Project no. **31638**
Project acronym: **CONNECT**
Project full name: **Design of Advanced Controllers for Economic, Robust and Safe Manufacturing Performance**
Project Web page: **http://www.cpi.umist.ac.uk/connect/**
Type of Instrument: Co-operative Research Project

Periodic Activity Report (FINAL)

Period covered: from 01/10/2006 to 30/09/2008
Date of preparation: 15/11/2008

Start date of project: 01/10/2006 Duration: 24 Months

Project coordinator name: Dr. Michael Georgiadis
Project coordinator organisation name: Process Systems Enterprise Ltd

Revision [Final]

Publishable Executive Summary

The main objective of the CONNECT project is to address the most important factors limiting the application of Model Predictive Control (MPC) and the extended use of advanced controllers in complex processing systems operating under tight economic, safety and environmental considerations. CONNECT will make extensive use of a field of mathematics, called parametric optimization, to shift offline (hence out of the controller) the computational burden traditionally associated with model-based optimal control techniques. The remarkable feature of the CONNECT parametric controllers is that the control performance is identical to what would have been achieved with a full on-line optimization approach but without the computational burden and related software. In fact, the CONNECT control performance is even better in many cases because the speed at which one can sample the system is no longer limited by the computation times associated with online optimization. The work in the underlying co-operative research project includes research activities for: (i) the development of more efficient and fast MPC techniques utilising recent advances developed by our RTD performers in the area of parametric programming, (ii) the design of robust model-based controllers, for hybrid and continuous time linear dynamic systems and (iii) the investigation of model reduction techniques. Software development activities, hardware designs (e.g. chips) and testing in real-life industrial case studies will constitute a key activity of the proposed project. The following key contributions/objectives and their quantified impact are expected:

- Avoid solving an optimisation problem on-line which is the current practise for advanced controllers. This is expected to lead to computational savings in the order of at least 70%.
- Design of robust controllers featuring significant computational complexity reduction. The performance of robust controllers is expected to improve product quality at least 20% by reducing off-spec products.
- Development of computationally-efficient algorithms for on-line monitoring and fault diagnosis with the ability to be executed at “real time” side-by-side with the experimental systems. Savings in the order of at least 15% are expected.
- Achievement of less conservative control action over the worst case design when uncertainty lies close to the nominal point. This is expected to reduce associated operating costs by at least 15%. For example a less conservative action in energy intensive systems will reduce energy consumption at least 15%, as indicated by several real studies performed by the consortium.
- Simple and fast implementation of the control policy. This is expected to lead to increased customer satisfaction (at least 25%) by delivering final products on time.
- Guaranteed satisfaction of all operating constraints typically met in real industrial systems. This will ensure high product quality.
- Consideration of hybrid systems by addressing the constraints switching time instants in an optimal way.

The contractors involved in the project are summarized below:

Partic. Role*	Partic. Type**	Partic. no.	Participant name	Participant short name	Country
CO	SMEP	1	Process Systems Enterprise Ltd	PSE	UK
CR	SMEP	3	ESTIA Simvouleftiki	ESTIA	Greece
CR	SMEP	4	PLASMAIT GmbH	PLASMAIT	Austria
CR	SMEP	5	Parametric Optimization Solutions Ltd	PAROS	UK
CR	OTH	6	INEA d.o.o.	INEA	Slovenia
CR	SMEP	7	AO Sodruzhestvo-T	SODRU	Ukraine
CR	RTD	8	Norwegian University of Science and Technology	NTNU	Norway
CR	RTD	9	The University of Manchester	UOM	UK
CR	RTD	10	Institute Josef Stefan	IJS	Slovenia
CR	OTH	12	Keramopoiia Kothali SA	KOTHALI	Greece

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The work performed and main results achieved over the entire duration of the project is summarized as follows:

New fast MPC algorithms (WP1). More specifically the following objectives have been achieved:

- Optimizing the prediction dynamics in MPC problems with parametric uncertainty, while obtaining an problem formulation for which efficient solvers do exist.
- Extension and simplification of existing results on reachability analysis to simplify look-up table search in online application of explicit MPC.

- ❖ Enlarging the domain of attraction (for a fixed prediction horizon length) by decomposing the current state and applying different controllers for each component. Paper.
- ❖ Enlarging the terminal region on MPC based on time-optimal control formulations, via interpolating between different terminal controllers.
- ❖ Accounting for uncertainty in the state estimates in the formulation of the MPC problem, combined with a large terminal region (and hence enabling the use of a shorter prediction horizon) via interpolating between different terminal controllers.
- ❖ Showing that the state estimation error converges to a terminal set when Moving Horizon Estimation is used. Use of this set to make the MPC formulation more robust. Publications
- ❖ Reduction of computation time in multi-step dynamic programming approaches to MPC by grouping multiple control samples into a single dynamic programming step.
- ❖ Two new methods for offset-free predictive tracking control. The offset- free predictive tracking with augment system and with constrained target calcutaion. The augment method increases the system dimension and also complexity, while target calculation leads to j controllers other than one.
- ❖ Application in a real-life polymirezation process, using a new offset-free tracking methods.
- ❖ A novel method for Robust tracking MPC through mp-QP using min-max formulation.
- ❖ A new approach in order to reduce the computation power of a multiparametric Dynamic Programmic algorith has been developed followed by two examples, one for SISO and one for MIMO are presented using both algorithms.

Original research contributions in WP1:

- ❖ Optimizing the prediction dynamics in MPC problems with parametric uncertainty, while obtaining an problem formulation for which efficient solvers do exist. Publication
- ❖ Showing that the state estimation error converges to a terminal set when Moving Horizon Estimation is used. Use of this set to make the MPC formulation more robust.
- ❖ Reduction of computation time in multi-step dynamic programming approaches to MPC by grouping multiple control samples into a single dynamic programming step.

New Robust MPC for hybrid and continuous systems (WP2). More specifically the following objectives have been achieved:

- ❖ New techniques for Tracking and disturbance rejection formulations for hybrid and continuous-time explicit MPC.
- ❖ Local performance & robustness analysis of hybrid explicit MPC
- ❖ Hybrid control of nonlinear processes approximated with PWL/PWA models
- ❖ A new disturbance rejection tuning case study of an offset-free output feedback tracking mp-MPC controller has been developed. A unified scheme with no TC is

used, and a KF is used for output feedback. The output feedback tracking concept is presented for constrained linear systems and may be extended to piecewise-affine (PWA) hybrid systems with no binary inputs. A case study on a two-input single-output system of pressure control in a vacuum chamber of a wire annealer is presented to make a comprehensive literature review of explicit MPC with hybrid models.

- A new approach has been developed of mp-MPC using piecewise affine (PWA) hybrid models for control of a nonlinear processes approximated with a continuous PWA model that contains a set of local linear dynamics. The recently developed methods of multi-parametric model predictive control (mp-MPC) for hybrid systems provide an interesting opportunity for solving this class of nonlinear control problems. Compared to linear model based MPC, they allow control with a set of nominal models instead of using a single nominal model; a performance improvement is expected with the reduction of plant-to-model mismatch.
- Extensive validation studies of the developed theoretical methods and algorithms including mp-MPC control for water temperature control in the engine cooling subsystem of a biogas-fuelled combined heat and power production (CHP) unit. In this case study, the ability of mp-MPC for suppression of disturbances violating output constraints was investigated.

New techniques Moving Horizon Estimation and Nonlinear Model Predictive Control (WP3).

- New algorithms accounting for uncertainty in the state estimates in the formulation of the MPC problem, combined with a large terminal region (and hence enabling the use of a shorter prediction horizon) via interpolating between different terminal controllers.
- Accounting for uncertainty in the state estimates in the formulation of the MPC problem, combined with a large terminal region (and hence enabling the use of a shorter prediction horizon) via interpolating between different terminal controllers.
- Showing that the state estimation error converges to a terminal set when Moving Horizon Estimation is used. Use of this set to make the MPC formulation more robust. Publications .
- A new approach showing that the state estimation error converges to a terminal set when Moving Horizon Estimation is used. Use of this set to make the MPC formulation more robust.
- A new method for reformulation of an existing robust MHE formulation as a multiparametric QP, allowing it so be solved and implemented as an explicit MHE. Application of explicit nonlinear MPC and explicit MHE to a case study of industrially relevant complexity.

New Model Reduction Techniques for Control Applications (WP4)

A new technique investigated in WP4 was Proper Orthogonal Decomposition (POD) or method of empirical eigenfunctions, as it is otherwise called. POD consists of taking appropriate (empirical) samples of system's outputs in time and correlating them in a 2-dimensional matrix. Through eigenanalysis of this matrix a number of global basis functions that span the hyperspace of (approximately) all systems outputs can be constructed. The (typically few) of this basis functions that capture almost all of the system's energy (the system's dynamics) are then identified. By projecting the original large-scale system onto these few basis functions a low-dimensional system can be obtained that can accurately represent the original large-scale one and that is amenable for on-line MPC. However, for non-linear systems the resulting reduced models are also non-linear. Nevertheless, in this project we wanted to take advantage of powerful linear MPC techniques including parametric MPC (the software for which was developed in WP5). For this purpose we developed technologies to automatically compute piece-wise linear approximations (subject to a pre-chosen error) of the reduced non-linear models.

One of the novelties in this work was to combine POD with the Finite Element method (FEM). Therefore, local FEM basis functions can be used to consistently compute the needed spatial numerical derivatives and FEM Galerkin projection is exploited to systematically project the (discretised) system onto the POD-derived global basis functions (the PODs).

Furthermore, a Trajectory Piece-Wise Linearisation (TPWL) method was developed to automatically compute the optimal number of linear segments (subject to a given error) of the reduced (1-D) non-linear model (constraints in the MPC formulation). This way the resulting quadratic problem with piece-wise linear constraints can be directly solved using quadratic programming (QP) or parametric MPC.

The developed Galerkin/POD methodology was tested for a benchmark reaction-diffusion distributed parameter problem the so-called Bratu problem with 1 unknown dynamic variable (distributed in space) and an exponential nonlinearity. The PODs were found to be able to capture accurately the nonlinear dynamics of the system for a satisfactory range of parameters. A benchmark MPC problem provided by PAROS UK, Ltd was investigated next. The problem consisted of a number of communicating tanks, the liquid level of which had to be controlled. This is a discrete problem in space so the Galerkin/POD formulation had be appropriately adapted. The simple case of 2 tanks and the more "interesting" case (from a model reduction perspective) of 10 tanks were investigated. Furthermore, both linear (for benchmarking) and non-linear cases were explored. Non-linear MPC was exploited in the non-linear case (using sequential quadratic programming -SQP) first. SQP-based MPC can produce accurate results, but is computationally expensive even when used with reduced models. TPWL was also used to produce a piece-wise affine representation of the reduced model and the QP-based MPC worked also extremely well at a fraction of the computational cost. Moreover, the parametric control software produced by PAROS UK, Ltd in WP5 was used here for control of the POD reduced 10-tank model. With the current capabilities of the software only the linear case was easily solved. The non-linear case requires a modified adaptive MPC formulation, which is not currently available in the software, but it is the subject of future collaboration between UoM and PAROS UK Ltd.

Software development and hardware (controller) designs (WP5).

The main results over the entire duration of the project are summarised as follows:

- We have mapped the overall architecture both in terms of the advanced optimization algorithms and the presentation layer that will be exposed to the control engineer. The major software components are (1) the core mpQP solver, (2) MPC design wizard, (3) offline controller validation and (4) embedded code generator. The design process will involve a feedback loop between (2) and (3) where alternative designs will be tested (through the solver 1) and gradually improved, and finally embedded code will be generated (4).
- We have considered the object oriented nature of the architecture and came up with a requirements analysis for each major component and software object/module. The inputs and outputs have been identified and the programming language was selected. This will be mostly done in MatLab, a de facto industry standard for control applications, which is both efficient for the numerical parts and expressive for the user interface parts. Its simulation software SimuLink will be used for validating the controller designs and probably its embedded code generation toolbox xPC target is a good candidate for the final on-chip code.
- The software design has two basic layers. An internal offline multiparametric quadratic programming solver which will concentrate on fast solution while being stable and minimizing its intermediate storage requirements, and an outer shell exposing the MPC design capabilities. The latter will have a quick-start mode for training or/and acquiring basic controllers quickly for screening purposes, and an expert mode for advanced tweaking and fine tuning for optimal controllers.
- We have scrutinized the hardware requirements for explicit MPC controllers. The explicit MPC controller is software (a large data table plus a small module that reads the map online) and as such admits a broad range of implementation platforms. Any microcontroller that offers RAM and flash (permanent) memory, arithmetic and logical operations and analog input/output channels is adequate for the task. For larger applications pMPC will require more storage and more advanced hardware, but in such cases it is possible to simply incorporate it in existing control hardware of large facilities (e.g. PLC or DCS).

Application in Industrial Case Studies (WP6).

The main objective was to apply the developed algorithms methodologies and tools (WP1 to WP5) to industrial case studies provided by the SME partners of the consortium. More specifically:

- **Control of a real industrial Polymerisation reactor (PSE, ParOS, NTNU).** In this work, we delivered the optimal design of a dynamic CSTR styrene polymerization reactor for PI controller and we demonstrate the procedure to produce an explicit multi-parametric controller. The PI controller manages to control the reactor temperature and satisfy the end-point quality constrains. However, the developed pMPC can achieve better results since incorporates the model design and guarantee stability and constrains satisfaction during the operation.

- **Plasma based reactors for In-Line wire manufacturing sector - Pressure control of the vacuum chamber (PLASMAIT, IJS, INEA).** The project was based on joint work of project partners JSI, INEA and PlasmaIt on one of the selected industrial case studies of the CONNECT project. The multi-parametric MPC algorithms were selected for pressure control in the vacuum atmosphere preparation subsystem of a machine used for annealing metal wires or bands by using magneto-focused plasma. Necessary mechanical adoptions on the machinery in Lebring were made in the first year of the project. Mp-MPC was considered for control of a non-square plant with two inputs and one output, as a replacement for a conventional control scheme comprising two PID controllers. A detailed assessment of the control problem and the disturbances was made. Mp-MPC methods based on linear and hybrid models were tested. The JSI work was tightly integrated with activities in theoretical workpackages WP1 and WP2. Firstly, an output feedback tracking scheme with steady-state offset elimination suitable for both linear and hybrid methods was developed. Then, linear model based methods were developed as a foundation. In the final stage, the work was focused on the hybrid model based methods and on alternative methods of disturbance rejection. Several sets of measurements on the machinery were performed. The results with the linear model based methods show that better performance in terms of response speed and robustness to variation of process dynamics over the operating range can be achieved than with the original PID scheme. However, it must be admitted that the advantage of mp-MPC is slight and that the PID scheme is remarkably efficient considering its relative simplicity. The hybrid model based methods can be used to improve performance by addressing the issue of variation of the process dynamics; effectively, rather than having one nominal model, a hybrid controller switches among three nominal local dynamics in different parts of the operating range, decreasing the plant-to-model mismatch. On the other hand, the off-line computation complexity forbids implementation of hybrid mp-MPC controllers with longer prediction horizons, impairing the disturbance rejection properties. It is estimated that sub-optimal control strategies, such as multiple-model control with a set of linear mp-MPC controllers with longer horizons, may most probably produce better practical results than hybrid mp-MPC.
- **Control of CHP Systems – case study 1 (ESTIA, KOTHALIS, ParOS, IJS, SODRU, INEA).** The cogeneration case study at the Domžale-Kamnik waste-water treatment plant (DKWWTP)was considered jointly by IJS and INEA. Control of a biogas-fueled engine operation that drives a generator producing electric energy and also provides heating water for the needs of the WWTP operation is investigated. Specifically, feasibility of advanced control algorithms based on multi-parametric model predictive control (mp-MPC) for control of the primary hot water circle temperature was investigated.
- **Control of CHP systems – case study 2 (ESTIA, ParOS).** A new case concerning the control and operation of a CHP systems installed in a real small hotel. The system can store heat and can trade electricity with an external energy supplier in a decentralized way. Results indicate that significant savings (in terms of energy and cost) can be achieved by optimising the integrated systems.
- **Optimal Kiln Temperature control in the manufacturing of Bricks and tiles (ESTIA, ParOS, KOTHALIS UoM).**

A tunnel-type industrial kiln, which is the case of the KOTHALI case-study, consists of several subsystems. The systems has been modelled in details in the gPROMS platform (product of PSE Ltd) and validated using data from the plant. Simulation results agree well with plat data. Several control studies were then performed to optimise the operation of the process in a view of energy savings while ensuring robust manufacturing performance.

- **Efficient Temperature control of Heat Exchanger in District Heating (SODRU, PAROS and UoM).** A detailed dynamic model of plate heat exchanger with outlet temperature control buy butterfly valve has been developed and validated in the gPROMS platform offered by PSE Ltd. The model was tested in a real system provided by SODRU. Control algorithms developed in WP1 have been applied and the main conclusions are:
  - Realized rotation angle accounting system provides constant regulation quality in every functioning mode of system.
  - It decreases common oscillation of system and optimizes system impact on change of value of controlled parameter.
  - The rotation angle accounting system may contain dynamic characteristic data of “butterfly” valve of any diameter.
  - The further improvement of regulation quality can be achieved by implementing the model of heat exchanger accounting the butterfly valve flow characteristic.

Publishable Results of the plan for using and disseminating the knowledge:

- D. Sui, L. Feng, M. Hovd: Algorithms for Online Implementations of Explicit MPC Solutions. Presented at IFAC World Congress, 2008.
- D. Sui, L. Feng, M. Hovd: Robust Explicit Time Optimal Controllers for Linear Systems via Decomposition Principle. Presented at IFAC World Congress, 2008.
- D. Sui, L. Feng, M. Hovd : Robust Output Feedback MPC for Linear Systems via Interpolation Technique. Presented at IFAC World Congress, 2008
- L. Feng, D. Sui, M. Hovd: On further optimizing prediction dynamics for robust model predictive control. Presented at American Control Conference 2008.
- D. Sui, L. Feng, M. Hovd : Robust Output Feedback Model Predictive Control for Linear Systems via Moving Horizon Estimation. Presented at American Control Conference 2008.
- D. Sui, L. Feng, M. Hovd : Interpolated explicit model predictive control for linear systems with bounded disturbances. Accepted for publication in International journal of robust and nonlinear control.
- D. Sui, L. Feng, M. Hovd : Decomposition Principle in Model Predictive Control for Linear Systems with Bounded Disturbances. Accepted for publication in Automatica.
- D. Sui, L. Feng, M. Hovd : Robust output feedback MPC for linear systems via moving horizon estimation.. Submitted to International journal of robust and nonlinear control.

- L. Feng, D. Sui, M. Hovd : A new formulation on further optimizing prediction dynamics for robust model predictive control. Planned journal paper based on a revised version of the American Control Conference paper.
- D. Sui, L. Feng, M. Hovd : Robust output feedback explicit time optimal controllers for linear systems via decomposition principle. Planned journal paper based on a revised version of the IFAC World Congress paper.
- L. Feng, D. Sui, M. Hovd : Explicit moving horizon control and estimation: a polymerization case study. Planned for submission to The 4th IEEE Conference on Industrial Electronics and Applications 2009
- L. Feng, D. Sui, M. Hovd : Robust explicit moving horizon control and estimation on a polymerization reactor. Planned for submission to the IFAC Symposium on Advanced Control of Chemical Processes (ADCHEM) 2009
- F. Scibilia, S. Olaru, M. Hovd : Approximate Explicit Linear MPC via Delaunay Tessellation. Planned for submission to the European Control Conference 200
- I Bonis and C. Theodoropoulos "A Model Reduction-Based Optimisation Framework for Large-Scale Simulators Using Iterative Solvers." Computer Aided Chemical Engineering 25(2008):545-550.A
- I. Bonis, C. Theodoropoulos Model reduction-based constrained optimisation for large-scale steady state systems using black-box simulators, Proc. Of 1000th Annual AIChE meeting, Nov 16-21, Philadelphia, USA.
- D. Sui, L. Feng, M. Hovd: Algorithms for Online Implementations of Explicit MPC Solutions. Submitted to IFAC World Congress, 2008.
- D. Sui, L. Feng, M. Hovd: Robust Explicit Time Optimal Controllers for Linear Systems
- *via Decomposition Principle*. Submitted to *IFAC World Congress*, 2008.
- D. Sui, L. Feng, M. Hovd : *Robust Output Feedback MPC for Linear Systems via Interpolation Technique*. Submitted to *IFAC World Congress*, 2008
- L. Feng, D. Sui, M. Hovd: *On further optimizing prediction dynamics for robust model predictive control*. Submitted to *American Control Conference* 2008.
- D. Sui, L. Feng, M. Hovd : *Robust Output Feedback Model Predictive Control for Linear Systems via Moving Horizon Estimation*. Submitted to *American Control Conference* 2008.
- D. Sui, L. Feng, M. Hovd : *Robust Output Feedback MPC for Linear Systems via Moving Horizon Estimation*. Submitted to *International journal of robust and nonlinear control*.
- D. Sui, L. Feng, M. Hovd : *Decomposition Principle in Model Predictive Control for Linear Systems with Bounded Disturbances*. Submitted to *Automatica*.
- K. Tseronis, I. Kookos and C. Theodoropoulos. Multi-dimensional, non-isothermal dynamic modeling and control of planar solid oxide fuel cells, (2007) Chemical Engineering Transactions, vol. 1, pp 55-60.
- K. Tseronis, I. Kookos and C. Theodoropoulos. Dynamic, Multi-Dimensional Electrochemical Modelling and Control of Direct Internal Reforming Solid Oxide Fuel Cells. (2007) Proc. Of Annual AIChE meeting, Nov 4-9, Salt Lake city, USA

Also about 6 journal publications are currently under preparation and more than 5 conference presentations in next year.

Project Objectives and Major Achievements during the reporting period

The general technical objectives of the project are summarised below:

- Model Predictive Control (MPC) on a single chip, ideal for target applications that were previously off limits for model-based control
- Lower costs. Simpler hardware is adequate for the reduced on-line computational requirements. Software costs (e.g. licensed numerical solvers) are nearly eliminated, too.
- Simple Implementation. The absence of complex software makes controller implementation much easier, and reduces the need for highly specialised engineers for controller implementation.
- Simplified operation and maintenance of advanced controllers due to simpler software and new monitoring and diagnosis tools. This reduces the need for trained engineers to operate the plant, and allows for a much more efficient utilization of their skills. Thus, the automation of the plant is enhanced while the operation becomes a significantly easier task.
- Increased control power. Traditional MPC may have to resort to simpler models so as to ensure the computational tractability of the optimization problems that have to be tackled at real time. The new MPC approach on the other hand can accommodate much larger — and more accurate — process models, since the computational burden is shifted off-line.
- Controllability map. As the full control law is available in a convenient map, the designers can easily identify uncontrollable operational regions and take action to remove the bottlenecks. This comes as a stark contrast to traditional MPC where there is no guarantee that the online controller will meet all the controllability objectives and/or satisfy all the operational constraints.
- Real Hardware Designs of novel controllers in single chips and testing / validation in real-life systems.

The objective of the CONNECT project is to push the transition of European SMEs providing high quality solutions to the process (chemical, polymer, pharmaceutical, etc), energy generation and automation industries towards more knowledge-based and customised production and systems organisations through the development of novel knowledge-based, low-cost and high-performance controllers in simple chips. To this end co-operation between SMEs and end-users from the control, software development and manufacturing sectors is vital to learn and share knowledge in order to support the implementation of the new advanced process controllers. This optimisation of the control processes will facilitate seamless knowledge information flow between suppliers and users.

The objectives for the reporting period are:

- New fast MPC algorithms.
- Robust MPC algorithms for hybrid and continuous systems.
- Non-linear MPC and receding horizon.
- Model reduction techniques.
- software development activities. Compliance with industrial requirements

- Completion of the industrial case studies according to Annec I of the contract. Detailed Validation, testing and assesement of the results.

More technical details are presented below:

New fast MPC algorithms (WP1). More specifically the following objectives have been achieved:

- Optimizing the prediction dynamics in MPC problems with parametric uncertainty, while obtaining an problem formulation for which efficient solvers do exist. .
- Extension and simplification of existing results on reachability analysis to simplify look-up table search in online application of explicit MPC.
- Enlarging the domain of attraction (for a fixed prediction horizon length) by decomposing the current state and applying different controllers for each component.
- Enlarging the terminal region on MPC based on time-optimal control formulations, via interpolating between different terminal controllers.
- Accounting for uncertainty in the state estimates in the formulation of the MPC problem, combined with a large terminal region (and hence enabling the use of a shorter prediction horizon) via interpolating between different terminal controllers.
- Showing that the state estimation error converges to a terminal set when Moving Horizon Estimation is used. Use of this set to make the MPC formulation more robust.
- Reduction of computation time in multi-step dynamic programming approaches to MPC by grouping multiple control samples into a single dynamic programming step.
- A general introduction to explicit MPC based on multi-parametric programming, and describing the properties of the solutions. Two methods for reducing the on-line computational and memory requirements for explicit MPC.
- Efficient ways of implementing controllers based on explicit MPC, how to organize the solutions in ways that permit efficient search to identify the partition of the state space to which the current state belongs.
- Modifications to the (overall) optimization problem formulation for the MPC in order to obtain a simpler solution.

Robust explicit MPC:

- Robustness to bounded disturbances.
- Robustness to parametric uncertainty.
- Handling constraint violations, and how to do so while only allowing constraint violations when no other possiblility exists.
- Changing setpoints (reference values).
- Disturbances, disturbance modelling, and how to remove steady-state offset using integral action.
- Studies on the use of multi-parametric approaches to multi-step dynamic programming (for constrained linear systems), and of how computation time can be reduced by grouping multiple control samples into a single dynamic programming step.

More specifically, in the second year of the project, work in WP1 has focussed on

- Testing and validating explicit MPC algorithms for industrial use, including both the off-line optimization and the efficient on-line evaluation. This is described in Deliverable 4.
- A novel formulation for approximate explicit MPC, allowing a systematic and controlled trade-off between complexity and degree of sub-optimality without first having to calculate the exact solution. This is described in publication #13.

Original research contributions of WP1:

- Optimizing the prediction dynamics in MPC problems with parametric uncertainty, while obtaining an problem formulation for which efficient solvers do exist.
- Extension and simplification of existing results on reachability analysis to simplify look-up table search in online application of explicit MPC. .
- Enlarging the domain of attraction (for a fixed prediction horizon length) by decomposing the current state and applying different controllers for each component..
- Enlarging the terminal region on MPC based on time-optimal control formulations, via interpolating between different terminal controllers.
- Accounting for uncertainty in the state estimates in the formulation of the MPC problem, combined with a large terminal region (and hence enabling the use of a shorter prediction horizon) via interpolating between different terminal controllers. Papers.
- Showing that the state estimation error converges to a terminal set when Moving Horizon Estimation is used. Use of this set to make the MPC formulation more robust. Publications.
- Reduction of computation time in multi-step dynamic programming approaches to MPC by grouping multiple control samples into a single dynamic programming step.
- Applications to a case study of industrially realistic complexity.
- A novel approach for approximate explicit MPC based on Delaunay tesselation. Paper.

The work in WP1 has been performed mainly by NTNU (RTD) while PSE (SME) and ParOS (SME) has provided useful input towards industrial requirements of the developed algoriths. More specifically ParOS has already identified applications of the developed theoretical algorithms in its parametric control technology.

New Robust MPC for hybrid and continuous systems (WP2). More specifically the following objectives have been achieved:

In the existing literature on industrial applicability of mp-MPC, there appears to be a certain degree of confusion arising from the desire of authors to keep the number of process states as low as possible and to exclude or limit discussion of output feedback issues, resulting in highly application-specific controllers with limited general applicability. The publicly available toolboxes provide only offset-free reference tracking, but not offset-free tracking with disturbances of integrating nature.

It is shown that the disturbance integration scheme is prone to integrator windup in case of unreachable set-points, and that the modification to the cost function may deteriorate tracking performance. Therefore, the disturbance estimation approach that is more commonly used in traditional MPC is more recommendable. While the simplest DMC-style form disturbance estimations is known to be simple and usually result in robust performance, more efficient feedback performance may be obtained by using a Kalman Filter (KF) or a Moving Horizon Estimator (MHE). The choice among a MPC controller of unified structure and a target calculator (TC) scheme is less clear. The introduction of the TC does not decrease the amount of computation as in online MPC. The TC also does not show an important advantage regarding the ability of system reconfiguration at saturations, as this is also facilitated by the unified scheme. The TC complicates performance analysis, because it introduces an outer control loop, which may also be interpreted as a PWA control law, and because fixing steady-state targets ignoring transient constraints violations, prior to the dynamic controller, may not be optimal. On the other hand, the TC allows application of theoretically advanced control approaches that demand control of the state to the origin.

A disturbance rejection tuning case study is presented of an offset-free output feedback tracking mp-MPC controller. A unified scheme with no TC is used, and a KF is used for output feedback. The output feedback tracking concept is presented for constrained linear systems and may be extended to piecewise-affine (PWA) hybrid systems with no binary inputs. A case study on a two-input single-output system of pressure control in a vacuum chamber of a wire annealer is presented. It is shown that efficient control of a non-square plant may be implemented with an mp-MPC controller of a "unified" structure (without a TC). Tuning is made primarily using local linear analysis (LLA); LLA enables closed-loop system analysis for the unconstrained or constrained regions of the controller, possibly with plant-to-model mismatch (with a set of candidate true models), in time domain, frequency domain, or on the complex plane. Issues of robustness to modelling error are elaborated. The Loop Transfer Recovery (LTR) technique was found to be effective also with mp-MPC, however of not very significant benefit could be achieved in the offset-free tracking context due to the difference in scopes of the controller and the estimator. The results of the case study indicate that mp-MPC controllers can provide robust and efficient performance in low level control, although the results may not come as easily as some optimistic references predict. There is a certain improvement in constrained performance compared to PID anti-windup, and better insight into constrained performance is available due to the explicit form of the mp-MPC control law.

Another case study application is concerned with new algorithms of mp-MPC using piecewise affine (PWA) hybrid models for control of a nonlinear process approximated with a continuous PWA model that contains a set of local linear dynamics. The recently developed methods of multi-parametric model predictive control (mp-MPC) for hybrid systems provide an interesting opportunity for solving this class of nonlinear control problems. Compared to linear model based MPC, they allow control with a set of nominal models instead of using a single nominal model; a performance improvement is expected with the reduction of plant-to-model mismatch. However, the scientific publications on hybrid mp-MPC mostly focus on the state feedback problem and related stability, feasibility and computational efficiency issues of the algorithms, while practical applications are scarce. In this work, the feasibility of the approach for application was evaluated in a case study, where an output feedback, offset-free tracking hybrid mp-MPC controller of the unified type was considered as a replacement for a PID controller based scheme for control of pressure in a wire annealing machine (the same as in the previous sections). Typically, such hybrid mp-MPC methods rely on multi-parametric mixed-integer linear or quadratic programming solvers (mp-MILP/MIQP), whereas the related on-line hybrid MPC methods employ conventional MILP or MIQP solvers. Due to the parametric explosion of the off-line mp-MILP/MIQP computation with the problem dimensions, this approach is practically feasible for MPC problems of small sizes.

With very short horizons, tuning for efficient and robust feedback performance is a particular challenge. Robustness to plant-to-model mismatch is very important, since the hybrid methods do not ensure stable performance of the closed-loop system including the actual nonlinear system. Particularly to hybrid models, predictable behaviour at switching among the dynamics is required, as discontinuities in the model may lead to formally correct results that are not useful in practice. Therefore, a continuous PWA model is used. For output feedback, a switching (KF) is used; the active dynamic can be determined directly from the control signals. The simulation results show that improved performance due to decreased plant-to-model mismatch is achieved with hybrid PWA model based mp-MPC, compared to the linear model based approach. However, the off-line computation time is reasonable for practical application (within a few minutes) only with very short horizons in our case study. The tuning parameters selected considering acceptable computation time result in impaired control performance and robustness compared to linear model based mp-MPC control with longer horizons (Section 2). Better practical results may be achievable with more efficient algorithms or with suboptimal simplifications.

Another validation study of mp-MPC control is concerned with the optimal water temperature control in the engine cooling subsystem of a biogas-fuelled combined heat and power production (CHP) unit. In this case study, the ability of mp-MPC for suppression of disturbances violating output constraints was investigated. This is relevant regarding the use of mp-MPC as an advanced PID replacement. Again, an output feedback, offset-free tracking mp-MPC controller with a KF is used. With the exception of simplified methods that do not provide constraints handling, MPC methods have not been very successful in low level control. Typical MPC methods require on-line optimization and cannot be implemented with inexpensive industrial control hardware; however, mp-MPC may break this barrier. Also, there are many low-level control applications that would benefit from an advanced PID replacement that would eliminate or reduce violation of critical constraints.) Despite the declared ability of advanced constraints handling with mp-MPC and the undisputed constraints handling advantages of industrial MPC controllers, where the ability to push the set-point closer to constraints is one of the main selling features, it is questionable whether a practical advantage due to constraints handling is achievable in single-input single-output (SISO) PID replacement applications: large-scale multivariate MPC applications have degrees of freedom in ranking of control priorities that SISO control applications lack, feedback performance and robustness issues: conventional MPC controllers are not brilliant feedback performers, whereas the variants that employ Kalman filters are closely related to LQG control that did not have much success in industrial practice despite good academic

reputation, more expressed issues with various types of nonlinearities in low-level control: nonlinear, hybrid, or multiple-model mp-MPC may be required for proper operation of constraints handling.
A detailed description of a developed software library LLAPC (Local linear analysis of tracking predictive control) is also analysed.

Other specific objectives:

- to make a comprehensive literature review of explicit MPC with hybrid models,
- to make a comprehensive literature review of explicit MPC with continuous-time models
- New techniques for Tracking and disturbance rejection formulations for hybrid and continuous-time explicit MPC.
- Local performance & robustness analysis of hybrid explicit MPC
- Hybrid control of nonlinear processes approximated with PWL/PWA models

This work has been done mainly by IJS in collaboration with NTNU.

New techniques Moving Horizon Estimation and Nonlinear Model Predictive Control (WP3). More specifically the following objectives have been achieved:

In state estimation, one uses measurements of plant outputs and knowledge of plant inputs to estimate the plant states, in the face of (possibly unmeasured) disturbances and measurement noise. The classical state estimation strategies are the Kalman filter (when starting from a stochastic problem description) and the Luenberger observer (starting from a deterministic problem description). Neither of these approaches are directly applicable when there are constraints in the possible values of the states. Motivated by the enormous success of Model Predictive Control (MPC), Moving Horizon Estimation (MHE) was developed as the tool of choice for constrained state estimation.

The first publications on explicit MPC using multi-parametric programmin appeared just around the year 2000. Despite the mathematical similarities of the MPC and MHE problem formulations, the first results on explicit MHE have taken long to appear in the open literature[1], appearing only after the start of the CONNECT project.

The first year technical report (in Deliverable 1) describes how MHE is formulated as a multi-parametric program. Whereas the number of parameters in an explicit MPC problem equals the number of states, the number of parameters in an explicit MHE problem equals the number of states, plus the numbers of current and past measured outputs and past inputs over the entire estimation horizon. Thus the dimensionality of the MHE problem can significantly higher than the corresponding MPC problem. Although this does not automatically translate into an equal increase in the complexity of the solution to the multi-parametric program

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[1] M. L. Darby and M. Nikolaou, *A parametric Programming Approach to Moving Horizon State Estimation*, *Automatica*, 43:885-891, 2007

(which depends more on the number of different combinations of constraints that can be active), the problem of managing the complexity of exlicit MHE is rather acute.

The report refers to the corresponding sections of the report for WP1 when it comes to descriptions of how to solve the multi-parametric program, and how to organize the solution for real time application. Likewise, some of the techniques for complexity reduction of the solution (merging regions and interpolating), are directly translatable from MPC to MHE. Whereas 'move blocking' is a well known method for reducing the size of MPC problems, the corresponding 'disturbance blocking' for MHE is less well known – and is included in the report as a result of discussion with industrial practitioners. The same is the case for the practice of not allowing independent disturbances on every model state, but rather to model disturbances only where they can physically enter the system. This has the added benefit of guaranteeing that the estimator updates are consistent with conservation of mass and energy (limited by the accuracy with which a linearized system model can represent a possibly nonlinear system).
The report also includes a brief discussion of how to ensure the existence of feasible solution, more detailed descriptions of the use of penalty functions / slack variables can be found in the WP1 report.

The report describes how explicit solution for MHE can be combined with the explicit solution for MPC into one very large look-up table. This significantly increases the computer memory required to represent the solution, but the resulting large table can be searched very effectively. There is thus a trade-off between execution time and memory requirement.

The last section in the part of the WP3 report that deals with estimation reviews results on unconstrained estimation in combination with MPC.

The second part of the WP3 report deals with MPC for nonlinear systems. It starts with describing conventional formulations of nonlinear MPC (if anything in this area is mature enough to deserve being called 'conventional'). Next, it describes two approaches for explicit MPC of such system. The first such approach is based on iteratively refining a linear approximation to the nonlinear problem formulation. The other approach divides the state space into hypercubes, and solves the nonlinear optimization problem at the vertices of the hypercube. Next a feedback controller affine in the state which optimally approximates the solution at all vertices of the hypercube is found, together with an estimate of the error involved in this approximation. If the error is unacceptable, the hypercube has to be divided into smaller hypercubes, and the process repeated.

Finally, the literature on nonlinear MPC with bounded disturbances is briefly reviewed.

In the second year of the project, work in Work Package 3 has focussed on testing and verifying algorithms for explicit nonlinear MPC and explicit MHE for industrial applications. This work is described in Deliverable 6, whereas the more detailed results of the applications are described in Deliverable 11.

For nonlinear MPC, the system is described by a piecewise affine (PWA) model, which can approximate a non-linear system to arbitrary accuracy at the cost of increasing complexity both in the model description and the controller design. The resulting MPC formulation has been applied with success to the polymerization case study.

Likewise, explicit MHE has been applied to the polymerization case study, also that with success. In addition, an existing formultaion for robust (in the presence of structured parametric uncertainty) MHE has been re-formulated as a multiparametric QP problem, allowing it to be solved and implemented as an explicit robust MHE.

Original research contributions of WP3:

- Accounting for uncertainty in the state estimates in the formulation of the MPC problem, combined with a large terminal region (and hence enabling the use of a shorter prediction horizon) via interpolating between different terminal controllers. Paper #1.
- Showing that the state estimation error converges to a terminal set when Moving Horizon Estimation is used. Use of this set to make the MPC formulation more robust. Publications # 2, 3.
- Reformulation of an existing robust MHE formulation as a multiparametric QP, allowing it so be solved and implemented as an explicit MHE.
- Application of explicit nonlinear MPC and explicit MHE to a case study of industrially relevant complexity. Publications # 4, 5.

The work in this WP has been done mainly by NTNU (RTD) and in collaboration with UoM (RTD).

New Model Reduction Techniques for Control Applications (WP4). More specifically the following objectives have been achieved:

This work package was led by UoM. Its main objective was to investigate, explore and develop model reduction technologies for on-line controller design of large scale distributed parameter systems (i.e. large-scale systems that exhibit both time and space variations). It is well-known that model predictive control (MPC) involves dynamic optimisation of the system, which is extremely computationally expensive and almost impossible to perform on-line directly for large-systems. Both off-line techniques, based on adequate sampling of the systems' responses, and on-line methodologies, based on adaptively computed Krylov subspaces (mostly useful in conjunction with black-box input/output simulators) were to be exploited. In this spirit the main technique investigated in WP4 was Proper Orthogonal Decomposition (POD) or method of empirical eigenfunctions, as it is otherwise called. POD is a powerful model reduction technique which first appeared in the literature about 30 years ago and has been used in a number of applications. It consists of taking appropriate (empirical) samples of system's outputs in time and correlating them in a 2-dimensional matrix. Through eigenanalysis of this matrix a number of global basis functions that span the hyperspace of (approximately) all systems outputs can be constructed. The (typically few) of this basis functions that capture almost all of the system's energy (the system's dynamics) are then identified. By projecting the original large-scale system onto these few basis functions a low-dimensional system can be obtained that can accurately represent the original large-scale one and that is amenable for on-line MPC. However, for non-linear systems the resulting reduced models are also non-linear. Nevertheless, in this project we wanted to take advantage of powerful linear MPC techniques including parametric MPC (the software for which was developed in WP5). For this purpose we developed technologies to automatically compute piece-wise linear approximations (subject to a pre-chosen error) of the reduced non-linear models.

One of the novelties in this work was to combine POD with the Finite Element method (FEM). Therefore, local FEM basis functions can be used to consistently compute the needed spatial numerical derivatives and FEM Galerkin projection is exploited to systematically project the (discretised) system onto the POD-derived global basis functions (the PODs).

There are two basic advantages in using the derived technology for MPC applications:
The output of the reduced system is given as a linear combination of the PODs (functions of space, φ_i) and time coefficients $\alpha_i(t)$ which are computed from the reduced system. Therefore the objective function used in MPC is by default quadratic (as it should be).
The corresponding constraints of the reduced system, although non-linear, depend only on time ($\alpha_i(t)$) so they are only 1-dimensional even if the original system is e.g a 3-D dynamic one.
Furthermore, a Trajectory Piece-Wise Linearisation (TPWL) method was developed to automatically compute the optimal number of linear segments (subject to a given error) of the reduced (1-D) non-linear model (constraints in the MPC formulation). This way the resulting quadratic problem with piece-wise linear constraints can be directly solved using quadratic programming (QP) or parametric MPC.

The developed Galerkin/POD methodology was tested for a benchmark reaction-diffusion distributed parameter problem the so-called Bratu problem with 1 unknown dynamic variable (distributed in space) and an exponential nonlinearity. The PODs were found to be able to capture accurately the nonlinear dynamics of the system for a satisfactory range of parameters. A benchmark MPC problem provided by PAROS UK, Ltd was investigated next. The problem consisted of a number of communicating tanks, the liquid level of which had to be controlled. This is a discrete problem in space so the Galerkin/POD formulation had be appropriately adapted. The simple case of 2 tanks and the more “interesting” case (from a model reduction perspective) of 10 tanks were investigated. Furthermore, both linear (for benchmarking) and non-linear cases were explored. Non-linear MPC was exploited in the non-linear case (using sequential quadratic programming -SQP) first. SQP-based MPC can produce accurate results, but is computationally expensive even when used with reduced models. TPWL was also used to produce a piece-wise affine representation of the reduced model and the QP-based MPC worked also extremely well at a fraction of the computational cost. Moreover, the parametric control software produced by PAROS UK, Ltd in WP5 was used here for control of the POD reduced 10-tank model. With the current capabilities of the software only the linear case was easily solved. The non-linear case requires a modified adaptive MPC formulation, which is not currently available in the software, but it is the subject of future collaboration between UoM and PAROS UK Ltd.

The classical chemical engineering problem of a tubular reactor with an exothermic reaction occurring was investigated next. This is a continuous problem with 2 dynamical unknowns (concentration and temperature) spatially distributed and a very rich parametric behaviour including a number of bifurcations and instabilities. The Galerkin/POD method produced an accurate significantly reduced model with explicit parametric dependence. The MPC problem constructed had the objective to destabilise the system at stable parametric conditions and to “drive” it to a reference oscillatory state. SQP-based non-linear MPC works extremely accurately with the POD-reduced model. Linear (QP-based) MPC produces less accurate results, but with low computational cost. By increasing the number of linear segments we can exert tighter control. In terms of applying this technology to the industrial cases of this project, we have used the case study provided by KOTHALIS S.A. Their kiln used for making tiles was modelled within WP6 by PAROS UK Ltd and ESTIA. The corresponding model was set up in gPROMS. The model for the firing stage has 60 dynamic variables. The POD reduced model has only 4 dynamic equations and can accurately reconstruct the tile temperature in the firing stage.

On-line model reduction in conjunction with optimisation of black-box models was also investigated here. The method is based on adaptively computing low-dimensional Krylov subspaces of the original problem using subspace iterations and projecting the high-dimensional system onto these subspaces to obtain reduced models. The method was tested for the optimisation of a tubular reactor giving very good results. Future relevant work includes the use of linear MPC technology on the locally linearised reduced systems for constructing efficient fast black-box controllers not only for large-scale, but also for multi-scale systems.

It should be noted that NTNU explored balanced truncation methodologies in conjunction with work performed in WP3 and UoM explored model reduction technologies also within the framework of WP3.

The worked performed in WP4 has been presented in a number of meetings and international conferences including the annual meeting of the American Institute of Chemical Engineers (AIChE) and the European Symposium for Computer Aided Process Engineering (ESCAPE) and the corresponding conference papers. Furthermore, we expect this work to produce more than 3 publications in refereed scientific journals.

Software development and hardware (controller) designs (WP5).

The general objective of work package 5 is to develop software tools for embedded controller design and implement the controller on cheap hardware. Finally, to test the developed controllers in benchmark problems. This task can be regarded as the culmination of all theoretical tasks 1-4, bridging the gap between advanced optimal control theory and industrial control practice. It begins studying the parametric optimization algorithms turning them into efficient and numerically stable software that generates explicit MPC controllers. But this is a small part of the end product. The objective is to develop a user friendly MPC controller design suite taking care of all the details that comprise the lifecycle of design, hiding the underlying complexities. The control engineer is to work in a high-level MPC design space without requiring any knowledge of the low level advanced mathematics. The second important component is embedding the resulting explicit parametric MPC on hardware, which can be either off the shelf microcontrollers, large PLCs or even custom designed chips for the ultimate trade-off between capabilities and cost.

In summary, here are the main results at the end of second year:

- We have mapped the overall architecture both in terms of the advanced optimization algorithms and the presentation layer that will be exposed to the control engineer. The major software components will be (1) the core mpQP solver, (2) MPC design wizard, (3) offline controller validation and (4) embedded code generator. The design process will involve a feedback loop between (2) and (3) where alternative designs will be tested (through the solver 1) and gradually improved, and finally embedded code will be generated (4).

- We have considered the object oriented nature of the architecture and came up with a requirements analysis for each major component and software object/module. The inputs and outputs have been identified and the programming language was selected. This will be mostly done in MatLab, a de facto industry standard for control applications, which is both efficient for the numerical parts and expressive for the user interface parts. Its simulation software SimuLink will be used for validating the controller designs and probably its embedded code generation toolbox xPC target is a good candidate for the final on-chip code.

- The software design will have two basic layers. An internal offline multiparametric quadratic programming solver which will concentrate on fast solution while being stable and minimizing its intermediate storage requirements, and an outer shell exposing the MPC design capabilities. The latter will have a quick-start mode for training or/and acquiring basic controllers quickly for screening purposes, and an expert mode for advanced tweaking and fine tuning for optimal controllers.

- We have scrutinized the hardware requirements for explicit MPC controllers. The explicit MPC controller is software (a large data table plus a small module that reads the map online) and as such admits a broad range of implementation platforms. Any microcontroller that offers RAM and flash (permanent) memory, arithmetic and logical operations and analog input/output channels is adequate for the task. For larger applications pMPC will require more storage and more advanced hardware, but in such cases it is possible to simply incorporate it in existing control hardware of large facilities (e.g. PLC or DCS).

- We have identified bottlenecks that prohibit the embedding of rigorous pMPC controllers on conventional hardware and came up with simplifications and workarounds, trading off strict theoretical optimal control accuracy with realistic constraints of memory and online computational power.

- We have performed an extensive review of relevant industrial control standards that will affect the software design and implementation. We came up with Cape-Open, a generic process simulation set of interfaces, and OPC which is control specific. They will mostly affect software integration at the simulation stage, e.g. interfacing pMPC to process simulators like gPROMS. Data files will be stored in XML whenever possible for maximum interoperability.

- We have develop a beta version of dynamic programming algorithm in Matlab to solve robust parametric MPC controller in order to guarantee feasibility and stability. The algorithm has been proposed by Proffessor E.N. Pistikopoulo and achieves to solve multiparametric controller avoiding overlapping in less time than the original MPC formulation.

The work in WP 5 has been done mainly by ParOS (SME) and PSE (SME) with input on the design specifications by INEA (OTH) and SODRU (SME).

Application in Industrial Case Studies (WP6).

The main objective over the last 12 months was to completed the industrial case studies including validation, testing and assesment of the results. More specifically:

- **Control of a real industrial Polymerisation reactor (joint work between PSE, ParOS and NTNU).**

The case study presents a comprehensive approach to modelling and control of styrene polymerization reactor. The process model consists of the material and energy balances for the reactor, and dynamic model for the downstream separator. The kinetic expressions are simplified by using the quasi-steady-state assumption for live polymer chains and the moments of chain length distribution for the live and dead polymer chains. The kinetic parameters in the process model are from popular papers for styrene polymerization models for CTSR and BATCH reactors. The process model is used to develop a model for feedback PID controller and multi-parametric predictive controller (mp-MPC) for the polymerization process

- **Plasma based reactors for In-Line wire manufacturing sector - Pressure control of the vacuum chamber(joint work between (PLASMAIT, IJS, INEA). Detailed**

- The project was based on joint work of project partners JSI and PlasmaIt on one of the selected industrial case studies of the CONNECT project. The multi-parametric MPC algorithms were selected for pressure control in the vacuum atmosphere preparation subsystem of a machine used for annealing metal wires or bands by using magneto-focused plasma. Necessary mechanical adoptions on the machinery in Lebring were made in the first year of the project. Mp-MPC was considered for control of a non-square plant with two inputs and one output, as a replacement for a conventional control scheme comprising two PID controllers. A detailed assessment of the control problem and the disturbances was made.

- **Control of Energy Generation Systems (joint work between ESTIA, IJS, SODRU, INEA).**

1. The control of heat exchanges for district heating applications has been considered and interesting results have been obtained (SODRU).
2. Two CHP casy studies has been finalised and the results obtained indicate improved performance and energy savings (INEA, ESTIA. IJS).
3. Optimal Kiln Temperature control in the manufacturing of Bricks and tiles (Joint work between ESTIA, ParOS, PSE, KOTHALIS, IJS, UoM). A detailed model has been developed and validated using real-life data from the KOTHALI plant. Improved operating strategies have been ivestigated in a view of energy savings and robust manufacturing performance,

A detailed technical report per each deliverable is attached in this report.

All objectives have been fully achieved according the initial plan based on close collaboration between the participants. In some of the WPs more progress has been made compared to the initial plan. No problems encountered during the reporting period and the collaboration is progressing very smoothly.

2 Workpackage progress of the period

WP1 “New fast MPC algorithms”

WP1 started on month 1 of the project and has been progressed according to the initial plan

Ever since the discovery of explicit formulations of MPC a few years ago, most publications in the area have considered a rather idealized regulation problem. This means that the states are all measured, the references are always zero, and persistent disturbances (with a non-zero steady state component) have not been considered. With such idealized regulation problems, the regulation task is to bring the system states from some given initial values to zero.

Although the above description is a rough generalization of the literature in the area, it nevertheless differs greatly from more conventional MPC - based on online optimization. Conventional MPC originated within the chemical processing industry, and there were always awareness of many practical issues that are required in order to apply the technology to practical problems.

The work package report (deliverable no. 1) is an extensive review of the area of explicit MPC based on multi-parametric programming. In addition, it also covers important practical aspect of the more conventional MPC literature, and thereby contributes to paving the way for more widespread practical use of explicit MPC.

The basic idea behind explicit MPC is to take the computationally expensive optimization problem, and solve it off-line (at the design stage). This is based on the fact that the solution to the optimization problems can be decomposed into polyhedral regions of the state space.

The on-line computational task therefore reduces to identifying which of the polyhedral regions the current state belongs to, and to apply the affine feedback (simple multiplication and addition) that is valid for that region.

The main drawback of explicit MPC is that the number of polyhedral regions required to cover the feasible region of the state space grows exponentially with problem size. This means that even for problems of realistic size, the required number of regions could be *huge*. The consequences are:

1. The computer memory required to store the solution could become very large.
2. The time required to identify the polyhedral region to which the current state belongs could become too large relative to the sampling time of the application.
3. The off-line calculations required (at the design stage) to describe the solution of the optimization problems within each of the partitions of the state space could become excessive.

The way conventional MPC has adapted to the requirements of practical applications generally results in further increasing the size of the optimization problem, thus compounding the problems listed above.

The report (Deliverable 1) contains:

1. A general introduction to explicit MPC based on multi-parametric programming, and describing the properties of the solutions.
2. Two methods for reducing the on-line computational and memory requirements for explicit MPC.
3. Efficient ways of implementing controllers based on explicit MPC, how to organize the solutions in ways that permit efficient search to identify the partition of the state space to which the current state belongs.
4. Modifications to the (overall) optimization problem formulation for the MPC in order to obtain a simpler solution.
5. Robust explicit MPC:
   - Robustness to bounded disturbances.
   - Robustness to parametric uncertainty.
6. Handling constraint violations, and how to do so while only allowing constraint violations when no other possiblility exists.
7. Changing setpoints (reference values).
8. Disturbances, disturbance modelling, and how to remove steady-state offset using integral action.
9. Studies on the use of multi-parametric approaches to multi-step dynamic programming (for constrained linear systems), and of how computation time can be reduced by grouping multiple control samples into a single dynamic programming step.

In the second year of the project, work in WP1 has focussed on

- Testing and validating explicit MPC algorithms for industrial use, including both the off-line optimization and the efficient on-line evaluation. This is described in Deliverable 4.

- A novel formulation for approximate explicit MPC, allowing a systematic and controlled trade-off between complexity and degree of sub-optimality without first having to calculate the exact solution. This is described in publication #13.

Original research contributions of WP1:

- A general introduction to explicit MPC based on multi-parametric programming, and describing the properties of the solutions.
- Two methods for reducing problems 1 and 2 above are described. After calculating the solution for the entire state space, on-line computational and memory requirements may be reduced by
    - Merging neighbouring partitions of the state space. In some cases the same controller may be optimal in neighbouring regions, and merging regions then will not result in the loss of optimality.
    - Interpolating between different solutions. This requires the on-line solution of very small optimization problems. It can dramatically reduce the computer memory requirement, but incurs some loss of optimality.
- Efficient ways of implementing controllers based on explicit MPC, how to organize the solutions in ways that permit efficient search to identify the partition of the state space to which the current state belongs.
- Modifications to the (overall) optimization problem formulation for the MPC in order to obtain a simpler solution:
    - The minimum-time MPC formulation.
    - Enlarging the terminal set within which the predicted value of the state at the end of the prediction horizon needs to be in order to guarantee closed loop stability.
    - Move blocking – reducing the size of the optimization problem by not allowing the input variables to move at every time step in the prediction horizon.
    - A (very) brief discussion of model reduction – a more complete treatment is given in WP4.
- Robust explicit MPC:
    - Robustness to bounded disturbances.
    - Robustness to parametric uncertainty.
- Handling constraint violations, and how to do so while only allowing constraint violations when no other possiblility exists.
- Changing setpoints (reference values).
- Disturbances, disturbance modelling, and how to remove steady-state offset using integral action.
- Studies on the use of multi-parametric approaches to multi-step dynamic programming (for constrained linear systems), and of how computation time can be reduced by grouping multiple control samples into a single dynamic programming step.

- Optimizing the prediction dynamics in MPC problems with parametric uncertainty, while obtaining an problem formulation for which efficient solvers do exist. Publications.
- Extension and simplification of existing results on reachability analysis to simplify look-up table search in online application of explicit MPC. .
- Enlarging the domain of attraction (for a fixed prediction horizon length) by decomposing the current state and applying different controllers for each component..
- Enlarging the terminal region on MPC based on time-optimal control formulations, via interpolating between different terminal controllers.
- Accounting for uncertainty in the state estimates in the formulation of the MPC problem, combined with a large terminal region (and hence enabling the use of a shorter prediction horizon) via interpolating between different terminal controllers.
- Showing that the state estimation error converges to a terminal set when Moving Horizon Estimation is used. Use of this set to make the MPC formulation more robust.
- Reduction of computation time in multi-step dynamic programming approaches to MPC by grouping multiple control samples into a single dynamic programming step.
- Applications to a case study of industrially realistic complexity.
- A novel approach for approximate explicit MPC based on Delaunay tesselation.

WP2 “Robust MPC for hybrid and continuous systems”

This WP has started in month 5 and had been completed according to the initial plan.

With hybrid (typically, piecewise affine) models, the outline of the proposed explicit MPC approach is to first formulate an open loop receding horizon optimal control problem and then recasts it as a multi-parametric mixed integer program. With continuous-time models, the approach is essentially similar, resulting in a multi-parametric dynamic optimization problem. An alternative solution path via the concept of dynamic programming is available. The resulting explicit parametric controller is calculated off-line, prior to actual process implementation. In closed-loop operation, the controller calculation is thus several orders of magnitude faster than with conventional on-line MPC controllers.

Fast calculation of the explicit control law opens up a vast new application field of processes with fast dynamics in the millisecond range. Previously, such processes could only be controlled by conventional linear controllers such as PID, ignoring the constrained nature of most real-life actual dynamic plants and solving some of the associated problems with ad-hoc anti-windup protection schemes. One must also be aware of the limitation of the multi-parametric approach due to parametric explosion of the off-line calculation time and memory requirement with large number of optimization parameters. This limitation prohibits the application of explicit MPC to large-scale control problems with multiple inputs and outputs, which are the typical application domain if "conventional" industrial MPC. For these reasons, the application domain of explicit MPC in the control hierarchy is shifted from mid-range towards low-level.

The literature review of scientific publications relevant to explicit MPC with hybrid models lists 30 publications in the last five years. 5 publications actually discuss explicit MPC with hybrid models, while other publications apply to related fields (non-explicit hybrid MPC; output feedback issues with hybrid MPC, such as observers and moving horizon estimators for hybrid systems; related multiple model approaches). It is noticed that various approaches to hybrid MPC control design are much more heterogeneous than of MPC for constrained linear systems. There is a wide range of possible choices and combinations that are selected according to the needs of various fields of application: hybrid model form (PWA, MLD, ...), types of discrete mode transitions considered (state, time, input events), discrete or continuous time models, norm type in the cost function: 1-norm, 2-norm, robust norms, finite or infinite time cost function and control signal (mostly finite-time), control parameterization (mostly open-loop), explicit or non-explicit solution, various complexity reduction issues (including approaches that are not entirely MPC), disturbance modelling, output feedback and tracking issues.

In the review of scientific publications in the period of the last five years relevant to explicit MPC with continuous-time (CT) models, 14 publications are listed. Only two publications are found for explicit MPC with CT models directly, while others mostly apply to on-line MPC with linear or nonlinear CT models, and output feedback issues. True continuous-time implementation, using analog electronics and similar, of advanced control is virtually inexistent in the era of digital computers. Considerable differences exist regarding the use of CT and DT in known CT methods and the point of discretisation for different application areas:

- There may be no discretisation at all, though this is mostly restricted to theoretical papers.
- The control signal is DT (piecewise constant) in most application-oriented papers. In some papers, two-level discretisation of control signal is used, where the main algorithm calculates parameters of basis functions at a slower rate and the realization of basis functions occurs at a faster rate.
- The cost function may be CT (integral) or DT (sum).
- Constraints may be enforced continuously or only at sample points.

Sources of motivation for contemporary CT methods include:

- Intersampling problems due to long sampling times that cannot be made shorter.
- Irregular sampling intervals.
- Strict constraint satisfaction under the abovementioned conditions.
- Hybrid model switching that does not occur at sampling instants which cannot be ignored.
- A CT explicit solution may have fewer regions than a corresponding DT explicit solution, and the partition is not related to the sampling time and horizon length (while the on-line implementation is more involved).
- The ability of using a CT first principles model directly (for example, model uncertainty in a single physical parameter may become obscured after conversion to DT)

The majority of the published CT methods are nonlinear and stem from the direct use of first principles models. In these methods, discretisation is often combined with various forms of linearisation; however, most of them do not deal with specific advantages of the CT approach that are the main motivation of the recent CT explicit MPC approaches.

In summary in the existing literature on industrial applicability of mp-MPC, there appears to be a certain degree of confusion arising from the desire of authors to keep the number of process states as low as possible and to exclude or limit discussion of output feedback issues, resulting in highly application-specific controllers with limited general applicability. The publicly available toolboxes provide only offset-free reference tracking, but not offset-free tracking with disturbances of integrating nature.

It is shown that the disturbance integration scheme is prone to integrator windup in case of unreachable set-points, and that the modification to the cost function may deteriorate tracking performance. Therefore, the disturbance estimation approach that is more commonly used in traditional MPC is more recommendable. While the simplest DMC-style form disturbance estimations is known to be simple and usually result in robust performance, more efficient feedback performance may be obtained by using a Kalman Filter (KF) or a Moving Horizon Estimator (MHE). The choice among a MPC controller of unified structure and a target calculator (TC) scheme is less clear. The introduction of the TC does not decrease the amount of computation as in online MPC. The TC also does not show an important advantage regarding the ability of system reconfiguration at saturations, as this is also facilitated by the unified scheme. The TC complicates performance analysis, because it introduces an outer control loop, which may also be interpreted as a PWA control law, and because fixing steady-state targets ignoring transient constraints violations, prior to the dynamic controller, may not be optimal. On the other hand, the TC allows application of theoretically advanced control approaches that demand control of the state to the origin.
A disturbance rejection tuning case study is presented of an offset-free output feedback tracking mp-MPC controller. A unified scheme with no TC is used, and a KF is used for output feedback. The output feedback tracking concept is presented for constrained linear systems and may be extended to piecewise-affine (PWA) hybrid systems with no binary inputs. A case study on a two-input single-output system of pressure control in a vacuum chamber of a wire annealer is presented. It is shown that efficient control of a non-square plant may be implemented with an mp-MPC controller of a "unified" structure (without a TC). Tuning is made primarily using local linear analysis (LLA); LLA enables closed-loop system analysis for the unconstrained or constrained regions of the controller, possibly with plant-to-model mismatch (with a set of candidate true models), in time domain, frequency domain, or on the complex plane. Issues of robustness to modelling error are elaborated. The Loop Transfer Recovery (LTR) technique was found to be effective also with mp-MPC, however of not very significant benefit could be achieved in the offset-free tracking context due to the difference in scopes of the controller and the estimator. The results of the case study indicate that mp-MPC controllers can provide robust and efficient performance in low level control, although the results may not come as easily as some optimistic references predict. There is a certain improvement in constrained performance compared to PID anti-windup, and better insight into constrained performance is available due to the explicit form of the mp-MPC control law.

Another case study application is concerned with new algorithms of mp-MPC using piecewise affine (PWA) hybrid models for control of a nonlinear process approximated with a continuous PWA model that contains a set of local linear dynamics. The recently developed methods of multi-parametric model predictive control (mp-MPC) for hybrid systems provide an interesting opportunity for solving this class of nonlinear control problems. Compared to linear model based MPC, they allow control with a set of nominal models instead of using a single nominal model; a performance improvement is expected with the reduction of plant-to-model mismatch. However, the scientific publications on hybrid mp-MPC mostly focus on the state feedback problem and related stability, feasibility and computational efficiency issues of the algorithms, while practical applications are scarce. In this work, the feasibility of the approach for application was evaluated in a case study, where an output feedback, offset-free tracking hybrid mp-MPC controller of the unified type was considered as a replacement for a PID controller based scheme for control of pressure in a wire annealing machine (the same as in the previous sections). Typically, such hybrid mp-MPC methods rely on multi-parametric mixed-integer linear or quadratic programming solvers (mp-MILP/MIQP), whereas the related on-line hybrid MPC methods employ conventional MILP or MIQP solvers. Due to the parametric explosion of the off-line mp-MILP/MIQP computation with the problem dimensions, this approach is practically feasible for MPC problems of small sizes.

With very short horizons, tuning for efficient and robust feedback performance is a particular challenge. Robustness to plant-to-model mismatch is very important, since the hybrid methods do not ensure stable performance of the closed-loop system including the actual nonlinear system. Particularly to hybrid models, predictable behaviour at switching among the dynamics is required, as discontinuities in the model may lead to formally correct results that are not useful in practice. Therefore, a continuous PWA model is used. For output feedback, a switching (KF) is used; the active dynamic can be determined directly from the control signals. The simulation results show that improved performance due to decreased plant-to-model mismatch is achieved with hybrid PWA model based mp-MPC, compared to the linear model based approach. However, the off-line computation time is reasonable for practical application (within a few minutes) only with very short horizons in our case study. The tuning parameters selected considering acceptable computation time result in impaired control performance and robustness compared to linear model based mp-MPC control with longer horizons (Section 2). Better practical results may be achievable with more efficient algorithms or with suboptimal simplifications.

Another validation study of mp-MPC control is concerned with the optimal water temperature control in the engine cooling subsystem of a biogas-fuelled combined heat and power production (CHP) unit. In this case study, the ability of mp-MPC for suppression of disturbances violating output constraints was investigated. This is relevant regarding the use of mp-MPC as an advanced PID replacement. Again, an output feedback, offset-free tracking mp-MPC controller with a KF is used. With the exception of simplified methods that do not provide constraints handling, MPC methods have not been very successful in low level control. Typical MPC methods require on-line optimization and cannot be implemented with inexpensive industrial control hardware; however, mp-MPC may break this barrier. Also, there are many low-level control applications that would benefit from an advanced PID replacement that would eliminate or reduce violation of critical constraints.) Despite the

declared ability of advanced constraints handling with mp-MPC and the undisputed constraints handling advantages of industrial MPC controllers, where the ability to push the set-point closer to constraints is one of the main selling features, it is questionable whether a practical advantage due to constraints handling is achievable in single-input single-output (SISO) PID replacement applications: large-scale multivariate MPC applications have degrees of freedom in ranking of control priorities that SISO control applications lack, feedback performance and robustness issues: conventional MPC controllers are not brilliant feedback performers, whereas the variants that employ Kalman filters are closely related to LQG control that did not have much success in industrial practice despite good academic reputation, more expressed issues with various types of nonlinearities in low-level control: nonlinear, hybrid, or multiple-model mp-MPC may be required for proper operation of constraints handling.
A detailed description of a developed software library LLAPC (Local linear analysis of tracking predictive control) is also analysed.

WP3 “Non-linear MPC and receding horizon estimation”

This WP started in month 5 and had been completed according to the initial plan.

In state estimation, one uses measurements of plant outputs and knowledge of plant inputs to estimate the plant states, in the face of (possibly unmeasured) disturbances and measurement noise. The classical state estimation strategies are the Kalman filter (when starting from a stochastic problem description) and the Luenberger observer (starting from a deterministic problem description). Neither of these approaches are directly applicable when there are constraints in the possible values of the states. Motivated by the enormous success of Model Predictive Control (MPC), Moving Horizon Estimation (MHE) was developed as the tool of choice for constrained state estimation.

The first publications on explicit MPC using multi-parametric programmin appeared just around the year 2000. Despite the mathematical similarities of the MPC and MHE problem formulations, the first results on explicit MHE have taken long to appear in the open literature[2], appearing only after the start of the CONNECT project.

The first year technical report (in Deliverable 1) describes how MHE is formulated as a multi-parametric program. Whereas the number of parameters in an explicit MPC problem equals the number of states, the number of parameters in an explicit MHE problem equals the number of states, plus the numbers of current and past measured outputs and past inputs over the entire estimation horizon. Thus the dimensionality of the MHE problem can significantly higher than the corresponding MPC problem. Although this does not automatically translate into an equal increase in the complexity of the solution to the multi-parametric program (which depends more on the number of different combinations of constraints that can be active), the problem of managing the complexity of exlicit MHE is rather acute.

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[2] M. L. Darby and M. Nikolaou, *A parametric Programming Approach to Moving Horizon State Estimation*, *Automatica*, 43:885-891, 2007

The report refers to the corresponding sections of the report for WP1 when it comes to descriptions of how to solve the multi-parametric program, and how to organize the solution for real time application. Likewise, some of the techniques for complexity reduction of the solution (merging regions and interpolating), are directly translatable from MPC to MHE. Whereas 'move blocking' is a well known method for reducing the size of MPC problems, the corresponding 'disturbance blocking' for MHE is less well known – and is included in the report as a result of discussion with industrial practitioners. The same is the case for the practice of not allowing independent disturbances on every model state, but rather to model disturbances only where they can physically enter the system. This has the added benefit of guaranteeing that the estimator updates are consistent with conservation of mass and energy (limited by the accuracy with which a linearized system model can represent a possibly nonlinear system).
The report also includes a brief discussion of how to ensure the existence of feasible solution, more detailed descriptions of the use of penalty functions / slack variables can be found in the WP1 report.

The report describes how explicit solution for MHE can be combined with the explicit solution for MPC into one very large look-up table. This significantly increases the computer memory required to represent the solution, but the resulting large table can be searched very effectively. There is thus a trade-off between execution time and memory requirement.

The last section in the part of the WP3 report that deals with estimation reviews results on unconstrained estimation in combination with MPC.

The second part of the WP3 report deals with MPC for nonlinear systems. It starts with describing conventional formulations of nonlinear MPC (if anything in this area is mature enough to deserve being called 'conventional'). Next, it describes two approaches for explicit MPC of such system. The first such approach is based on iteratively refining a linear approximation to the nonlinear problem formulation. The other approach divides the state space into hypercubes, and solves the nonlinear optimization problem at the vertices of the hypercube. Next a feedback controller affine in the state which optimally approximates the solution at all vertices of the hypercube is found, together with an estimate of the error involved in this approximation. If the error is unacceptable, the hypercube has to be divided into smaller hypercubes, and the process repeated.

Finally, the literature on nonlinear MPC with bounded disturbances is briefly reviewed.

In the second year of the project, work in Work Package 3 has focussed on testing and verifying algorithms for explicit nonlinear MPC and explicit MHE for industrial applications. This work is described in Deliverable 6, whereas the more detailed results of the applications are described in Deliverable 11.

For nonlinear MPC, the system is described by a piecewise affine (PWA) model, which can approximate a non-linear system to arbitrary accuracy at the cost of increasing complexity both in the model description and the controller design. The resulting MPC formulation has been applied with success to the polymerization case study.

Likewise, explicit MHE has been applied to the polymerization case study, also that with success. In addition, an existing formultaion for robust (in the presence of structured parametric uncertainty) MHE has been re-formulated as a multiparametric QP problem, allowing it to be solved and implemented as an explicit robust MHE.

Original research contributions of WP3:

- Accounting for uncertainty in the state estimates in the formulation of the MPC problem, combined with a large terminal region (and hence enabling the use of a shorter prediction horizon) via interpolating between different terminal controllers. Paper #1.
- Showing that the state estimation error converges to a terminal set when Moving Horizon Estimation is used. Use of this set to make the MPC formulation more robust. Publications # 2, 3.
- Reformulation of an existing robust MHE formulation as a multiparametric QP, allowing it so be solved and implemented as an explicit MHE.
- Application of explicit nonlinear MPC and explicit MHE to a case study of industrially relevant complexity. Publications # 4, 5.

WP4 “Model reduction technologies for MPC Applications“

This package started in month 3 and has been completed according to the initial plan.

This work package was led by UoM. Its main objective was to investigate, explore and develop model reduction technologies for on-line controller design of large scale distributed parameter systems (i.e. large-scale systems that exhibit both time and space variations). It is well-known that model predictive control (MPC) involves dynamic optimisation of the system, which is extremely computationally expensive and almost impossible to perform on-line directly for large-systems. Both off-line techniques, based on adequate sampling of the systems’ responses, and on-line methodologies, based on adaptively computed Krylov subspaces (mostly useful in conjunction with black-box input/output simulators) were to be exploited. In this spirit the main technique investigated in WP4 was Proper Orthogonal Decomposition (POD) or method of empirical eigenfunctions, as it is otherwise called. POD is a powerful model reduction technique which first appeared in the literature about 30 years ago and has been used in a number of applications. It consists of taking appropriate (empirical) samples of system’s outputs in time and correlating them in a 2-dimensional matrix. Through eigenanalysis of this matrix a number of global basis functions that span the hyperspace of (approximately) all systems outputs can be constructed. The (typically few) of this basis functions that capture almost all of the system’s energy (the system’s dynamics) are then identified. By projecting the original large-scale system onto these few basis functions a low-dimensional system can be obtained that can accurately represent the original large-scale one and that is amenable for on-line MPC. However, for non-linear systems the resulting reduced models are also non-linear. Nevertheless, in this project we wanted to take advantage of powerful linear MPC techniques including parametric MPC (the software for which was developed in WP5). For this purpose we developed technologies to automatically compute piece-wise linear approximations (subject to a pre-chosen error) of the reduced non-linear models.

One of the novelties in this work was to combine POD with the Finite Element method (FEM). Therefore, local FEM basis functions can be used to consistently compute the needed spatial numerical derivatives and FEM Galerkin projection is exploited to systematically project the (discretised) system onto the POD-derived global basis functions (the PODs).

There are two basic advantages in using the derived technology for MPC applications:

(a) The output of the reduced system is given as a linear combination of the PODs (functions of space, φ_i) and time coefficients $\alpha_i(t)$ which are computed from the reduced system. Therefore the objective function used in MPC is by default quadratic (as it should be).

(b) The corresponding constraints of the reduced system, although non-linear, depend only on time ($\alpha_i(t)$) so they are only 1-dimensional even if the original system is e.g a 3-D dynamic one.

Furthermore, a Trajectory Piece-Wise Linearisation (TPWL) method was developed to automatically compute the optimal number of linear segments (subject to a given error) of the reduced (1-D) non-linear model (constraints in the MPC formulation). This way the resulting quadratic problem with piece-wise linear constraints can be directly solved using quadratic programming (QP) or parametric MPC.

The developed Galerkin/POD methodology was tested for a benchmark reaction-diffusion distributed parameter problem the so-called Bratu problem with 1 unknown dynamic variable (distributed in space) and an exponential nonlinearity. The PODs were found to be able to capture accurately the nonlinear dynamics of the system for a satisfactory range of parameters. A benchmark MPC problem provided by PAROS UK, Ltd was investigated next. The problem consisted of a number of communicating tanks, the liquid level of which had to be controlled. This is a discrete problem in space so the Galerkin/POD formulation had be appropriately adapted. The simple case of 2 tanks and the more "interesting" case (from a model reduction perspective) of 10 tanks were investigated. Furthermore, both linear (for benchmarking) and non-linear cases were explored. Non-linear MPC was exploited in the non-linear case (using sequential quadratic programming -SQP) first. SQP-based MPC can produce accurate results, but is computationally expensive even when used with reduced models. TPWL was also used to produce a piece-wise affine representation of the reduced model and the QP-based MPC worked also extremely well at a fraction of the computational cost. Moreover, the parametric control software produced by PAROS UK, Ltd in WP5 was used here for control of the POD reduced 10-tank model. With the current capabilities of the software only the linear case was easily solved. The non-linear case requires a modified adaptive MPC formulation, which is not currently available in the software, but it is the subject of future collaboration between UoM and PAROS UK Ltd.

The classical chemical engineering problem of a tubular reactor with an exothermic reaction occurring was investigated next. This is a continuous problem with 2 dynamical unknowns (concentration and temperature) spatially distributed and a very rich parametric behaviour including a number of bifurcations and instabilities. The Galerkin/POD method produced an accurate significantly reduced model with explicit parametric dependence. The MPC problem constructed had the objective to destabilise the system at stable parametric conditions and to “drive” it to a reference oscillatory state. SQP-based non-linear MPC works extremely accurately with the POD-reduced model. Linear (QP-based) MPC produces less accurate results, but with low computational cost. By increasing the number of linear segments we can exert tighter control. In terms of applying this technology to the industrial cases of this project, we have used the case study provided by KOTHALIS S.A. Their kiln used for making tiles was modelled within WP6 by PAROS UK Ltd and ESTIA. The corresponding model was set up in gPROMS. The model for the firing stage has 60 dynamic variables. The POD reduced model has only 4 dynamic equations and can accurately reconstruct the tile temperature in the firing stage.

On-line model reduction in conjunction with optimisation of black-box models was also investigated here. The method is based on adaptively computing low-dimensional Krylov subspaces of the original problem using subspace iterations and projecting the high-dimensional system onto these subspaces to obtain reduced models. The method was tested for the optimisation of a tubular reactor giving very good results. Future relevant work includes the use of linear MPC technology on the locally linearised reduced systems for constructing efficient fast black-box controllers not only for large-scale, but also for multi-scale systems.

It should be noted that NTNU explored balanced truncation methodologies in conjunction with work performed in WP3 and UoM explored model reduction technologies also within the framework of WP3.

The worked performed in WP4 has been presented in a number of meetings and international conferences including the annual meeting of the American Institute of Chemical Engineers (AIChE) and the European Symposium for Computer Aided Process Engineering (ESCAPE) and the corresponding conference papers. Furthermore, we expect this work to produce more than 3 publications in refereed scientific journals.

WP5 “Software development and hardware (controller) designs”

The general **objectives** of task 5 as stated in the workprogramme are:

- To develop software tools for embedded controller design.
- To implement the developed controllers on cheap hardware (e.g. chips)
- To test the developed controllers in benchmark problems.

This WP has started on month 7 and has been completed according to the initial plan.

The general objective of work package 5 is to develop software tools for embedded controller design and implement the controller on cheap hardware. Finally, to test the developed controllers in benchmark problems. This task can be regarded as the culmination of all theoretical tasks 1-4, bridging the gap between advanced optimal control theory and industrial control practice. It begins studying the parametric optimization algorithms turning them into efficient and numerically stable software that generates explicit MPC controllers. But this is a small part of the end product. The objective is to develop a user friendly MPC controller design suite taking care of all the details that comprise the lifecycle of design, hiding the underlying complexities. The control engineer is to work in a high-level MPC design space without requiring any knowledge of the low level advanced mathematics. The second important component is embedding the resulting explicit parametric MPC on hardware, which can be either off the shelf microcontrollers, large PLCs or even custom designed chips for the ultimate trade-off between capabilities and cost.

In summary, here are the main results at the end of second year:

- We have mapped the overall architecture both in terms of the advanced optimization algorithms and the presentation layer that will be exposed to the control engineer. The major software components will be (1) the core mpQP solver, (2) MPC design wizard, (3) offline controller validation and (4) embedded code generator. The design process will involve a feedback loop between (2) and (3) where alternative designs will be tested (through the solver 1) and gradually improved, and finally embedded code will be generated (4).

- We have considered the object oriented nature of the architecture and came up with a requirements analysis for each major component and software object/module. The inputs and outputs have been identified and the programming language was selected. This will be mostly done in MatLab, a de facto industry standard for control applications, which is both efficient for the numerical parts and expressive for the user interface parts. Its simulation software SimuLink will be used for validating the controller designs and probably its embedded code generation toolbox xPC target is a good candidate for the final on-chip code.

- The software design will have two basic layers. An internal offline multiparametric quadratic programming solver which will concentrate on fast solution while being stable and minimizing its intermediate storage requirements, and an outer shell exposing the MPC design capabilities. The latter will have a quick-start mode for training or/and acquiring basic controllers quickly for screening purposes, and an expert mode for advanced tweaking and fine tuning for optimal controllers.

- We have scrutinized the hardware requirements for explicit MPC controllers. The explicit MPC controller is software (a large data table plus a small module that reads the map online) and as such admits a broad range of implementation platforms. Any microcontroller that offers RAM and flash (permanent) memory, arithmetic and logical operations and analog input/output channels is adequate for the task. For larger applications pMPC will require more storage and more advanced hardware, but in such cases it is possible to simply incorporate it in existing control hardware of large facilities (e.g. PLC or DCS).

- We have identified bottlenecks that prohibit the embedding of rigorous pMPC controllers on conventional hardware and came up with simplifications and workarounds, trading off strict theoretical optimal control accuracy with realistic constraints of memory and online computational power.

- We have performed an extensive review of relevant industrial control standards that will affect the software design and implementation. We came up with Cape-Open, a generic process simulation set of interfaces, and OPC which is control specific. They will mostly affect software integration at the simulation stage, e.g. interfacing pMPC to process simulators like gPROMS. Data files will be stored in XML whenever possible for maximum interoperability.

- We have develop a beta version of dynamic programming algorithm in Matlab to solve robust parametric MPC controller in order to guarantee feasibility and stability. The algorithm has been proposed by Proffessor E.N. Pistikopoulo and achieves to solve multiparametric controller avoiding overlapping in less time than the original MPC formulation.

WP6: Application in several realistic industrial case studies

This WP started on month 7 and has been completed according to the initial plan.

To implement an effective collaboration scheme the consortium decided since the kick-off meeting the following collaborations for each one of the industrial case studies.

- ❖ **Control of a real industrial Polymerisation reactor. Here the involved partners are PSE, ParOS and NTNU.**

The case study presents a comprehensive approach to modelling and control of styrene polymerization reactor. The process model consists of the material and energy balances for the reactor, and dynamic model for the downstream separator. The kinetic expressions are simplified by using the quasi-steady-state assumption for live polymer chains and the moments of chain length distribution for the live and dead polymer chains. The kinetic parameters in the process model are from popular papers for styrene polymerization models for CTSR and BATCH reactors.
The process model is used to develop a model for feedback PID controller and multi-parametric predictive controller (mp-MPC) for the polymerization process with the following typical characteristics.

- Plant operations: following the temperature profile
- Manipulated variables: flow rate of cool and hot water.
- Control variables: ideal temperature profile that guarantees best polymer production rate.

The mathematical model of the batch polymerization reactor is non-linear dynamic and linearization during different plant operations is needed. Even though linearized nonlinear model predictive controller is more complicated, is preferred since gives superior performance compared to a linear model predictive controller.

- **Plasma based reactors for In-Line wire manufacturing sector - Pressure control of the vacuum chamber.** Here the partners involved are PLASMAIT, IJS, and INEA.

- Mp-MPC methods based on linear and hybrid models were tested in the industrial case study of PLASMAIT. The JSI work was tightly integrated with activities in theoretical workpackages WP1 and WP2. Firstly, an output feedback tracking scheme with steady-state offset elimination suitable for both linear and hybrid methods was developed. Then, linear model based methods were developed as a foundation. In the final stage, the work was focused on the hybrid model based methods and on alternative methods of disturbance rejection. Several sets of measurements on the machinery were performed.
- The results with the linear model based methods show that better performance in terms of response speed and robustness to variation of process dynamics over the operating range can be achieved than with the original PID scheme. However, it must be admitted that the advantage of mp-MPC is slight and that the PID scheme is remarkably efficient considering its relative simplicity.
- The hybrid model based methods can be used to improve performance by addressing the issue of variation of the process dynamics; effectively, rather than having one nominal model, a hybrid controller switches among three nominal local dynamics in different parts of the operating range, decreasing the plant-to-model mismatch. On the other hand, the off-line computation complexity forbids implementation of hybrid mp-MPC controllers with longer prediction horizons, impairing the disturbance rejection properties. It is estimated that sub-optimal control strategies, such as multiple-model control with a set of linear mp-MPC controllers with longer horizons, may most probably produce better practical results than hybrid mp-MPC.

- **Optimal Kiln Temperature control in the manufacturing of Bricks and tiles**

A tunnel-type industrial kiln, which is the case of the KOTHALI case-study, consists of several subsystems in operational interrelation and is divided usually in three zones, the pre-heating zone, the firing zone and the cooling zone as shown in Fig. 1. Two basic subsystems are responsible for the thermal and aerodynamic states created inside the kiln. The system's heart is the firing zone consisting of a matrix-set of burners. A typical number is eighty burner flames or more located on the roof of the kiln.

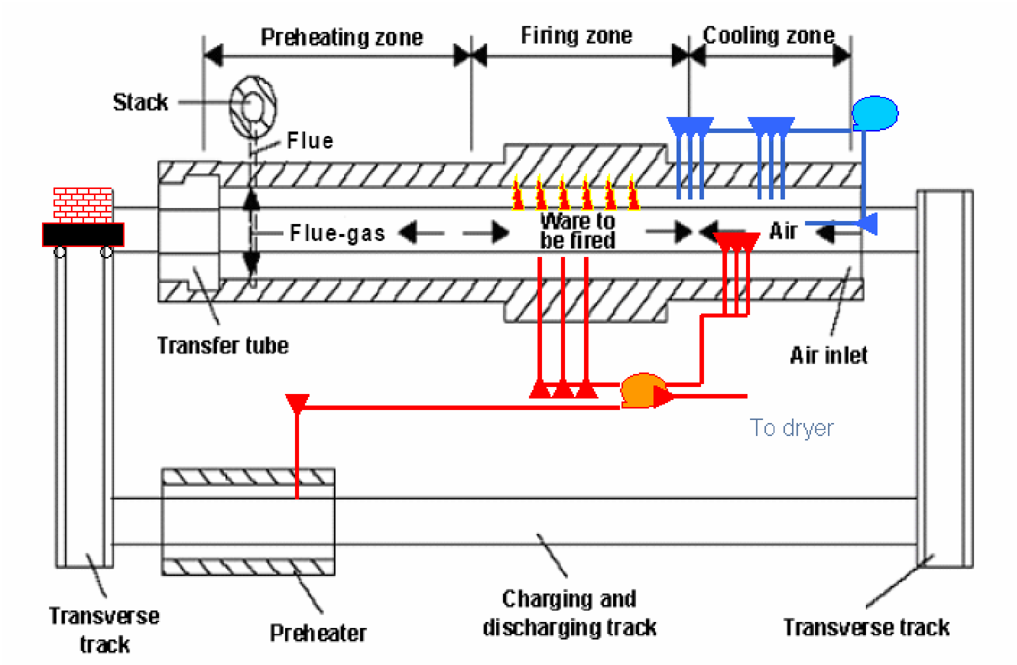

Figure 1 : Typical tunnel kiln arrangement

In this production process, the products have to be dehydrated before entering the kiln. A parallel passive kiln (preheater) operates with hot air from the kiln. Hence, another subsystem is that of hot air extraction from the furnace and specifically from the cooling zone. The hot air flow is regulated in various points of the furnace by on/off tampers performing mixing with environment air in order to keep hot air flow and temperature constant. Immediately after the firing zone, there is a small subsystem performing a rapid reduction of the temperature. Another subsystem with multiple air fans feeds cool air from the environment at the end of the tunnel. To keep the tunnel temperature constant from top to bottom, there is a subsystem for recycling hot air before the heating zone. Finally, a stack at the beginning of the tunnel forces exhaust emissions to the environment affecting so the overall aerodynamic state inside the kiln.

Details on the kiln dimensions and operational characteristics can be found in D7 reporting material and are not reproduced here. The case study has been concerned in developing a model for the optimum kiln operation. For this a series of measurement campaigns, Computational Fluid Dynamics Simulations campaigns and literature review has been performed, in order to identify parameters such as pressure drop characteristics along the kiln, convective heat transfer coefficient, radiation coefficient and attain overall mass balances. Based on the results, a steady state kiln model has been formed, as reported in D7. Partners ESTIA, KOTHALI have been mainly involved, in close collaboration with partner ParOS.

The steady-state model served as a start for developing a dynamic model for the kiln, that will be described in detail in the following paragraph, by partner ParOS. The model has been implemented in the modelling environment of gPROMS by ParOS and has been evaluated against real-case data retrieved from the industrial installation of KOTHALI, in close collaboration of all partners involved. Simulation campaigns have been performed and energy and effluents optimisation measures have been identified.

The tunnel-type industrial kiln is a very complex system in terms of modelling and control, because multiple exchange of energy occurs in it due to the nature of process that leads to complex mathematical models describing its dynamics. Most industrial kilns of the kind are controlled using classical control algorithms such as ON-OFF or PID controllers. The popularity of PID control can be attributed to both its good performance over a wide range of operating conditions and to its functional simplicity. A common problem with PID controllers used for control of highly nonlinear processes is that the set of controller parameters produces satisfactory performance only when the process is within a small operational window. Outside this window, other parameters or set points are necessary, and these adjustments may be done automatically by a high level strategy. The new control systems require looking for new and better control algorithms. All the heuristic rules derived from model-based simulation tests, refer to the primary system variables including the air flow rate to kiln, the temperature in various points along the kiln and the corresponding set points. The evaluation of these decision rules lead to control actions. The overshoot, damping and period variables characterize the system transient response and are calculated before the adjustment of the controller parameters.

- **Optimal Control of Energy Generation Systems (Heat Exchangers). Here the partners mainly involved are SODRU, ParOS and UoM.**

To maintain the temperature of stream heated or cooled in a heat exchanger at given preset value with limited deviations is one of the most frequently encountered control problems in industry, District Heating (DH) and hot water supply. For this purpose the flow rate regulators are usually used, which control the flow of steam, heating or cooling water at the rate that ensure the specified temperature value of heated or cooled stream at the exit of heat exchanger. Such regulator consists of a control valve with mounted on it actuator and valve control device which governs the valve position according to signal data from temperature sensor. Types of valves are categorized according to their design style. The main of these types, which can be used for flow control are globe, angle, ball, plug, needle and butterfly valves. The most effective for regulation are globe or saddle regulative valves. Its construction provides linear characteristic of fluid flow passing in the range from open state to close one. This allows keeping the defined parameters with high precision. This valve type production is made on the high precision costly equipment. As a result the price is high and it increases with the increase of valve passage diameter. Temperature controllers are one of the important parts of heat substations of District Heating (DH) and hot water supply. (Figure below).

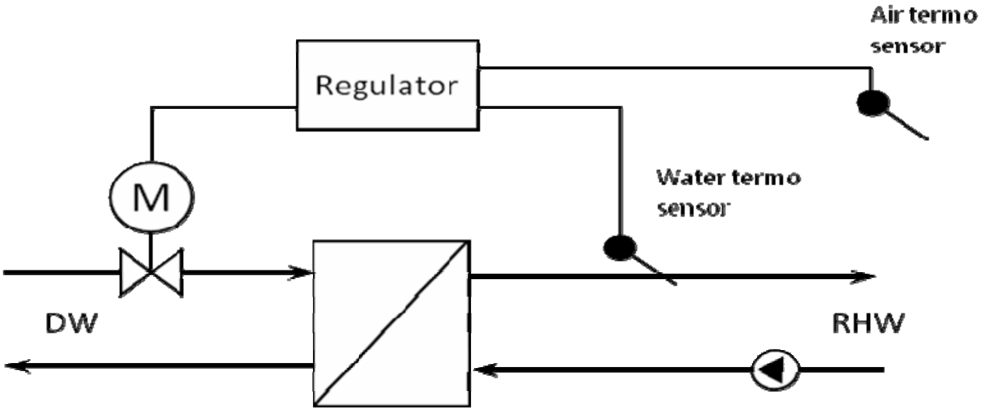

Figure 1a. District heating scheme

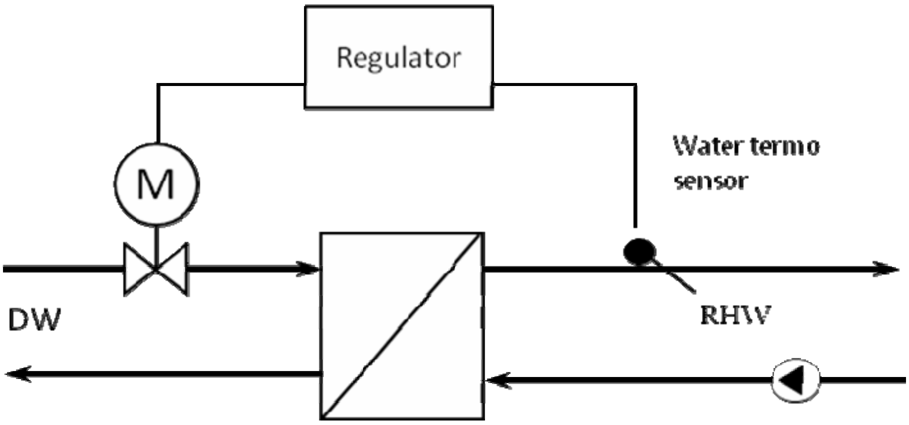

Figure 1b. Hot water supply scheme

One of significant factors for heat substations optimal work is the correct selection of control valve from view point of hydraulic.

The butterfly valve is one of the most common and its chief advantage is high capacity in a small package and very low cost comparing to saddle valves (see e.g.[1]).

As may be seen from the table 1, the flow rate of butterfly valve is much greater in comparison with saddle valve's one.

There is a considerable drawback in such type of valve when used for automatic flow control, resulting from its design. The dynamic flow characteristic nonlinearity of such valve directly influences the controlling quality. In this work the technique to improve flow control quality of butterfly valve with the use of parametric model predictive control and microcontroller device and microchip as valve positioner was developed and implemented on pilot unit in industrial application.

- **Optimal Operation and Control of CHP systems. Here the partners involved are ESTIA, INEA and IJS.**

CHP case study 1. The cogeneration case study at the Domžale-Kamnik waste-water treatment plant (DKWWTP) is one of several case studies performed in the CONNECT project. Control of a biogas-fueled engine operation that drives a generator producing electric energy and also provides heating water for the needs of the WWTP operation is investigated. Specifically, feasibility of advanced control algorithms based on multi-parametric model predictive control (mp-MPC) for control of the primary hot water circle temperature was investigated. This document contains a process description and measurement reports.

CHP case study 2. Distributed low and medium scale power generators, electricity storages, and load management options, can play a crucial role in supporting the European Union's key policy objectives of combating climate change by increased energy saving. The environmental benefits, reduced fossil fuel consumption, fuel diversification and energy autonomy, and increased energy efficiency (less line losses, cogeneration options). The effort focuses on cogeneration of heat and power at the micro level (μCHP) applied to the hotel sector.

We consider the case in which a small hotel has the capability of generating its own power with a μCHP unit. It can store heat and can trade electricity with an external energy supplier in a decentralized way. In the following paragraphs we discuss the application of model predictive control on the particular application, formulated as a scheduling problem. The controller implemented has the task to automatically determine which actions should be taken in order to minimize the operational costs of fulfilling hotel electricity and heat requirements subject to operational constraints. The controller uses a model predictive control (MPC) strategy such that it can:

- take into account the decision freedom due to heat storage possibilities;
- incorporate predictions on electricity and heat demands;
- incorporate models of the dynamics and constraints of installed generators and storages.

Scheduling is based on solving at each control step an optimization problem over a prediction horizon subject to system dynamics, an objective function, and constraints on states, actions, and outputs, see figure below. At each control step the optimization yields a sequence of actions optimizing expected system behaviour over the horizon. Actions (control inputs) are implemented by the system until the next control step, after which the procedure is repeated with new system measurements. MPC is successful mainly due to its explicit way of handling constraints, its possibility to operate without intervention for long periods, and its built-in robustness properties.

No deviations have been noticed from project workprogramme and all WPs have been running according to the original plan. Thus, it was not necessary to take any corrective actions.

List of Deliverables

Del. no.	Deliverable name	Work package no.	Date due	Actual/Forecast delivery date	Estimated indicative person-months (Total)	Used indicative person-months (over the entire period)	Lead contractor
1.1	Report on New fast MPC algorithms	WP1	30/09/2007	30/09/2007	34	19	NTNU
1.2	Report on Robust MPC algorithms for hybrid and continuous systems	WP2	30/09/2007	30/09/2007	20	17	IJS
1.3	Report on Non-linear MPC and receding horizon	WP3	30/09/2007	30/09/2007	19	8	NTNU
1.4	Report on Model reduction techniques	WP4	30/09/2007	30/09/2007	25	19	UoM
2	Report on Design specifications for software development activities. Compliance with industrial requirements	WP5	30/09/2007	30/09/2007	36	9,5	ParOS
3	Report on Definition and Data Collection for the industrial case studies. Preliminary Validation and testing	WP6	30/09/2007	30/09/2007	103	48	PSE
4	A complete set of tested algorithms	WP1	31/03/2008	31/03/2008	29	19	ParOS
5	A set of tested robust MPC techniques for hybrid and continuous systems	WP2	31/03/2008	31/03/2008	14	17	IJS
6	Tested algorithms for non-linear MPC and receding horizon estimation	WP3	31/03/2008	31/03/2008	10	8	NTNU
7	Tested model reduction techniques	WP4	31/03/2008	31/03/2008	19	19	UoM

8	Beta version of the software prototype for advanced process control. Application of fast MPC algorithms and model reduction techniques Chips and other hardware designs implementing the control software and MPC algorithms.	WP5	31/03/2008	31/03/2008	18	18	ParOS
9	Intermediate results of the selected industrial case studies.	WP6	31/03/2008	31/03/2008	30	10	PSE
10	Final version of the software prototype implementing new MPC algorithms for robust, hybrid and continuous systems and efficient model reduction techniques.	WP5	30/09/2008	30/09/2008	12	16	ParOS
11	Results on the selected industrial case studies:	WP6	30/09/2008	30/09/2008	43	62	PSE
12	FINAL REPORT. Assessment of the developed algorithms, software tools and hardware designs (e.g. chips and controllers). Final Report of the project	ALL	30/09/2008	30/09/2008	16	12	PSE
13	Plan for using and Disseminating Knowledge		30/09/2008	30/09/2008	16	2,5	ESTIA

List of Milestones

Milestone no.	Milestone name	Workpackage no.	Date due	Actual/Forecast delivery date	Lead contractor
1	A set of Fast MPC algorithms	1	31/03/2008	31/03/2008	NTNU
2	Testing and validation of the algorithms in benchmark problems	1	31/03/2008	31/03/2008	NTNU
3	New MPC algorithms for both hybrid and continuous systems	2	31/03/2008	31/03/2008	IJS
4	Testing and validation of the algorithms (hybrid and continuous systems) in benchmark problems	2	31/03/2008	31/03/2008	IJS
5	RHE techniques based on parametric programming	3	31/03/2008	31/03/2008	NTNU
6	New Model reduction techniques	4	31/03/2008	30/09/2008	UoM
7	Testing and validation of the model reduction algorithms in benchmark problems	4	31/03/2008	30/09/2008	UoM
8	Software development activities. Compliance with industrial requirements	5	30/09/2008	30/09/2008	ParOS
9	Final Results for the specific industrial case studies	6	30/09/2008	30/09/2008	PSE

2 Project Management

The project has been managed very smoothly and communication between the participants has been proven fruitful based on:

Scheduled project meeting. Several project meeting organised in the second year.

- The kick-off meeting took place in Thessaloniki Greece, in October 2006.
- The next meeting was held in Slovenia (co-hosted hosted by IJS and INEA) in 30 March 2007.
- Another meeting took place in Austria (hosted by PLASMAIT) in Juy 2007.
- The mid-term review meeting of the project was held in London (hosted by ParOS) in 22-23 October 2007.
- A meeting was held in Thessaloniki, Greece on 14 March 2008 (hosted by ESTIA).
- A meeting was held in Tronheim, Norway, on 27 June 2008 hosted by NTNU
- The final meeting was held in Manchester on 11-12 September 2008 hosted by UoM.

Other Frequent meetings between selected partners such as:

- ESTIA and KOTHALI had more than 4 meetings in year 1 regarding the activities of WP6
- ParOS, ESTIA and KOTHALI had in year 1 another meeting in Greece to collaborate in the industrial case study of KOTHALI.
- PSE and ParOS had a series of meetings in year 1 in London regarding the polymerisation case study.
- IJS, KOTHALI, ESTIA and ParOS have a one-day meeting in Slovenia just after the scheduled meeting organised there in March 2007.
- IJS and PLASMAIT have a series of meetings in year 1 regarding the industrial case study of PLASMAIT.
- SODRU had one meeting in year 1 with UoM in Manchester regarding the industrial case study of the former.
- ESTIA and KOTHALI had more than 3 meetings in year 2 regarding the activities of WP6
- ParOS, ESTIA and KOTHALI had two meetings (November 2007 and February 2008) in Greece regarding the industrial process of KOTHALI.
- PSE and ParOS had a series of meetings in London regarding the polymerisation case study.
- IJS, and ParOS have a one-day meeting in London for software development activities.

- IJS and PLASMAIT had a series of meetings regarding the industrial case study of PLASMAIT.
- NTNU had meeting with ParOS and PSE in London (Nov. 2007) regarding the polymerisation case study.
- SODRU had one meeting with ParOS in London regarding the industrial case study of the former.

The CONNECT web page (http://www.cpi.umist.ac.uk/CONNECT/Home.asp) has been proven an efficient mechanism for exchanging information and promoting communication between the partners.

The minutes of all meeting are attached as separate Annexes. It is important to mention that all partners participated actively in the meeting with at least one representative.

The progress of the project has been closely monitored by the submission of internal reports (every 4 months) to the coordinator. In all cases good progress has been made with only minor deviations from the original workplan.

During the kick-off meeting 3 committees were set up. It was decided that the following persons will represent the participants to the various Committees.

Project Steering Committee:

PSE: Dr. Michael Georgiadis
ESTIA: Mr. Dimitris Konstantinidis
PLASMAIT: Dr. Primoz Eiselt
PAROS: Dr. Nikos Bozinis
INEA: Mr. Igor Steiner
SODRU: Dr. Petro Kapustenko
NTNU: Prof. Morten Hovd
UoM: Dr. Jiri Klemes
IJS: Samo Gerksic
KOTHALI: Mr. George Koutsoupas

SME Committee:

PSE: Dr. Michael Georgiadis
ESTIA: Mr. Dimitris Konstantinidis
PLASMAIT: Dr. Primoz Eiselt
PAROS: Dr. Nikos Bozinis
SODRU: Dr.. Petro Kapustenko

RTD Committee

NTNU: Prof. Morten Hovd
UoM: Dr. Kostas Theodoropoulos
IJS: Samo Gerksic

Mr. Dimitris Constantinidis was appointed as the exploitation manager of the project on behalf of ESTIA.

A Workpackage Leader has been nominated for the coordination of each Workpackage (as described in the previous Figure). He is responsible for the detailed coordination, planning, monitoring and reporting of the workpackage and for the smooth coordination of the task with the other workpackages in the project. Technical management activities such as planning of technical work and deliverables, detailed monitoring of technical progress, consolidation of technical progress reports, preparation and review of technical publications, etc. has been carried out by Dr. Georgiadis and his team of management assistants.

The project timetable and status follows the original plan as depicted in the next page barchart.

	Work Planning																							
WP description	Year 1												Year 2											
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
WP1: New fast MPC algorithms	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨									
WP2: Robust MPC for hybrid and continuous systems					▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨						
WP3: Non-linear MPC and receding horizon estimation					▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨						
WP4: Model reduction technologies for MPC Applications			▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨									
WP5: Software development and hardware (controller) designs							▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨		
WP6: Application in realistic industrial case studies							▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
WP7: Project Management	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
WP8: Dissemination and Exploitation Activities	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨

4. Other Issues

The work performed so far by the RTD performers has been proven particularly useful to the industrial needs of the participating SME and other end-users More specifically:

- The algorithmic development of NTNU (RTD) in relation to WP1 “New fast MPC algorithms” have been implemented in ParOS (SME) control tools in a view of improving their performance. Both NTNU and ParOS already planned a close collaboration towards this direction in the years to come.

- Some of the algorithmic developed by NTNU(RTD) have been implemented in the polymerization case study provided by PSE (PSE). To this end, both partners will work closely in the next few years.

- The new model reduction technologies (WP4) developed mainly by UoM (RTD) have been implemented in the KOTHALI industrial case study (control of tiles and bricks manufacturing) in close collaboration with ESTIA and ParOS. A well designed plan has been decided during the last mid-term review meeting for the achievement of this objective.

- The new model reduction technologies (WP4) developed mainly by UoM (RTD) has been applied in the ParOS (SME) control tools in order to derive accurate reduce order models suitable for fast control applications. Both UoM and ParOS have already started working on this.

- The control technology developed by IJS (RTD) has already found excellent applications in the industrial case study of PLASMAIT (SME) concerning the Pressure control of a Plasma-based reactor for in-line wire manufacturing. Results already presented in the corresponding technical deliverable and the collaboration is expected to continue in the second year of the project.

- The new model reduction technologies (WP4) developed mainly by UoM (RTD) will be also applied in SODRU’s (SME) case study concerning the control of heat exchangers. The idea is to derive accurate reduce order models suitable for on-line control applications of heat exchange systems. Both UoM and ParOS have already started working on this.

- The control and modelling technology developed by IJS (RTD) has been implemented in the Combined-heat and power case study provided by INEA. A close collaboration towards this directions has already been planned for the next few years