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PROJECT PERIODIC REPORT

Grant Agreement number: 600708

Project acronym: QUANTICOL

Project title: A Quantitative Approach to Management and Design of Collective and Adaptive Behaviours

Funding Scheme: Small or Medium scale focused research project (STREP)

Topic: : ICT-2011 9.10: FET-Proactive `Fundamentals of Collective Adaptive Systems' (FOCAS)

Date of latest version of Annex I against which the assessment will be made: 26/6/2015

Periodic report: 1st ☐ 2nd ☐ 3rd X 4th ☐

Period covered: from 1/10/2015 to 31/3/2017

Name, title and organisation of the scientific representative of the project's coordinator[1]:

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

[2] The home page of the website should contain the generic European flag and the FP7 logo which are available in electronic format at the Europa website (logo of the European flag: http://europa.eu/abc/symbols/emblem/index_en.htm logo of the 7th FP: http://ec.europa.eu/research/fp7/index_en.cfm?pg=logos). The area of activity of the project should also be mentioned.

Declaration by the scientific representative of the project coordinator

I, as scientific representative of the coordinator of this project and in line with the obligations as stated in Article II.2.3 of the Grant Agreement declare that:

- The attached periodic report represents an accurate description of the work carried out in this project for this reporting period;
- The project (tick as appropriate) :

  X has fully achieved its objectives and technical goals for the period;
  ☐ has achieved most of its objectives and technical goals for the period with relatively minor deviations.
  ☐ has failed to achieve critical objectives and/or is not at all on schedule.

- The public website, if applicable

  X is up to date
  ☐ is not up to date

- To my best knowledge, the financial statements which are being submitted as part of this report are in line with the actual work carried out and are consistent with the report on the resources used for the project (section 3.4) and if applicable with the certificate on financial statement.
- All beneficiaries, in particular non-profit public bodies, secondary and higher education establishments, research organisations and SMEs, have declared to have verified their legal status. Any changes have been reported under section 3.2.3 (Project Management) in accordance with Article II.3.f of the Grant Agreement.

Name of scientific representative of the Coordinator: ....Jane Hillston..................................

Date: .....05..../ ....05....../ ....2017.....

For most of the projects, the signature of this declaration could be done directly via the IT reporting tool through an adapted IT mechanism and in that case, no signed paper form needs to be sent

QUANTICOL

A Quantitative Approach to Management and Design of Collective and Adaptive Behaviours

quanticol
http://www.quanticol.eu

D7.3

Periodic project report for months 31–48

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Author(s): Jane Hillston (UEDIN)

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Part. no.	Participant organisation name	Acronym	Country
1 (Coord.)	University of Edinburgh	UEDIN	UK
2	Consiglio Nazionale delle Ricerche – Istituto di Scienza e Tecnologie della Informazione "A. Faedo"	CNR	Italy
3	Ludwig-Maximilians-Universität München	LMU	Germany
4	Ecole Polytechnique Fédérale de Lausanne	EPFL	Switzerland
5	IMT Lucca	IMT	Italy
6	University of Southampton	SOTON	UK
7	Institut National de Recherche en Informatique et en Automatique	INRIA	France

COOPERATION

Contents

1 Publishable Summary

Project Description The design of collective adaptive systems (CAS for short) must be supported by a powerful, well-founded framework that offers formal modelling and quantitative analysis. CAS consist of a large number of spatially distributed heterogeneous entities with decentralised control and varying degrees of complex autonomous behaviour. These entities or agents may be competing for shared resources even when collaborating to reach common goals. Often humans are both agents within such systems and end-users standing outside them. As end-users, they may be completely unaware of the sophisticated underlying technology needed to fulfil critical socio-technical goals such as effective transportation, communication, and work. The pervasive but transparent nature of CAS, together with the importance of the goals that they address, mean that it is imperative that thorough *a priori* analysis of their design is carried out to investigate all aspects of their behaviour, including quantitative and emergent aspects, before they are put into operation. We want to have high confidence that, once operational, they can adapt to changing requirements autonomously without operational disruption. Unfortunately, the defining characteristics of these systems mean that their (possibly non-linear) behaviour is often highly unpredictable or counter-intuitive. Formal, scalable, quantitative analysis, which provides multiple perspectives on system behaviour while being based on well-established reasoning techniques, is imperative to master such complex systems.

One of the main goals of the project is the development of an innovative formal design framework that provides a unique specification language for CAS and a large variety of tool-supported, scalable quantitative analysis and verification techniques. This design framework will also enable and facilitate experimentation and discovery of new design patterns for emergent behaviour and control over spatially distributed CAS. It will support both agent-based modelling techniques and equation-based techniques starting from system specifications at the individual (micro) level.

The work in the project is driven by smart city applications which can be very large scale CAS comprised of heterogeneous entities with spatially inhomogeneous distribution. These demand computationally scalable approaches. Therefore, the primary focus of the project is on the extension and exploitation of mean field and fluid flow techniques rather than simulation-based approaches. However, the latter play an important role in the exploration of smaller systems and in the validation of new techniques.

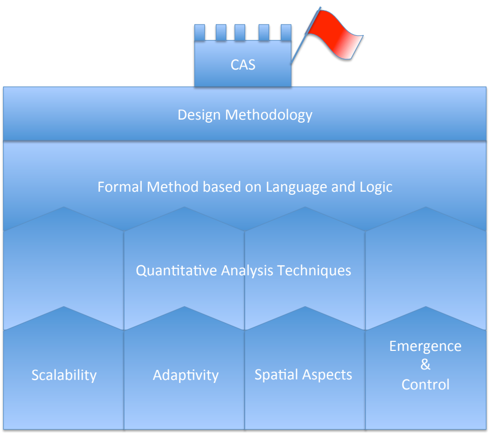


Figure 1: Quanticol research vision

Figure 1 shows the QUANTICOL vision of the development of the research in this project. Starting from the basement of the castle, the principal case studies have driven the development of theoretical extensions of mean field and fluid approaches tackling four distinct challenges: 1) scalability 2) (self-)adaptivity 3) spatial inhomogeneity and 4) design and control of emergent behaviour. Through the first two periods of the project we have developed a deeper understanding of these areas and established some foundational results. Meanwhile, higher up in the castle, process algebraic verification techniques are being developed and integrated into a uniform design framework supported by analysis and verification tools exploiting existing results in mean field and quantitative formal methods based on process algebra and temporal logics. Subsequently, in the final period of the project, the new theoretical results will be transformed into extensions of the tools that populate the framework, making the results available in a software engineering context. The techniques and tools will then be tested and validated on various case studies ranging from small exemplifying systems (for the purpose of illustration of the techniques and for tutorials), to existing benchmarks and variants of the smart city applications that were driving the theoretical parts of the project. Furthermore, the experience in the design and analysis of the wide range of case studies will be exploited to develop pathways for design and analysis that will guide software engineers in the development of CAS for smart cities.

Research Objectives The structure of the project reflects the major QUANTICOL objectives. The main objectives and the work packages, as originally defined, are listed below, and these remain valid for the project.

1. Development of a rigorous mathematical framework to engineer emergent behaviour in multi-scale systems.
2. Definition of a formal framework enabling the description of systems with spatial aspects with a process algebraic language, and supporting different kinds of representation of space and abstractions based on mean field techniques in an automatic way.
3. Development of stochastic temporal logics and novel forms of scalable model-checking approaches exploiting mean-field/fluid flow approximations that can address the verification of properties at the macro and micro level and their combination.
4. Development of a generic language offering linguistic support for high-level CAS modelling, expressing adaptivity and spatial awareness and enabling emergent behaviour.
5. Design and implementation of a software tool suite will be pursued which will provide a unified formal framework for the specification, analysis, and verification of models of CAS.

The target outcomes of the project include a scalable, quantitative design and verification framework and tools for large heterogeneous CAS to make model-based design of CAS of unprecedented size and complexity feasible where traditional agent-based approaches, reliant on extensive simulations, would be prohibitively costly. Potential outcomes of our case studies include enhancing the design of urban transportation systems through formal design and verification. For example, we have already published work detailing better predictive strategies for journeys within an urban bike sharing system, and improved timetabling for Edinburgh buses. As the project progresses we will aim to also exploit mean field techniques, in order to demonstrate that they operate in a safe and controlled way whilst also meeting user demand for scalable modelling and predictive tools. Similar considerations hold for the design of smart grid applications that adaptively maintain the lowest possible peak demand while providing clients with the best possible service in a safe and reliable way.

Major Achievements of the Project The project has made substantial progress towards the research objectives identified in the proposal, and exceeded our expectations with respect to several of them. In particular:

1. We have thoroughly explored rigorous mathematical analysis of the emergent behaviour in multi-scale systems, through both modelling and data analysis, and proposed a number of novel techniques which can be used in practice by designers, operators and users to better understand and predict the behaviour of systems. For example we have shown how data from existing bike sharing systems can be used to parameterise predictive models, how these models can be

suitably abstracted so that predictions can be made in real time, and offered algorithms for making predictions. Such an approach could be implemented as a mobile phone application helping users plan their journey and reducing the frustrations caused by non-availability of bikes or parking slots.

Key results in this area have substantially extended the class of models for which mean-field approximations can be meaningfully derived. We have established new mean-field approximations for CAS with multiple scale behaviour (either with respect to time or population sizes) and imprecise and uncertain behaviour. In the most recent period we have also established a new refined approximation that depends on the system size N. This offers much more accurate results for moderately-sized systems than classic mean-field approximations that rely on convergence as the system size tends to infinity. We have developed numerical methods to analyse the class of limit models for uncertain and imprecise population models allowing the properties of such systems to be studied quantitatively.

Understanding and predicting the behaviour of CAS is not enough — we need also to be able to control the behaviour so that it stays within acceptable bounds. We have developed generic methods for constructing control algorithms that lead to efficient use of resources. These methods are applicable to a wide variety of CAS, but we have demonstrated them on specific smart-grid and electricity market applications.

2. Much of this work is centred on the formal process algebraic language, Carma (Collective Adaptive Resource-sharing Markovian Agents), developed during the project. This richly expressive language has been shown to be capable of capturing a wide range of collective adaptive systems, dealing with problems such as open-ness, scale and spatial restrictions through attribute-based communication, explicit representation of locations and an explicit representation of the environment in which agents operate. The language is equipped with a structured operational semantics giving rise to an underlying continuous time Markov chain, which forms the basis of quantitative analysis both through agent-based and population-based simulation and mean-field approximations.

   In the final period we have paid particular attention to making this language accessible to a wide range of users. As a consequence

   - models are now specified in CaSL, the Carma specification language, providing a more programmatic-style of modelling;
   - we offer a rich set of spatial constructs which ease the description of systems in which space plays a major role;
   - the language is equipped with a rich set of syntactic and static analysis checks which help to ensure that models are free from trivial errors;

3. Throughout the project we have investigated a number of scalable verification techniques and developed innovative and efficient fluid and on-the-fly model checking algorithms that address local, global and local-to-global properties. These ordinary differential equation-based approaches are now additionally supported by formally-defined and automated model reduction techniques which can substantial reduce the size of the system of ODEs that must be considered. Since the conditions for fluid approximation are not always satisfied, we have also enhanced and integrated the statistical model checker MultiVeStA and developed a number of other model reduction techniques suitable for CAS. During the first period of the project we initiated a study of the logical approaches to the treatment of spatial information based on closure spaces, and this has been consolidated throughout the project, resulting in the topochecker tool which has been demonstrated to be applicable to a wide range of case studies including computer-assisted medical image analysis.

Designers are often concerned with a set of alternative configurations or system which could be deployed. Thus another form of scalable analysis is based on approaches to family-based verification of many alternative but closely related models to be carried out without resorting to complete enumeration of the alternatives to be verified individually. Within the project we have developed a number of new approaches to this problem including the the quantitative feature-oriented language QFLan which may be used to study properties such as quality of service, reliability or performance of dynamically reconfigurable product lines. Moreover we have pioneered a product-line approach to smart urban transport systems.

4. The Carma specification language, CaSL, provides a generic language offering linguistic support for high-level CAS modelling. The inclusion of an environment, with functions to determine rates and probabilities within the model and allowing those functions to depend on the current *state* of the components undertaking the actions allows a rich form of adaptivity to be incorporated into models (here *state* is comprised of both the logical state and attribute values or knowledge within a component). The attributes associated with components, readily lend themselves to capturing spatial awareness, and coupled with attribute-based communication and functional rates and probabilities, means that *what* a component can do, depends on *where* the component is located, a common feature of CAS. The adaptive nature of rates, probabilities, and even which actions are possible means that the behaviour of the system is emergent upon the behaviour of the individual components and their interactions. Moreover models are *open* in the sense that components can join or leave during the system evolution.

5. The QUANTICOL framework is supported by an extensive software tool suite, much of it developed as Eclipse plug-ins, offering portability and familiarity to many potential users. Even many of the techniques which are not yet incorporated in the core tool suite have been implemented in software as a proof of concept and in order to allow ourselves and others to thoroughly experiment with the techniques on realistic case studies. We have implemented an Eclipse plug-in to support the construction and analysis of Carma models, using CaSL. This is publicly available and demonstrated on a number of case studies. We also have Eclipse plug-in tools for reduction of systems of ODEs (*ERODE*), on-th-fly mean-field model checking for bounded Probabilistic Computation Tree Logic (PCTL) (FlyFast), specification and verification of Signal Spatio-Temporal Logic (SSTL) (*jSSTL*) and specifying and analysing PALOMA models. Further tools are currently independent of the Eclipse environment: *topochecker* a spatio-temporal model checker based on closure spaces and Kripke frames, moment closure based analysis, numerical solution of differential inclusions and a bus visualisation tool.

   This software suite is visible from the project website and freely downloadable. We provide guidance on installation, example models and mechanisms for users to report problems. Moreover over the final period of the project a number of tutorials have been presented by members of the team to explain the use of the tools and seek to attract users to them.

Expected results and their potential impact Our long term research vision is the development of a comprehensive software engineering environment, supporting a model-based design methodology for the development of CAS for smart city applications taking non-functional properties into account. The QUANTICOL project has contributed substantially to this vision, establishing a formal quantitative modelling framework.

1.1 Project website

Further details of the project can be found on our website `www.quanticol.eu`. In addition software developed during the project and suitable for use by third parties is available from download from `quanticol.github.io` and a number of other sites as detailed on `www.quanticol.eu`.

1.2 Project partners

	Partner	Acronym	Site leader	Dates
1 (Coord.)	University of Edinburgh	UEDIN	Prof Jane Hillston	1/4/13 onwards
2	Consiglio Nazionale delle Ricerche – Instituto di Scienza e Tecnologie della Informazione "A Faedo"	CNR	Dr Mieke Massink	1/4/13 onwards
3	Ludwig-Maximilians-Universität München	LMU	Dr Mirco Tribastone	1/4/13 – 31/8/13
4	Ecole Polytechnique Fédórale de Lausanne	EPFL	Prof Jean-Yves Le Boudec	1/4/13 – 31/1/14
5	IMT Lucca	IMT	Prof Rocco De Nicola	1/04/13 onwards
6	University of Southampton	SOTON	Dr Mirco Tribastone	1/9/13–30/06/15
7	Institut National de Recherche en Informatique et en Automatique	INRIA	Dr Nicolas Gast	1/2/14 onwards

2 Project Objectives for the Period

The second period of the project saw the rapid development of the QUANTICOL design and analysis framework, realising the original vision of the project. The final period of the project have been about consolidating this framework, both in terms of further enhancing the theoretical results and techniques, and ensuring that the promising approaches are enshrined in software. There has been effort to further explore the applicability of mean field approximation, even in moderately-sized systems, and to find efficient algorithms for the solution of uncertain models; these are reported in D1.4. The work on scalable model checking and spatio-temporal model checking has been further elaborated and applied within WP3, and this is reported in D3.3 together with new results, both theoretical and practical, on variability analysis. The representation and analysis of systems with a strong spatial aspect has been a key focus of the project. This proved to be a difficult topic; nevertheless a number of new results and their applications on case studies have been reported in D2.3.

There has been substantial effort on software development during the third period of the project, resulting in a multifaceted suite of tools. The software development has been informed by both theory and practice, and a number of case studies have been undertaken in order to ensure the applicability of the techniques and their implementation. We have also placed some emphasis on ensuring the framework is accessible and suitable to users. For example, the process algebra-based language Carma is now supported by the Carma Specification Language, CaSL, providing a more programmatic style of model-building, a graphical interface for model construction and a command-line tool for model execution and experimentation. These are all reported in D4.3. Moreover, a design workflow and analysis pathway has been developed, embedded in the tool, to guide the user to apply appropriate methods to their model. In a further step to enhance usability we have considered how available spatial data can be usefully deployed in spatial models (D2.2) particularly in the context of smart urban transportation systems. In addition to the software tools centred on Carma, a number of auxiliary tools, supporting various techniques developed in other work packages have also been developed and many of these are reported in D5.3.

Together these results completed the final milestone of the project, *CAS Tool Workbench, Design Methods and Case Studies*

Another major objective of the final period has been the wide dissemination of the result of the project. Our work on this is detailed in Section 4.6, but we particularly highlight here the Summer School (reported in D6.3) on *Formal Methods for the Design of Computer, Communication and Software Systems: Quantitative Evaluation of Collective Adaptive Systems* which took place in June 2016, and the accompanying book which was published by Springer in the well-known LNCS series, and the FORECAST workshop which was organised at the STAF multi conference in Vienna in July 2016, specifically to target the software engineering community.

At the second review the reviewers were happy with the progress of the project; they made a number of recommendations with respect to the future work.

- The reviewers correctly highlighted that simulation-based approaches are often complementary to mean field approaches and recommended that this be explicitly recognised. This has been the case in the final period of the project. Indeed the statistical model checker, MultiVesta, based on simulation approaches has been further developed as an alternative to fluid and mean field model checking.

- It was pointed out that a wide variety of methods have been developed to tackle the problem of scalable computational effort. We believe that this was the correct thing to do because some methods have restricted applicability and therefore offering a suite of techniques and tools, enhances the chances of a modeller being able to access one appropriate to their model. However, effort within the project has been limited so we have focused implementation effort on the most promising approaches.

- As recommended by the reviewers we have sought to build into the software tools more guidance of the modeller in order to ensure that methods are applied appropriately with respect to the constraints on their applicability.

3 Work Progress and Achievements during the Period

3.1 Work Package 1

Throughout the project, work package 1 has sought to extend the applicability of mean-field approximation. Mean-field approximation refers to a collection of techniques that make the analysis of large collective stochastic systems easier, through taking advantage of asymptotic results about the behaviour of the collective when the population tends to infinity. Before the start of the QUANTICOL project, these approximations were known to be applicable to systems composed of a large population of homogeneous individuals. In earlier deliverables, we reported new techniques that allowed us to study multi-scale systems, hybrid behaviour and uncertain systems. We illustrated the use of these techniques with our case studies, and focusing in particular on bike-sharing and smart-grid systems. During this reporting period, we continued this work, by developing both the theory and its application, including tool development in collaboration with work package 5. Several significant contributions have been made in this final reporting period.

Our first contribution has been to analyse the accuracy of mean-field approximation. Classical mean-field approximation consists of replacing the study of a system with N objects by its limit as N goes to infinity. We obtained conditions under which the distance between these two quantities decreases as c/N, where c is a constant that depends on the system's parameters. This allowed us to defined a **refined approximation** that depends on the system size N. For small N (*e.g.*, $N = 10$ or $N = 20$), this new approximation is much more accurate than the original mean-field approximation. For example the table below shows results for average queue length for a two-choice model, for models of varying but small sizes.

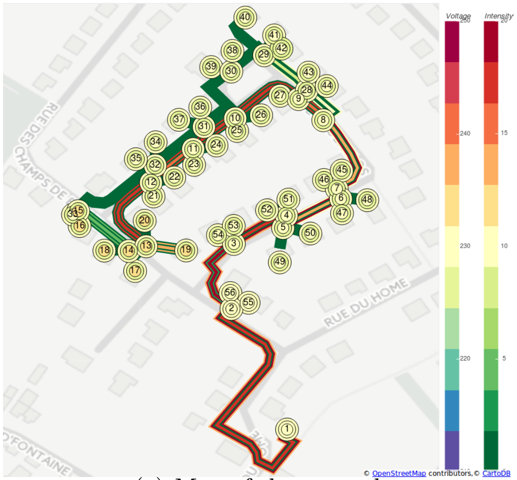
	$N = 10$	$N = 20$	$N = 30$	$N = 50$
Average queue length (simulation)	2.8040	2.5665	2.4907	2.4344
Refined approximation	2.7513	2.5520	2.4855	2.4324
Classical mean-field approximation (independent of N)	2.3527	2.3527	2.3527	2.3527

It can be observed that even for relatively small systems ($N = 10$) the refined approximation is very accurate, and a significant improvement on the classical mean-field approximation. This will make mean-field applicable to systems of small or moderate population size (composed of a few tens of individuals for example) for which the mean-field approximation was not accurate enough before. This result opens many interesting questions that will continue after this project.

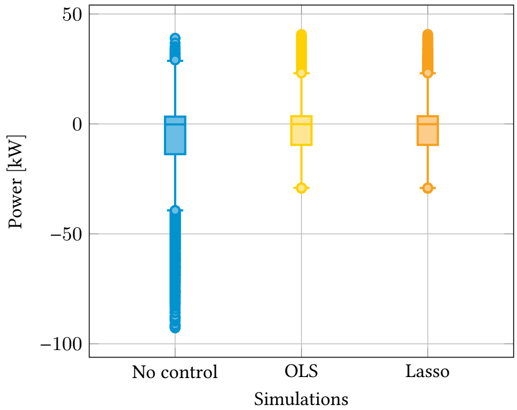
The second reported contribution concerns the development of **numerical algorithms to quantity the effect of uncertainties** on the parameters of the systems. Within the QUANTICOL project, we construct and study stochastic models of collective adaptive systems. These models assume that the sequence of events that will occur in a system is unknown but they assume that the probability of the occurrence of an event is known. When these probabilities are not known, we talk of an uncertain system. In this work, we developed different numerical techniques that allowed us to study quantitatively the properties of such systems.

The above methods are descriptive. They allow one to estimate the performance of a given policy, which can in turn be used to compare between different heuristics and choose the most appropriate one. Another strand of the work within this work package has been related to exerting control over systems to achieved desirable outcomes. Our third contribution in this period concerns the use of mean-field approximations to **create efficient control policies**. Using this approach we have compared centralised and decentralised policies. In particular, we obtained a counter-intuitive result, that mean-field games are not the unique limit of stochastic N-players games.

Our last contribution concerns the design of **control algorithms for smart-grid systems**. These algorithms are motivated by the increasing share of renewable sources of energy – like photovoltaic panels or wind turbines. This creates two problems: (1) these sources of energy are distributed and produce locally; and (2) they are volatile and intermittent. We develop two approaches to deal



(a) Map of the network



(b) Power flow at the transformer : the transformer should operate between -30 and +40 kW. Without control, this limit is often violated. This is no more the case with our control mechanism (OSL and Lasso correspond to two variants of our algorithm).

Figure 2: Map of the electrical distribution network and power flow at the transformer in the model.

with this issue: a real-time control algorithm that we plan to deploy on a distribution network; a market framework that could be used to encourage people to smooth their consumption. Figure 2 shows the effectiveness of the real-time control algorithm in the distribution network.

This work about the control of distribution networks, that started thanks to the QUANTICOL project, has now become an active collaboration between the company Schneider Electric and Inria.

3.2 Work Package 2

During the final period of the project, this work package has produced two distinct deliverables, reflecting work in tasks T2.1 and T2.3.

D2.2 describes the research for task T2.3 into the use of spatial data for spatial modelling. Space plays an important role in QUANTICOL because of the nature of the case studies we have chosen as examples of collective adaptive systems. The deliverable focuses on the use of spatial data both in model construction and in parameter estimation.

When considering public transport systems there is often a wealth of data because the service operators collect GPS data of vehicle locations. We have developed a methodology for taking such vehicle data and developing parameterised patch-based (discrete-space) models of vehicle routes. The methodology includes a phase of patch identification once automated map generation has been used to identify routes. GPS data can then be used to derive parameters for the time taken to cross a patch. In particular we investigated the use of hyper-Erlang and shifted Erlang distributions for these dwell times. The models developed and parameterised with this approach have been used to assess the impact of speed limit reductions on timetable adherence and for statistical model checking of temporal properties, such as those describing punctuality.

Space can also be considered in a static manner, and we have characterised the spatial distribution of various bike sharing schemes. Furthermore, we have investigated which distributions can be used to generate topologies of bike stations that are closest to the actual arrangement for a number of cities. The approaches under consideration were the regular grid, the Poisson spatial point process, the Ginibre spatial point process, and a placement based on rating of amenities. Using street map data to exclude areas where stations cannot be placed, pixels are weighted as to their likelihood of being the position of a bike station. Two different approaches to the assessment of the coverage of the generated topologies when compared with the actual topologies have been presented. As illustrated in Figure 3, the rating-weighted scheme was able to create realistic patterns for several cities. Having such a technique for generating "artificial" bike sharing systems could be a valuable planning tool for town planners exploring the provision of a bike sharing scheme.

Journey data can also be used in model development and parameterisation. This data can be synthetic or real. An example of the use of real journey data from a bike-sharing scheme is in determining which bike stations have an influence on other stations, thus capturing the spatial layout and interactions of these stations. By considering only the stations with a high level of influence, the model can be reduced in size and thus its analysis becomes possible. As reported in D2.3 synthetic journey data has been used in the transformation of an individual continuous-space model to a population discrete-space model using patches. Here, a description of movement was used to create a small simulation of individual movement, and from this parameters were estimated for the population model.

D2.3 describes research into mathematical and computational methods for scalable spatial modelling for CAS. In the initial investigation phase of QUANTICOL, we decided to focus our attention on discrete models of space, in which space is described by a set of locations, connected by edges representing the connections between locations. However, such a discrete representation of space poses formidable computational challenges, as complexity of model analysis scales at least linearly with the number of locations. In D2.3 we reported several techniques to abstract and transform space in order to ease the computational burden. These can be grouped into three classes of approach:

- **Pragmatic approximations**: a spatial model can be simplified using some heuristic criterion which is shown to work well in practice. Within this umbrella, we reported on a method based on behavioural distances to aggregate locations, thus simplifying the space structure. We also discussed approaches to simplify second order moment equations in the presence of localities, by setting to zero moments of population variables in locations which are too distant. In particular, we described an approach, illustrated on bike sharing, to identify the most important locations influencing a given one, and a method based on a syntactic distance between agents interacting in space.

- **Transformation of space**: here the spatial attributes of a model are kept, but space is transformed into a qualitatively different mathematical object, which makes the analysis simpler. In particular, we reported on techniques that take a grid describing a discretised 2-dimensional space, and approximate it with a continuous state space. The model itself changes from a patch-based population Markov chain to a set of partial differential equations, that can be solved more efficiently. Limit theorems were proved to establish the correctness of the method. The approach was also extended to a fast simulation result, allowing us to track the behaviour of a single agent, approximating it as a switched Brownian motion, which is faster to analyse than the full stochastic model. We also reported on a method to construct patches from an agent based model in which agents move in continuous space.

- **Full abstraction from space**: sometimes a spatial model can be replaced by a simpler one without an explicit representation of space. In this class, we developed three methods: the use of mean-field techniques that guarantee the asymptotic decoupling of the behaviour in different locations, allowing us to analyse each location independently; spatial moment closures, that can be used to capture mean and variance of the total population over all locations though a system of differential equations which is independent of localities; and pair approximation, a technique to capture local structure in spatially non-homogeneous models, by counting pairs of neighbour individuals. Figure 4 demonstrates how this approach is able to accurately approximate the behaviour of a full model, in a situation where mean-field approximation fails.

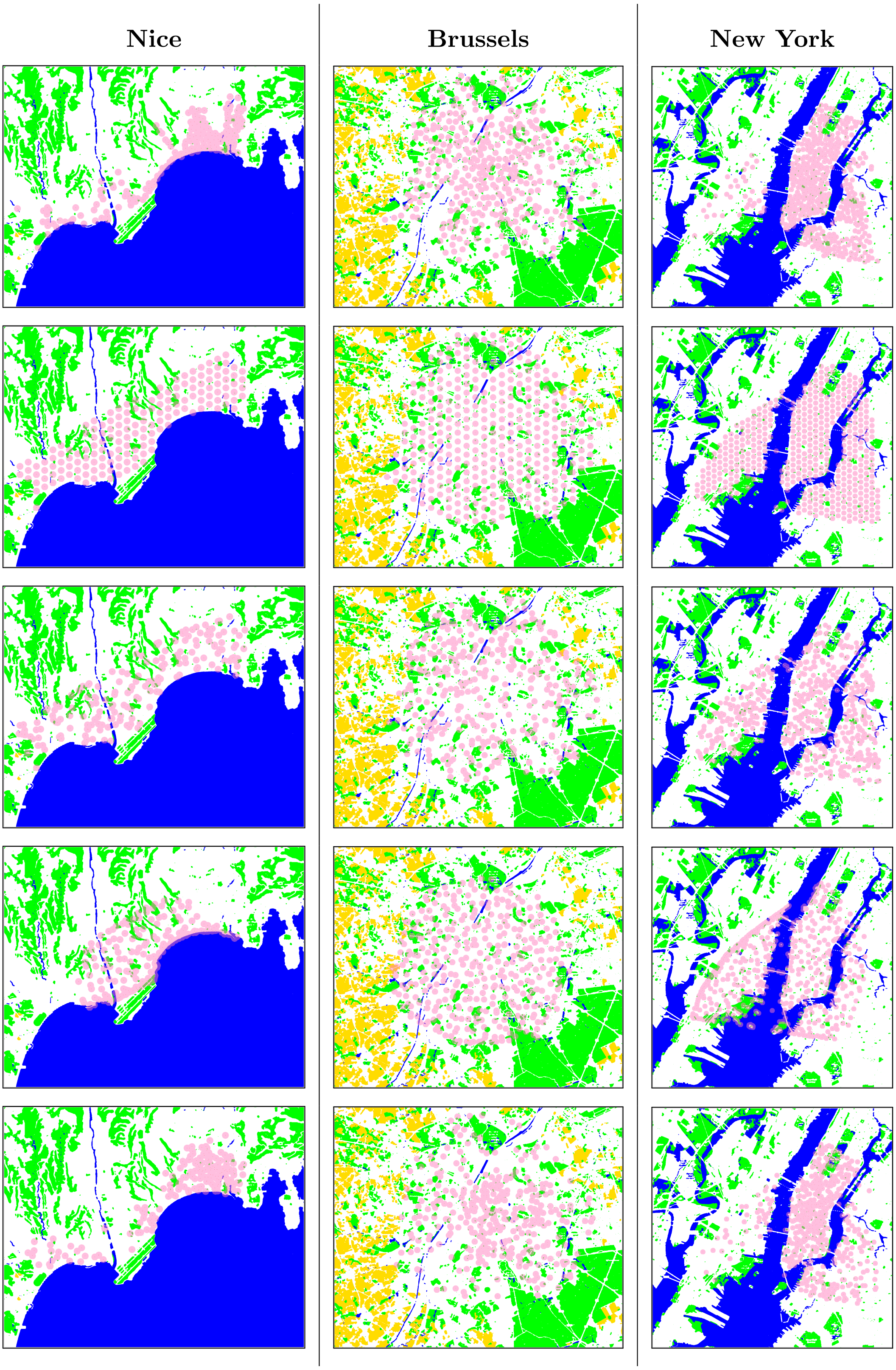
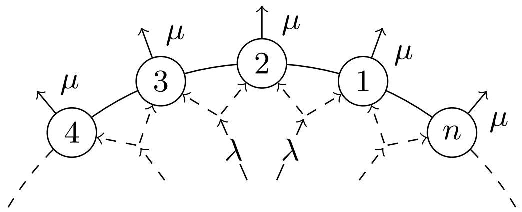
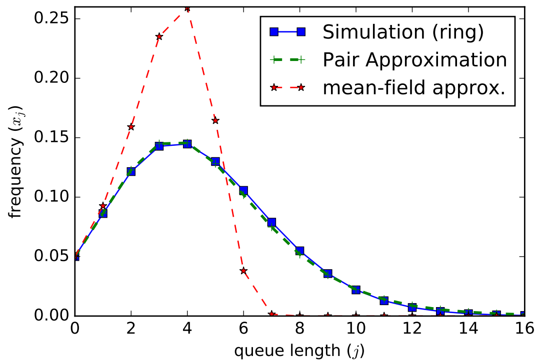


Figure 3: Top to bottom: real system, regular grid (without noise), Poisson, Ginibre, rating-weighted.



(a) Model: Jobs arrive at rate $N\lambda$ in the system. For each arrival, $i \in \{1 \dots n\}$ is picked at random and the job is allocated to the server i or $i+1$ (mod n) that has the least number of jobs. The size of each job is exponentially distributed of mean $1/\mu$.



(b) Simulation results

Figure 4: Pair-approximation: Model and simulation results.

3.3 Work Package 3

Work Package 3 is focused on the development of the theoretical foundations of novel, scalable and spatial formal analysis techniques and the underlying theories to support the design of large scale CAS. The work is organised into three tasks, considering Spatial Stochastic Logics and Scalable Verification (Task 3.1), Abstraction Techniques for Scalability beyond Population Size (Task 3.2) and Relating Local and Global System Views with Variability Analysis (Task 3.3). Work has progressed well in all three tasks during the third period.

Throughout the project a common objective of all three tasks has been to make substantial contributions to the theoretical foundations of scalable and spatial formal analysis methods in order to underpin the development of a formal verification framework for Collective Adaptive Systems (CAS). This theoretical work has been expanded in the final reporting period and consolidated with tool development and consideration of applications, including some outside the domain of CAS.

Specifically, we have extended fluid model checking and on-the-fly mean field model checking previously developed for the analysis of *local* reachability properties of an individual object in the context of one or more large populations, to consider fluid model checking to address time-bounded *global* reachability properties of the system, for example, properties concerning the probability that the size of a particular population exceeds certain levels within a certain time interval. Moreover, we have also shown how fluid model checking can be enhanced to deal with various types of *reward* properties. This allows more sophisticated queries to be used to interrogate the behaviour of models; for example Figure 5 considered issues of user satisfaction, modelled as a reward, which can be increased or decreased according to the user's experience of integration with the system.

The discrete time, probabilistic mean field model checking approach, that led to the open source model checking tool FlyFast, has been further improved and used for a number of case studies, such as the analysis of a benchmark gossip protocol as well as a bike sharing model. In this latter case a CaSL model is reduced to a FlyFast model, linking the work in work package 4 with work in work package 3 and demonstrating the overall vision for how the theoretical foundations established in this work package can be incorporated into the QUANTICOL framework. The bike sharing example also illustrates that, under some suitable conditions, the discrete time approach can be used to approximate fluid model checking results. As a further step towards the integration of FlyFast with specification languages based on a predicate-based communication paradigm, a front-end for the FlyFast modelling language has been developed that incorporates components and predicate-based communication inspired by the CARMA language.

In the previous reporting periods several spatial and spatio-temporal logics have been proposed and efficient related model checking and monitoring algorithms have been developed. In the third reporting period this work has proceeded by developing novel spatial logic operators on one hand, and

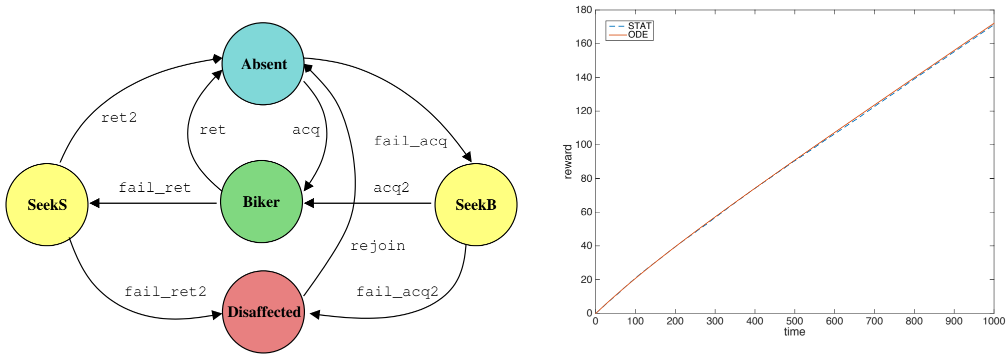


Figure 5: States and transitions of a single member in the bike sharing system (left) .Rewards are gained through successful completion of acquire and return actions, but lost upon failures. Comparison of the fluid approximation solution $z(t)$ for the reward associated with dissatisfaction with the statistical estimation (5000 runs) of the state probabilities for $Z^{(N)}(t)$.

by the development of more efficient prototypes. Some of these have been made available as an Eclipse plug-in and their front-end made compatible with the Carma language. Others have been developed as a stand-alone model checker and have been shown to be applicable not only to CAS but also to unforeseen areas such as medical imaging (see Figure 6). Spatio-temporal model checking has also been combined with statistical model checking exploiting a feature of the MultiVeStA tool to analyse a property on all points in space simultaneously for each simulation run, making it feasible to apply stochastic spatio-temporal model checking on large CAS such as a bike sharing system of the size of that of London. Furthermore MultiVeStA itself has been extended to incorporate checking of steady state properties in addition to transient properties.

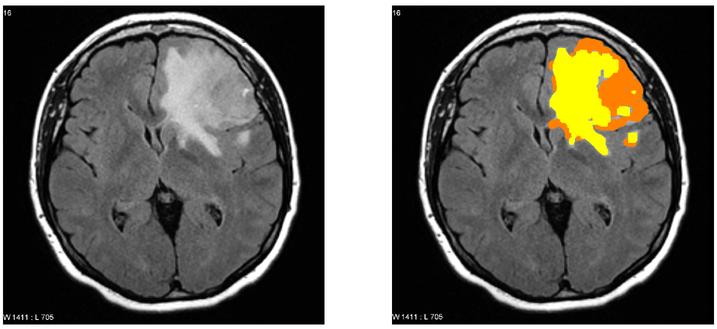


Figure 6: (left) A slice of a FLAIR MR acquisition of a brain affected by a glioblastoma. (right) Final result of application of threshold, distance, and the texture operator. The yellow area is the identified oedema; the orange area is the tumor (case courtesy of A.Prof Frank Gaillard, Radiopaedia.org, rID: 5292).

The scale of CAS means that even fluid and mean field approximations can suffer from the curse of dimensionality, motivating the substantial work that has been carried out in this work package on model reduction for systems of ordinary differential equations (ODEs). During this period the full characterisation of equivalence relations for Ordinary Differential Equations has been addressed. These relations were in part developed during the previous reporting periods, but have now been refined, and efficient, fully automatic minimisation techniques have been developed that can be used in a much more general setting. Such model reduction techniques, that go beyond fluid approximation, are important because they enable the analysis of models of a size that was impossible to handle with existing methods. Furthermore, these equivalences offer possibilities for symbolic computation. This leads, for

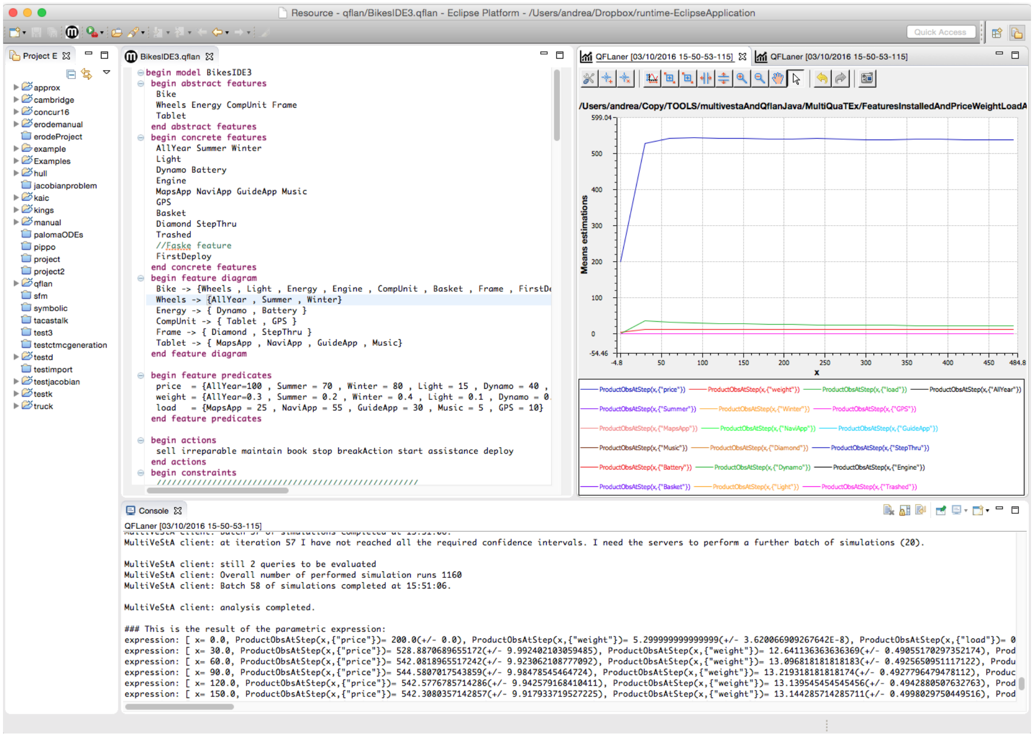


Figure 7: Screenshot of the `QFLan` tool framework

example, to very efficient methods for the analysis of models with one or more parameter variables. Moreover these reduction techniques have been incorporated into software tools, thus providing a link to work package 5.

However, mean field and fluid approximation techniques are not suitable for the analysis of *all* large scale CAS. This is for example the case in systems that involve uncertain parameter values, which occurs frequently in performance analysis. Exploiting a technique involving simulation-based model checking has shown to be a promising solution in such cases. This technique, also known as *smoothed model checking*, exploits properties of Gaussian processes to verify properties of models with several parameters.

The final task of work package 3 has focused on software product lines (SPL) and variability analysis. Here the large scale of the models is not always due to the presence of large populations, but rather to the large number of combinations of possible features that are present in families of products. To address such problems, a family-based approach to model checking has been pursued. In particular, an Eclipse-based tool for the quantitative feature-oriented language QFlan, introduced during the second reporting period, has been developed, using statistical model checking, to address properties such as quality of service, reliability, or performance of dynamically reconfigurable product lines (see Figure 7).

3.4 Work Package 4

The main aim of Work Package 4 is to support the development of CAS in a specifically designed language, supporting large numbers of spatially distributed components, capturing and manipulating knowledge and amenable to scalable quantitative analysis. This language, originally called CAS-CEL, was instantiated as a process algebra-based language CARMA (Collective Adaptive Resource-sharing Markovian Agents) during the second reporting period. This is now supported by `CaSL`, the CARMA specification language, providing a less mathematically-oriented, programming-style language. Developing this specification language is intended to make modelling with CARMA accessible to a wide

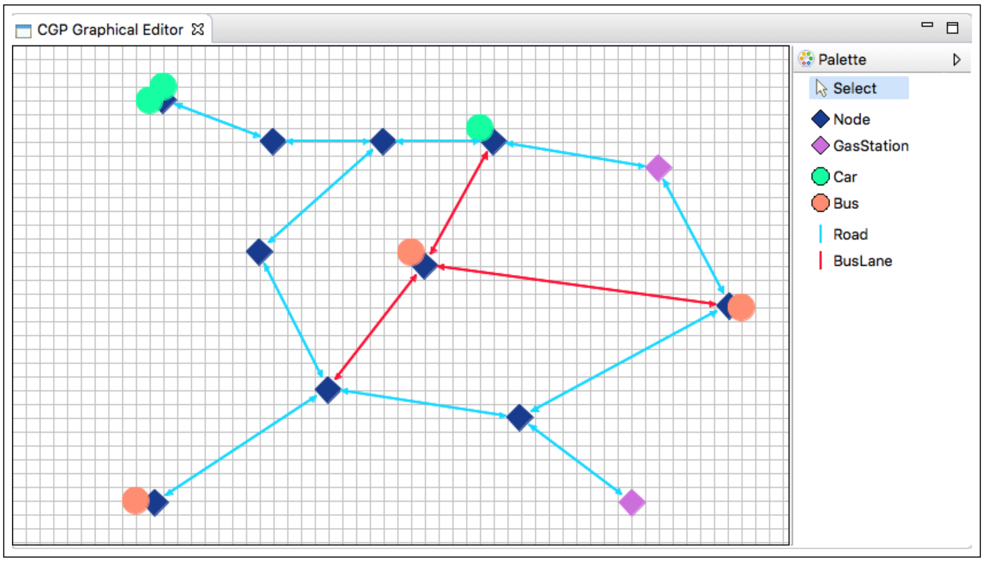


Figure 8: A screenshot of the graphical interface for path and components layout.

audience of potential users interested in CAS, not just those already familiar with formal modelling with process algebras and address questions about usability that were raised in the previous review. To this end we have further developed the CARMA Specification Language (CaSL) and the software tools that support it; we have developed exemplar models, some of which are reported in this deliverable, and extended the suite of tools to offer a modeller different approaches to model analysis.

Without formally extending the expressiveness of CARMA, CaSL presents a more programmatic style of modelling, which will be usable by a wider set of people. Space plays a key role in many CAS and we have revisited the support that is offered to faithfully capture the spatial aspects within a model, resulting in improved syntax to assist the modeller and a graphical front end which can be used to automatically generate the spatial aspects of models. Throughout this development process we have informed our design and improved our implementation by developing a number of different exemplar models, even going beyond the smart cities application domain in order to ensure that our languages are sufficiently expressive to capture a wide range of systems.

Of course, to be practically useful a modelling language must be implemented in a robust set of software tools to allow the modeller to construct and analyse the model with confidence. In addition to the editing and model simulation facilities previously presented in the Eclipse plug-in tool, the CARMA tool suite now also incorporates a graphical plug-in to assist in the specification of the spatial aspects of models (see Figure 8), links to the MultiVeStAtool for statistical model checking, and a command line interface with support for experimentation. The software tool suite for CARMA is available at `https://quanticol.github.io`. To ease the access to CaSL and its tool, a specific web site has been instantiated where users can access tool documentation and examples. Moreover, a bug reporting system is also now available.

We have also elucidated a design workflow and analysis pathway, which is supported in the tools. This takes into account the different phases that a model goes through, from initial design, elaboration, parameterisation and then use as a tool to investigate the behaviour of the system under study. The modeller needs different support at each of these stages and we have sought to provide what is appropriate for each stage, as far as is feasible within the limited time and resource of the project. Building within Eclipse has allowed us to provide many consistency-checking features which greatly enhance the support for the modeller. These internal checks seek to ensure that CaSL models are free from the type of minor error that can be frustrating and time-consuming during model development. However, once a modeller is fully confident of their model, a graphical user interface can become cumbersome and inconvenient. Thus we also provide a command line interface to support efficient exploitation of models under different experimental frames. Moreover, the results of model analysis are automatically enhanced with metadata to assist with their interpretation and reproducibility.

Whilst we have explored other applications ranging from epidemiological models to food security models, our primary focus for applications and case studies has remained smart cities, and the recent deliverable D4.3 reports a demonstration of the analysis of CaSL models of two of the scenarios from our smart city case studies. Specifically we consider a mesoscale model of buses within a city, particularly paying attention to the congestion that occurs when multiple routes share the same bus stopes, and issues related to regulatory compliance and appropriate spacing on frequent bus services. In the second example, we consider the key issue related to user satisfaction within urban bike sharing systems — whether a user will find a bike or a slot at a convenient location when they want one.

To study the expressive power of attributed based communication, a simple calculus named *AbC* (a calculus for Attribute-Based Communication) has been introduced. The expressiveness and effectiveness of attribute based communication are demonstrated both in terms of modeling scenarios featuring collaboration, reconfiguration, and adaptation and of the possibility of encoding channel-based interactions and other interaction patterns. Behavioral equivalences for *AbC* are introduced for establishing formal relationships between different descriptions of the same system. Finally, a Java run-time environment, named $Ab\overset{a}{C}uS$, has been developed to support deployment of systems based on attribute-based communication. This runtime environment enables programming of collective adaptive systems by relying on the communication primitives of the *AbC*/CARMA. By means of a number of examples, we also show how opportunistic behaviors, achieved by run-time attribute updates, can be exploited to express different communication and interaction patterns and to program challenging case studies.

3.5 Work Package 5

Work Package 5 is focused on the development of case studies of smart cities in public transportation and smart grid, and the integration of software tools emerging from the theoretical work undertaken in other work packages. This includes the implementation of CARMA and CaSL, but also a variety of other tools which have been developed in order to test our theoretical developments and make them available to other researchers. The long-term goal would be for all these techniques to be incorporated into a single framework, centred on CARMA, but such a substantial programming effort was beyond the scope of this project.

The final period has seen substantial activity on software tool development as we sought to consolidate the results of other work packages in a form which is useful both within the project, and to other researchers. These software tools, the QUANTICOL software tool suite, form a valuable dissemination channel to a variety of communities. Several of the tools developed, and their application to smart city scenarios, are reported in D5.3.

Specifically, the presented tools are:

- FlyFast, a first-of-its-kind, *on-the-fly mean-field* probabilistic model checker for bounded PCTL (Probabilistic Computation Tree Logic) properties of a *selected individual* in the context of systems that consist of a *large number* of independent, *interacting objects*. The underlying on-the-fly mean field model checking algorithm was developed and proven correct in the context of WP3 task 3.1. FlyFast is provided within the jSAM (java StochAstic Model Checker) framework which is an open source Eclipse plug-in[1] integrating a set of tools for stochastic analysis of concurrent and distributed systems specified using process algebras.

- *jSSTL*, a Java tool for the specification and the verification of Signal Spatio-Temporal Logic (SSTL) properties also developed in WP3 task 3.1. It consists of a library (the *jSSTL* API) and a front-end developed as an Eclipse plug-in. The plug-in provides a user friendly interface

[1]http://quanticol.github.io/jSAM/

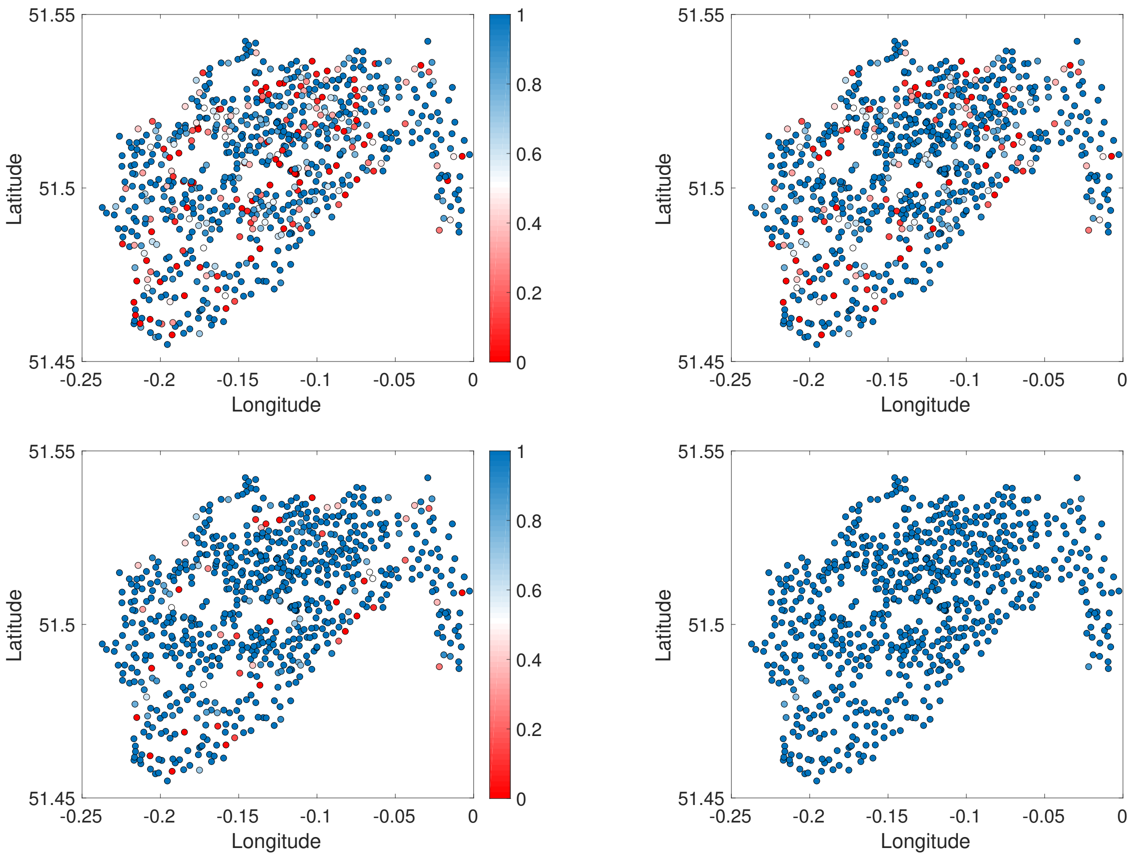


Figure 9: Approximate probability satisfaction degree of formula ϕ_1 for 1000 runs for each BSS station for (a) $d = 0$, (b) $d = 0.2$, (c) $d = 0.3$ and (d) $d = 0.5$. The value of the degree is given by the colour legend.

to the tool, whereas the library can be used to integrate *jSSTL* within other applications and tools. The objective is to explore a question pertaining to bike sharing systems: *if I do not find a bike/free slot, is there another station at the distance less than a certain value where I can find a bike/free slot?* A station ℓ satisfies ϕ_1 if and only if it is always true that, between 0 and T_{end} minutes, there exists a station at a distance less than or equal to d, where there is at least one bike and a station at a distance less than or equal to d where there is at least one free slot.

- *ERODE*, a tool for the evaluation and reduction of ordinary differential equations implemented as an Eclipse plug-in, and consolidating work carried out in WP3, task 3.2, its architecture is shown in Figure 10.
- *UTOPIC*, which supports an under-approximation technique for the reachability analysis of nonlinear systems of ordinary differential equations (ODEs). It implements an algorithm based on control-theoretic principles of optimal control, developed in the context of WP1. *UTOPIC* itself is implemented as an extension of *ERODE*.
- *topochecker*, a spatio-temporal model checker based on closure spaces and Kripke frames. Currently it checks a spatial extension of Computation Tree Logic named STLCS (Spatio-Temporal Logic for Closure Spaces). The underlying theory has been developed in the context of WP3.

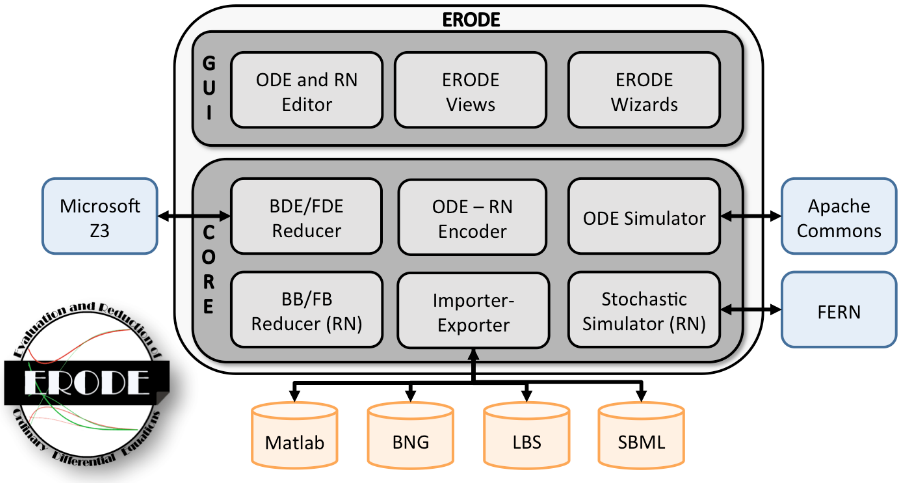


Figure 10: *ERODE*'s Architecture.

3.6 Work Package 6

Work Package 6 of QUANTICOL is concerned with the dissemination activities of the project. In line with the dissemination plan, D6.1, the focus of dissemination during the final period of the project has continued across the three major dissemination channels that we identified: our peer community, the broader scientific community and users and other stakeholders, with a growing proportion of activity with respect to the latter two communities.

In particular during the final period the project team focussed on reaching a broader academic community and encouraging uptake of our tools and techniques, as this was deemed to be the most promising route for impact and future exploitation. A key element of this was the summer school organised at the Centro Universario Residenziale di Bertinoro in June 2016. This formed part of a well-established series organised by Professor Marco Bernardo for more than 15 years, "Formal Methods for...". The 2016 edition was "Formal Methods for Quantitative Evaluation of Collective Adaptive Systems" and members of the QUANTICOL project presented half the tutorials that formed the school. The other tutorials were provided by eminent computer scientists in related fields, and the School also provided opportunities for them to learn more about the work of QUANTICOL. Full details of the summer school were reported in deliverable D6.3. There is an associated volume published by Springer in the LNCS series, providing access to the material to a much wider audience than those students who were able to attend.

We also organised a workshop targeted at exposing our ideas to the software engineering community. This took place in Vienna in July 2016, as part of the STAF (Software Technologies: Applications and Foundations) federation of conferences related to software engineering. This workshop, FORECAST (FORmal methods for the quantitative Evaluation of Collective Adaptive SysTems) gained good visibility amongst the conference attendees, and provided a venue for presenting results from the QUANTICOL project, as well as attracting participants from outside the project.

Carma and its use for the design and the analysis of Collective Adaptive System was presented at the Annual Meeting of IFIP Working Group 2.2 that was held in September 2016 in Singapore. The primary aim of the Working Group 2.2 is to explain programming concepts through the development, examination and comparison of various formal models of these concepts. In 2016, the annual meeting of IFIP WP2.2 was part of "Automata, Logic and Games held at Institute for Mathematical Sciences at National University of Singapore. An objective of the "Automata, Logic and Games seminars was to promote interactions between researchers working in the theory and foundations of automata, logic and games, and those who build tool implementations of model checking algorithms, perform empirical studies, and work with the verification industry. Carma and the work of the QUANTICOL project was explained in this context.

In addition at the conclusion of the project, we have organised an industry day, to be held in Lucca in May 2017. This is targeting a non-academic audience and will give project members an opportunity to present results from the project to a selection of participants from industry, exploring possibilities for future collaboration and exploitation.

Meanwhile dissemination through the usual academic channels has continued, with a significant number of papers presented at top conferences and in prime journals. Members of the QUANTICOL team have received a number of international invitations to talk about the work of the project, an indication that the work that has been undertaken is novel and interesting to the community, and that our dissemination has been effective. Details of dissemination activities completed during this period are detailed in Section 4.6. Forthcoming invitations include speaking at the Integrated Formal Methods conference in Turin, Italy, in September 2017, at the QAPL workshop in Uppsala, Sweden, in April 2017, and at other venues. Moreover, several members have been invited to serve as Programme Committee Co-chairs of two main conferences, one in the field of performance analysis, QEST 2017, that will be held in August in Berlin, Germany and one on design and analysis of collective adaptive systems, COORDINATION 2017, that will be held in June in Neuchâtel, Switzerland. Two members of the CNR-ISTI team are involved in teaching courses on topics of the QUANTICOL project in the context of the PhD program in Smart Computing (http://smartcomputing.unifi.it) and are members of the Doctoral Committee.

The project website `www.quanticol.eu` continues to provide a primary communication channel for the work developed in the project. Increasingly this includes, software as well as publications, and several software tools are available for download via this site.

4 Project Management

4.1 Management and Communication

The management of the project has been achieved through the work of the coordinator, in conjunction with the Management Board, which consists of site leaders and work package leaders. This group meets monthly by teleconference to monitor progress and discuss future plans. The management of the project during the second period has continued broadly according to plan without significant difficulties. Following on from the previous period:

- One of the investigators of the partner UEDIN, Stephen Gilmore, had had severe health problems since early 2015 and was not able to work from April 2015. Prof Gilmore had two primary responsibilities: leading the Edinburgh work related to WP5 and Task 4.3 of WP4, and leading WP6 on dissemination. During the second period Prof Hillston took two remedial actions. Firstly, she employed a temporary replacement, Adam Duguid, to cover Prof Gilmore's contributions to WP4 and WP5. Secondly, Prof Hillston temporarily took over leadership of WP6, contributing additional hours to the project at no extra cost. During the third period Prof Gilmore made a phased return to work and rapidly re-assumed his responsibilities for WP4 and WP5, and more recently resumed leadership of WP6.

The project wiki and mailing lists have continued to be used very effectively for internal communication within the project. As in other periods we have organised a number of focused project workshops tackling particular topics and the wiki has been used to share pertinent information in preparation for these meetings. Moreover for all meetings the slides and an account of the meeting are posted on the wiki rapidly after the meeting, allowing those that were not able to participate to keep up with developments in the project. The wiki is also used as an early dissemination platform within the project where work in progress, technical reports and submitted papers can be shared with project partners for information and feedback. In addition meeting reports and minutes, for example of the monthly teleconference, are also made available via the wiki. We have continued to develop the project website `www.quanticol.eu`. We regard this as the main interface between the project and our scientific peers. The final period of the project has resulted in a significant number of software tools (as detailed in D4.3 and D5.3) and these have also been made available to our scientific peers via `www.quanticol.eu`.

There have been no amendments or changes to the consortium during the final period.

The management of the project has continued to run smoothly during the third period with no significant difficulties.

4.2 Project meetings

There have been a number of project meetings during the third period of the project, two plenary meetings, and several with more focussed topics of discussion. Although the non-plenary meetings had specific agendas all partners were invited and in many cases all partners were represented at these meetings.

15th-16th December 2015, Lucca — Plenary Project Meeting This meeting was held shortly after the second review to discuss research plans and priorities for the final period. It also provided an opportunity to discuss collaborations and further meetings for the following months. There was a meeting of the Management Board as part of this meeting.

20th-24th June, Bertinoro — Scientific Discussion Meeting This meeting was held in parallel with the QUANTICOL Summer School on *Formal Methods for the Design of Computer, Communication and Software Systems: Quantitative Evaluation of Collective Adaptive Systems.* The QUANTICOL team took the opportunity to discuss work amongst themselves, but also with other presenters at the summer school, raising the profile of the project with international research leaders in related fields (see the report D6.3 for details). There was a meeting of the Management Board as part of this meeting.

22nd-23rd September 2016, Edinburgh — Plenary Project Meeting This meeting was used to review progress since the last plenary meeting, and to make detailed plans for the final set of deliverables. One half day of the meeting focused on the smart city case studies and we discussed different scenarios in which our tools could be applied to the case studies, selecting the most representative cases to be included in the material for the final review (deliverables and presentations). There was a meeting of the Management Board as part of this meeting.

7th-8th February 2017, Pisa — Plenary Project Meeting The focus of this meeting was to review progress on the deliverables and make the final selection of work to be presented at the final review. We also discussed the industry day which will be held the day after the final review, presenting our work to potential future collaborators from industry. There was a meeting of the Management Board as part of this meeting.

Additionally there have been regular monthly teleconferences for the Management Board, comprised of representatives of all sites and work packages, to monitor the scientific progress of the project. These are documented and minuted on the project wiki.

4.3 Project planning and status

The project has continued to proceed smoothly during the final period. As described in the account of the work packages, all work packages broadly progressed in line with the plan originally set out in Annex I, with only minor variations.

4.4 List of Scientific Publications in Months 31–48

1. L. Bortolussi and C. Feng. Location Aggregation of Spatial Population CTMC Models. 14th international workshop on Quantitative Aspects on Programming Languages and systems (QAPL 2016). (⋆ *UEDIN/CNR collaboration* ⋆)

2. D. Reijsbergen. Probabilistic Modelling of Station Locations in Bicycle-Sharing Systems. In Software Technologies: Applications and Foundations, LNCS 9946, 83–97, 2016

3. D. Bacciu, A. Carta, S. Gnesi, and L. Semini. Adopting a Machine Learning Approach in the Design of Smart Transportation Systems. ERCIM News 105: Special theme Planning and Logistics. April 2016.

4. M.H. ter Beek, M.A. Reniers, and E.P. de Vink. Supervisory Controller Synthesis for Product Lines using CIF 3. In Proceedings of the 7th International Symposium on Leveraging Applications of Formal Methods, Verification and Validation: Foundational Techniques (ISoLA'16), Corfu, Greece (T. Margaria and B. Steffen, eds.), Lecture Notes in Computer Science 9952, Springer, Berlin, 2016, 856–873.

5. M.H. ter Beek, A. Legay, A. Lluch Lafuente and A. Vandin. Statistical Model Checking for Product Lines. In Proceedings of the 7th International Symposium on Leveraging Applications of Formal Methods, Verification and Validation: Foundational Techniques (ISoLA'16), Corfu, Greece (T. Margaria and B. Steffen, eds.), Lecture Notes in Computer Science 9952, Springer, Berlin, 2016, 114–133. (⋆ *CNR/IMT collaboration* ⋆)

6. M.H. ter Beek, A. Fantechi, S. Gnesi, and L. Semini. Variability-Based Design of Services for Smart Transportation Systems. In Proceedings of the 7th International Symposium on Leveraging Applications of Formal Methods, Verification and Validation: Discussion, Dissemination, Applications (ISoLA'16), Corfu, Greece (T. Margaria and B. Steffen, eds.), Lecture Notes in Computer Science 9953, Springer, Berlin, 2016, 465–481.

7. M.H. ter Beek, E.P. de Vink, and T.A.C. Willemse. Family-Based Model Checking with mCRL2. In Proceedings of the 20th International Conference on Fundamental Approaches to Software Engineering (FASE'17), Uppsala, Sweden (M. Huisman and J. Rubin, eds.), Lecture Notes in Computer Science 10202, Springer, Berlin, 2017, 387–405.

8. N. Gast and B. Van Houdt. Transient and Steady-state Regime of a Family of List-based Cache Replacement Algorithms (extended version). Queueing Systems: Theory and Applications (QUES)

9. N. Gast, J. Doncel and B. Gaujal Are mean-field games the limits of finite stochastic games? ACM MAMA Workshop, 2016.

10. N. Gast Construction of Lyapunov functions via relative entropy with application to caching. ACM MAMA workshop 2016.

11. L. Cardelli, M. Tribastone, M. Tschaikowski and A. Vandin. Comparing Chemical Reaction Networks: A Categorical and Algorithmic Perspective. LICS 2016.

12. L. Cardelli, M. Tribastone, M. Tschaikowski and A. Vandin. Symbolic Computation of Differential Equivalences. POPL 2016.

13. L. Cardelli, M. Tribastone, M. Tschaikowski and A. Vandin. Efficient Syntax-driven Lumping of Differential Equations. TACAS 2016

14. J. Hillston and M. Loreti. CARMA Eclipse plug-in: A tool supporting design and analysis of Collective Adaptive Systems. In Proceedings of 13th International Conference on Quantitative Evaluation of Systems (QEST), Quebec, Canada, August 2016 (⋆ *UEDIN/IMT collaboration* ⋆)

15. M. Michaelides, D. Milios, J. Hillston and G. Sanguinetti. Property-driven State-Space Coarsening for Continuous Time Markov Chains, In Proceedings of 13th International Conference on Quantitative Evaluation of Systems (QEST), Quebec, Canada, August 2016.

16. N. Zon, S. Gilmore and J. Hillston. Rigorous graphical modelling of movement in Collective Adaptive Systems. In Proceedings of ISOLA 2016, Leveraging Applications of Formal Methods, Verification and Validation: Foundational Techniques, LNCS 9952, pp. 674–688, Corfu, October 2016.

17. L. Bortolussi, D. Milios and G. Sanguinetti. Smoothed Model Checking for Uncertain Continuous Time Markov Chains. Information and Computation. 247, 235-253, 2016.

18. E. Incerto, M. Tribastone and C. Trubiani. Symbolic Performance Adaptation. SEAMS'16.

19. L. Bortolussi. Hybrid Behaviour of Markov Population Models. Information and Computation. 247, 37-86, 2016.

20. D. Bacciu, A. Carta, S. Gnesi, and L. Semini. An experience in using machine learning for short-term predictions in smart transportation systems. Journal of Logical and Algebraic Methods in Programming 87 (2017), 52–66.

21. V. Ciancia, D. Latella, M. Massink, R. Paskauskas, and A. Vandin A Tool-Chain for Statistical Spatio-Temporal Model Checking of Bike Sharing Systems. In T. Margaria and B. Steffen, editors, Leveraging Applications of Formal Methods, Verification and Validation: Foundational Techniques, volume 9952 of LNCS, pages 657-673. Springer-Verlag, 2016.

22. V. Ciancia, D. Latella, M. Loreti, and M. Massink. Model Checking Spatial Logics for Closure Spaces. Logical Methods in Computer Science, 12(4):151, 2016. Published on line: 11 Oct. 2016. ISSN: 1860-5974. (⋆ *CNR/IMT collaboration* ⋆)

23. C. Feng, J. Hillston and D. Reijsbergen, Moment-Based Probabilistic Prediction of Bike Availability for Bike-Sharing Systems. 13th International Conference on Quantitative Evaluation of Systems (QEST 2016), LNCS 9826, 139-155, Springer, 2016.

24. Cheng Feng. The Process Algebra for Located Markovian Agents and Scalable Analysis Techniques for the Modelling of Collective Adaptive Systems. PhD thesis. University of Edinburgh. 2016.

25. Paul Piho. Spatial and Stochastic Equivalence Relations for PALOMA. Master of Science by Research dissertation, University of Edinburgh, 2016.

26. M. Bernardo, R. De Nicola and J. Hillston (Eds). Formal Methods for the Quantitative Evaluation of Collective Adaptive Systems. LNCS 9700, Springer, 2016. (⋆ *UEDIN/IMT collaboration* ⋆)

27. L. Bortolussi and N. Gast. Mean-Field Limits Beyond Ordinary Differential Equations. SFM 2016, LNCS 9700, Springer, pp. 61-82, 2016. (⋆ *CNR/INRIA collaboration* ⋆)

28. M. Loreti and J. Hillston. Modeling and Analysis of Collective Adaptive Systems with CARMA and its Tools. SFM 2016, LNCS 9700, Springer, pp. 83-119, 2016 (⋆ *UEDIN/IMT collaboration* ⋆)

29. V. Galpin. Spatial Representations and Analysis Techniques. SFM 2016, LNCS 9700, Springer, pp. 120-155, 2016.

30. V. Ciancia, D. Latella, M. Loreti and M. Massink. Spatial Logic and Spatial Model Checking for Closure Spaces. SFM 2016, LNCS 9700, pp.156-201, Springer, 2016. (⋆ *CNR/IMT collaboration* ⋆)

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4.6 List of Dissemination Activities

4.6.1 Presentation of research results

As the list of publications indicates, a substantial number of results from QUANTICOL were presented at conferences and workshops throughout the second period of the project. Here we record the additional presentations of QUANTICOL research that took place.

- Invited talks at international conferences and workshops:
  - 23/10/16: Luca Bortolussi gave an invited talk at the MEMICS 2016, Doctoral Workshop on Mathematical and Engineering Methods in Computer Science, Telc, Czech Republic. The talk was entitled ”The Machine Learning Way to Formal Verification”.
  - 27/09/16: Luca Bortolussi gave an invited talk at the RiSE Workshop, in Pollenberg, Austria. The talk was entitled ”Mean-Field Approximation for Stochastic Verification”.
  - 14/09/16: Luca Bortolussi gave an invited talk at the 7th International Symposium on Games, Automata, Logics and Formal Verification (GandALF 2016), in Catainia, Italy. The talk was entitled ”Machine Learning Meets Formal Verification”.
  - 21/06/16: Luca Bortolussi gave an invited talk at the 16th edition of the Schools on Formal Methods (SFM) on Dynamical Systems, in Bertinoro, Italy. The talk was entitled ”Introduction to Mean Field”.
  - 30/08/16: Nicolas Gast gave an invited talk at the ”Journes MAS” about electricity markets. The audience was about 50 persons (mostly academic).
  - 21/09/16:, Jane Hillston gave an invited talk at the Computational Methods in Systems Biology conference in Cambridge UK on *Embedding Machine Learning in Formal Stochastic Models of Biological Processes* to an audience of about 100 international researchers at all levels (PhD students to full Professors).
  - 19/11/16: Jane Hillston gave an invited talk at the Christopher Strachey Centenary Celebration in Oxford. The talk was entitled *A modelling language approach to defining mathematical structures via semantics*, and was attended by approximately 100 researchers (mostly senior academics with some PhD students and postdocs).

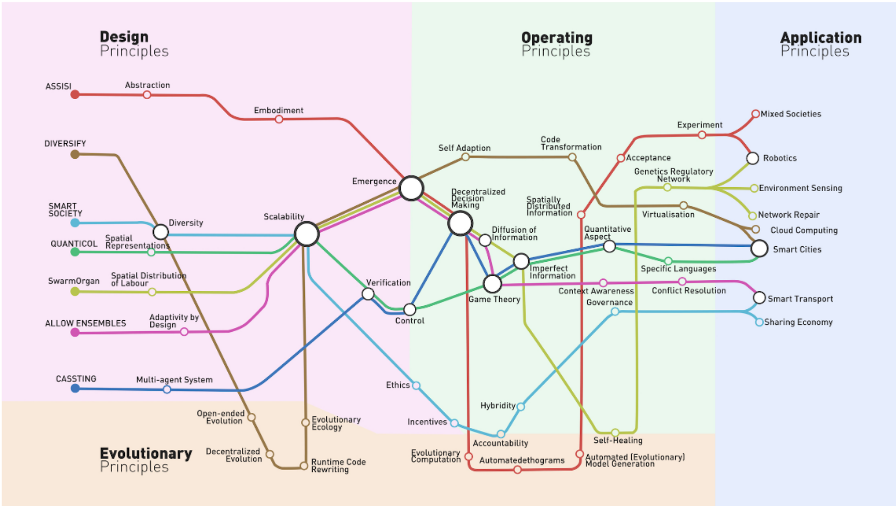
  - 28/02/17: Rocco De Nicola gave a talk at the computer science department of Kalifa University Abu Dhabi entitled *Languages and Models for Collective Adaptive Systems*
  - 15/03/17: Jane Hillston gave a keynote talk at the 10th EAI International Conference on Bio-inspired Information and Communications Technologies. The talk was entitled *Studying Smart Cities as Collective Adaptive Systems.* There were approximately 65 people in the international audience.

- Invited seminars in academic departments:
  - 02/12/15: Luca Bortolussi gave an invited seminar at Dagstuhl Seminar, entitled *Stochastic Approximation for Stochastic Model Checking.*
  - 04/02/16: Luca Bortolussi gave an invited seminar at Max Plank for Software Systems, Kaiserslautern, entitled *Logic-based design of Spatio-Temporal Behaviours.*
  - 15/02/16: Jane Hillston gave an invited seminar to the Programming Languages and Systems research group in the School of Computing at the University of Kent, entitled *Quantitative Analysis of Collective Adaptive Systems.* There were approximately 16 people in the audience, a mix of PhD students, postdoctoral researchers and faculty.
  - 06/04/16: Mirco Tribastone gave an invited seminar at DISIA, University of Florence, Italy, entitled *Equivalence relations for ordinary differential equations.*
  - 14/04/16: Mirco Tribastone gave an invited seminar at Microsoft Research Cambridge, UK, entitled *Equivalence relations for ordinary differential equations.*
  - 18/04/16: Jane Hillston gave an invited seminar in the Mathematics Department of the University of Strathclyde, entitled *High-level languages for fluid approximation of agent-based models.* There were approximately 25 people in the audience, a mix of PhD students, postdoctoral researchers and (mostly) faculty from the Departments of Mathematics and Computer Science.
  - 12/07/16: Mirco Tribastone gave an invited seminar at Technical University Braunschweig, Germany, entitled *Fluid models of software performance.*
  - 19/07/16: Mirco Tribastone gave an invited seminar at University of Rostock, Germany, entitled *Equivalence relations for ordinary differential equations.*
  - 02/08/16: Andrea Vandin gave an invited seminar at Microsoft Research Cambridge, UK, entitled *ERODE: Evaluation and Reduction of Ordinary Differential Equations.*
  - 02/08/16: Max Tschaikowski gave an invited seminar at Microsoft Research Cambridge, UK: *Seminar on Fluid limits for reaction-diffusion systems.*
  - 04/10/16: Nicolas Gast gave an invited talk in the math department of the University of Grenoble about *The use of mean-field method for performance evaluation.* There ware approximately 15 people in the audience (all academic)
  - 11/10/16: Vashti Galpin gave a talk about the CARMA modelling language titled *From PEPA to CARMA* at the Lab Lunch of the Laboratory for Foundations of Computer Science in the School of Informatics at the University of Edinburgh. The audience consisted of academics, researchers and doctoral students.
  - 13/10/16: Jane Hillston gave a Collective Adaptive Systems seminar to the group of Scott Smolka at State University of New York - Stony Brook, on *Quantitative Analysis of Collective Adaptive Systems.* There were approximately 12 researchers in the audience, mostly PhD students and postdocs.
  - 18/10/16: Luca Bortolussi gave an invited seminar at ICTP, Trieste, entitled *Statistical Learning and the Analysis of Stochastic Models.*

- 26/10/16: Jane Hillston gave the Logical Structures in Computation Seminar at the Simons Institute, Berkeley University, on *Model checking single agent behaviours by fluid approximation.* The talk was attended by approximately 20 international researchers participating in the Logical Structures in Computation program, (mostly senior researchers and leaders in their field).
- 17/11/16: Max Tschaikowski gave an invited seminar at University of Verona, Italy: *Seminar on Equivalence relations for ordinary differential equations.*
- 22/11/16: Mieke Massink gave a presentation at central CNR in Rome at the yearly Conference of the CNR DIITET Department of Engineering, ICT and Technologies for Energy and Transportation. The presentation, *A Quantitative Approach to Management and Design of Collective and Adaptive Behaviours* was an overview of the CNR-ISTI contribution to the QUANTICOL project. The presentation was attended by approximately 150 researchers (mostly senior researchers from CNR institutes nationwide and invited researchers from Industry) and was also live streamed for remote participants.
- 24/11/16: Luca Bortolussi gave an invited seminar at Life Science Department, University of Trieste, entitled *Introduction to Computational Systems Biology.*
- 04/12/16: Nicolas Gast gave a talk at INRIA (Paris) about *What is the accuracy of mean-field approximation?*. The audience was composed of 15 researchers.
- 17/01/17: Luca Bortolussi gave an invited seminar at TU Wien, University of Trieste, entitled *Monitoring Spatio-Temporal Properties.*
- 23/02/17: Andrea Vandin gave an invited seminar at DTU Compute Denmark, entitled *Language-based abstractions for dynamical systems.*
- 22/03/17: Vashti Galpin gave a talk titled *CARMA: A quantitative formal language for modelling collective adaptive systems* at the lunch seminar of the Pervasive Parallelism Centre for Doctoral Training in the School of Informatics at the University of Edinburgh. The audience consisted of academics, researchers and doctoral students.
- 19/01/17: Luca Bortolussi gave an invited seminar at TU Wien, University of Trieste, entitled *Statistical Learning and the Analysis of Stochastic Models.*

4.6.2 Participation in FoCAS community events

- 6-8/01/16: Michele Loreti, Jane Hillston, Laura Nenzi and Yehia Abd Alrahman participated in the VideoSprint meeting organised by the FoCAS coordinating action in Napier University, Edinburgh. The QUANTICOL team were active participants in the discussions and the video that was filmed, and Jane Hillston and Laura Nenzi instigated the ”tube map” representation of all the FoCAS projects.



4.6.3 Engagement with other projects and communities beyond FoCAS

- 4-10/10/15: Rytis Paskauskas attended the Summer School on "Large Fluctuations and Extreme Events - Theory and Applications" in Dresden. He presented work on bike sharing, disseminating the results that have been previously presented at the ITSC15 and the SCOPES15 conferences. Title of the presentation was *Model-based assessment of aspects of user satisfaction in bicycle sharing systems* and it was attended by over 30 international participants and lecturers of the school.

- 11/05/16: Daniël Reijsbergen organised a workshop under the auspices of the Scottish Informatics and Computer Science Alliance (SICSA) in Edinburgh. The theme of the workshop was probabilistic modelling of urban transportation systems; the workshop featured several presentations by QUANTICOL researchers, mostly concerning work done on WP5. A particular focus was on the modelling of bike-sharing systems. The workshop was attended by roughly 25 people, including QUANTICOL researchers from three sites (Edinburgh, Grenoble, Lucca), non-QUANTICOL Informatics researchers from Edinburgh, researchers from other Scottish universities (including Heriot Watt and the University of the West of Scotland) and several people from industry (including Scottish Enterprise and Transport for Edinburgh). The workshop featured two invited speakers: Oliver O'Brien from UCL and Güneş Erdoğan from the University of Bath.

- 17/06/16: Mieke Massink took part in the DeCPS 2016 workshop in Pisa, co-located with the ADA-Europe conference and presented a position paper on the QUANTICOL project focussing on Spatial and Spatio-temporal model checking. In that international workshop on "Challenges and New Approaches for Dependable and Cyber-Physical Systems Engineering" the following European research projects were presented: INTO-CPS, U-TEST H2020, AXIOM, Industry 4.0, PROXIMA, CONCERTO, AMASS, ASSUME and QUANTICOL. The workshop provided a good occasion to exchange ideas and for networking purposes. The workshop was attended by approximately 15 to 20 people.

- 20-24/06/16: The 16th International School on Formal Methods for the Design of Computer, Communication, and Software Systems at Bertinoro was organised by the QUANTICOL team on the topic of *Formal Methods for the Quantitative Evaluation of Collective Adaptive Systems*

- 06/07/16: Nicolas Gast gave a tutorial on *Mean-field methods* at the French Summer School of Operations Research. There was about 40 PhD students plus 10-20 faculty.

- 08/07/16: Maurice ter Beek and Michele Loreti organised the Workshop on FORmal methods for the quantitative Evaluation of Collective Adaptive SysTems (FORECAST 2016) in Vienna, Austria, as a satellite event of the 4th federated event on Software Technologies: Applications and Foundations (STAF 2016) which includes the 14th International Conference on Software Engineering and Formal Methods (SEFM 2016). Part of QUANTICOL's dissemination plan, FORECAST's primary goal was to raise awareness in the Software Engineering and Formal Methods communities of the particularities of Collective Adaptive Systems and the design and control problems which they bring. The workshop definitely succeeded in this dissemination task of the project, with workshop participation reaching peaks of over 20 attendants. The proceedings of FORECAST 2016 have been published as volume 217 of the Electronic Proceedings in Theoretical Computer Science (EPTCS). The whole proceedings can be downloaded as PDF or browsed via its DOI.

- 15/09/16: Michele Loreti presented a tutorial on Carma and its use for the design and the analysis of CAS, *Modelling and Analysis of Collective Adaptive Systems* at the Annual Meeting of IFIP Working Group 2.2 that was held in Singapore. The primary aim of the Working Group 2.2 is to explain programming concepts through the development, examination and comparison of various formal models of these concepts. The event was attended by 50 researchers and PhD students from around the world.

- 28/03/17: Maurice ter Beek gave an invited presentation on *Family-based model checking with a feature mu-calculus* at the VARIETE Closing Workshop at the IT University of Copenhagen, Denmark. This workshop served as the final meeting of the Danish project VARIETE (Variability in Portfolios of Dependable Systems) for which Maurice was also invited to speak at the kick-off meeting in 2013 (see Deliverable 6.1). The audience consisted of 13 computer scientists (about half of them visitors from abroad and the others participants of the project from ITU Copenhagen) with affinity to formal (variability) modelling and analysis.

4.6.4 Meetings with stakeholder and user communities

- 06/04/16, Jane Hillston took part in a sustainable transport event organised by the charity Sustrans and the Edinburgh City Council which took place at the Edinburgh Centre for Carbon Innovation. She took the opportunity to talk to several people about the QUANTICOL project, including Sally Kerr (leader of the Digital Team at Edinburgh City Council), Katie Swann (Partnership Development Officer at Edinburgh City Council) and Tracy McKen (Transport Scotland, a branch of the Scottish Government).

- 20/01/17: a QUANTICOL Meeting took place between ISTI-CNR, PisaMo and BicinCittà at the CNR premises in Pisa organised by Mieke Massink. PisaMo (Ufficio Bici) is the in-house public mobility company of the city of Pisa's administration responsible for the CicloPi bike-sharing system in Pisa (currently $\pm$ 200 bikes and 24 stations), supplied and maintained by BicinCittà. The audience consisted of Marco Bertini from PisaMo, Manuela Quario and Marco Giuppone from BicinCittà, and about 10 researchers associated with ISTI–CNR, among which the participants in the QUANTICOL project Mieke Massink, Maurice ter Beek, Stefania Gnesi, Rytis Paskausas and Vincenzo Ciancia. The meeting was centred around the following presentations: *Model-based Assessment of Aspects of User-satisfaction in Bicycle Sharing Systems* (by Rytis Paskausas), *A Tool-chain for Statistical Spatio-temporal Model-checking of Bike Sharing Systems* (by Vincenzo Ciancia), *Analyzing the Performance of Bike-Sharing Systems* (by Maurice ter Beek), and *Services for Smart Transportation Systems* (by Laura Semini).

4.7 Exploitation and engagement with industry

- 16/07/16: Vashti Galpin met with Jake Beal of Raytheon BBN Technologies to discuss research carried out in the QUANTICOL project with a particular focus on the CARMA language and tools with applications to aggregate programming and synthetic biology.

- 15/09/16, Diego Latella and Mieke Massink attended a meeting with representatives of ALES-UTRC (United Technologies Research Center), including the General Manager of ALES Alberto Ferrari. The meeting was organised by Prof. Rocco De Nicola of IMT Lucca. Mieke Massink gave a 15 min presentation introducing the CNR-ISTI Team and sketching briefly recent research on spatio-temporal model checking developed within the QUANTICOL project. Mirco Tribastone presented work on model reduction. Laura Nenzi presented work on her PhD thesis on spatial signal temporal logic that was developed in the context of the QUANTICOL project at IMT Lucca.

- 09/02/17: Members of QUANTICOL participated in an exploitation seminar with Dr Giovanni Zazzerini, organised through the Common Exploitation Booster service of the Commission. This involved a general session to raise awareness throughout the project on the potential for exploitation of various forms, followed by a more focused session considering the specific proposal to develop the spatial model-checker topochecker for medical image analysis applications.

5 Deliverables and Milestones Tables

Table 1. Deliverables (first period)

Del. no	Deliverable name	Version	WP no	Lead	Nature Beneficiary	Dissemination Level	Delivery date from Annex I	Actual/Forecast delivery date	Status	Comments
D1.1	Multiscale modelling informed by smart grids	1.0	1	EPFL/INRIA	R	PU	31/3/2014	31/3/2014	Approved	
D2.1	A preliminary investigation of capturing spatial information for CAS	1.0	2	UEDIN	R	PU	31/3/2014	31/3/2014	Approved	
D3.1	Foundations of scalable variation for stochastic logics	1.0	3	CNR	R	PU	31/3/2014	31/3/2014	Approved	
D4.1	CAS-SCEL language design	1.0	4	IMT	R	PU	31/3/2014	31/3/2014	Approved	
D5.1	Data validation and requirement for case studies	1.0	5	SOTON	R	PU	31/3/2014	31/3/2014	Approved	
D6.1	Dissemination plan for the project	1.0	6	UEDIN	O	PU	31/3/2014	31/3/2014	Approved	

Table 1. Deliverables (second period)

Del. no	Deliverable name	Version	WP no	Lead	Nature Beneficiary	Dissemination Level	Delivery date from Annex I	Actual/Forecast delivery date	Status	Comments
D1.2	A framework for hybrid limits under uncertainty	1.0	1	INRIA	R	PU	30/9/2015	30/9/2015	Approved	
D1.3	Distributed control of CAS	1.0	1	INRIA	R	PU	30/9/2015	30/9/2015	Approved	
D3.2	Scalability beyond population size and quantitative product family engineering	1.0	3	CNR	R	PU	30/9/2015	30/9/2015	Approved	
D4.2	CAS-SCEL semantics and implementation	1.0	4	IMT	R	PU	30/9/2015	30/9/2015	Approved	
D5.2	A CAS-SCEL implementation for smart-city modelling	1.0	5	SOTON/IMT	R	PU	30/9/2015	30/9/2015	Approved	

Table 1. Deliverables (third period)

Del. no	Deliverable name	Version	WP no	Lead	Nature Beneficiary	Dissemination Level	Delivery date from Annex I	Actual/Forecast delivery date	Status	Comments
D2.2	From spatial data to spatial models	1.0	2	UEDIN	R	PU	30/3/2016	30/3/2016	Submitted	
D6.3	QUANTICOL 2016 Summer School	1.0	6	UEDIN	R	PU	30/6/2016	30/6/2016	Submitted	
D2.3	Transformations and limit results between spatial representations	1.0	2	CNR	R	PU	30/9/2016	30/9/2016	Submitted	
D1.4	A mean field framework for controlling CAS	1.0	1	INRIA	R	PU	30/3/2017	30/3/2017	Submitted	
D3.3	Combining spatial verification with model education and relating local and global views	1.0	3	CNR	R	PU	30/3/2017	30/3/2017	Submitted	
D4.3	CaSL at work	1.0	4	IMT	R	PU	30/3/2017	30/3/2017	Submitted	
D5.3	Modelling smart cities with the QUANTICOL software tool suite (final)	1.0	5	IMT	R	PU	30/3/2017	30/3/2017	Submitted	

Table 2. Milestones

Milestone no.	Milestone name	WP nos.	Lead beneficiary	Delivery date from Annex I	Achieved Yes/No	Actual/Forecast achievement date	Comments
MS1	Initial Design of the Language and Logic	WP3, WP4	CNR	31/3/2014	Yes	31/3/2014	Verification: D3.1, D4.1
MS2	Specification of the Quantitative Analysis Framework for the Language	WP1, WP2	INRIA	30/11/2014	Yes	31/3/2014	Verification: D1.1 D2.1
MS3	Requirements Analysis of the Case Studies	WP5	SOTON	31/3/2014	Yes	31/3/2014	Verification: D5.1
MS4	Language Extensions for Scalable and Spatial Analysis	WP1, WP2, WP4	UEDIN	31/12/2015	Yes	31/12/2015	Verification: internal report T1.3, internal report T2.2, D4.2
MS5	CAS Tool Workbench, Design Methods and Case Studies	WP3, WP4, WP5	IMT	31/3/2017	Yes	31/3/2017	Verification: D3.3, D4.3, D5.3