probability the system executes a given transition; this may by an input given to the system, an output delivered by the system, or an internal computation step. Thus it may express information about distributions of both expected uses and expected responses. We have worked on probabilistic testing theories that support several applications in model-based testing, including (1) Operational Usage profile testing/statistical usage testing, where test input sequences are generated in correspondence with the distributions of the model such that they reflect the expected use of the system. This is the basis for performance evaluation and reliability estimation. (2) Guiding: Guiding either towards an area in the model that is of particular interest or is particularly critical, or to increase coverage of the model (utilizing information of likely outputs) and (3) Statistical hypothesis testing: Here the goal is to estimate the probability of conformance. Techniques used here are embeddings of the resulting mathematical objects into partially observable Markov decision processes (POMDPs).

Combinations. A very important topic is the integration of the testing frameworks above. Considerable progress has been made in this direction: symbolic methods have been explored for timed testing, probabilistic methods have been combined with timed testing in the context of statistical real-time model checking, and time, symbolic and probabilistic features come together in the MoDeST language.

An important milestone is the integration of Uppaal-Tron with external tools. Simulink is one of the most widely used system design tools, and PhaVer/SpaceEx is a state-of-the-art model checker for hybrid systems. The integration with Simulink and PhaVer enables extensive co-simulation of hybrid systems, and of system aspects that are not supported by Uppaal-Tron. Since these results are very promising, connecting to external tools with specific strengths seems a viable way to go.

It should however be noted that dealing with one quantitative modality (real-time, quantitative data, probability) is already extremely challenging. Hence, full integration of the developed framework is foreseen in the (near) future.

Test selection and test coverage. Testing is inherently incomplete, since complete testing requires infinitely many scenarios. Therefore, it is of vital importance to come up with efficient test suites that have high impact. The test coverage measures we have developed for quantitative systems are instrumental here: they assess which parts of the SUT and/or system specification have been examined by the test suite. A very important topic we tackled concerns risk-based testing. Here, we give a notion of coverage in a probabilistic setting, and we quantify the probability (and their impact) of remaining faults in a SUT that passed a given test suite.

Also, we have developed test generation methods for timed automata with complete edge coverage, and subject to several optimization criteria. Finally, we assessed the impact of coverage criteria in practice, and compared the impact of three well-known white-box coverage measures in three software projects for a software development company.

Task 4.2 - Approximate Testing

Approximate testing is concerned with dealing the imprecisions that come into play when handling quantitative information from a continuous domain (time, physical quantities, and continuous data). For instance, the observed timing of the events may not coincide with the actual timing of the occurrence of the events. The goal of Task 4.2 is to develop a testing framework that is able to cope with these issues. This task has strong ties with T3.2 since code generation faces the dual problem of implementability of abstract models on real physical platforms.

For Task 4.2, the following activities were identified: (i) the definition of quantitative notions of correctness (conformance); (ii) the extension of the model-based testing framework with approximateness; (iii) the investigation of discretisation; (iv) the study of the relation between approximate testing and partial observability.

A test framework for measurement imprecisions. We have done seminal work in developing a notion of quantitative conformance (q-ioco), which expresses the level of conformance as a value in the range [0,1], rather than as a boolean. We have developed online as well as offline test case generation methods that estimate the conformance level between a specification and the system under test. Alternatively, the maximal slack in conformance can be given as an input parameter to the test case derivation algorithms.

Testing under uncertainty. Another source of approximativity in the ioco-approach to conformance testing is rooted in the communication between the testing tool and the SUT: the synchronicity assumed by the testing theories can only be approximated by asynchronous communications. The handling of these aspects is the task of the Adaptor. But although a crucial component, there is no systematic method of obtaining one. We have created a more generic Adaptor, facilitating easier communication with a new SUT in the future. This is done in the context of a LEGO bricks sorting machine.

In a real-time setting, the MBT machinery often interacts with the system under test on the basis of discretised values. At the same time, it must evaluate the timeliness of the SUT. To account for these complications, the testing process needs to be made adaptive to uncertainty in the implementation's responses, but in a sound and effective manner. We have developed a variety of techniques like time over-approximation and value over-approximation to approximate the uncertainty and imprecision properly and effectively, and incorporated these in the Uppaal-Tron testing environment.

Approximative learning. MBT relies on the existence of a model of the SUT. Since this model is not always available (especially for legacy software), Quasimodo has embarked on concerted efforts to turn the MBT testing technology into an automata learning technology. The original approaches to automata learning relies – as a crucial component – on a component that is able to decide language equivalence queries. This is approximated in the automata learning approach by an MBT testing tool that feeds the SUT with long test sequences, thereby approximating the original question.

Furthermore, MBT technology can also be used to approximatively learn probabilistic specifications. For complex systems that are only partially observable via their interactions with the user, it might be unrealistic to assume that an adequate deterministic model exists.

We have made it possible to learn probabilistic quantitative models of a system's observable (and possibly non-deterministic) behaviour. The data we require for learning only consists of previously observed system behaviours, that is obtainable through active or passive testing.

Conclusions

From the work described above, we conclude that all activities of WP4 have been fulfilled with great success: all activities have been accomplished with great success. Also, truly spectacular results have been obtained in timed testing, coverage, and the use of techniques from machine learning in the MBT technology. Task 4.1, activity (v), the comparison between stochastic model-based testing and other techniques gained less attention, but we note that we have already used a wide variety of techniques from related areas within our quantitative MBT machinery.

Furthermore, almost all techniques developed in Task 4.1 and Task 4.2 have been implemented in the model-based testing tools Uppaal-Tron and JTorX. Extensive case studies with industrial partners within and outside the project have convincingly shown the practical applicability of these methods, and the advantage of model-based testing over traditional testing techniques. Thus, we conclude that WP4 has developed an efficient and effective testing framework for testing quantitative embedded system aspects.

1.3.5 WP5: Case Studies, Tools, Dissemination and Exploitation

Work package WP5 is concerned with case studies (Task 5.1), tools (Task 5.2), and dissemination and exploitation (Task 5.3).

Task 5.1 - Case Studies

The goal performing case studies is to demonstrate and challenge the usefulness of the Quasimodo methods and tools, and assess their strengths and weaknesses, by applying them to realistic problems. In the Description of Work, three case studies were initially identified, one from each of the industrial partners:

1. The Accumulator Charge Controller, provided by HYDAC;
2. The MyriaNed Wireless Sensor Network, provided by CHESS;
3. Attitude and orbit control software for satellites Hershel and Planck, provided by TERMA.

One additional case study from CHESS was added before the start of the project, one additional case study was provided by end-user panel member ASML, and one was added from the joint project Octopus in which, amongst others, OCE, ESI, and ESI/RU participate:

4. The Self-Balancing Scooter, provided by CHESS;
5. A Rapid Input-Output packet switch, provided by ASML;
6. Adaptive scheduling of data paths , provided by Octopus/OCE;

The Quasimodo methods, techniques, and tools were also applied to a number of smaller case studies, mostly in cooperation with related research projects. These case studies and their results described and summarized below. Details about the case studies have been reported in the deliverables: D5.2: "Preliminary description of case studies"; D5.5: "Case studies: Models", D5.7: “Case studies: validation”; D5.10: “Final Report: Case Studies and Tool Integration”.

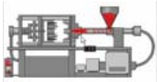
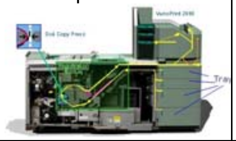
Case study	Problems	Results
Hydraulic pump Ctrl. 	– Synthesis of Controllers – Software Testing	– Application of our tool suite for automated controller synthesis resulted in a safe controller with 33% improved energy efficiency – Model-based testing revealed significant defects in an existing implementation.
MAC protocols in Wireless Sensor Networks 	– Modelling – Timing analysis – Performance analysis – Software Testing	– Real-time model-checking identified a design-flaw in the studied MAC protocol (demonstrated that clocks may become de-synchronized in certain topologies). – Message collision rates and effectiveness of collision detection were analysed using stochastic models and discrete event simulation – Real-time model-based testing identified unexpected behaviour during start-up and re-synchronization
Satellite attitude and control software 	– Schedulability Analysis	– A framework was developed for model-based schedulability analysis that may be more optimistic that classical response time analysis
Self-balancing Scooter 	– Specification and modelling	– A timed automata model was made by industrial engineers. This gave them a big gain in their understanding of the system, and made specifications more precise.
Adaptive scheduling of data paths 	– Analysis of worst case latency – scheduling	– Uppaal was used to determine worst case latency for scan jobs with uncertain arrival times. – Uppaal-Tiga was used to compute optimal adaptive scheduling strategies.
Rapid I/O packet switch	– Task allocation – Verification of worst case latencies	– Different configurations simulated and formally verified wrt. satisfaction of periodic timing constraints. Simulation results could be confirmed with model-checking (for reduced sized models) thus giving high confidence in the results. – Verification of deadlock freedom and satisfaction of user defined properties.
Electronic Passport	– Testing	– MBT using TorXakis shown feasible for this application domain. Several points of under- and unclearly specified requirements identified. Deep testing performed.
Software Bus	– Specification and Design – Testing	– Model based development helped create a well-tested software bus with a maintainable architecture with limited effort (17% of development time) for modelling and testing. – MBT identified 5 subtle defects that would be hard to find using conventional techniques.
Zeroconf Protocol	– Modelling – Verification	– Model derived from the RFC Specification (Request for Comments) and model-checked using Uppaal. Many imprecisions and ambiguities identified.
Impact of GSM-R on Railway Capacity	– Performance Analysis	– Stochastic models of the line capacity with GSM communication developed, analysed and compared.
Trust anchor Update in Autotrust	– Testing	– Uppaal-Tron shown feasible for this domain; increased coverage compared to manual testing
Printer Controller	– Testing	– Model-based testing using JTorX and TorXakis. Shown fesible for this case, and some defects identified. Quasimodo techniques for handling concurrency and non-determinism and data were essential for this case.

Table 1: Summary of case studies

1. Accumulator Charge Controller (HYDAC)

The Accumulator Charge Controller (ACC) is used in molding machines, and its purpose is to press oil in hydraulic components under high pressure. The main requirements are to keep the accumulator within safe pressure margins, and to optimize energy and wear. The case study consists of first analyzing a newly developed HYDAC control algorithm for the ACC, in particular for optimality with respect to energy consumption, and second to test the control algorithm with automatically generated tests from a formal model.

For analysis and optimization of the ACC algorithm several Simulink-Stateflow models (Matlab), Timed-Gamed Automata models (Uppaal-Tiga), and PhaVer-models were developed. The Simulink-Stateflow models, using the simulation capabilities provided by Simulink, enabled us to get various insights into the functioning of the different components. Moreover, with the Simulink-Stateflow models we could experimentally validate (no proof) some properties: the HYDAC controllers always keep the pressure in safe margins, and the new HYDAC ACC controller always uses considerably less energy than the original HYDAC 2-point controller. The Timed-Gamed Automata and PHAVER models were used for both analysis and controller synthesis. The results show that the controller synthesized with Uppaal-TIiga is robust. Moreover, the simulation reveals that the performances of the Uppaal-Tiga synthesized controllers provide a vast improvement over the new HYDAC ACC controller (33%) and over the original HYDAC 2-point Controller (45%).

We have worked on model-based testing of the ACC controller, in particular to test for safety properties. A Matlab/Simulink implementation of the controller was tested against a formal model derived from the earlier formal analysis work. A test environment was developed that connects the model-based tester developed in Java to the Matlab/Simulink implementation. A few design flaws and bugs in the controller were detected and reported to HYDAC. The experiment showed that safety strongly depends on the assumptions that are incorporated in the model about oil consumption. The feasibility and benefits of automatic model-based testing were clearly demonstrated.

In this case study we used several techniques and tools: controller synthesis, model-based analysis, simulation, and model-based testing. The techniques proved usable and very useful; HYDAC is currently investigating how to incorporate the results into their product. A Quasimodo Book chapter explaining the controller synthesis results has been written.

2. Wireless Sensor Network (CHESS)

The MyriaNed Wireless Sensor Network (WSN) provided by CHESS, and in particular its gossip Medium Access Control (gMAC) protocol, was used as case study for various kinds of analyses.

We analyzed the clock synchronization between nodes specified in the gMAC protocol by means of model checking with Uppaal. Flaws in the synchronization protocol were detected: a static, fully synchronized WSN network may eventually become unsynchronized when using the median synchronization algorithm proposed by CHESS. This result was also reproduced experimentally on a network of real nodes. Improvements have been proposed and analyzed, yet, still not all synchronization problems were solved. It should be noted that these synchronization problems only occur in very rare situations. In addition, a full, parametric analysis of the protocol for the special case of cliques (networks with full connectivity) was performed, from which constraints on the parameters were derived that are necessary and sufficient for correctness. These results were checked with the proof assistant Isabelle.

Evaluation of this case study shows that clock synchronization is very challenging for quantitative formal methods. The models and their analysis resulted in a much better understanding of the protocol. Model-checking with Uppaal is applicable, and is effective in finding design flaws, but it must be done with care. Powerful abstractions, and careful consideration of what to model, and what not, are necessary to cope with the complexity of the problem and make model-checking feasible.

Another aspect of WSN analysis was to gain insight in the end-to-end behaviour of MyriaNed protocols, study collision rates, the effectiveness of the collision detection mechanism, and how this affects performance and energy consumption and message propagation speed. For this purpose, several quantitative, probabilistic models were developed in the language MoDeST, in various stages of detail, and analyzed using the stochastic discrete-event simulation tool Möbius[9]. Understanding of WSN behaviour was greatly improved, interesting, yet not completely unequivocal results were obtained; see D5.10. Evaluation shows that discrete event simulation is applicable, improves understanding of the behaviour, and gives interesting results, but that interpretation of these results is not always straightforward. Constructing a model puts the question of what to take into account to obtain reliable results which can be compared with practical experiments, e.g., radio reflection was not incorporated in the models, but turned out to be an important issue in practical experiments.

We extended this work to include model-based testing (MBT) for the WSN. A protocol conformance test of the gMAC protocol layer of a single WSN node was performed using three Quasimodo MBT tools: Uppaal-Tron, JTorX, and TorXakis. This test was performed on the gMAC production code in a host environment in simulated real-time. For MBT, first a model of the required gMAC protocol behaviour has to be developed. This turned out to be difficult, due to lack of documentation. Consequently, we started with a very abstract model, and then tried to refine this model based on observations made during the test with the abstract model, i.e., a kind of ad-hoc 'model learning'. At the end a reasonably precise model was obtained with which many long test cases were executed. This learning and testing process helped the testers as well as the gMAC developers to understand the intricacies of the gMAC protocol behaviour, especially start-up and re-synchronization behaviour, and to detect some unexpected behaviours. Moreover, it triggered, and provided practical input to the research on model learning; see D4.4: 'Approximate Testing'. A Quasimodo Book chapter is written based on the WSN MBT experience.

A fourth direction of WSN research was a practical case study that investigated the suitability of the CHESS WSN for real-time applications. A wireless bike braking system was designed, modelled, simulated, verified, constructed, deployed, and (manually) tested. Probabilistic analysis using MoDeST, *mcpta*, *modes*, and PRISM showed some critical safety issues, such as the amount of delay before braking, which were confirmed by experiments on the bike. This is one of the first uses of PTA model checkers on real systems; see D5.10.

Altogether, the WSN case study proved fruitful and very successful. Different aspects were analyzed using different techniques and tools: model-checking, discrete event simulation, probabilistic model checking, and model-based testing. Making models already greatly helps in increasing understanding and asking the right

[9] https://www.mobius.illinois.edu/

questions to the developers, because complete documentation of the system was missing. Automated analysis then further improves this understanding. The Quasimodo tools Uppaal, Möbius, Uppaal Tron, JTorX, TorXakis, MoDeST, *mcpta*, and *modes*, and the related tool PRISM, were applicable to this case study and gave valuable results. All three aspects of analysis are reflected in a Chapter in the Quasimodo Book.

3. *Attitude and orbit control software (TERMA)*

Within the Herschel and Planck satellite systems the ACC ASW software is responsible for satellite attitude and orbit control. We worked mainly on schedulability analysis using Uppaal. Schedulability analysis was so far performed by TERMA using classical worst-case response-time analysis. The conclusion of using Uppaal is that schedulability analysis can be approached as a model-checking problem, and that Uppaal can incorporate more details about tasks and therefore is able to produce more realistic and more precise response times. Most importantly, it shows that the TERMA system is indeed schedulable in contrast to a negative result from the classical response time analysis, which is over-pessimistic, and which has never been observed in neither stress testing nor deployment. The experiences resulted in a chapter for the Quasimodo Book.

Towards the end of the project a model-based testing (MBT) activity has started to test the software components responsible for the communication link between the satellites and the earth via telemetry commands. Models of this behaviour have been developed for use with the MBT tool Uppaal Tron. Actual testing has not progressed far enough yet to draw specific conclusions with respect to model-based testing.

4. *Self-Balancing Scooter (CHESS)*

A high-level model of the behaviour of a self-balancing scooter under development by CHESS (Chessway/Segway) was developed in Uppaal. This model was of great help in increasing understanding of this supposedly simple system, and in making the specification more precise. Although a couple of (simple, qualitative) properties were verified, it was the modelling activity itself, and making ideas precise by expressing them in timed automata, that was the big gain in this case study. These results are presented in a Quasimodo Book chapter. Since there were not that many quantitative aspects in the developed model, we decided not to continue this case study.

5. *Adaptive scheduling of data paths (OCE)*

The OCE case was performed in close cooperation with the Octopus project[10] in which, among others, OCE, ESI/RU, and ESI participate. It concerns the data path of a printer/copier encompassing the complete path of the image data (the bit stream) from source (e.g., the network) to target (the imaging unit). Using Uppaal, the dynamic behaviour of the memory bus was modelled in Timed Automata, and the worst case latency (WCET) was analyzed of scan jobs with uncertain arrival times in a setting where the printer is concurrently processing a stream of print jobs. It was shown that Uppaal can handle the complexity of dynamic memory bus behaviour in a realistic model of a complex industrial application, though a couple of abstractions had to be made in order to deal with state-space explosion. In addition, Uppaal-Tiga was applied to automatically compute optimal adaptive scheduling strategies.

[10] http://www.esi.nl/octopus/

Based, among others on the results of this case study, the Octopus project will develop a high level language for describing designs, together with a translation to Uppaal, so that communication with the engineers will be facilitated, the chances of introducing errors in the Uppaal model will be reduced, yet designs can be formally analyzed.

6. Rapid Input-Output packet switch (ASML)

The case study on the Rapid Input-Output packet switch was provided by ASML in the context of the ESI project WINGS[11]. The project concerns a multi-processor platform where processors are interconnected by Rapid Input-Output (RIO) packet switches. The main challenge is how to map a specific application on the platform such that periodic timing constraints (all packets are delivered in time) are met. The goal was to formally model-check, using Uppaal, initial approximate results about worst-case case latencies obtained with simulation using POOSL (Parallel Object-Oriented Specification Language) in WINGS. For this, we transformed the POOSL model to a network of Timed Automata for Uppaal. With this Uppaal model we formally verified some functional behaviours such as deadlock freedom as well as worst–case packet latencies. Results obtained via simulation were confirmed with model-checking. Although the approach works in principle, the required properties could only be verified on systems of reduced size, due to scalability issues, despite applying heuristics and improving abstractions in Uppaal.

In a second effort, initial experiments were started to check the correctness of the Uppaal model with respect to the POOSL model by means of model-based testing (MBT). The POOSL model, being the SUT, was tested against the Uppaal model that served a specification. Results look very promising but more work is needed to make this a completely viable way of checking models in different languages with respect to each other.

7. Additional Case Studies

A number of additional smaller case studies were performed, mostly in close cooperation with other projects. In these case studies the Quasimodo methods and tools were applied, providing valuable feedback about tools and methods. Details about these case studies can be found in D5.10.

Model-based testing of electronic passports. The access protocols for the new, Dutch biometric electronic passport were tested using the model-based testing tool TorXakis. Long test runs, up to 1,000,000 test events, were executed, showing the feasibility of the MBT approach for this kind of systems.

Model-based testing of a software bus at Neopost. A software bus was modelled, verified, and the resulting implementation tested with JTorX. It was shown that a model-based approach certainly pays off.

Formal specification and analysis of Zeroconf using Uppaal. In this case study, a model of the IP Zeroconf protocol was developed and subsequently analyzed using a combination of manual abstraction an model checking using Uppaal. Already constructing the model from the RFC pointed to many ambiguities and imprecisions in the RFC. A fragment of Zeroconf was verified with the model-checker Uppaal.

The impact of GSM-R on railway capacity. The impact of the new GSM-R communication system on line capacity was analyzed using stochastic modelling.

[11] http://www.esi.nl/research/applied-research/current-projects/wings/

Testing automated trust anchor updating in Autotrust. An implementation of the IP protocol DNSsec was model-based tested using Uppaal Tron. The test was successful, in the sense that timed model-based testing with Uppaal-Tron was feasible, increased coverage with respect to manual testing, and no defects were detected in the implementation.

Testing a printer controller. A model-based testing was applied to printer controllers. This was done in two separate projects: one addressing the reactive, stateful job handling task, and one handling the stateless job processing task. Testing the reactive part was done using the Quasimodo tools JTorX and ToRXakis, the external tool Gast, and a home-made Python tool. MBT was successful: a couple of software problems were detected. A trial with the commercial tool Qtronic[12] failed because it did not support parallelism and resulting nondeterminism which were essential for this case. For testing this kind of applications, dealing with parallelism, nondeterminism, and data is important. Another result was that usability of the Quasimodo MBT tools is still insufficient: the original aim of having test engineers work with the tools was not achieved.

Testing the stateless job processing task used Boolean predicates. It showed that for a relatively simple, stateless system, the quantity of data, and dependencies between data, can be enormous, leading to a data-space explosion, independent of state-based behaviour. This requires good strategies to deal with this explosion through test selection. We used combinatorial (pair-wise) testing, which turned out to be effective to reduce the test suite size in a controlled way.

Task 5.2 - Tools and Tool Integration

The ambition of the Quasimodo project has been to develop tool components (plug-ins) and integration of tools for the modelling, analysis and code generation based on quantitative models. As can be seen in the Figure 1, the development of tools has been following two main directions:

1. A number of tools aiming at probabilistic and stochastic analysis for Markovian models (DTMC, CTMC, CTMDP, ..) or probabilistic extensions of timed automata, and

2. A collection of branches of the tool Uppaal – based on timed automata – for verification, optimal scheduling, controller synthesis, testing, as well as schedulability analysis and worst-case execution time analysis.

[12] http://www.conformiq.com/

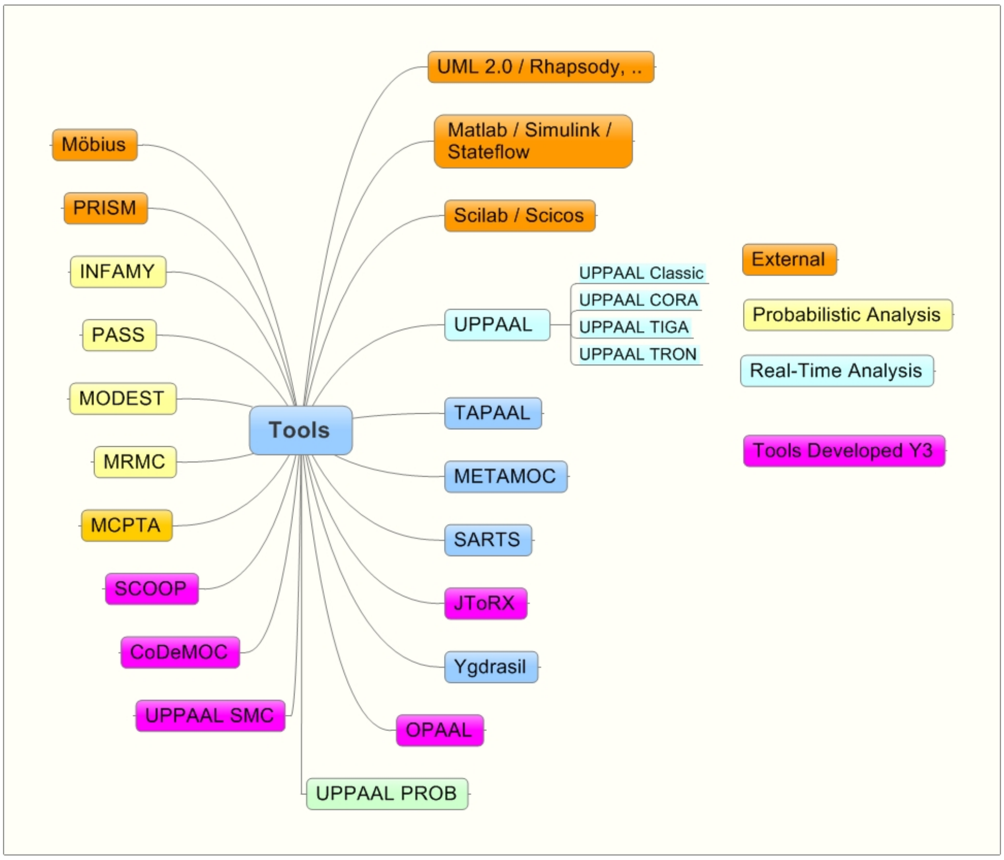


Figure 1: Tools developed during Quasimodo (left side emphasize probabilistic tools; right hand side real-time tools)

For the probabilistic tools several experiments with exchange of models between tools – including the external tool PRISM – has been made and are planned in order exploit the most efficient analytical approach for a given example. For the real-time tools based on Uppaal, interaction with external UML-based tools as well as Matlab/Simulink has been carried out. In particular:

- A tool chain has been implemented which – given a user defined timed game model in Uppaal-Tiga – allow for winning strategies to be automatically imported to Simulink as an S-function allowing for simulation, validation and automatic generation of code.
- A framework allowing for linking Uppaal-Tron and Simulink models has been implemented. The framework can be used in several ways: a) in testing conformance of a real-time system with respect to a timed automata model one may augment the model with dynamic behaviour using co-simulation by Simulink for environment emulation purposes; b) the framework can be used to test conformance of Simulink models against timed automata specifications.

Also support for integrating testing tools has been developed:

- JTorX has been connected with the STSimulator through a defined XML exchange format. The STSimulator is a prototype Java library enabling simulation of Symbolic Transition Systems, allowing for explicit notions.

Finally, exchanges of models between members of the two families of tools (probabilistic and timed) have been established. In particular:

- Support for exporting MoDeST PTA (probabilistic timed automata) models to the Uppaal XML format has been implemented. Dually, Uppaal models may be imported based on implementation of broadcast and binary synchronization making MoDeST compatible with Uppaal timed automata.
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Task 5.3 - Dissemination and Exploitation

To foster innovation based on the exploitation of the project results Quasimodo has invested substantial effort into dissemination and knowledge transfer activities. Various activities have been organized to communicate about the Quasimodo project and its results. A full list is described in Deliverable D5.11: "Final Report on Dissemination and Exploitation”. The major points are repeated here:

1. Quasimodo has created and maintains a website with all information regarding the project, its organization, results, publications, events, related projects, and activities.

2. A Quasimodo workshop was organized during the FM week, November 6, 2009, in Eindhoven (NL), with participants from academia, industry, and Quasimodo itself. A keynote was given by Prof. Rance Cleaveland (University of Maryland), and the workshop was concluded with an industrial panel with members from Reactive Systems, Philips, OCE, and ESI/ASML.

3. A half-day tutorial session on *Quantitative System Validation in Model Driven Design*, at the Embedded Systems Week in Phoenix (AZ, USA), on October 24 2010.

4. A Quasimodo session at FMCO (Formal Methods for Objects and Components), in Graz (A) on December 1 2010.

5. A special session at ETAPS 2011 in Saarbrücken, within the Rocks symposium, on Saturday March 26, 2011.

6. A final dissemination event “From Model-Driven Development to System Engineering Science” organized as a joint DANES/Quasimodo/ITEK Mini-conference, on June 15, 2011, in Copenhagen, Denmark.

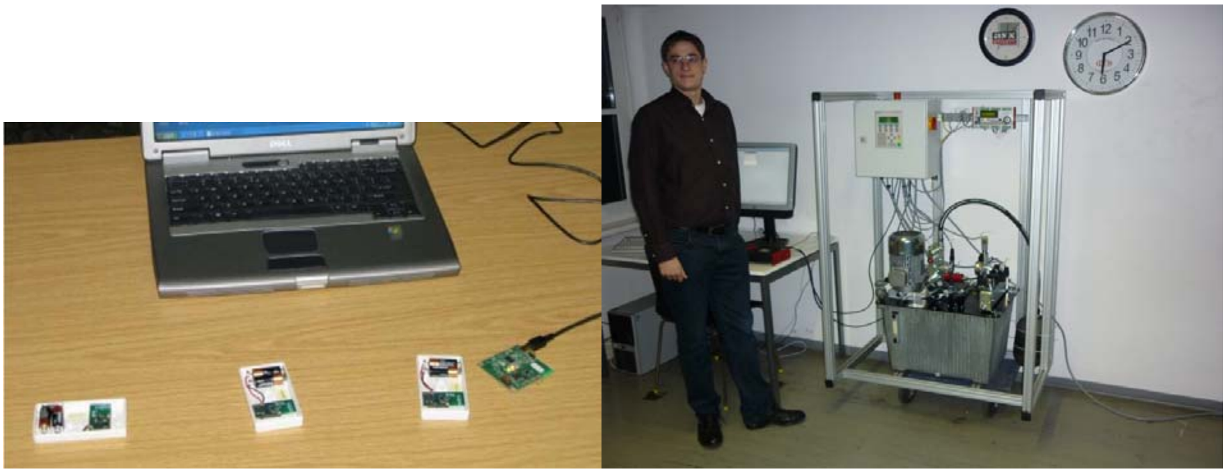

Figure 2: Two demonstrators. Left Part of ChessWSN. Right Hydac Hydraulic Machine

7. Quasimodo developed a number of demonstrators:

    a. The Hydac demonstrator: a mini-hydraulic system with its controller for evaluating and demonstrating the effect of different control strategies for the hydraulic pump, see Figure 2.

    b. Loss of node synchronization in the CHESS Wireless Sensor Network case, see Figure 2.

    c. Model-based conformance testing of the WSN protocol.

    d. Real-time model-based testing: the temperature controller and alarm monitor, as described in the model-based testing chapter of the Quasimodo Book.

    e. Automated controller synthesis using Uppaal-Tiga and Simulink, for keeping a safe temperature range in two tanks of liquid sharing a single heating device.

8. An *Industrial Handbook on Quantitative Analysis of Embedded Systems*, presenting the Quasimodo results for a non-scientific audience, such as engineers working in the area of embedded systems, is under preparation, and will be published by Springer. The book will contain 15 chapters covering the different Quasimodo topics, with each an introductory tutorial chapter and a case study chapter.

Work on the book is a little delayed. Almost all chapters are available now but some chapters are still being reviewed. We expect to finalize this book around the summer.

9. The Quasimodo Project is presented and advertised by a short summary description in the ICT 2010 Special Issue (no 14 September 2010) of the Parliament Magazine’s Research Review. Also a dedicated presentation of Quasimodo results appeared in Ercim News No. 75 (the European Research Consortium for Informatics and Mathematics: Special theme on Safety-Critical Software).

10. Quasimodo partners have been involved in the organization of some 50 conferences, local and international workshops, (summer) schools, events, and courses related to Quasimodo work.

11. The Quasimodo results have been presented in more than 120 keynotes, invited talks, tutorials, summer school lectures, industry seminars, etc. (not including regular conference and workshop presentations of accepted papers).

12. About 250 scientific papers about Quasimodo results were published.

13. Some of the Quasimodo results are currently exploited via spin-off activities.

14. Courses and teaching activities make abundant use of Quasimodo results.

15. More than 30 PhD. Students have contributed to, and, inversely, have been influenced by Quasimodo.

16. Quasimodo has, directly or indirectly, cooperated and cross-fertilized with more than 30 related projects and networks, among which academic, research, as well as industrial ones.

17. The three industrial partners have obtained analyses of their products, and they have seen potential problems detected. They are currently investigating how Quasimodo methods and tools can be incorporated in their daily business.

Conclusions

Quasimodo has worked intensively on the development of new tools, improvement of usability of existing tools, completion of the envisaged set of tool components, and completion of integration between internal as well as external tools. We believe that we have made significant steps towards improving the state-of-the-art in terms of useful tool environments for model-based analysis, implementation, and testing of quantitative system properties.

In Quasimodo we have worked on a broad selection of case studies which address almost all of the Quasimodo methods, techniques, and tools, and which have provided interesting feedback for the project as well as for the systems being analyzed. We have shown that the methods, techniques, and tools developed in Quasimodo are applicable, useful, and can provide great benefits in analysis and testing of systems. Moreover, in several case studies it was noted that already the construction of models by itself improves understanding, leads to the detection of problems in informal documents, or asking the right questions to domain experts.

Common challenges in the case studies are scalability and usability. Dealing with large systems is a fundamental challenge due to the problem of state-space explosion. Quasimodo has made enormous improvements, and much larger systems can be analyzed than before, yet some systems remain challenging. Concerning usability, Quasimodo tools were mainly developed to provide evidence those analysis techniques and algorithms work. In the case studies, the methods and tools were mostly used by Quasimodo experts. Continued development of such tools and training in their use will enable engineers routinely to apply the techniques in existing development processes.

Quasimodo has been very successful in dissemination and exploitation of the developed methods and tools, both academically and industrially. This provides a very good basis for further exploitation and innovation.

1.3.6 Overall Conclusions

Quasimodo has improved modelling and specification of system behaviour in several ways. We have identified 7 properties that a good formal model should have. Aided by the improved tutorials in the Industrial Handbook, a systematic and explicit check of these properties will lead to better and more usable models. Quasimodo has proposed numerous quantitative formalisms that precisely capture (multiple) quantitative aspects. These include variations of (timed) Markov models (possibly non-deterministic and parametric), Constraint Markov Chains, Probabilistic Priced Timed Automata, Probabilistic hybrid automata, Energy Timed Automata and Games, and Timed Interfaces, etc. Quasimodo has applied several of these as the underlying formalism for in industrial notations and tools, like the Architecture Analysis and Design Language, stochastic state charts, and domain specific languages. We have developed tool support for AADL and STATEMATE enabling behavioural timing and dependability analysis.

Quasimodo has dramatically advanced analysis techniques for quantitative models. The technique may be classified according to the richness of the aspects captured by the model/verification property, and by whether exact or approximate analysis techniques are being used. Quasimodo has advanced state of the art both in the richness and performance of the analysis techniques, using both exact and approximate techniques, by pushing the frontier of analyzable problems, as suggested in the Figure 3. In more cases, performance have been improved by orders of magnitude, enabling industrial systems that before were out of reach to be analyzable now. Yet, the state space explosion problem is a fundamental challenge.

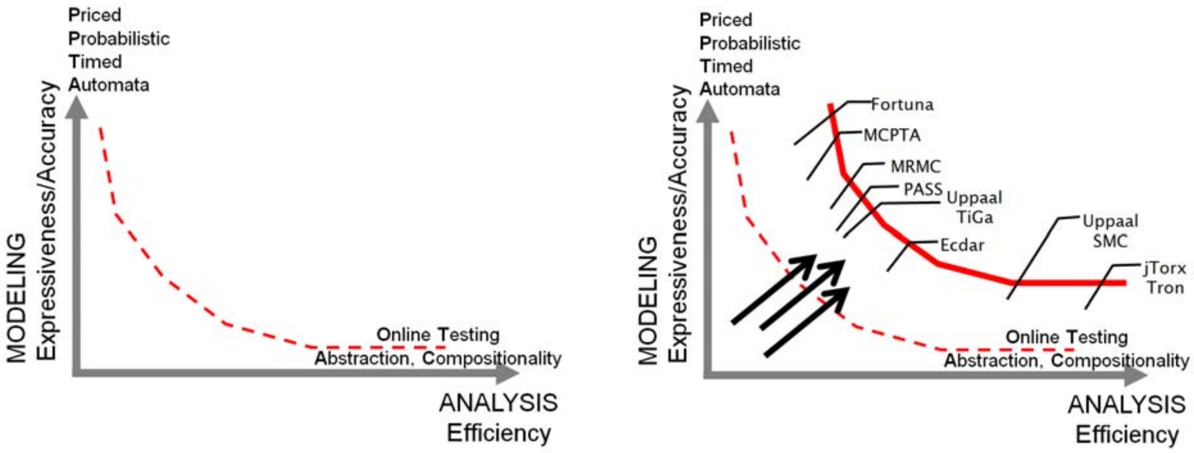

Figure 3: Quasimodo pushing the analysis capabilities. Before (dashed) and after Quasimodo (solid).

Quasimodo goes beyond analysis, but also considers synthesis of implementations and model-based testing. We have shown how to compute (finite and infinite mean-payoff) schedules of how best to exploit the given (energy, memory, cost) resources from specific classes of models with multi-dimensional quantitative costs. Quasimodo has developed new theories and algorithms for controller synthesis, in particular for games with imperfect information, enabling algorithmic synthesis of resource optimal control strategies for embedded controllers. When a model is used as basis for creating an implementation, it is essential that it is implementable on physical hardware. This however is difficult to ensure for quantitative properties; we have therefore invested significant effort in developing techniques and tools for implementability checking of timed automata, and we have proposed techniques for a model-based approach to schedulability analysis. Code generation from the synthesized strategies has been accomplished through a systematic automated translation to Matlab/Simulink. Convincing results have been achieved in the Hydac case study.

Testing is an immensely widespread and costly activity in industrial practice. Quasimodo has improved the techniques for online and offline model-based testing for quantitative models with time, complex data, hybrid behaviour or probabilities. In particular we address practically important issues like non-determinism and under-specification. These improvements are based on new solid timed and quantitative testing theories. Testing of hybrid systems is accomplished through an integration of real-time online testing with Matlab/Simulink. As a new direction we have investigated model-based testing in combination with learning to derive approximate models of systems. This may prove important for testing of legacy or 3rd party components where models (or the information to make them) do not exist.

The techniques have been implemented in a rather large collection of unique powerful tool components for modelling, analysis, synthesis and testing. In specific instances these are linked to - and integrated with - industrial tool chains. Quasimodo has successfully applied and evaluated a wide variety to 6 larger industrial case studies and numerous smaller ones. We have identified problems in both proposed designs and implementations, see below. Quasimodo staff has been extremely active in disseminating research results (numerous organized events and invited lectures, demonstrators, and 250 scientific publications) towards academia and industry. An Industrial Handbook of the Quasimodo techniques will be printed autumn 2011.

Thus, Quasimodo has been very successful in dissemination and exploitation of the developed methods and tools, both academically and industrially. This provides a very good basis for further exploitation and innovation.

1.4 Potential Impact

The intensive work on case studies clearly demonstrates that Quasimodo techniques can have impact on industrial development. They have identified potentially expensive defects, optimized designs, and raised confidence in several designs and produces.

- Quasimodo has identified flaws in the clock synchronization protocol proposed by CHESS for the gMAC wireless sensor network protocol that cause stable synchronized network to become unsynchronized in specific (possibly rare) situations. Also the efficiency of the protocol (considering collision rates and energy consumption) were analysed using discrete event simulation yielding interesting results and a better understanding of the protocol behaviour.

- In the modelling of the Chessway, Chess has reported that "The case study taught us that the specification could be made more precise due to the development of an Uppaal model of the system behaviour and that the resulting implementation worked first time right according to what was specified in the model." (See D5.10).

- We have used our tool chain for model-based algorithmic synthesis of embedded controllers to the Hydac Accumulator Charge Controller for a hydraulic pump. The result is a proven robust controller that is 45% better energy wise than a 2-point controller and 35% better than Hydac's current controller. This technique is thus an important supplement to existing control engineering approaches for complex mixed time and discrete problems.

- During Hydac's test in a real environment and the application of model-based test from Quasimodo project they were able to detect some problems. Currently Hydac analyses these problems and is developing a new strategy to encounter them. On the basis of these experiences Hydac intend to use model-driven software engineering for some upcoming projects and in particular plan to use automatically generated test cases to validate our products.

- Application of model-based testing at Chess has improved specification and understanding of gMAC protocol behaviour.

- Application of model-based testing at Novo Nordic has reduced turn-around time (script maintenance) when performing regression testing of graphical user interfaces for medical devices from 30 person days to 3 person days.

- Model-based testing of electronic passports: before issuing the new biometric electronic passport the Ministry of Internal Affairs in NL wanted to have it tested in different ways. Model-based testing was one of the tests performed to give them confidence that the passport could be issued.

- In a project with OCE of testing printer controller a number of defects were detected; OCE is taking steps to continue with model-based testing. However, a requirement of OCE is that they should be able to make models and use the tools, and that is still a bit difficult, especially since their test engineers usually neither have a PhD nor a M. Sc, but mostly B.Sc. from professional school for higher education.

- Terma finds the possibly more optimistic model-based approach to schedulability analysis promising, but also that further development is needed before it can be fully deployed.

The methods and tools developed by Quasimodo are already being used in other industrial projects, e.g., the WINGS project with ASML (ESI), and likewise the Octopus and Falcon projects (see ESI website[13]). Also the timed analysis and model-based testing techniques and tools will be further developed and exploited by the new Artemis MBAT (Combined Model-based analysis and Testing) project (AAU).

As noted model-based approaches are still foreign to many companies, and further training and education is generally needed. Here we hope that the Industrial Handbook with its tutorials and demonstrators may play an important role in the wider dissemination and exploitation of the Quasimodo results.

Although difficult to scientifically quantify financially, it is widely recognized that finding defects early in the development cycle is dramatically cheaper and more productive than later. As demonstrated by the above examples the Quasimodo approach is promising in this respect and may thus help Europe maintain and advance its competitive edge in complex systems design.

[13] http://www.esi.nl/research/applied-research/current-projects/

1.5 Contact Information

http://www.quasimodo.aau.dk/

Contact information:
Coordinator: Kim G. Larsen (kgl@cs.aau.dk)
Co-Coord.: Brian Nielsen (bnielsen@cs.aau.dk)

Quantitative System Properties in Model-Driven-Design of Embedded Systems

Coordination Team

Coordinator	*Assistant Coordinator*	*Administrative Project Manager*
Professor Kim G. Larsen	Assoc. Prof. Brian Nielsen	Head of Section Esben Ahlmann Hjuler
Room 0.2.32 Dept. of Computer Science Selma Lagerlöfs Vej 300 DK-9220 Aalborg Ø Denmark	Room 1.2.10 Dept. of Computer Science Selma Lagerlöfs Vej 300 DK-9220 Aalborg Ø Denmark	Room: A1-01-06 Fundraising and Project Office Niels Jernes Vej 10, Dk-9220 Aalborg Ø Denmark
+45 9940 88 93 (direct) +45 9940 80 80 (switch) +45 9940 9798 (fax)	+45 9940 88 83 (direct) +45 9940 80 80 (switch) +45 9940 9798 (fax)	+45 9940 7340 (direct) +45 9940 80 80 (switch) +45 9815 9757 (fax)
kgl@cs.aau.dk	bnielsen@cs.aau.dk	eah@adm.aau.dk

Partners

Center for Embedded Software Systems, Department of Computer Science at Aalborg University, Denmark
Contact: Assoc. Prof. Brian Nielsen (bnielsen@cs.aau.dk)

Embedded Systems Institute, The Netherlands
Contact: Dr. Ir. Jan Tretmans (jan.tretmans@esi.nl)

In collaboration with the Informatics for Technical Application Group, Radboud University Nijmegen, Contact: prof. Frits Vaandrager (F.Vaandrager@cs.ru.nl), and the Formal Methods and Tools Group, University of Twente, Contact: Prof. Jaco van de Pol (j.c.vandepol@ewi.utwente.nl)

Laboratoire Spécification et Vérification at CNRS & ENS, France Contact: Assoc. Prof. Nicolas Markey (markey@lsv.ens-cachan.fr)

Software Modelling and Verification Group at RWTH Aachen University, Germany
Contact: Professor Joost-Pieter Katoen (katoen@cs.rwth-aachen.de)

Dependable Systems and Software Group at University of Saarland , Germany
Contact: Professor Holger Hermanns (hermanns@cs.uni-saarland.de)

Centre Fédéré en Vérification at Université Libre de Bruxelles, Belgium
Contact: Assoc. Prof. Jean-Francois Raskin (jraskin@ulb.ac.be)

Terma A/S, Space Division, Denmark
Contact: Senior Software Engineer Poul Hougaard (poh@terma.com)

Chess, The Netherlands
Contact: M.Sc., Technical Manager Marcel Verhoef (Marcel.Verhoef@chess.nl)

HYDAC ELECTRONIC GMBH, Germany
Contact: Senior Software Engineer, Michael Schneider (michael.schneider@hydac.com)

2 Use and dissemination of foreground

A plan for use and dissemination of foreground (including socio-economic impact and target groups for the results of the research) shall be established at the end of the project. It should, where appropriate, be an update of the initial plan in Annex I for use and dissemination of foreground and be consistent with the report on societal implications on the use and dissemination of foreground (section 4.3 – H).

The plan should consist of:

- *Section A*

This section should describe the dissemination measures, including any scientific publications relating to foreground. ***Its content will be made available in the public domain*** *thus demonstrating the added-value and positive impact of the project on the European Union.*

- *Section B*

This section should specify the exploitable foreground and provide the plans for exploitation. All these data can be public or confidential; the report must clearly mark non-publishable (confidential) parts that will be treated as such by the Commission. Information under Section B that is not marked as confidential ***will be made available in the public domain*** *thus demonstrating the added-value and positive impact of the project on the European Union***.**

Section A (public)

This section includes two templates

- *Template A1: List of all scientific (peer reviewed) publications relating to the foreground of the project.*
- *Template A2: List of all dissemination activities (publications, conferences, workshops, web sites/applications, press releases, flyers, articles published in the popular press, videos, media briefings, presentations, exhibitions, thesis, interviews, films, TV clips, posters).*

These tables are cumulative, which means that they should always show all publications and activities from the beginning until after the end of the project. Updates are possible at any time.

TEMPLATE A1: LIST OF SCIENTIFIC (PEER REVIEWED) PUBLICATIONS, STARTING WITH THE MOST IMPORTANT ONES

General

2010

Joost-Pieter Katoen, Advances in Probabilistic Model Checking, in: Verification, Model Checking, and Abstract Interpretation (VMCAI), pages 25, Springer-Verlag, 2010

Christel Baier, Boudewijn R. Haverkort, Holger Hermanns and Joost-Pieter Katoen, Performance Evaluation and Model Checking Join Forces (2010), in: Communications of the ACM

2008

Joost-Pieter Katoen, Perspectives in Probabilistic Verification, in: 2nd IEEE International Symposium on Theoretical Aspects of Software Engineering (TASE), pages 3-10, IEEE CS Press, 2008

Christel Baier and Joost-Pieter Katoen, Principles of Model Checking, MIT Press, 2008

WP1: Modelling and Specification

2011

Uli Fahrenberg, Line Juhl, Kim G. Larsen and Jiri Srba, Energy Games in Multiweighted Automata, 2011

J. Berendsen, B. Gebremichael, Frits Vaandrager and M. Zhang, Formal Specification and Analysis of Zeroconf using Uppaal (2011), in: ACM Transactions on Embedded Computing Systems, 10:3

F. Houben, G. Igna and Frits Vaandrager, Modeling Task Systems Using Parameterized Partial Orders, 2011

Holger Hermanns, Augusto Parma, Roberto Segala, Björn Wachter and Lijun Zhang, Probabilistic Logical Characterization (2011), in: Information and Computation, 209:2(154-172)

Bernoit Caillaud, Constraint Markov Chains -- full version (2011), in: Theoretical Computer Science

2010

Joost-Pieter Katoen, Jaco van de Pol, Marielle Stoelinga and Mark Timmer, A Linear Process Algebraic Format for Probabilistic Systems with Data, in: Applications of Concurrency to System Design (ACSD), IEEE CS Press, 2010

Joost-Pieter Katoen, J. van de Pol, Marielle Stoelinga and Mark Timmer, A linear process-algebraic format for probabilistic systems with data (extended version), University of Twente, number TR-CTIT-10-11, 2010

Christian Eisentraut, Holger Hermanns and Lijun Zhang, Concurrency and Composition in a Stochastic World, in: CONCUR 2010, pages 21-39, Springer, 2010

P. Ganty, G. Geeraerts, Jean-François Raskin and Laurent Van Begin, Le problème de couverture pour les réseaux de Petri. Résultats classiques et développements récents (2010), in: Techniques et Sciences Informatiques, 28:9(1107-1142)

T. Basten, Benthum E. van, M. Geilen, M. Hendriks, F. Houben, G. Igna, F. Reckers, Smet S. de, L. Somers, E. Teeselink, N. Trcka, Frits Vaandrager, J. Verriet, M. Voorhoeve and Y. Yang, Model-Driven Design-Space Exploration for Embedded Systems: The Octopus Toolset, in: Leveraging Applications of Formal Methods, Verification, and Validation - 4th International Symposium on Leveraging Applications, ISoLA 2010, Heraklion, Crete, Greece, October 18-21, 2010, Proceedings, Part I, pages 90-105, Springer, 2010

Christian Eisentraut, Holger Hermanns and Lijun Zhang, On Probabilistic Automata in Continuous Time, in: LICS, pages 342-351, IEEE Computer Society, 2010

Benedikt Bollig, Paul Gastin, Benjamin Monmege and Marc Zeitoun, Pebble weighted automata and transitive closure logics, in: Proceedings of the 37th International Colloquium on Automata, Languages and Programming (ICALP'10)—Part II, pages 587-598, Springer, 2010

Holger Hermanns and Joost-Pieter Katoen, The How and Why of Interactive Markov Chains, in: Formal Methods for Components and Objects (FMCO), pages 311-337, Springer-Verlag, 2010

D. K. Kaynar, N. A. Lynch, R. Segala and Frits Vaandrager, The Theory of Timed I/O Automata (second edition), Morgan & Claypool Publishers, 2010

Kim Guldstrand Larsen, Shuhao Li, Brian Nielsen and Saulius Pusinskas, Scenario-Based Analysis and Synthesis of Real-Time Systems Using Uppaal, in: Proc. 13th Conf. on Design, Automation and Test in Europe (DATE'10), pages "", IEEE, 2010

2009

Hichem Boudali, Pepijn Crouzen and Marielle Stoelinga, A Rigorous, Compositional, and Extensible Framework for Dynamic Fault Tree Analysis (2009), in: IEEE Trans. Dependable Sec. Comput., 7:2(128-143)

Hichem Boudali, Marielle Stoelinga and Hasan Sozer, Architectural Availability Analysis of Software Decomposition for Local Recovery, in: Proceedings of the Third IEEE International Conference on Secure Software Integration and Reliability Improvement, Los Alamitos, pages 14-22, IEEE Computer Society, 2009

Marco Bozzano, Alessandro Cimatti, Marco Roveri, Joost-Pieter Katoen, Viet Yen Nguyen and Thomas Noll, Codesign of Dependable Systems: A Component-Based Modeling Language, in: Proc. 7th ACM-IEEE Int. Conf. on Formal Methods and Models for Codesign (MEMOCODE 2009), pages 121-130, IEEE CS Press, 2009

Eckard Böde, Marc Herbstritt, Holger Hermanns, Sven Johr, Thomas Peikenkamp, Reza Pulungan, Jan Rakov, Ralf Wimmer and Bernd Becker, Compositional Dependability Evaluation for STATEMATE (2009), in: IEEE Transaction on Software Engineering, 35:2(274-292).

Marielle Stoelinga, Compositional dependability modeling using Arcade, in: Proceedings of the 9th Workshop on Specification and Verification of Component-based systems, 2009

Patricia Bouyer and Antoine Petit, On extensions of timed automata, in: Perspectives in Concurrency Theory, pages 35-63, Universities Press, 2009

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Kim Guldstrand Larsen, Shuhao Li, Brian Nielsen and Saulius Pusinskas, Verifying Real-Time Systems against Scenario-Based Requirements, in: Proc. 16th International Symposium on Formal Methods (FM'09), pages 676-691, Springer, 2009

Benedikt Bollig and Paul Gastin, Weighted versus Probabilistic Logics, in: Proceedings of the 13th International Conference on Developments in Language Theory (DLT'09), pages 18-38, Springer, 2009

2008

Claus Thrane, Ulrich Fahrenberg and Kim G. Larsen, : Quantitative simulations of weighted transition systems, in: Proceedings of Nordic Workshop on Programming Theory, 2008

Hichem Boudali, Pepijn Crouzen, Boudewijn R. Haverkort, Matthias Kuntz and Marielle Stoelinga, Architectural dependability evaluation with Arcade, in: The 38th Annual IEEE/IFIP International Conference on Dependable Systems and Networks, DSN 2008, June 24-27, 2008, Anchorage, Alaska, USA, Proceedings, pages 512-521, IEEE Computer Society, 2008

Tingting Han, Joost-Pieter Katoen and Alexandru Mereacre, Compositional Modeling and Minimization of Time-inhomogeneous Markov Chains, in: Hybrid Systems: Computation and Control (HSCC), pages 244-258, Springer Verlag, 2008

Ulrich Fahrenberg and Kim G. Larsen, Discount-Optimal Infinite Runs in Priced Timed Automata., in: Proceedings of INFINITY 2008 10th International Workshop on Verification of Infinite-State Systems, 2008

Patricia Bouyer, Ulrich Fahrenberg, Kim G. Larsen, Nicolas Markey and Jiri Srba, Infinite Runs in Weighted Timed Automata with Energy Constraints, in: 6th International Conference on Formal Modelling and Analysis of Timed Systems (FORMATS'08), Saint-Malo, France, pages 33-47, Springer, 2008

Patricia Bouyer, Kim G. Larsen and Nicolas Markey, Model Checking One-clock Priced Timed Automata (2008), in: LMCS, 4:2:9

Patricia Bouyer, Nicolas Markey, Joel Ouaknine and James Worrell, On Expressiveness and Complexity in Real-time Model Checking, in: ICALP'08, Reykjavik, Iceland, pages 124-135, Springer, 2008

Pepijn Crouzen, Holger Hermanns and Lijun Zhang, On the Minimisation of Acyclic Models, in: CONCUR 2008 - Concurrency Theory, 19th International Conference, CONCUR 2008, Toronto, Canada, August 19-22, 2008. Proceedings, pages 295-309, Springer, 2008

Kim G. Larsen and Jacob I. Rasmussen, Optimal reachability for multi-priced timed automata. (2008), in: Theoretical Computer Science, 390:2-3(197-213)

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Taolue Chen, Tingting Han and Joost-Pieter Katoen, Time-Abstracting Bisimulation for Probabilistic Timed Automata, in: 2nd IEEE International Symposium on Theoretical Aspects of Software Engineering (TASE), pages 177-184, IEEE CS Press, 2008

Publications for topic: WP2: Analysis

2011

Joost-Pieter Katoen, J. van de Pol, Marielle Stoelinga and Mark Timmer, A linear process-algebraic format with data for probabilistic automata (2011), in: Theoretical Computer Science

Benoit Delahaye, Joost-Pieter Katoen, Kim G. Larsen, Axel Legay, Mikkel Pedersen, Falak Sher and Andrzej Wasowski, Abstract Probabilistic Automata, in: Verification, Model Checking and Abstract Interpretation (VMCAI), pages 324-339, Springer-Verlag, 2011

Benoit Delahaye, Kim G. Larsen, Axel Legay, Mikkel Larsen Pedersen and Andrzej Wasowski, APAC: a tool for reasoning about Abstract Probabilistic Automata, 2011

Mark Timmer, Marielle Stoelinga and J. van de Pol, Confluence Reduction for Probabilistic Systems, in: Proceedings of the 17th International Conference on Tools and Algorithms for the Construction and Analysis of Systems, pages 311-325, Springer Verlag, 2011

Radu Mardare, Luca Cardelli and Kim G. Larsen, Continuous Markovian Logic - From Complete Axiomatization to the Metric Space of Formulas, 2011

Benoit Delahaye, Kim G. Larsen, Axel Legay, Mikkel Larsen Pedersen and Andrzej Wasowski, Decision Problems for Interval Markov Chains, 2011

Uli Fahrenberg, Claus Thrane and Kim G. Larsen, Distances for Weighted Transition Systems: Games and Properties, 2011

Benoit Barbot, Taolue Chen, Tingting Han, Joost-Pieter Katoen and Alexandru Mereacre, Efficient CTMC Model Checking of Linear Real-Time Objectives, in: Tools and Algorithms for the Construction and Analysis of Systems (TACAS), pages 128-142, 2011

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Sebastian S. Bauer, Line Juhl, Kim G. Larsen, Axel Legay and Jiri Srba, Extending Modal Transition Systems with Structured Labels, 2011

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Peter Buchholz, Ernst Moritz Hahn, Holger Hermanns and Lijun Zhang, Model Checking Algorithms for CTMDPs, in: 23rd Int. Conf. on Computer Aided Verification (CAV 2011), Springer, 2011

Taolue Chen, Tingting Han, Joost-Pieter Katoen and Alexandru Mereacre, Model Checking of Continuous-Time Markov Chains Against Timed Automata Specifications (2011), in: Logical Methods in Computer Science, 7:1-2(1-34)

Radu Mardare, Luca Cardelli and Kim G. Larsen, Modular Markovian Logic, 2011

Benoit Delahaye, Joost-Pieter Katoen, Kim G. Larsen, Axel Legay, Mikkel Larsen Pedersen, F. Sher and Andrzej Wasowski, New Results on Abstract Probabilistic Automata, 2011

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TEMPLATE A2: LIST OF DISSEMINATION ACTIVITIES

NO.	Type of activities[14]	Main leader	Title	Date	Place	Type of audience[15]	Size of audience	Countries addressed
1	Website	AAU	Quasimodo website	26 February 2008				
2	Conference	AAU	Coping with Complexity and Quantitative Constraints in Embedded Systems Design	November 6, 2009	The Netherlands	Industry, Research	30	All
3	Tutorial		*Quantitative System Validation in Model Driven Design*	October 24, 2010	U.S.A	Research Industry	25	

[14] A drop down list allows choosing the dissemination activity: publications, conferences, workshops, web, press releases, flyers, articles published in the popular press, videos, media briefings, presentations, exhibitions, thesis, interviews, films, TV clips, posters, Other.

[15] A drop down list allows choosing the type of public: Scientific Community (higher education, Research), Industry, Civil Society, Policy makers, Medias ('multiple choices' is possible.

4	Conference		Quasimodo session at FMCO (Formal Methods for Objects and Components)	December 2010	Graz, Austria	Research	35	
5	Conference	ESI	A special Quasimodo session at ETAPS 2011 in Saarbrücken, within the Rocks symposium	March 26, 2011	Germany	Research	25	
6	Conference	AAU	“From Model-Driven Development to System Engineering Science” organized as a joint DANES/Quasimodo/ITEK Mini-conference	March 26, 2011	Denmark	Industry Research	25	
8	Publication	AAU	Presentation of Quasimodo results appeared in Ercim News No. 75 (the European Research Consortium for Informatics and Mathematics: Special theme on Safety-Critical Software).	October 2008	EC			EC
8	Publicity	AAU	Presentation of Quasimodo in the ICT 2010 Special Issue of the Parliament Magazine’s Research	September 2010	EC			EC

			Review no 14					
9	Invited Talks and summer school lectures		Quasimodo results have been presented in more than 120 keynotes, invited talks, tutorials, summer school lectures, industry seminars, etc. (not including regular conference and workshop presentations of accepted papers)	*)				World
10	Conferences and workshops		Quasimodo partners have been involved in the organization of some 50 conferences, local and international workshops, (summer) schools, events, and courses related to Quasimodo work.	*)				EC
11	Industrial Handbook		Industrial Handbook on Quantitative Analysis of Embedded Systems	2012	Springer Verlag 2012	Industry		

**) A complete list of* Invited Talks and summer school lectures *and organized* Conferences and workshops *can be found in Delivarble 5.11)*

Section B (Confidential[16] or public: confidential information to be marked clearly)

Part B1

No applications for patents, trademarks, registered designs, etc such applications has been submitted as direct result of Quasimodo work.

The applications for patents, trademarks, registered designs, etc. shall be listed according to the template B1 provided hereafter.

The list should, specify at least one unique identifier e.g. European Patent application reference. For patent applications, only if applicable, contributions to standards should be specified. This table is cumulative, which means that it should always show all applications from the beginning until after the end of the project.

Template B1: List of applications for patents, trademarks, registered designs, etc.					
Type of IP Rights[17]:	Confidential Click on YES/NO	Foreseen embargo date dd/mm/yyyy	Application reference(s) (e.g. EP123456)	Subject or title of application	Applicant (s) (as on the application)

[16] Note to be confused with the "EU CONFIDENTIAL" classification for some security research projects.

[17] A drop down list allows choosing the type of IP rights: Patents, Trademarks, Registered designs, Utility models, Others.

Part B2

Type of Exploitable Foreground[18]	Description of exploitable foreground	Confidential Click on YES/NO	Foreseen embargo date dd/mm/yyyy	Exploitable product(s) or measure(s)	Sector(s) of application[19]	Timetable, commercial or any other use	Patents or other IPR exploitation (licences)	Owner & Other Beneficiary(s) involved
Commercial	**Uppaal tool suite for embedded systems validation**	**NO**		**Software**	**C26,J62, M72**	**2012**	**Licence**	**AAU**
Commercial	**TorX tool suite for embedded systems Testing**	**NO**		**Software**	**C26,J62, M72**	**2012**	**Licence**	**ESI**
Commercial	**Modest/Motor tool suite for embedded**	**NO**		**Software**	**C26,J62, M72**	**2012**	**Licence**	**USAAR**

[19] A drop down list allows choosing the type of foreground: General advancement of knowledge, Commercial exploitation of R&D results, Exploitation of R&D results via standards, exploitation of results through EU policies, exploitation of results through (social) innovation.

[19] A drop down list allows choosing the type sector (NACE nomenclature) : http://ec.europa.eu/competition/mergers/cases/index/nace_all.html

Type of Exploitable Foreground[18]	Description of exploitable foreground	Confidential Click on YES/NO	Foreseen embargo date dd/mm/yyyy	Exploitable product(s) or measure(s)	Sector(s) of application[19]	Timetable, commercial or any other use	Patents or other IPR exploitation (licences)	Owner & Other Beneficiary(s) involved
	SYSTEMS DESIGN AND VALIDATION							
Commercial	MRMC TOOL FOR EMBEDDED SYSTEMS VALIDATION	NO		SOFTWARE	C26,J62, M72	2012	LICENCE	RWTH

In addition to the table, please provide a text to explain the exploitable foreground, in particular:

- Its purpose
- How the foreground might be exploited, when and by whom
- IPR exploitable measures taken or intended
- Further research necessary, if any
- Potential/expected impact (quantify where possible)

The purpose of the listed software tools is to enable early, correct, and efficient development of embedded systems especially with respect to resource usage, real-time and stochastic behaviour. The tools may benefit to developers, manufacturers, consultants, researchers in the area of analysis, design, implementation, test, and debugging of complex embedded system by applying them in the development process. The tool components may be licensed from the beneficiaries.

3 Report on societal implications

Replies to the following questions will assist the Commission to obtain statistics and indicators on societal and socio-economic issues addressed by projects. The questions are arranged in a number of key themes. As well as producing certain statistics, the replies will also help identify those projects that have shown a real engagement with wider societal issues, and thereby identify interesting approaches to these issues and best practices. The replies for individual projects will not be made public.

A General Information *(completed automatically when **Grant Agreement number** is entered.*

Grant Agreement Number:	214755
Title of Project:	Quasimodo
Name and Title of Coordinator:	Professor Kim G. Larsen

B Ethics

1. Did your project undergo an Ethics Review (and/or Screening)? • If Yes: have you described the progress of compliance with the relevant Ethics Review/Screening Requirements in the frame of the periodic/final project reports? Special Reminder: the progress of compliance with the Ethics Review/Screening Requirements should be described in the Period/Final Project Reports under the Section 3.2.2 *'Work Progress and Achievements'*	***No***
2. Please indicate whether your project involved any of the following issues (tick box) :	***NO***
RESEARCH ON HUMANS	
• Did the project involve children?	***No***
• Did the project involve patients?	***No***
• Did the project involve persons not able to give consent?	***No***

• Did the project involve adult healthy volunteers?	***No***
• Did the project involve Human genetic material?	***No***
• Did the project involve Human biological samples?	***No***
• Did the project involve Human data collection?	***No***
Research on Human embryo/foetus	
• Did the project involve Human Embryos?	***No***
• Did the project involve Human Foetal Tissue / Cells?	***No***
• Did the project involve Human Embryonic Stem Cells (hESCs)?	***No***
• Did the project on human Embryonic Stem Cells involve cells in culture?	***No***
• Did the project on human Embryonic Stem Cells involve the derivation of cells from Embryos?	***No***
Privacy	
• Did the project involve processing of genetic information or personal data (eg. health, sexual lifestyle, ethnicity, political opinion, religious or philosophical conviction)?	***No***
• Did the project involve tracking the location or observation of people?	***No***
Research on Animals	
• Did the project involve research on animals?	***No***
• Were those animals transgenic small laboratory animals?	***No***
• Were those animals transgenic farm animals?	***No***
• Were those animals cloned farm animals?	***No***
• Were those animals non-human primates?	***No***
Research Involving Developing Countries	
• Did the project involve the use of local resources (genetic, animal, plant etc)?	***No***
• Was the project of benefit to local community (capacity building, access to healthcare, education etc)?	***No***
Dual Use	
• Research having direct military use	***No***
• Research having the potential for terrorist abuse	***No***

C Workforce Statistics

3. Workforce statistics for the project: Please indicate in the table below the number of people who worked on the project (on a headcount basis).

Type of Position	**Number of Women**	**Number of Men**
Scientific Coordinator		2
Work package leaders	1	4
Experienced researchers (i.e. PhD holders)	2	18
PhD Students	3	7
Other	3	13

4. How many additional researchers (in companies and universities) were recruited specifically for this project?	**6**
Of which, indicate the number of men:	4

D Gender Aspects

5. Did you carry out specific Gender Equality Actions under the project?	○ ○	 No

6. Which of the following actions did you carry out and how effective were they?

		Not at all effective … **Very effective**
☑	Design and implement an equal opportunity policy	○ ○ ✓ ○ ○
❑	Set targets to achieve a gender balance in the workforce	○ ○ ○ ○ ○
❑	Organise conferences and workshops on gender	○ ○ ○ ○ ○
❑	Actions to improve work-life balance	○ ○ ○ ○ ○
✓	Other:	Several Women worked on an equal basis in this otherwise highly male dominated domain

7. Was there a gender dimension associated with the research content – i.e. wherever people were the focus of the research as, for example, consumers, users, patients or in trials, was the issue of gender considered and addressed?

○ Yes- please specify

✓ No

E Synergies with Science Education

8. Did your project involve working with students and/or school pupils (e.g. open days, participation in science festivals and events, prizes/competitions or joint projects)?

✓ Yes- please specify

High school children were taught aspects modelling computer system behaviour. Quasimodo modelling and analysis tools and techniques are widely used in university courses.

○ No

9. Did the project generate any science education material (e.g. kits, websites, explanatory booklets, DVDs)?

✓ Yes- please specify

Uppaal model-cheking guide for high-schools (in Dutch); Industrial Handbook

○ No

F Interdisciplinarity

10. Which disciplines (see list below) are involved in your project?

○ Main discipline[20]: 1.1

○ Associated discipline[20]: 2.2	○	Associated discipline[20]:

G Engaging with Civil society and policy makers

11a Did your project engage with societal actors beyond the research community? *(if 'No', go to Question 14)*	○ ✓	Yes No

11b If yes, did you engage with citizens (citizens' panels / juries) or organised civil society (NGOs, patients' groups etc.)?

○ No

○ Yes- in determining what research should be performed

○ Yes - in implementing the research

○ Yes, in communicating /disseminating / using the results of the project

11c In doing so, did your project involve actors whose role is mainly to organise the dialogue with citizens and organised civil society (e.g. professional mediator; communication company, science museums)?	○ ○	Yes No

12. Did you engage with government / public bodies or policy makers (including international organisations)

○ No

○ Yes- in framing the research agenda

○ Yes - in implementing the research agenda

○ Yes, in communicating /disseminating / using the results of the project

13a Will the project generate outputs (expertise or scientific advice) which could be used by policy makers?

○ Yes – as a **primary** objective (please indicate areas below- multiple answers possible)

○ Yes – as a **secondary** objective (please indicate areas below - multiple answer possible)

[20] Insert number from list below (Frascati Manual).

○ No

13b If Yes, in which fields?

Agriculture

Audiovisual and Media

Budget

Competition

Consumers

Culture

Customs

Development Economic and Monetary Affairs

Education, Training, Youth

Employment and Social Affairs

Energy

Enlargement

Enterprise

Environment

External Relations

External Trade

Fisheries and Maritime Affairs

Food Safety

Foreign and Security Policy

Fraud

Humanitarian aid

Human rights

Information Society

Institutional affairs

Internal Market

Justice, freedom and security

Public Health

Regional Policy

Research and Innovation

Space

Taxation

Transport

13c If Yes, at which level?

○ Local / regional levels

○ National level

○ European level

○ International level

H Use and dissemination

14. How many Articles were published/accepted for publication in peer-reviewed journals?	**250**
To how many of these is open access[21] provided?	**unknown**
How many of these are published in open access journals?	
How many of these are published in open repositories?	
To how many of these is open access not provided?	**unknown**
Please check all applicable reasons for not providing open access:	
☑publisher's licensing agreement would not permit publishing in a repository □ no suitable repository available ☑ no suitable open access journal available □ no funds available to publish in an open access journal ☑lack of time and resources ☑ lack of information on open access □ other[22]: ……………	

15. How many new patent applications ('priority filings') have been made? *("Technologically unique": multiple applications for the same invention in different jurisdictions should be counted as just one application of grant).*		**0**
16. Indicate how many of the following Intellectual Property Rights were applied for (give number in each box).	Trademark	**0**
	Registered design	**0**
	Other	**0**

[21] Open Access is defined as free of charge access for anyone via Internet.

[22] For instance: classification for security project.

17. How many spin-off companies were created / are planned as a direct result of the project?	**0**
Indicate the approximate number of additional jobs in these companies:	

18. Please indicate whether your project has a potential impact on employment, in comparison with the situation before your project:

❑ Increase in employment, or

☑ Safeguard employment, or

❑ Decrease in employment,

❑ Difficult to estimate / not possible to quantify

☑ In small & medium-sized enterprises

☑ In large companies

❑ None of the above / not relevant to the project

19. For your project partnership please estimate the employment effect resulting directly from your participation in Full Time Equivalent (*FTE = one person working fulltime for a year*) jobs:	*Indicate figure:*
Difficult to estimate / not possible to quantify	☑

I Media and Communication to the general public

20. As part of the project, were any of the beneficiaries professionals in communication or media relations?

○ Yes ✓ No

21. As part of the project, have any beneficiaries received professional media / communication training / advice to improve communication with the general public?

○ Yes ✓ No

22 Which of the following have been used to communicate information about your project to the general public, or have resulted from your project?

☑	Press Release	☑	Coverage in specialist press
□	Media briefing	☑	Coverage in general (non-specialist) press
□	TV coverage / report	☑	Coverage in national press
□	Radio coverage / report	□	Coverage in international press
☑	Brochures /posters / flyers	☑	Website for the general public / internet
□	DVD /Film /Multimedia	☑	Event targeting general public (festival, conference, exhibition, science café)

23 In which languages are the information products for the general public produced?

☑	Language of the coordinator	☑	English
☑	Other language(s)		

Question F-10: Classification of Scientific Disciplines according to the Frascati Manual 2002 (Proposed Standard Practice for Surveys on Research and Experimental Development, OECD 2002):

FIELDS OF SCIENCE AND TECHNOLOGY

1. NATURAL SCIENCES

1.1 Mathematics and computer sciences [mathematics and other allied fields: computer sciences and other allied subjects (software development only; hardware development should be classified in the engineering fields)]

1.2 Physical sciences (astronomy and space sciences, physics and other allied subjects)

1.3 Chemical sciences (chemistry, other allied subjects)

1.4 Earth and related environmental sciences (geology, geophysics, mineralogy, physical geography and other geosciences, meteorology and other atmospheric sciences including climatic research, oceanography, vulcanology, palaeoecology, other allied sciences)

1.5 Biological sciences (biology, botany, bacteriology, microbiology, zoology, entomology, genetics, biochemistry, biophysics, other allied sciences, excluding clinical and veterinary sciences)

2 Engineering and technology

2.1 Civil engineering (architecture engineering, building science and engineering, construction engineering, municipal and structural engineering and other allied subjects)

2.2 Electrical engineering, electronics [electrical engineering, electronics, communication engineering and systems, computer engineering (hardware only) and other allied subjects]

2.3. Other engineering sciences (such as chemical, aeronautical and space, mechanical, metallurgical and materials engineering, and their specialised subdivisions; forest products; applied sciences such as geodesy, industrial chemistry, etc.; the science and technology of food production; specialised technologies of interdisciplinary fields, e.g. systems analysis, metallurgy, mining, textile technology and other applied subjects)

3. Medical Sciences

3.1 Basic medicine (anatomy, cytology, physiology, genetics, pharmacy, pharmacology, toxicology, immunology and immunohaematology, clinical chemistry, clinical microbiology, pathology)

3.2 Clinical medicine (anaesthesiology, paediatrics, obstetrics and gynaecology, internal medicine, surgery, dentistry, neurology, psychiatry, radiology, therapeutics, otorhinolaryngology, ophthalmology)

3.3 Health sciences (public health services, social medicine, hygiene, nursing, epidemiology)

4. Agricultural sciences

4.1 Agriculture, forestry, fisheries and allied sciences (agronomy, animal husbandry, fisheries, forestry, horticulture, other allied subjects)

4.2 Veterinary medicine

5. Social sciences

5.1 Psychology

5.2 Economics

5.3 Educational sciences (education and training and other allied subjects)

5.4 Other social sciences [anthropology (social and cultural) and ethnology, demography, geography (human, economic and social), town and country planning, management, law, linguistics, political sciences, sociology, organisation and methods, miscellaneous social sciences and interdisciplinary , methodological and historical S1T activities relating to subjects in this group. Physical anthropology, physical geography and psychophysiology should normally be classified with the natural sciences].

6. HUMANITIES

6.1 History (history, prehistory and history, together with auxiliary historical disciplines such as archaeology, numismatics, palaeography, genealogy, etc.)

6.2 Languages and literature (ancient and modern)

6.3 Other humanities [philosophy (including the history of science and technology) arts, history of art, art criticism, painting, sculpture, musicology, dramatic art excluding artistic "research" of any kind, religion, theology, other fields and subjects pertaining to the humanities, methodological, historical and other S1T activities relating to the subjects in this group]