FRONT PAGE

PROJECT PERIODIC REPORT

Grant Agreement number: 223854

Project acronym: HD-MPC

Project title: Hierarchical and Distributed Model Predictive Control of Large-Scale Systems

Funding Scheme: STREP

Date of latest version of Annex I against which the assessment will be made: 08/06/11 (approved by commission on 01/07/11)

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

Period covered: from 01/09/10 to 31/12/11

Name, title and organisation of the scientific representative of the project's coordinator[1]: Bart De Schutter, Full Professor, Delft University of Technology

Tel: +31-15-2785113

Fax: +31-16-2786679

E-mail: b.deschutter@tudelft.nl

Project web site[2] address: http://www.ict-hd-mpc.eu

[1] Usually the contact person of the coordinator as specified in Art. 8.1. of the grant agreement

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

Declaration by the scientific representative of the project coordinator[1]

I, as scientific representative of the coordinator[1] of this project and in line with the obligations as stated in Article II.2.3 of the Grant Agreement declare that:

- The attached periodic report represents an accurate description of the work carried out in this project for this reporting period;
- The project (tick as appropriate):
  - ☑ has fully achieved its objectives and technical goals for the period;
  - ☐ has achieved most of its objectives and technical goals for the period with relatively minor deviations[3];
  - ☐ has failed to achieve critical objectives and/or is not at all on schedule[4].
- The public website is up to date, if applicable.
- To my best knowledge, the financial statements which are being submitted as part of this report are in line with the actual work carried out and are consistent with the report on the resources used for the project (section 6) and if applicable with the certificate on financial statement.
- All beneficiaries, in particular non-profit public bodies, secondary and higher education establishments, research organisations and SMEs, have declared to have verified their legal status. Any changes have been reported under section 5 (Project Management) in accordance with Article II.3.f of the Grant Agreement.

Name of scientific representative of the Coordinator[1]: Bart De Schutter

Date: 29 / 12 / 2011

Signature of scientific representative of the Coordinator[1]: Bart De Schutter

[3] If either of these boxes is ticked, the report should reflect these and any remedial actions taken.

[4] If either of these boxes is ticked, the report should reflect these and any remedial actions taken.

1. Publishable summary

Project at a Glance: HD-MPC

Hierarchical and distributed model predictive control of large-scale systems

Objective:
HD-MPC focuses on the development of new and efficient methods for distributed and hierarchical model-based predictive control of large-scale complex networked systems.

Partners:
Delft University of Technology (*The Netherlands),* Electricité de France SA (*France*), Katholieke Universiteit Leuven (*Belgium*), Politecnico di Milano (*Italy*), Rheinisch-Westfälische Technische Hochschule Aachen (*Germany*), Universidad de Sevilla (*Spain*), Universidad Nacional de Colombia (*Colombia*), Ecole Supérieure d'Electricité (*France*), Inocsa Ingeniería S.L. (*Spain*)

Cooperation partner: University of Wisconsin-Madison (*USA*)

Project web site: http://www.ict-hd-mpc.eu

Project coordinator: Bart De Schutter (*Delft University of Technology*)
Duration: 40 months
Start: September 1, 2008
Total Cost: € 2768861
EC Contribution: € 2000000
Contract Number: INFSO-ICT-223854

Summary: HD-MPC

HD-MPC: Hierarchical and Distributed Model Predictive Control of Large-Scale Systems

Abstract: In this project we develop new and efficient methods for distributed and hierarchical control of large-scale, complex, networked systems with many embedded sensors and actuators, and characterized by complex dynamics and mutual influences.

Keywords: control of complex large-scale systems, hierarchical and distributed control, networked and embedded systems, model-based control

Main Objectives

Manufacturing systems, traffic networks, process plants, electricity networks are often composed of multiple subsystems, characterized by complex dynamics and mutual influences such that local control decisions may have long-range effects throughout the system. This results in a huge number of problems that must be tackled for the design of an overall control system. Improper control and insufficient coordination of these large-scale systems could result in a hugely suboptimal performance or in serious malfunctions or disasters. Current centralized control design methods cannot deal with large-scale systems due to the tremendous computational complexity of the centralized control task and due to scalability issues and communication bandwidth limitations, all of which make on-line, real-time centralized control infeasible.

The main objective of this project is therefore to develop new and efficient methods and algorithms for distributed and hierarchical model-based predictive control of large-scale, complex, networked systems with embedded controllers, and to validate them in several significant applications. We design these methods to be much more robust than existing methods in the presence of large disturbances, and component, subsystem, or network failures, with a performance approaching that of a fully centralized methodology. The resulting control methods can be applied in a wide range of application fields such as power generation and transmission networks, chemical process plants, manufacturing systems, road networks, railway networks, flood and water management systems, and large-scale logistic systems.

Technical Approach

The new structured and tractable control design methods for large-scale systems we develop are based on a hierarchical, distributed model-based control approach in which a multi-level model of the system is used to determine optimal control signals, and in which the controllers operate along several time scales and at different control levels (see figure below). We develop both the necessary new theory and the corresponding control design methods for using a combination and integration of techniques from computer science, operations research, optimization, and control engineering. This will result in systematic approaches that outperform existing control strategies, which are often case-dependent and based on heuristics and simplifications.

In order to adapt to dynamic changes in the demands, the structure of the system, and the environment, adaptive on-line control is required. Therefore, we use a model-based approach, which allows the controller to predict the effects of future control actions on the system, and to take external inputs and demands into account.

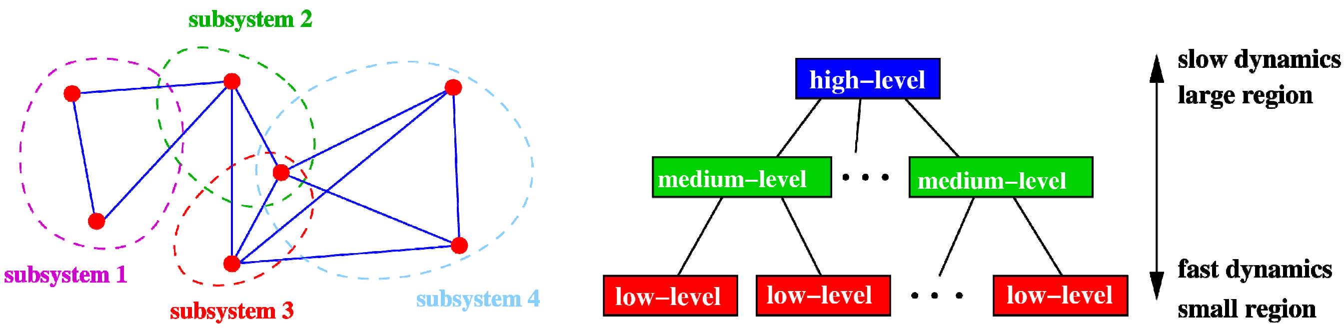


Figure: Illustration of the spatially distributed (left) and hierarchical control (right).

We also take various aspects of large-scale complex systems into account that are often not considered in current control methods such as their hybrid nature, the variety of – often conflicting – objectives and constraints that play a role, and the interactions between the different time scales of

the system dynamics and the control actions. This implies that we need a multi-level, multi-objective, distributed control approach.
Other important aspects of our approach are communication of information between subsystems, and cooperation between their controllers towards a common goal.

Key Issues
The key challenges that have to be addressed are:

- developing new, efficient, robust, and scalable methods for on-line, real-time hierarchical and distributed control of large-scale systems,
- appropriately dealing with the computational complexity issues, various types of uncertainty, and coordination and cooperation between the controllers both within and across the control levels,
- integrating the methods within currently deployed embedded sensor and controller structures, so as to allow practical implementation and smooth adoption of the new methods by industry.

In order to address these challenges and to achieve the objectives the research team gathers fundamental and technical core expertise in various fields such as systems and control, chemical engineering, mechanical engineering, electrical engineering, optimization, operations research, and computer science.

Main Results
The HD-MPC project has focused on *distributed control*, *hierarchical control*, and *distributed estimation*.

New *distributed control methods* have been rigorously developed and successfully tested at the industrial benchmark problems as well as in a number of real world and simulation examples. They guarantee strong theoretical convergence properties and are based on two complementary principles:

- distribution of the optimization task among multiple subsystems to allow for an efficient decomposition of large-scale optimal control problems; these algorithms have been developed according to sensitivity-based coordination and distributed multiple shooting approaches;
- design of a set of local controllers requiring only limited inter-communication and relying on the predicted future evolution of the neighbors; the underlying approaches are based on game-theoretical formulations and robust control results.

Hierarchical control has been considered to deal with typical industrial control situations where multi-level structures are used with different goals (local low-level control of actuators, control of the process units, overall plant optimization). Within the framework of hierarchical control, a number of structures and design algorithms with strong theoretical basis have been developed and applied to road traffic networks and baggage handling systems. The possibility to resort to flexible control structures, where actuators can be added, removed or replaced has also been investigated and significant results have been achieved.

New *distributed state estimation* methods based on the moving horizon approach and with guaranteed convergence properties have also been developed. They can incorporate constraints on the values of the variables to be estimated. These algorithms deal with the following problems:

- estimation of the whole state of the system made by a number of sensors that can communicate with their neighbors in order to reach a global consensus on their state estimate. This problem arises in large sensor networks where communications among the sensors are limited by energy constraints;
- design of a set of local estimators, each one in charge of estimating the state of a subsystem and communicating it to its neighbors. This is the case of large plants where the state of each

process unit can be locally estimated also based on the estimated states of the units connected to it.

In addition to performing fundamental research on hierarchical and distributed control of large-scale systems the HD-MPC project concentrated on three applications that were formulated by the industrial partners in the consortium: combined cycle power plants, hydro-power valley operations, and water capture systems. Moreover, the HD-MPC methods have also been applied to freeway and urban traffic networks, surface water networks, and baggage handling systems.



Impact and Benefits

The HD-MPC project has considerably widened the domain, in terms of system size, of large-scale control problems that can be addressed with Model Predictive Control (MPC) techniques by developing new methods and algorithms for distributed estimation, optimization, and control. All methods have been rigorously and successfully tested at the industrial benchmark problems.

Due to the use of massive parallel computation and newly developed advanced optimization and coordination approaches the new MPC methods for large-scale networked systems developed in this project will ultimately result in efficient and scalable control methods that – at a fraction of today's effort – can deal with systems that are one or more orders of magnitude larger than what current methods can handle. The new methods will also result in much higher dependability and availability, and significantly reduce maintenance times and costs.

The HD-MPC project has resulted in a special issue of the Journal of Process Control on HD-MPC (vol. 21, no. 5, June 2011), as well as more than 35 international journal papers, 7 contributions to books, and about 100 international conference papers. In addition, two dedicated HD-MPC workshops have been organized in Leuven, Belgium (June 2011) and in Milano, Italy (August 2011). More details on these activities can be found at the project's web site: http://www.ict-hd-mpc.eu

Organization of the Project

In order to carry out the research objectives detailed above, the following work packages have been established:

WP1: Management and coordination
WP2: Definition of the hierarchical architecture for control design
WP3: Development of hierarchical and distributed MPC methods
WP4: Optimization methods for hierarchical and distributed MPC
WP5: Distributed state estimation algorithms
WP6: Hardware and software implementation, and benchmarking
WP7: Validation and applications on simulated plants
WP8: Dissemination

Highlights for Period 3 (01/09/2010-31/12/2011)
In the third year (and 4 months) of the project we have accomplished the following results:

- A special issue of the Journal of Process Control on HD-MPC has been published (vol. 21, no. 5, 2011). The joint paper on the four-tank benchmark was on the 4th place in the list of the most downloaded papers of the journal in the period April-June 2011.
- We have organized two successful HD-MPC workshops, viz. the HD-MPC Industrial Workshop in Leuven, Belgium in June 2011 and the final HD-MPC Workshop in Milano, Italy in August 2011.
- Several approaches have been considered for the development of hierarchical and distributed model predictive control methods. On the one hand, a sensitivity-based coordination algorithm has been considered for the decomposition of large-scale optimal control problems. On the other hand, robust MPC techniques have been extended for the use in hierarchical and distributed MPC topologies. In particular, the newly developed "Distributed Predictive Control" method, can guarantee stable operation of large-scale plants, although it is a non-cooperative approach for the distributed control problem.
- Novel optimization methods were developed for linear as well as nonlinear MPC schemes. First, a distributed version of Han's parallel algorithm for a class of convex programs was investigated. A cooperative distributed linear MPC strategy was introduced based on local communication attaining plant-wide stability. For nonlinear deterministic distributed systems a variant of multiple shooting was thoroughly investigated, having attractive convergence properties and a high level of parallelization. In the context of uncertain large-scale systems, a multi-objective MPC approach was developed for the dial-a-ride problem. Finally, robust distributed MPC was considered for load scheduling of large-scale irrigation channels.
- Distributed state estimation algorithms with convergence properties have been developed for linear and nonlinear systems. An algorithm has been developed for the adaptive tuning of the noise covariance matrices used by the distributed state estimators.
- For the three industrial case studies, viz., the combined cycle start-up, the hydro-power valley, and the water capture system we have developed approaches for hierarchical and distributed MPC. The approaches have been implemented and assessed using simulation-based case studies.
- In the context of the demonstration of HD-MPC results, five HD-MPC approaches have been applied to the public hydropower valley benchmark. Economic indices have been defined to compare the different approaches. The best results are obtained with the distributed multiple shooting approach, with a nearly perfect tracking and a negligible economic cost. Good results are obtained also with the fast gradient-based distributed MPC approach and with the hierarchical infinite horizon MPC approach.
- Two special sessions on hierarchical and distributed model predictive control have been organized for the IFAC World Congress 2011 in Milano, Italy.

In addition, three joint progress meetings were held in Delft, Chatou, and Leuven, and the cooperation between work packages and partners was further intensified by more dedicated technical meetings, mutual visits, and exchanges of researchers.

Since this report is a cumulative report we also briefly recall the highlights of the preceding periods:

Highlights for Period 2 (01/09/2009-31/08/2010)
In the second year of the project we have accomplished the following results:

- A hierarchical control structure with reconfiguration capabilities has been proposed to emphasize the performance of predictive controllers in response to changes in the subsystems.

Multi-level models have been used to derive hierarchical control systems for cases where a global approach is not suitable due to the complexity of the underlying optimization problem, such as Intelligent Vehicle Highway Systems and baggage handling systems.

- We have proposed a new control design method using a two-layer hierarchical structure, where the high layer corresponds to a system characterized by slower dynamics, whose control inputs are provided by subsystems with faster dynamics and placed at the low layer. A convergence result for the overall system has been obtained by resorting to a robust MPC approach.
- We have developed two new methods for nonlinear optimal control of large-scale systems. The GDBBD algorithm allows separate subsystems to optimize independently. This algorithm is shown to be able to converge to the true nonlinear minimum despite distributed computations. The distributed Multiple Shooting approach allows to decouple multiple subsystems, while only a large-scale quadratic program needs to be solved in a coordinated way. These algorithms have been applied to the hydro-power valley case study, resulting in considerable speed-ups in computing the exact solution, compared to a centralized algorithm.
- A nonlinear distributed moving horizon estimation algorithm with convergence properties has been developed for nonlinear systems characterized assuming that any sensor of the network measures some variables, computes a local estimate of the overall system state, and transmits to its neighbors both the measured values and the computed state estimation. Moreover, three partition-based moving horizon estimation algorithms have been proposed for linear and nonlinear systems that can partitioned into interconnected but non-overlapping subsystems.
- Different distributed algorithms have been tested on the defined benchmark cases resulting in a paper for the Journal of Process Control with a comparative study of different distributed controllers developed by HD-MPC partners applied to the four-tank system. Moreover, two new benchmark cases related to the WP7 applications (viz. the hydro-power valley and irrigation channels) have been prepared.
- For the three industrial case studies, viz., the combined cycle start-up, the hydro-power valley, and the water capture system we have developed prediction models required for the application of hierarchical and distributed control. The models have been implemented using various software tools, and the integration of the modeling software with the control software has been addressed.
- A special session on hierarchical and distributed model prediction control has been organized for the 2010 American Control Conference (ACC'10).

In addition, three joint progress meetings were held in Rennes, Aachen, and Seville.

Highlights for Period 1 (01/09/2008-31/08/2009)

In the first year of the project we have accomplished the following results:

- We have compiled a definition and classification of the problems where a distributed or hierarchical control structure is useful. This has resulted in a general formulation of hierarchical MPC.
- We have developed a nonlinear distributed dynamic optimization method for MPC with promising convergence properties. This method has also been successfully applied to a nonlinear process model.
- Several optimization algorithms for linear and nonlinear distributed MPC have been proposed.
- Four benchmark cases have been prepared (including a complete description, models, and related papers): four-tank system, chemical plant, electric network, and heat system.
- For the three industrial case studies, viz., the combined cycle start-up, the hydro-power valley, and the water capture system we have defined the control specification required for the application of hierarchical and distributed control.

- A special session on hierarchical and distributed model prediction control has been organized for the 14th Belgian-French-German Conference on Optimization (BFG'09).

In addition, two joint progress meetings were held in Leuven and Milan.

2. Project objectives for the period

According to the updated Description of Work of 08/06/11 the following tasks indicated in bold[5] should have been carried out during the reporting period, i.e. M25-40 (M indicates the month counted from the start of the project):

- WP1: Management and coordination
  - **Task 1.1: Management (M1-40)**
  - **Task 1.2: Monitoring and reporting (M1-40)**
  - **Task 1.3: Knowledge management (M1-40)**
  - Task 1.4: Design and implementation of a Virtual Portal (VP) (M1-6)
- WP2: Definition of the hierarchical architecture for control design
  - Task 2.1: Survey (M1-3)
  - Task 2.2: Definition of the control architecture (M4-9)
  - Task 2.3: Extension of the control architecture (M10-15)
  - Task 2.4: Multi-level models (M4-15)
- WP3: Development of hierarchical and distributed MPC methods
  - **Task 3.1: Hierarchical and distributed nonlinear MPC (M4-36)**
  - **Task 3.2: Hierarchical and distributed robust nonlinear MPC (M7-36)**
  - **Task 3.3: Coordination mechanisms (M7-30)**
  - **Task 3.4: Timing and delay issues (M13-27)**
- WP4: Optimization methods for hierarchical and distributed MPC
  - **Task 4.1: On-line optimization methods for hierarchical and distributed MPC (M1-36)**
  - **Task 4.2: Optimization of uncertain large-scale systems (M1-27)**
  - **Task 4.3: Optimization methods for robust distributed MPC (M4-33)**
- WP5: Distributed state estimation algorithms
  - **Task 5.1: State estimation (M16-33)**
  - **Task 5.2: Variance estimation (M19-36)**
- WP6: Hardware and software implementation, and benchmarking
  - Task 6.1: Analysis of hardware and software (M4-24)
  - Task 6.2: Development and implementation of a benchmark model guide (M4-6)
  - Task 6.3: Preparation of benchmarking cases (M7-9)
  - Task 6.4: Implementation of benchmark exercises (M9-18)
  - **Task 6.5: Maintenance of the benchmarking service (M19-36)**
  - **Task 6.6: Dissemination of benchmarking and results (M10-36)**
- WP7: Validation and applications on simulated plants
  - **Task 7.1: Application to the start-up of a combined cycle plant (M4-36)**
  - **Task 7.2: Application to the operation of a hydro power valley (M4-40)**
  - **Task 7.3: Short-term and long-term control of a large-scale water capture system (M4-36)**

[5] For completeness we list all tasks for the entire project period, as in the subsequent sections we will also briefly recapitulate the results obtained in the first and the second year of the project.

- WP8: Dissemination
  - Task 8.1: Setting up a website (M4-6)
  - **Task 8.2: Organizing special sessions at conferences or special issues of journals (M10-15, M25-30)**
  - **Task 8.3: HD-MPC workshop (M31-33)**
  - **Task 8.4: Industrial short courses (M19-24, M28-33)**

The tasks listed above can be detailed as follows according to the updated Description of Work of 08/06/11 (pp. 28-56):

WP1: Management and coordination

- *Task 1.1: Management (M1-40):*
  This includes the establishment of a steering committee (with one member per participant), the organization of the kick-off meeting, the annual project meetings, and the regular work package meetings (at least twice a year).
- *Task 1.2: Monitoring and reporting (M1-40):*
  This includes regular monitoring of the progress within the work packages, managing the annual report, etc.
- *Task 1.3: Knowledge management (M1-40):*
  This includes putting information on the project's (intranet) web site (see also Task 1.4) with a list of available equipment, software, and set-ups, so as to facilitate integration of resources, establishing links with potential users of results developed in project and other interested parties, solving IPR issues, etc.
- *Task 1.4: Design and implementation of a Virtual Portal (VP) (M1-6):*
  The VP has to permit the communication among partners and the integration of remote experiences in a unique virtual space. This task will state the requirements of this environment and will design and implement the software infrastructure to support it. The development will be based on open source tools.

WP2: Definition of the hierarchical architecture for control design

- *Task 2.1: Survey (M1-3):*
  We will start with a survey of the state-of-the-art with focus on hierarchical and distributed control architectures that could be used for MPC. We will perform a qualitative assessment of strong and weak points of existing architectures, and identify options for improvement.
- *Task 2.2: Definition of the control architecture (M4-9):*
  This includes the definition of a hierarchical control architecture that integrates sequential decisions in the global MPC scheme, and the definition of a hierarchical control architecture that integrates at each level various optimization criteria (quadratic, linear, etc.) and control schemes (MPC, classical PID, etc.)
- *Task 2.3: Extension of the control architecture (M10-15):*
  We will adapt the architecture and control schemes to improve the availability in response to changes in the subsystems. Moreover, we will adapt global control to take in account the availability of distributed controllers and of the communication network as well as other network constraints for distributed subsystems that could arise in practical applications.
- *Task 2.4: Multi-level models (M4-15):*
  In this task we will explore ways to define and to construct models that are consistent with the hierarchical level of each controller. This includes multi-level, multi-resolution models, i.e., models with various levels of spatial and temporal aggregation. We will also investigate and assess existing reduction and aggregation methods to obtain such models, and select those that are most suited for hierarchical and distributed MPC.

WP3: Development of hierarchical and distributed MPC methods

- *Task 3.1: Hierarchical and distributed nonlinear MPC (M4-36):*
  This task has the following subtasks:
  - Task 3.1.1: Literature review: In order to assess the strong and weak points of existing methods and to identify the most suitable methods that can serve as a starting point for the hierarchical and distributed nonlinear MPC we first review relevant literature from the 60s and 70s. Main ideas and concepts are summarized. Recent literature will be reviewed as well. Existing approaches are analyzed, evaluated, and compared. This comparison will reveal the relationship between the approaches. A common framework will be established comprising all concepts. Based on this, a focus is put on nonlinear approaches.
  - Task 3.1.2: Method development: Based on the literature review, new ideas on extending concepts from linear distributed MPC to the nonlinear case are further developed based on the results of WP2. Step by step, complexity is increased starting from linear, stationary, and unconstrained problems up to nonlinear, dynamic, and constrained control problems. It is very likely that there is a balance between speed of convergence of the approaches and the amount of information that needs to be shared among the agents and/or the higher-level coordinators. Hence, variants of the methods are developed which differ in the amount of required information. This is also closely related to the coordination mechanisms that are examined and developed in Task 3.3. Appropriate methods are finalized that are tailored to the amount of possible sharing in real-life processes
  - Task 3.1.3: Implementation: The proposed methods as well as selected approaches from literature are implemented in a suitable programming environment as, e.g., Matlab or Octave, such that the methods can easily be shared among the partners.
  - Task 3.1.4: Evaluation: All developed approaches are evaluated using case studies of varying complexity. Benefits and drawbacks are highlighted. The expected impact and economical potential are evaluated and documented. Suggestions for application to real life processes are given (see also WP7: "Validation and applications on simulated plants").

- *Task 3.2: Hierarchical and distributed robust nonlinear MPC (M7-36):*
  This task has the following subtasks:
  - Task 3.2.1: Literature review: In order to assess the strong and weak points of existing methods and to identify the most suitable methods that can serve as a starting point for the development of our own methods, the literature for optimization methods of uncertain and disturbed systems in general with a focus on centralized robust MPC is reviewed. Recent articles on distributed robust and fault-tolerant MPC are also reviewed and compared.
  - Task 3.2.2: Method development: Interaction of single controlled subsystems has to be taken into account by hierarchical and distributed robust MPC schemes, additionally to model uncertainties and external disturbances, which are also common to centralized robust MPC approaches. The influence of control actions and state trajectories of one subsystem on other subsystems are treated as additional disturbances. Methods for hierarchical and distributed robust MPC are developed starting from our own robust optimization approaches. Initially, investigations focus on strategies for distributed robust steady-state optimization. Complexity is gradually increased, ultimately resulting in a method to solve hierarchical and distributed robust and fault-tolerant nonlinear dynamic problems. These robust approaches have to guarantee that process constraints are not violated despite uncertainties, disturbances and interactions between subsystems. Generally, more conservative results are obtained for larger uncertainties. Therefore, the developed methods also allow to quantify the economic impact of robustness and to assess the potential gain of increased information sharing.

- Task 3.2.3: Implementation and applications: The developed robust optimization methods are implemented in a suitable programming environment such as Matlab or Octave to enable easy sharing of methods and code among the partners (this task is closely related to Task 4.3 of work package WP4: "Optimization methods for hierarchical and distributed MPC").
- Task 3.2.4: Evaluation: All developed approaches are evaluated using case studies of increasing complexity, and benefits and drawbacks are highlighted. The impact on the economics and on safe operability of distributed processes is evaluated.

Note that Task 3.2 is closely related to Task 4.3: "Optimization methods for robust distributed MPC". Both tasks will interact and cooperate, where Task 3.2 mainly focuses on problem formulation and method development for robust distributed MPC and where Task 4.3 deals with the development (stochastic) optimization algorithms for robust distributed MPC.

- *Task 3.3: Coordination mechanisms (M7-30):*

  Two features required for achieving high performance in hierarchical and distributed control systems are communication between and cooperation among the subsystems. Using MPC for the low-level or local subsystem controllers provides rich capabilities for both communication and cooperation. MPC allows communication not only of the current control moves, but also the full horizon of planned control moves. The availability of each subsystem's future plans enables a high degree of coordination between the many interconnected systems. A goal of this research is to design the communication protocols between these subsystems.

  For strongly interacting subsystems, it is generally insufficient to achieve only closed-loop stability by damping the behavior of strongly interacting subsystems. However, the performance loss is large in these cases. By instead changing the objective functions to achieve cooperation and coordination, closed-loop performance near that of centralized control is achievable while maintaining the modularity of separate subsystems. A specific goal of this task is to design the protocols to modify the local agents' objective functions to ensure cooperation and coordination between strongly interacting subsystems. Naturally a further consideration in this design is to achieve these goals while minimizing the overhead in communication and cooperation imposed on the subsystems. All this is closely related to Task 3.1, in which methods for hierarchical and distributed MPC are developed. The strong interaction between the participants of both tasks will yield high mutual benefits and integrated solutions.

- *Task 3.4: Timing and delay issues (M13-27):*

  The main objectives are to reduce the performance degradation due to delays and timing issues, and to provide tools for control design for integrated networks. Large-scale systems, and especially distributed and flow involved systems (such as water networks) present delays in the measured and action signals. These delays strongly affect the control performance. Approaches to take into account the delays as well as asynchronous timing should be developed.

WP4: Optimization methods for hierarchical and distributed MPC

- *Task 4.1: On-line optimization methods for hierarchical and distributed MPC (M1-36):*

  The first goal of this task is to provide all partners with a collection of existing state-of the-art MPC optimization algorithms, and to apply these algorithms to the hierarchical and distributed MPC and estimation formulations developed in the other work packages. Second, in addition to the stability questions of distributed MPC formulations that is investigated in other work packages, the suboptimality of existing distributed MPC formulations will be assessed and new distributed optimization methods shall be developed that provably converge to the optimal solution of the centralized optimization problem. For these newly developed algorithms we will also provide an analysis of the convergence speed towards the centrally optimal solution. Finally, efficient optimization algorithms and hot-starting techniques will be developed that exploit the specific structures of the distributed MPC formulations for fast real-time optimization. The newly developed algorithms will be documented, shared with the partners and in a later phase made public as open-source software.

- *Task 4.2: Optimization of uncertain large-scale systems (M1-27):*
  Decision making under uncertainty, both on medium-term and long-term basis, requires a redefinition of the criteria and methodologies used in current static optimization methods. Criteria such as mini-max, risk avoidance, multi-goal and probabilistic issues play an important role. The uncertainty level in the process model parameters must also be taken into account. This task involves the following steps:
  - Problem analysis and choice of most appropriate approaches that can serve as the starting point for newly developed methods
  - Redefinition of optimality criteria
  - Generation of optimal solutions
  - Sensitivity analysis with respect to parameters
  - Analysis of scalability of solutions and computing cost.

  Task 4.2 will closely interact with Task 3.2: "Hierarchical and distributed robust nonlinear MPC", where Task 3.2 mainly focuses on problem formulation and method development for robust distributed MPC and where Task 4.3 deals with the development of (stochastic) optimization algorithms for robust distributed MPC.

- *Task 4.3: Optimization methods for robust distributed MPC (M4-33):*
  The design of hierarchical control systems presents several opportunities for the use of optimization techniques that are the focus of extensive current research. They also present several challenges.
  Simplified models of subsystems at the lower levels, or cooperating subsystems on the same level, will inevitably be inexact. Moreover, the measurements that are made in the process of evaluating functions will contain noise and possibly other, more systematic errors. The function and gradient evaluations that are occurring in the optimization/control process running on an individual subsystem will thus contain errors of different kinds. How can we ensure that the decisions produced by these optimization processes are robust in the presence of these errors? Can we quantify the suboptimality of the decisions, as a function of model and measurement error, and thus understand which of these errors has the biggest impact on the quality of the control decisions? How can we propagate the random error distributions (see also the discussion of variance estimation in WP5) through the model into the objective, and thus into the control decisions?
  The rapidly developing field of robust optimization (to which researchers in control have already contributed a great deal) may be able to contribute to resolving these issues. Cross-fertilization with formulation and solution techniques from stochastic optimization, along with recent applications to financial problems, has yielded results that should be investigated in the setting of control problems, including distributed control. Among topics that may be applicable are chance constraints (guaranteeing satisfaction of constraints to a specified level of probability) and value-at-risk objectives (in which the underlying objective is recognized as being a distribution, rather than a single objective, and we will optimize some function of the "tail" of this distribution, that is, its performance in the worst cases).

WP5: Distributed state estimation algorithms

- *Task 5.1: State estimation (M16-33):*
  Consider the discrete-time, possibly nonlinear system subject to random disturbances in the state evolution and measurement: $x(k+1) = F(x(k),u(k)) + Gw(k)$, $y(k) = H(x(k)) + v(k)$, in which w, v are zero-mean, normally distributed random variables. The state estimation problem can be compactly summarized as finding the maximum of the conditional probability $p(x(k)|y(0),$

$y(1),\dots,y(k)$), written as $p(x(k)|Y(k))$. This close link between state estimation and optimization allows us to formulate and solve many distributed state estimation problems in the same fashion that we formulate and solve distributed regulation and control problems in the other working packages. The two problems of regulation and state estimation are similar, but not identical, however, and we focus here on their differences and the special requirements for state estimation that are unnecessary for distributed regulation.

The first important difference is the disturbance model used in the state estimation problem. In order to remove steady offset in selected outputs (which may be states or functions of states), the system model above is augmented with integrating disturbance models. The augmented model then takes the form $x(k+1) = F(x(k),u(k),d(k))+Gw(k)$, $d(k+1) = d(k)+\xi(k)$, $y(k) = H(x(k),d(k))+v(k)$, and the state estimation problem is now to find the maximum of the state, disturbance pair conditioned on the measurements $p(x(k),d(k))|Y(k))$. So a significant design issue for the distributed system is to choose the number and location of the integrating disturbances. The goals of this disturbance design are (i) to remove offset in the outputs of interest, and (ii) to create a detectable system so each subsystem's measurements are adequate to estimate the subsystem's state and disturbance pair.

- *Task 5.2: Variance estimation (M19-36):*
  In order to design state estimators, we require the statistics of the random disturbances (w,v,ξ) in addition to the deterministic system models (F,G,H). Because of the central limit theorem, we almost universally represent the random disturbances as zero-mean, normally distributed random variables. So the problem reduces to estimating the variances (covariances) of the noises. In the distributed context, this problem becomes more challenging. In the distributed case, we restrict correlations to be nonzero only between driving noises and states and outputs in selected subsystems. One goal of this research therefore is to develop methods to estimate from data the noise variances restricted to obey the supplied structure of nonzero correlations. But a second goal is to develop modeling methods to provide the nonzero correlation structure itself for a large, interconnected system. There will be interaction between these two issues, and an iterative design procedure will be required. We may also require a monitoring system that can flag changes in plant operation in which the currently chosen correlation structure is no longer adequate to describe the actual $u(t)$, $y(t)$ behavior that is being observed.

WP6: Hardware and software implementation, and benchmarking

- *Task 6.1: Analysis of hardware and software (M4-24):*
  - Hardware: Distributed systems require a network of sensing devices as well as local actuators to enhance the effectivity of decisions.
  - Software: Analysis of operating systems, middleware incorporation with high-level communication capabilities, visualization components of the system state.
- *Task 6.2: Development and implementation of a benchmark model guide (M4-6):*
  This task consists of developing a model guide to help partners to develop benchmark exercises and will take the shape of a web-based computer tool.
- *Task 6.3: Preparation of benchmarking cases (M7-9):*
  A collection of real and simulated benchmark cases will be prepared using the tool developed in the previous subtask. For each test case, an exhaustive description of its main technological and operational data as well as of the main performance criteria will be provided. Also, best existing solutions and their performance values will also be included. The test cases will be provided by partners and they will consist of processes and research infrastructure, simulation models, and other tools already existing in the labs of the partners (see also WP7).

- *Task 6.4: Implementation of benchmark exercises (M9-18):*
  This task will start with the collection and selection of proposals and will go on with the implementation of the experiments. It also includes the preparation of test reports, the analysis of benchmark tests, and adoption of best practises.
- *Task 6.5: Maintenance of the benchmarking service (M19-36):*
  This is a key task because benchmarking is, above all, a practical and heuristic tool which is constantly evolving in the light of ever increasing experience. This task consists of maintaining alive the benchmark library by the introduction of new test results on existing experiments, deletion of obsolete test cases, introduction of new test cases, and modification of existing test cases.
- *Task 6.6: Dissemination of benchmarking and results (M10-36):*
  The main objective of this task is to disseminate the benchmark library and knowledge acquired from the benchmarking exercises inside and outside the project (see also Tasks 1.3 and 1.4 of work package WP1).

WP7: Validation and applications on simulated plants

- *Task 7.1: Application to the start-up of a combined cycle plant (M4-36):*
  Power plants are complex systems that are usually hierarchically controlled. The global control structure and the coordination between local controllers are in general determined using heuristics and experience, and the question remains open whether the chosen solution is optimal. The project proposes a new scientific approach to find a global optimal solution. In this task we will study the applicability of the control design methods for hierarchical and distributed MPC to power plant applications. First, we will build a model of a combined cycle plant. The plant model will be decomposed in several interconnected submodels. A distributed and hierarchical control system will also be simulated in order to implement the global distributed MPC scheme. In order to validate the applicability of the approach and its robustness, some loops of the lower level will be controlled by classical PID controllers. This task will consist of the following subtasks:
  - Subtask 7.1.1: Control specification,
  - Subtask 7.1.2: Modeling of the plant,
  - Subtask 7.1.3: HD-MPC design validation.
- *Task 7.2: Application to the operation of a hydro power valley (M4-40):*
  In this application the control will be hierarchical with several local controllers regulating a dam (water level and turbine power) and a global controller that coordinates the sum of the productions. We will build a model of a valley and will test the distributed MPC. This task will consist of the similar subtasks as for Task 7.1:
  - Subtask 7.2.1: Control specification,
  - Subtask 7.2.2: Modeling of the plant,
  - Subtask 7.2.3: HD-MPC design validation.

  In addition, there will also be a subtask on the demonstration of HD-MPC results[6]:
  - **Task 7.2.4: Demonstration of HD-MPC results**

  The work on this subtask is detailed as follows:
  The aim of the demonstration is to show the usefulness and potential benefits of one or more of the methods developed within the framework of the HD-MPC project for industry. To this aim we will test one or more of the HD-MPC methods on a given benchmark, compare them with the

[6] This is a task that was added in the updated Description of Work of 08/06/2011.

currently used control method(s), and assess advantages and disadvantages as well as performance gains.
Based on (earlier) discussions within the HD-MPC project regarding the suitability of the various WP7 applications for an in-depth assessment of HD-MPC methods as well as regarding confidentiality issues, the choice is made to use the public version of the WP7 hydro-power valley (HPV) benchmark[7] for this assessment and to take an approach that is similar to the joint four-tanks study published in the Special Issue on HD-MPC of *Journal of Process Control* (vol. 21, no. 5, June 2011, pp. 800–815).
The following overview lists some of the approach and design decisions that were made in order to complete the assessment within the given time frame and with the available resources:

- Each method will be tested and implemented using the platform that is best suited for the given method. The detailed public HPV benchmark model will be used as simulation model and it will be made available in C, and several interfaces (e.g., to Matlab, Simulink, and gproms) will be provided. We will use OPC for the transparent coupling of the control methods to the simulation model.
- Due to confidentiality of EDF economic data, publicly available knowledge will be used for the economic assessment. Therefore, to this aim we will use the spot prices that can be found at, e.g., http://www.nordpoolspot.com/reports/systemprice
- Due to confidentiality concerning the operations of the EDF installation, publicly available knowledge will be used to distill the real-life strategies that the operators could use. In addition, EDF can provide some information on target levels that should be held.

- *Task 7.3: Short-term and long-term control of a large-scale water capture system (M4-36):*
  This application involves a water capture system consisting of rivers, reservoirs and watering channels. The objective is to design short-term and long-term control systems for the water reception in the different sources: rivers, reservoirs, channels, etc., so that flows requested are guaranteed for the different types of users while also guaranteeing the ecological minimum flows. At the same time the control systems will keep in mind the meteorological forecasts with the objective to predict possible periods of rain/dryness that can affect the available storage notably. This task will consist of two subtasks:
  - Subtask 7.3.1: Modeling for hierarchical and distributed MPC,
  - Subtask 7.3.2: Predictive management of water resources.

WP8: Dissemination

- *Task 8.1: Setting up a web site (M4-6):*
  We will set up a dedicated web site for the project that will be used to disseminate the project results (including press releases, downloads of reports, presentations, videos, open-source software, and a database of benchmark problems). To reach a broad audience we will provide interfaces for the developed software with Matlab and/or Octave. The web site will also contain two restricted access entry points, one for the Commission, and one for the reviewers, so that they can also access deliverables and other documents that are not available to the general public.

- *Task 8.2: Organizing special sessions at conferences or special issues of journals (M10-15, M25-30):*
  We will organize invited sessions at leading international control conferences (IEEE CDC, IFAC, ECC, ACC, etc.), or a special issue or a special section of international control journals

[7] The HD-MPC public hydro-power valley benchmark can be downloaded from the HD-MPC web site at http://www.ict-hd-mpc.eu/index.php?page=benchmarks.

(Automatica, IEEE Transactions on Automatic Control, International Journal of Control, European Journal of Control, ...).

- *Task 8.3: HD-MPC workshop (M31-33):*
  At the end of the project we will organize a special project workshop which will be open to the general public. This workshop could be a satellite event of a leading international control conferences (IEEE CDC, IFAC, ECC, ACC, etc.) or a postgraduate summer school (e.g., within the framework of the Dutch Institute of Systems and Control (DISC)).
- *Task 8.4: Industrial short courses (M19-24, M28-33):*
  We will offer industrial short courses on the topics of the project to transfer the developed methods to industry. The goal of these industrial short courses is to present the state-of-the-art and the new methods for hierarchical and distributed control of large-scale networked systems to industry, consultancy and engineering firms, and other interested parties, to give them insight in the applicability of the methods in a broad range of fields (including, but not limited to, the benchmarks considered in WP6 and the case studies of WP7), and to give them a hands-on experience via case studies and assignments in which the tools developed in this project will also be used.

The following milestones should have been reached during the reporting period (see also Section 4):

- M1.1.5: Third annual meeting (M40)
- M3.1.3: Evaluation of the results completed (M36)
- M3.2.2: Methods developed for decentralized robust nonlinear dynamic MPC problems (M27)
- M3.2.3: Validation and evaluation of robust methods (M36)
- M3.3.2: Extensive assessment of the developed coordination mechanisms completed, including case studies (M30)
- M3.4.2: New methods for dealing with timing and delay issues in hierarchical and distributed MPC (M27)
- M4.1.2: Development of new methods with guaranteed convergence and high rate of convergence (with an emphasis on increased optimality, speed of convergence, efficiency, and on-line applicability) (M30)
- M4.3.1: New stochastic optimization methods for robust distributed MPC (M33)
- M5.2: Definition of new algorithms for distributed state estimation and of new methods for the choice of the number and location of integrating disturbances (M27)
- M5.3: New methods for distributed variance estimation (M33)
- M6.6.1: Results of benchmark proposals shared with partners and other interested parties (M36)
- M7.1.3/M7.2.3: Closed-loop validation results for the combined cycle start-up and for the hydro-power valley available, including stability and constraints issues, as well as the HD-MPC demonstration of results (40)
- M7.3.3: Methods and/or tools to optimize the distribution of water (M36)
- M8.2.2: Organization of special issue of an international journal (M27)
- M8.3.1: Organization of an HD-MPC international workshop and publication the workshop proceedings (M36)
- M8.3.2: Communication of the project results to the *scientific community* (M36)

The milestones reached in the first and the second year are not listed here explicitly, but they are included in the table in Section 4.

In addition, the following deliverables should have been produced during the reporting period (see also Section 4); these deliverables document how the milestones listed above have been realized and reached:

- D1.2.3: Third annual progress report/Final report (M40)
- D3.1.4-software: Software tool with different methods and variants for different problem classes (M33)
- D3.1.4: Reports on the evaluation results, including economical potential and suggestions for real-life applications (M36)
- D3.2.3: Reports and publications on the evaluation results, impact on the economics and operability of distributed processes (M36)
- D3.3.3: Report on extensive assessment of the developed coordination mechanisms, including case studies (M30)
- D4.1.3: Report on new algorithms with guaranteed convergence to an optimum of the global system, at a high rate of convergence, and with intelligent hot-starting (M30)
- D4.3.1: Report on new stochastic optimization methods for robust distributed MPC (M33)
- D5.2: Intermediate report on new methods for distributed state and covariance estimation for large-scale interconnected systems (M30)
- D5.3: Final report on new methods for distributed state and covariance estimation (M36)
- D6.5.1/D6.6.1: Final report on maintenance of benchmark service and dissemination results (M36)
- D7.1.3/D7.2.3: Report that presents the closed-loop validation results for the combined cycle start-up and for the hydro-power valley, including stability and constraints issues, as well as the HD-MPC demonstration of results (M38)
- D7.3.3: Report on optimization of distribution of water (M36)
- D8.2.2: (Report on) special issue of an international journal (M33)
- D8.3.1: Proceedings of the international HD-MPC workshop (M36)

The deliverables produced in the first and the second year are not listed here explicitly, but they are included in the table in Section 4.

3. Work progress and achievements during the period

WP1: Management and coordination

Please note that – as requested in the guidelines for producing this report – Tasks 1.1 (Management) and 1.2 (Monitoring and reporting) of this work package will be reported upon in Section 5.

Objectives

The goal of this WP is to coordinate, to monitor, and to supervise the progress of the project as a whole, and to coordinate the interactions between the work packages and participating groups. Related activities are the coordination of the dissemination package that is associated with the periodic and the concertation with other FP6 and FP7 ICT projects working in the area (see also WP8).

Progress and achievements

All tasks within this work package have been executed as required. The project's public web site can be found at http://www.ict-hd-mpc.eu, while the intranet web site/Virtual Portal can be found at http://www.nyquist.us.es/hdmproject (this Virtual portal is password-protected and only accessible for HD-MPC participants, reviewers, and the commission).

During the entire project period we have maintained and updated the public web site and added information on the publications produced within the project, links to software, links to related STREP projects and events, the HD-MPC public benchmarks[8] (in particular the four-tanks process benchmark and the hydro-power valley benchmark) as well as the pdf files of the public deliverables.

In the first reporting period we had set up a separate intranet web site (tied to the main public web site) and the Virtual Portal with the URL given above. In the second reporting period the intranet web site has been merged into the Virtual Portal so as to get increased efficiency and a more clear way of accessing the internal information for the HD-MPC participants. The intranet/Virtual Portal provides the participants (as well as the reviewers and the commission) access to information about the HD-MPC meetings (agenda, minutes, presentations), the HD-MPC logo as well as a dedicated HD-MPC style for presentations, the cover page for HD-MPC deliverables, pdf files of papers published by other participants within the framework of the project, and presentations by other participants within the framework of the project, as well as dedicated areas for the work packages, where in particular the WP6 area contains all the required information (description, models, software, …) on the benchmarks. In the current reporting period as well as in the previous one the Virtual Portal has also been maintained and extended with new sections and articles.

In conjunction with WP8 we have also publicized the results of the HD-MPC project towards the academic community and potential users through the special issue of the Journal of Process Control on HD-MPC, the HD-MPC Industrial Workshop in Leuven (June 2011), the final HD-MPC Workshop in Milano (August 2011), our website, publications, presentations, special sessions at conferences, seminars, visits, and joint projects/proposals. This is described in more detail in

[8] See http://www.ict-hd-mpc.eu/index.php?page=benchmarks.

deliverable D1.3.1 (“Report on knowledge management, links with potential users of results, and future perspectives”).

Resources
Resources for this work package have been used as planned in the updated description of work.

WP2: Definition of the hierarchical architecture for control design

Objectives

The objective of this work package is to define and to establish appropriate *control architectures* for distributed and hierarchical control. This will serve as a basis for the other work packages.

Progress and achievements

According to the timing of the project, this work package has been completed in the first two years of the project and the performed activity has been extensively described in the reports of the first and second year. The WP was organized in four tasks; the main results achieved for each task are now briefly summarized.

Task 2.1: Survey (M1-3)

The literature on hierarchical and distributed control has been reviewed and a classification of the approaches adopted so far has been proposed. Specifically, the main characteristics of decentralized, distributed, hierarchical and coordinated control schemes have been specified in terms of information and communication requirements. The main results achieved have been described in Deliverable D2.1 and in the papers [1], [2], [3].

Task 2.2: Definition of the control architecture (M4-9)

The research activity has focused on the development of a mathematical formulation of hierarchical control systems made by three layers working at different time scales. For any layer, starting from the highest one which corresponds to the representation of the system in the slowest time scale, an MPC problem is formulated and its solution is transmitted to the lower layer until the procedure is completed. It has been shown how this structure allows one to consider the majority of industrial control solutions. The main results achieved have been described in Deliverable D2.2 and in [4], [5]. Another significant application of a hierarchical control architecture has been discussed in [6].

Task 2.3: Extension of the control architecture

With reference to the hierarchical architecture developed in Task 2.2, the communication protocol regulating the information exchange among the layers has been considered, so as to coordinate the control actions computed at the different levels.

The final results concern the design of a reconfigurable two layer hierarchical controller for cascade systems, see [7], [8] and the results achieved in work package WP3. In order to deal with the problems considered in WP2 and to emphasize the reconfiguration capabilities of optimization-based predictive controllers in response to changes in the subsystems (actuators), it has been shown how this two-layer control structure may be readily extended to cope with the self reconfiguration of the controller, owing to an actuator replacement/addition (i.e. the “Plug and Play” approach), see [9].

Task 2.4: Multi-level models

A number of approaches were analyzed (see deliverables D2.1, D2.3) for the decomposition of a dynamical system into a number of weakly interacting subsystems and for the representation of a dynamical system at different levels of abstraction. Multi-level models have also been considered for the application of hierarchical control of intelligent vehicle highway systems, see [10]-[12], and baggage handling systems, see [13]-[16].

References

[1] R. Scattolini, "Architectures for distributed and hierarchical model predictive control – A review", *Journal of Process Control*, vol. 19, pp. 723-731, 2009, doi:10.1016/j.jprocont.2009.02.003.

[2] L. Magni, R. Scattolini, "An overview of nonlinear Model Predictive Control", in *Automotive Model Predictive Control: Models, Methods and Applications* (L. Del Re ed.), *Lecture Notes in Control and Information Science*, Springer, 2009 (in print).

[3] F. Valencia, and J. Espinosa, "Decentralized and Distributed Model Predictive Control", Internal Report N°3 HD-MPC of large-scale systems. Universidad Nacional de Colombia, 2009.

[4] B. Picasso, C. Romani, R. Scattolini, "On the design of hierarchical control systems with MPC", *Proceedings of the European Control Conference 2009 (ECC'09)*, Budapest, Hungary, Aug. 2009.

[5] R.R. Negenborn, S. Leirens, B. De Schutter, and J. Hellendoorn, "Supervisory nonlinear MPC for emergency voltage control using pattern search", *Control Engineering Practice*, vol. 7, no. 7, pp. 841-848, July 2009. doi: 10.1016/j.conengprac.2009.02.003

[6] R.R. Negenborn, P.-J. van Overloop, and B. De Schutter, "Coordinated distributed model predictive reach control of irrigation canals", *Proceedings of the European Control Conference 2009 (ECC'09)*, Budapest, Hungary, Aug. 2009.

[7] B. Picasso, C. Romani, and R. Scattolini, "Hierarchical model predictive control of Wiener Models", in *Nonlinear Model Predictive Control*, L. Magni, D. Raimondo, F. Allgöwer eds., *Lecture Notes in Control and Information Science*, Vol. 384, pp. 139-152, Springer, 2009.

[8] B. Picasso, D. De Vito, R. Scattolini, and P. Colaneri, "An MPC approach to the design of two-layer hierarchical control systems", *Automatica*, Vol. 46, n. 5, pp. 823-831, 2010.

[9] D. De Vito, B. Picasso, and R. Scattolini, "On the design of reconfigurable two-layer hierarchical control systems with MPC", *Proceedings of the 2010 American Control Conference*, 2010.

[10] L.D. Baskar, B. De Schutter, and H. Hellendoorn, "Dynamic speed limits and on-ramp metering for IVHS using model predictive control", *Proceedings of the 11th International IEEE Conference on Intelligent Transportation Systems (ITSC 2008)*, Beijing, China, pp. 821-826, Oct. 2008a.

[11] L. Baskar, B. De Schutter, and H. Hellendoorn, "Intelligent speed adaptation in intelligent vehicle highway systems - A model predictive control approach", *Proceedings of the 10th TRAIL Congress 2008 - TRAIL in Perspective - CD-ROM*, Rotterdam, The Netherlands, 13 pp., Oct. 2008b.

[12] L.D. Baskar, B. De Schutter, J. Hellendoorn, and A. Tarau, "Traffic management for intelligent vehicle highway systems using model-based predictive control", *Proceedings of the 88th Annual Meeting of the Transportation Research Board*, Washington, DC, 15 pp., Jan. 2009. Paper 09-2107.

[13] A.N. Tarău. *Model-Based Control for Postal Automation and Baggage Handling*. PhD thesis, Delft University of Technology, Delft, The Netherlands, January 2010.

[14] A.N. Tarău, B. De Schutter, and J. Hellendoorn, "Predictive route choice control of destination coded vehicles with mixed integer linear programming optimization", *Proceedings of the 12th IFAC Symposium on Transportation Systems*, Redondo Beach, California, pp. 64-69, Sept. 2009.

[15] A.N. Tarău, B. De Schutter, and H. Hellendoorn, "Hierarchical route choice control for baggage handling systems", *Proceedings of the 12th International IEEE Conference on Intelligent Transportation Systems (ITSC 2009),* St. Louis, Missouri, pp. 679-684, Oct. 2009.

[16] A.N. Tarău, B. De Schutter, and J. Hellendoorn, "DCV route control in baggage handling systems using a hierarchical control architecture and mixed integer linear programming", *Proceedings of the 3rd International Conference on Information Systems, Logistics and Supply Chain (ILS 2010)*, Casablanca, Morocco, 12 pp., Apr. 2010.

Resources

Resources for this work package have been used as planned in the updated description of work.

WP3: Development of hierarchical and distributed MPC methods

Objectives
The objectives of this work package are
- to develop methods for determining appropriate spatial and temporal divisions,
- to develop coordination mechanisms,
- to define communication and computational algorithms for MPC based on the hierarchical control architecture defined in WP2, taking into account linear as well as nonlinear models of the local agents,
- to analyze the control methods and algorithms with respect to their properties (stability, robustness and fault tolerance, local/global convergence, (sub)optimality, ...) using the results from WP4 and WP5, and
- to apply the results to selected simulation case studies.

Progress and achievements
The progress and achievements for the various tasks within this work package is detailed next.

Task 3.1: Hierarchical and distributed nonlinear MPC
First a literature survey has been conducted on existing methods and approaches to illustrate the state-of-the art of hierarchical and distributed model-predictive control [1]. The main point is that although, hierarchical and distributed methods have been considered since the 1970s, recently the research is mainly focused on methods for linear dynamical systems. Further many of the existing methods lack from poor computing performance. With this knowledge, several approaches have been followed for new developments in hierarchical and distributed model predictive control.

A new methodology for the design of two level hierarchical control systems has been developed. The higher level corresponds to a system with slow dynamics and whose control inputs must be provided by the subsystems (actuators) with faster dynamics and placed at the lower level. MPC control laws are synthesized for both the levels and overall convergence properties are established. The use of different control configurations is also considered by allowing the switching on/off of the subsystems at the lower level. In so doing, it is possible to consider overactuated plants, often built up for physical redundancy purposes to tackle damage events or to meet secondary objectives. The problem of distributing the control effort among a number of actuators is usually called control allocation and is of paramount importance in applications ranging from the automotive to the aerospace, aircraft, robotics, marine, power of wireless nodes and demands in free market fields.

The hierarchical control synthesis algorithm has been developed according to a robust control approach, which allows to obtain convergence of the overall system. Specifically, the discrepancy between the ideal control actions, requested by the high level controller, and those actually achieved by the actuators is considered as a disturbance term to be rejected in the design phase of the high level controller. The results achieved have been extensively described in [2].

The hierarchical approach presented in [2] has been developed in many ways. First, it has been extended to consider the case where the system at the higher level is described by a nonlinear Wiener model, i.e. a model with linear dynamics followed by a nonlinear static characteristic, while the subsystems at the lower level are described by linear or nonlinear models. In this case, an MPC regulator is designed at a slow time scale to guarantee robust steady-state zero error regulation for constant reference signals by including a suitable integral action in the control law. Also the actuators are controlled with the MPC approach, so that it is possible to cope with control and/or state constraints. The results of this research activity have been published in [3]. This approach has also been extended in [4] to allow for the switching between different configurations at the higher level of the control hierarchy. Specifically, if in given operating conditions the actuators are not fast enough, an alert signal is sent from the lower level to the higher one, which switches to a more robust mode in order to recover stability and convergence properties.

Another significant extension has concerned the reconfigurability issue. The two-layer MPC algorithm has been extended to cope with the self reconfiguration of the controller, owing to an actuator replacement/addition. The proposed approach can take a significant role within the "Plug and Play" research community, which studies an emerging control strategy acting as soon as a new device, in general a sensor or actuator, is plugged/substituted into an already functioning control system. When many actuators are present in the plant, a complete re-design of the controller further to the addition/replacement of only one actuator may often be undesirable for various reasons. Hence, an on-line reconfiguration is advisable; in order to guarantee an incrementally self updatable control apparatus still ensuring desired stability and performance properties. The results of this research activity have been described in [5].

Another research focus for hierarchical MPC methods has been the application of time-scale decomposition approaches to large-scale industrial plants. In [6], a two-layer nonlinear and economic MPC architecture has been applied to a simulated continuous polymerization plant. The plant is characterized by approximately 2000 variables and equations. On both control layers, i.e. the fast and the slow layer, an economic optimal control problem is considered. On the slow layer, a rigorous solution of the nonlinear optimal control problem is conducted to achieve the economically most efficient trajectories also during plant transients such as load or grade changes. However, as the computing time required for the rigorous solution of the economic NMPC problem is not negligible caused by the large-scale problem, an additional fast controller is implemented with higher sampling rate. This fast controller is based on Neighboring Extremal Updates, i.e. the optimal control problem is considered as a parametric NLP, where the parameters are given by some measurable disturbances. In order to derive a solution without computational delay, a suboptimal solution is used. Hence, the SQP iteration is stopped before convergence. The two-layer architecture proves to outperform a single-layer NMPC structure (with computational delay) and almost reproduces the performance of a single layer NMPC scheme, where computational delay is neglected.

A different research focus has been on distributed MPC, in particular on dual-decomposition-based distributed MPC, for large-scale interconnected systems with coupled dynamics and coupled constraints, and demonstrated its application on canal systems. In [7], we present a distributed version of Han's parallel algorithm for a class of convex programs, in order to address the presence of convex coupling constraints. The distributed algorithm relies on local iterative updates only, instead of system-wide information exchange as in Han's parallel algorithm. Convergence to the global optimum, recursive feasibility, and stability are established using only local communications between the subsystems. In [8], we propose an improved version of the distributed MPC method based on Han's parallel algorithm, and apply it to a canal system. The simulation results show that the modifications lead to faster convergence of the method, thus making it more practical in control of water networks. Both versions of the distributed Han's method are presented and applied to an interconnected canal system in [9]. Our methods are able to deal with both the couplings in dynamics and the couplings in constraints. More over, it can be implemented in a distributed fashion. This research is strongly related not only to WP3 but also to WP4 [10,11,12].

Another focus related to distributed MPC has been on sensitivity-driven distributed MPC (S-DMPC), which is a new approach based on the sensitivity-driven coordination approach discussed in Task 3.3 [13,14]. In this cooperative MPC approach, each of the controllers uses local information of the system model and the system constraints to calculate the local inputs. However, in order to achieve a Pareto optimal control law, linear information about the neighbor's cost is included in the local cost function. In order to derive the optimal control law, the optimizations have to be solved iteratively.

The main focus for this approach has so far been on linear-quadratic optimal control problems. While in [15] discrete-time systems have been considered, an approach for continuous-time systems has been presented in [14]. In both cases, a condition for convergence of the method has been derived. The method has been applied to different applications. In [15], a synthetic, but unstable system has been considered. In [14] a medium-scale chemical plant described in literature has been considered. While the controller model has been a linear time-invariant model, the plant replacement has been given by the full nonlinear model, involving reaction kinetics and nonlinear phase equilibria. Finally, the method has successfully been applied to the HD-MPC four tanks benchmark: Not only in simulations but also on the real laboratory plant [16]. In any of the applications the controller could reproduce the optimal control performance results of centralized MPC controllers. In [16] the new controller is compared to a variety of distributed model predictive controllers.

An important characteristic of the new S-DMPC algorithm observed in the applications so far is the fact, that only a few iterations have been required for each sample time to achieve the optimal performance results, thus leading to low computing time. In [15], the computing times reported for S-DMPC are lower than those reported for a centralized MPC scheme, which is a key requirement and justification for the application of a distributed MPC scheme. However, the main work on this controller, as for many other distributed controllers, so far has been on linear MPC. Hence, one of the future challenges still is to extend the theory for nonlinear distributed MPC.

An application-driven research is the design of advanced control and prediction systems which enable to regulate or predict the flow of vehicles on a freeway requires the knowledge of a suitable model of the specific portion of the freeway to be considered. In [17], we have studied distributed identification schemes of a macroscopic first order traffic density model. In particular, the Cell Transmission Model (CTM) was considered. The parameters to be identified characterize the dynamics of the density in different sections of the freeway (cells). Those parameters are: the free velocity, the maximum density and the backward congestion propagation speed. As the identification of the whole highway section is computationally prohibitive (the optimization problem we solve is highly non-linear), we have analyzed different configurations of the communication between the sensors of the highway, in order to split the nonlinear identification performed in smaller and more tractable ones. By relying on experimental data measured on a portion of the Highway A12 of The Netherlands, we have shown that it is possible to find a good trade-off between the prediction error and computation time required to obtain the parameters of the model. Finally, to show the good properties of the identified model for HD-MPC purposes, an evaluation of the performance in terms of virtual sensors, and some preliminary distributed MPC results in different scenarios were presented.

In [18], a hierarchical method for the identification of non-linear hybrid systems that have mixed continuous and discrete states is presented. The method first determines the hybrid characteristic of the system inspired by an inverse form of the merge method for clusters, which makes it possible to identify the unknown switching points of a process based on just input-output data. Using the switching points, a hard partition of the input-output space is obtained. Then, we propose to use Takagi-Sugeno (TS) fuzzy models with Gaussian membership functions (MFs) as sub-models for each partition. Thus, the overall model is hybrid-fuzzy and will include explicitly the hybrid behavior of the system (the detected switching points) by means of binary MFs, and in each partition all the other non-linearities by means of TS sub-models. An illustrative experiment on a hybrid-tank system is conducted to present the benefits of the proposed approach. Also, an empirical validation of the method is presented in the hybrid-fuzzy identification problem of first order traffic model, using real-life data measured on a portion of the Highway A12 of The Netherlands. Hybrid-fuzzy models have been used in MPC schemes, so then to show the good properties of the identified models, an evaluation of the performance in terms of virtual sensors and many-step-ahead prediction error are presented. Further developments are reported in [19].

Task 3.2: Hierarchical and distributed robust nonlinear MPC

The research in hierarchical and distributed control with MPC has witnessed the necessity to resort to control design algorithms guaranteeing some robustness properties. There are nowadays many ways to formulate stabilizing MPC methods in nominal conditions. However, it is also well known that nominal MPC can be non-robust with respect to even arbitrarily small disturbances. Moreover, discontinuity of the closed-loop dynamics, and of the Lyapunov functions for the nominal system, can emphasize such a lack of robustness. This issue is crucial in MPC, where both the resulting feedback law and the available Lyapunov function. For this reason, in the last years, attention has been focused on the development of MPC algorithms robust with respect to specific classes of disturbances. These methods, based either is on a min-max formulation of the underlying optimization problem or on the a-priori evaluation of the effect of the disturbance over the prediction horizon, are much more complex than those developed for nominal conditions, requiring either a heavy on-line computational burden, or a long off-line design phase. For this reason, in the HD-MPC project it has been analyzed under which conditions nominal MPC can guarantee robustness in the face of specific classes of disturbances. The research activity has been based on the notions of Input-to-State Stability (ISS) and Input-to-State practical Stability (ISpS), and the main results achieved concern the characterization of stability properties in perturbed conditions which can be deduced by the properties of a Lyapunov function for the nominal system. It has been proven that, under mild and easily testable assumptions, robustness properties can be enforced by properly selecting the free tuning parameters of an MPC algorithm designed for the nominal model. The results of this research activity have been extensively described in [20,21,22].

Distributed MPC algorithms can be developed (i) assuming that there exists exchange of information between the subsystems (as described for the methods developed in Task 3.1), or (ii) considering that there does not exist any information exchange yielding to a fully decentralized control structure. The second case, that is, fully decentralized MPC has been studied and robust design procedures have been proposed. In this case, the possible interactions between subsystems are considered as unknown disturbances that the controller must accomplish.

The robustness approach followed for the design of hierarchical control schemes, described in the last paragraph, has also been applied for the definition of a new distributed MPC algorithm, henceforth called Distributed Predictive Control, or DPC. The model of the system is assumed to be described by a number of interconnected linear models, whose state and input variables are restricted to lie in prescribed regions. Additional linear constraints coupling the state variables of the submodels can also been considered to include in the problem formulation a number of interesting cases, such as the coordination of vehicles with independent dynamics which must follow a prescribed path without collisions. DPC is a non-iterative, non-cooperative MPC algorithm where a neighbor-to-neighbor (i.e., partially connected) communication network and partial (regional) structural information are needed. The rationale of the proposed technique is that, at each sampling time, each subsystem sends to its neighbor information about its future reference trajectory, and guarantees that the actual trajectory lies within a certain bound in the neighborhood of the reference one. Then, a robust MPC approach provides a tool for the statement of the local optimization problems solved by each subsystem.

The highlights of DPC can be summarized as follows: (i) it is not necessary for each subsystem to know the dynamical models governing the trajectories of the other subsystems (not even the ones of the neighbors); (ii) the transmission of information is limited, in that each subsystem needs the reference trajectories only of the variables of one's neighbors, i.e. the subsystems which actually affect its dynamics and the ones which share one's global constraints; (iii) its rationale is very similar to the MPC algorithms presently employed in industry, where reference trajectories tailored on the dynamics of the system under control are used. The basic DPC algorithm has been described in [23,51].

The state feedback DPC algorithm presented in [23] has been extended in [24] to the output feedback case by the use of Luenberger observers for the estimation of the subsystems' states. It has been proven that, under standard assumptions in MPC, the subsystems' state trajectories starting from given sets in the state space converge to the origin. This result is achieved by considering the state estimation error as a further disturbance to be rejected by the control system. Notably, the same considerations could also be used to show the robustness of the proposed approach also with respect to exogenous unknown (but bounded) disturbances.

Another robust approach for the design of DMPC is the design of a fully decentralized MPC can be done relying on a robust design of each predictive controller [25]. In this case particularly interesting are those approaches that provide robustness based on the solution of a nominal optimization problem. Input-to-state stability appears as a suitable framework for the robust stability analysis while constraint satisfaction can be ensured by means of approximations of the reachable sets. See [26] and the references there in for a survey on this topic.

In [25] a decentralized min-max MPC is proposed. Stability of the whole plant is achieved relying on the ISS property of each single min-max MPC controller and assuming certain bounds on the coupling terms. In this work we extend this result to the case of nominal MPC, which avoids the computational complexity of the solution of the min-max optimization problem. The methodology to design the nominal MPC for each subsystem has also proposed. Under a certain design, which generalizes [27], the nominal MPC can ensure ISS of the system with a less conservative stability margin. The uncertainty is modeled as a parametric uncertain signal, not as an additive disturbance. Assuming that the model function is uniformly continuous, enhanced design of the robust controller is achieved: in the calculation of the constraints of the optimization problem and in the stabilizing conditions. The obtained stabilizing design of the controller turns out to be particularly interesting to relax the terminal conditions for a certain class of model functions, yielding a less conservative control law [29]. Furthermore the proposed robust MPC formulation allows us to use a general class of guaranteed estimators of the reachable sets for the robust constraint fulfillment.

The real implementation of the MPC controller on a real plant is typically done in a hierarchical structure, with en economic optimizer on the top that provides the optimal operation point of the plant to the steady-state optimizer. This layer is responsible to calculate the set-points of the predictive controllers.

Most of the predictive controllers ensure asymptotic stability to the target and constraint satisfaction by adding a terminal cost function together with an additional constraint on the terminal constraint. The stabilizing design conditions make these ingredients valid for a certain set-points. If this changes, these might be not valid and the stabilizing properties might be lost. In order to overcome this problem, a novel MPC has been proposed for the case of linear systems [29]. This is based on the addition of virtual references as decision variables of the controller and using a suitable cost function and terminal constraint to ensure convergence and recursive feasibility. This controller has been extended to nonlinear MPC to deal with both the problem of changing set-points [30]. This controller allows us to deal with the problem of hierarchical steady-state optimization. Under conditions similar to the standard stabilizing MPC, the proposed MPC for tracking is capable to ensure asymptotic stability to any reachable set-point. But, in the case of unreachable set-points, which is a common case in real plants, due for instance to disturbances, prediction model inaccuracies, the proposed controller ensures that the plant converges to the steady state that minimized the offset-cost function. This function is added to the optimization problem for convergence issues, but it has been demonstrated that this plays an important role since this characterizes the steady state where the system will evolve to. Then, taking as offset cost function the cost function of the steady-state optimizer, the proposed controller integrates this layer in the MPC formulation.

This idea has also been used to deal with an industrial relevant problem: the zone control. This problem has been posed as the tracking problem of target sets and ad-hoc offset-cost functions have been proposed [31]. Furthermore, the integration of economic criterion in the optimization has also been studied. In this case, the economic criterion is considered along the trajectory of the plant, not only at the steady state [32].

The proposed predictive controllers for changing set-points can be extended to deal with model mismatches and uncertainties, as it has been proposed in [33], exploiting the robust MPC design based on nominal predictions, as tightened constraints and tube-based approaches.

All these controllers have been implemented in Matlab/Simulink and a suite of functions for the design and implementation of the controllers has been developed. The resulting controllers have been successfully tested in the HDMPC benchmark based on the 4-tanks plant [33,16].

Based on the MPC for tracking previously presented and on [35], a cooperative distributed linear model predictive control strategy has been proposed. The proposed distributed controller is able to steer the system to any admissible set-point in an admissible way. Feasibility under any changing of the target steady state and convergence to the set-point are ensured. Furthermore, the design of the distributed controller is such that it is ensured that the distributed control system steers the system to the centralized optimum equilibrium point in spite of the decentralized implementation of the predictive controller. The proposed controller can also be robustified based on tube-based methods as proposed in [33].

The proposed controller has also been implemented in Matlab/Simulink and integrated in the previous suite. This controller has also been applied to a four tanks system. The obtained results demonstrate the benefits of the proposed controller [33,36].

The design of robust Distributed MPC based on game theory has also been studied: We have studied the problem of controlling two linear systems coupled through the inputs. This class of systems considered arises naturally in multi-input multi-output processes in which a transfer function model is obtained using standard identification techniques. For this class of problems, a novel distributed model predictive control method based on game theory has been proposed [37]. This control law is based on two different agents that share some information in order to find a cooperative solution to the centralized control problem. We assume that each agent only has partial information of the model and the state of the system. The performance and the robustness of the proposed control scheme with respect to data losses in the communications have been analyzed [38].

This controller has been generalized to multiple agents in [39]. This extension is not straightforward and some subtleties have been solved obtaining stabilizing design procedures. It is assumed that each agent has only partial state and model information. Agents communicate in order to find a cooperative solution to the problem of controlling a set of constrained linear systems coupled through the inputs. At each sampling time, a negotiation takes place in which the agents make different proposals, from which only one of them is chosen following a paretian criterion. Game theory is used in this way to reduce the complexity of the problem. This scheme is equivalent to a strategic game played by the agents. The proposed controller guarantees that the closed-loop system is practically stable and has a reduced computation and communication burden which makes it especially suited for low-resource systems. In addition, we provided sufficient conditions that guarantee practical stability of the closed-loop system. These conditions are based on a linear feedback controller which not only stabilizes the whole system, but also each of the subsystems considered as an independent system; and on a new concept of invariance for distributed systems denoted jointly invariant sets. Convex optimization based procedures to design both the local controller and the jointly invariant sets so that these conditions are satisfied are also presented.

The proposed controllers have been implemented in Matlab/Simulink and have been extensively analyzed in simulation. In order to demonstrate the good properties of the developed controllers, these have been applied to number of systems and benchmarks. In [40] this has been applied to a supply chain problem. In [37] the MIT beer supply chain problem has been controlled by the two-agents controller, while in [39] a supply chain with up to 20 firms involved has been controlled by the extended controller. The extended controller has been also tested on a simulation plant based on real data: an irrigation canal of the postrasvase Tajo-Segura. The simulation model is based on experimental data and describes 24 kilometers of the canal with 7 main gates and 17 off-take gates.

The DMPC based on game theory has been experimentally tested on the HD-MPC benchmark [16]. The comparative study carried out demonstrates that this controller exhibit a good performance.

The proposed Distributed MPC based game theory has also been extended to a hierarchical controller aimed to the risk mitigation of the overall plant. The paper [41] presents a hierarchical distributed model predictive control approach applied to irrigation canal planning from the point of view of risk mitigation. Two levels in optimization are presented. At the lower level, a distributed model predictive controller optimizes the operation by manipulating flows and gate openings in order to follow the water level set-points. The higher level implements a risk management strategy based on the execution of mitigation actions if risk occurrences are expected. Risk modeling involves risk identification, assigning probabilities, and devising a strategic plan to mitigate risks; therefore, getting information from weather forecasts, failures in operations and trained personnel to generate these models is crucial to the success of this approach. Risk factors such as unexpected changes in demand, failures in operation or maintenance costs are considered in the optimization. Decision variables are mitigation actions which reduce risk impacts that may affect the system. This work shows how model predictive control can be used as a decision tool which takes into account different types of risks affecting the operation of irrigation canals. The presented approach provides recommendations on the actions to undertake in order to mitigate risks that could appear. The procedure can be considered as a helpful tool to assist experts in evaluating different scenarios providing a definitive set of mitigation actions and values of control variables.

Task 3.3: Coordination mechanisms

The problem of distributed sensing, and in particular the definition of strategies for the efficient deployment of sensors over regions to be measured, has been considered in the framework of hierarchical control. Specifically, the goal was to develop leader-following control strategies solving the containment problem, in which a number of leader agents are required to define a (possibly time-variant) geometrical shape in the space, consisting in their convex hull, while the followers, i.e. sensing units, are forced to move confined in it. This research activity has been described in [44].

In [45], we proposed a gradient-based dual decomposition method that is suitable for hierarchical MPC of large-scale systems. The new method relies on a hierarchical coordination mechanism, in which there is one coordinator that can communicate with all local controllers. Each local controller can also communicate with its neighbors for doing parallel computations. The algorithm generates a primal feasible solution within a finite number of iterations and solves the problem by applying a hierarchical conjugate gradient method in each dual iterative ascent step. The proposed scheme uses constraint tightening and a suboptimality bound to ensure stability and feasibility in a hierarchical MPC problem.

A new coordination mechanism for distributed MPC has been proposed [13], which is based on the exchange of sensitivities. The idea is to divide a large scale optimal control problem such that each subproblem has to solve a smaller optimal control problem, i.e. for each of the subproblems, the number of degrees of freedom is reduces, as well as the number of equality and inequality constraints, so that the computing required to solve the subproblems is decreased. However, in order to achieve a Pareto optimum, rather than a Nash equilibrium, it is required that the cost functions of each of the subproblems are modified in order to take into account the interactions of the subproblems, which are the result of the coupled subsystems. In this new approach, the sensitivity-driven coordination, the modification of the objective function is based on a linear extension of the local objective functions, i.e. it is necessary to add a linear term incorporating first-order sensitivities of the neighbor's cost function as well as the neighbor's constraint functions with respect to the local degrees of freedom. Then, based on convergence of the iterative algorithm, Pareto optimality will be achieved [14].

Task 3.4: Timing and delay issues

Firstly, a literature survey and analysis regarding timing and delay issues have been carried out and a report has been written. This report describes the results of a literature survey regarding timing and delay issues and delay present in the distributed predictive issues in the context of hierarchical and distributed MPC. More specifically, the following topics are considered:

When a control system is implemented in a distributed fashion, with multiple processors communicating over a network, both the communication delays associated with the network and the computation delays associated with the processing time can degrade the systems performance. In this case, the performance of the system may depend not only on the performance of the individual components but also on their interaction and cooperation. Therefore, the deliverable discusses modeling and control of time-delay systems, including stability and robustness.

Next, we focus on communication and computational delay in MPC in the context of networked control systems. We characterize the issues related to communication delays and dropped network packets. Afterwards, we discuss model-based compensation of the dynamic effects of the network, and efficient schemes for on-line optimal control and MPC in networked control systems.

In this topic, the existing results on predictive controller for time-delay systems based on predictors has been extended to deal with the stabilizing hierarchical and distributed stabilizing predictive controllers. The literature review stemmed that the predictor-based structure of the MPC is one of the simplest strategies to cope with the timing and delays issues in the implementation of the controller. Then we focus on the development of new methods to design predictive controllers for delayed system based on the delay-free model of the plant.

Using time-stamped methods, a tight estimation of the delay can be obtained. Then, an open-loop predictor is typically used to estimate the future state and compensate the effect of the delay. Under absence of uncertainty this technique provides good results, but in the case that the prediction model differs from the real plant or the estimation of the delay is not accurate, the controller may exhibit a loss of performance or even of stability. To overcome this problem we have proposed predictive controllers that takes the uncertainty (modeled as additive) explicitly into account in the design. Particularly, the problem of explicit delay compensation in robust tube based MPC strategies has been addressed. The underlying idea is to robustly control a constrained process with dead-time by considering a prediction model without dead-time. As consequence, the prediction model order does not depend on dead-time length. Moreover, the effect of the uncertainty on the predicted state and the real state are studied and based on this, it has been proposed a slight different output tighter constraint in order to ensure robust constraint satisfaction. The proposed controller enjoys the input to state stability property and has demonstrated to provide robust controllers less sensible to the uncertainty in the model and in the estimated delay [33,34,16].

These methods have been experimentally tested on a lab-plant where the objective is control the temperature of the outlet flow of a heater and the delay is induced by mass transfer effect. The designed predictive controllers have demonstrated to enjoy robustness and constraint satisfaction in presence of uncertainties and delay.

Finally we considered the explicit consideration of computational delay in nonlinear model-predictive control (NMPC) algorithms. If the optimal control problem relies on a large-scale system model or has to deal with very short sampling times, a compromise is inevitable to trade off solution accuracy and computational delay, which refers to the delayed availability of the updated controls caused by the computing time of the numerical algorithm applied. If the solution accuracy of the updated controls is to be improved for better control performance, the solution time of the optimal control problem increases. However, long computing times result in the delayed availability of the updated controls and thus decrease control performance because outdated controls are applied as long as the control update is not available. Motivated by the deterioration of control performance due to computational delay and the shortcomings of available methods, a method has been developed to improve the performance of nonlinear model predictive control (NMPC) by compromising between the time delay caused by the computational algorithm and the accuracy of the resulting control law in order to achieve best possible closed-loop performance. The main feature of the method is an a-priori error approximation derived for the neighboring-extremal update (NEU) algorithm, a fast NMPC algorithm presented recently [49], which is based on an initial value embedding in the parametric NLP as well as a suboptimal solution of the optimal control problem. Hence, the SQP algorithm is not iterated to convergence, but stopped after a sufficient number of QP iterations.

The new error estimate provides the deviation of the current control trajectory from the (unknown) optimal control trajectory. The a-priori error estimator is incorporated in a fast on-line decision making process which simultaneously decides on the quality of the computed controls and the computational delay. In particular, the optimal number of QP iterations in an SQP strategy is determined on each horizon prior to the computation of the current control move. As a result, the control performance can be increased compared to suboptimal NMPC algorithms with other stopping criteria for the QP iterations [50].

References

[1] H. Scheu, W. Marquardt, “Report on literature survey on hierarchical and distributed nonlinear MPC, including analysis and comparison, and description of the resulting methodological framework“, HD-MPC Deliverable D3.1.1, 2009.

[2] B. Picasso, D. De Vito, R. Scattolini, and P. Colaneri, “An MPC approach to the design of two-layer hierarchical control systems”, *Automatica*, vol. 46, no. 5, pp. 823-831, 2010.

[3] B. Picasso, C. Romani, and R. Scattolini, “Hierarchical model predictive control of Wiener Models”, in *Nonlinear Model Predictive Control*, L. Magni, D. Raimondo, F. Allgöwer eds., *Lecture Notes in Control and Information Science,* vol. 384, pp. 139-152, Springer, 2009.

[4] B. Picasso, C. Romani, and R. Scattolini, “Tracking control of Wiener models with hierarchical and switching MPC”. Submitted.

[5] D. De Vito, B. Picasso, and R. Scattolini, “On the design of reconfigurable two-layer hierarchical control systems with MPC”, *Proceedings of the 2010 American Control Conference*, Baltimore, pp. 4707-4712, 2010.
[6] L. Würth, R. Hannemann, and W. Marquardt, “A two-layer architecture for economically optimal process control and operation”, *Journal of Process Control*, 21, 311-321, 2011.
[7] D. Doan, T. Keviczky, I. Necoara, M. Diehl, and B. De Schutter, “A Distributed Version of Han’s Method for DMPC of Dynamically Coupled Systems with Coupled Constraints”, *Proceedings of the 1st IFAC Workshop on Estimation and Control of Networked Systems (NecSys 2009)*, Venice, Italy, pp. 240-245, Sept. 2009.
[8] M. D. Doan, T. Keviczky, and B. De Schutter, “An improved distributed version of Han's method for distributed MPC of canal systems”, *12th Symposium on Large Scale Systems: Theory and Applications*, Villeneuve d'Ascq, France, July 2010.
[9] M. D. Doan, T. Keviczky, and B. De Schutter, “An iterative scheme for distributed model predictive control using Fenchel's duality”, *Journal of Process Control*, Special Issue on Hierarchical and Distributed Model Predictive Control, vol. 21, no. 5, pp. 683-816, 2011.
[10] D. Doan, T. Keviczky, I. Necoara, M. Diehl, and B. De Schutter, “A distributed version of Han's method for DMPC using local communications only”, *Journal of Control Engineering and Applied Informatics*, Special Issue on Distributed Control in Networked Systems, vol. 11, no. 3, pp. 6-15, 2009.
[11] M.D. Doan, T. Keviczky, and B. De Schutter, “A distributed optimization-based approach for hierarchical MPC of large-scale systems with coupled dynamics and constraints”, Accepted for the *50th IEEE Conference on Decision and Control and European Control Conference,* Orlando, Florida, Dec. 2011.
[12] P. Giselsson, M.D. Doan, T. Keviczky, B. De Schutter, and A. Rantzer, “A distributed optimization algorithm with convergence rate O(1/k^2) for distributed Model Predictive Control”, Submitted to Automatica, Sept. 2011.
[13] H. Scheu, J. Busch, and W. Marquardt, “Nonlinear distributed dynamic optimization based on first order sensitivities”, *Proceedings of the 2010 American Control Conference*, Baltimore, Maryland, USA, 2010.
[14] H. Scheu and W. Marquardt, “Sensitivity-based coordination in distributed model predictive control”, *Journal of Process Control*, 21(5), 715 – 728, 2011.
[15] H. Scheu and W. Marquardt “Distributed Model-Predictive Control Driven by Simultaneous Derivation of Prices and Resources”, *Proceedings of the 18th IFAC World Congress*, 398-403, 2011.
[16] I. Alvarado, D. Limón, D. Muñoz de la Peña, J.M. Maestre, M.A. Ridao, H. Scheu, W. Marquardt, R.R. Negenborn, B. De Schutter, F. Valencia and J. Espina, “A comparative analysis of distributed MPC techniques applied to the HD-MPC fou-tank benchmark”, *Journal of Process Control*, vol. 21-5, pp. 800-815, June 2011.
[17] M. Rinaldi, L. Capisani, A. Ferrara, A. Núñez, M. Hajiahmadi, and B. De Schutter, “Distributed Identification of the Cell Transmission Model for Control purposes: A case study.” To be submitted to American Control Conference 2012.
[18] A. Núñez, D. Sáez, I. Škrjanc, and B. De Schutter, “A new method for hybrid-fuzzy identification”. *Proceedings of the 18th IFAC World Congress*, Milano, Italy, August 28 - September 2, 2011.
[19] A. Núñez, D. Sáez, I. Škrjanc, and B. De Schutter, “A new hybrid-fuzzy identification method”. To be submitted to Engineering Applications of Computational Intelligence.
[20] B. Picasso, D. Desiderio, and R. Scattolini, “Robustness analysis of nominal Model Predictive Control for nonlinear discrete-time systems”, *8th IFAC Symposium on Nonlinear Control Systems,* Bologna, 2010.
[21] B. Picasso, D. Desiderio, and R. Scattolini, “Inherent robustness of nonlinear discrete-time systems”, *18th IFAC World Congress*, Milan, 2011.
[22] B. Picasso, D. Desiderio, and R. Scattolini, “Robust stability analysis of nonlinear discrete-time systems with application to MPC”, *IEEE Transactions on Automatic Control*, to appear (January 2012).
[23] M. Farina and R. Scattolini, “Distributed non-cooperative MPC with neighbor-to-neighbor communication”, *18th IFAC World Congress*, Milan, 2011.
[24] M. Farina and R. Scattolini, “An output feedback distributed predictive control algorithm”, *IEEE Conference on Decision and Control*, Orlando, 2011.
[25] D.M. Raimondo, L. Magni, and R. Scattolini, “Decentralized MPC of nonlinear systems: An input-to-state stability approach”, *International Journal of Robust and Nonlinear Control*, vol. 17, pp. 1651–1667, 2007.
[26] D. Limon, T. Alamo, D.M. Raimondo, D. Muñoz de la Peña, J.M. Bravo, A. Ferramosca, and E.F. Camacho, “Input-to-state stability: a unifying framework for robust model predictive control”, In L. Magni et al. (Eds.): *Nonlinear Model Predictive Control*, volume LNCIS 384. Springer-Verlag Berlin Heidelberg, 2009.

[27] D. Limon, T. Alamo, and E.F. Camacho, “Input-to-state stable MPC for constrained discrete-time nonlinear systems with bounded additive uncertainties”, *Proceedings of the 41st IEEE CDC*, pp. 4619–4624, 2002.
[28] D. Limon, I. Alvarado, A. Ferramosca, T. Alamo, and E.F. Camacho, “Enhanced robust NMPC based on nominal predictions”, *NOLCOS 2010*, 2010.
[29] D. Limon, I. Alvarado, T. Alamo, and E. Camacho, “MPC for tracking of piece-wise constant references for constrained linear systems”, *Automatica*, vol. 44, pp. 2382–2387, 2008.
[30] D. Limón, A. Ferramosca, I. Alvarado Aldea, T. Alamo Cantarero, and E.F. Camacho, “MPC for Tracking of Constrained Nonlinear Systems”, *Workshop on Assessment and Future Directions of NMPC*. Pavia, Italy, 2008.
[31] A. Ferramosca, D. Limón, A.H. González, D. Odloak, and E.F. Camacho, “MPC for trucking zone regions”. *Journal of Process Control*. vol. 20-4, pp. 506-516. April 2010.
[32] A. Ferramosca, J.B. Rawlings, D. Limon and E.F. Camacho, “Economic MPC for a changing economic criterion”, *49th IEEE Conference on Decision and Control*. pp. 6131-6137. Atlanta, GA, USA, December 15-17, 2010.
[33] A. Ferramosca. Model Predictive Control of systems with changing set-points. PhD Thesis. Universidad de Sevilla 2011.
[34] A. Ferramosca, D. Limón, J.B. Rawlings y E.F. Camacho, “Cooperative distributed MPC for tracking”, *18th IFAC World Congress*, pp. 1584-1589. Milan, Italy, August 28 – Sept. 2, 2011.
[35] B.T. Stewart, A.N. Venkat, J.B. Rawlings, S.J. Wright, and G. Pannocchia, “Cooperative distributed model predictive control”. *Systems & Control Letters*, 59, 460–469, 2010.
[36] A. Ferramosca, D. Limon, and E.F. Camacho, “Cooperative distributed MPC for tracking. Application to the 4 tanks plant”, Submitted to the ACC’12.
[37] J.M. Maestre, D. Muñoz de la Peña, and E.F. Camacho, “Distributed Model Predictive Control based on a cooperative game”. *Optimal Control Applications and Methods*, vol. 32-2, pp. 153-176. March – April 2011.
[38] J.M. Maestre, D. Muñoz de la Peña, and E.F. Camacho, “A Distributed MPC scheme with Low Communicatin Requirements”. *Proceedings of the 2009 American Control Conference,* pp. 2797-2802, St. Louis, USA. June 10-12, 2009.
[39] J.M. Maestre, D. Muñoz de la Peña, E.F. Camacho, and T. Álamo, “Distributed model Predictive Control based on agent negotiation”. *Journal of Process Control*, vol. 21-5, pp. 685-697, June 2011.
[40] J.M. Maestre, D. Muñoz de la Peña, and E.F. Camacho, “Distributed MPC; a supply chain case study”. *Proceedings of the 48th IEEE Conference on Decision and Control held jointly with 2009 Chinese Control Conference. (CDC-CCC 2009)*. pp. 7099-7105, Shanghai. China. December 16-18, 2009.
[41] A. Zafra-Cabeza, J.M. Maestre, M.A. Ridao, E. F. Camacho, and L. Sánchez, “A hierarchical distributed model predictive Control approach to irrigation canals: A risk mitigation perspective”. *Journal of Process Control*, vol. 21-5, pp. 787-799. June 2011.
[42] J.M. Maestre, D. Muñoz de la Peña, A. Jiménez Losada, E. Algaba Durán, and E.F. Camacho, “An Application of Cooperative Game Theory to Distributed Control”, *18th IFAC World Congress*. pp. 9121-9126. Milan, Italy, August 28 – Sept. 2, 2011.
[43] J.M. Maestre. Distributed Model Predictive Control Based on Game Theory. PhD Thesis. Universidad de Sevilla 2011.
[44] L. Galbusera, G. Ferrari Trecate, and R. Scattolini, “A hybrid model predictive control scheme for multi-agent containment and distributed sensing”, *IEEE Conference on Decision and Control*, pp. 7006-7011, Shanghai, 2009.
[45] M. D. Doan, T. Keviczky, and B. De Schutter, “A dual decomposition-based optimization method with guaranteed primal feasibility for hierarchical MPC problems”, *Proceedings of the 18th IFAC World Congress*, Milan, Italy, pp. 392-397, Aug.-Sept. 2011.
[46] T.L.M Santos, J.E. Normey, and D. Limon, “Explicit input-delay compensation for robustness improvement in MPC”, *IFAC TDS 2009*.
[47] T.L.M. Santos, D. Limón, T. Álamo, and J.E. Normey-Rico, “Robust tube based model predictive control for constrained systems with dead-time”. *Proceedings of the UKACC International Conference on Control 2010*, pp. 920-925. Conventry. UK. Sept. 2010.
[48] T.L.M. Santos, D. Limón, J.E. Normey-Rico, and T. Álamo, “On the explicit dead-time compensation for robust model predictive control”. *Journal of Process Control*. In Press.
[49] L. Würth, R. Hannemann, and W. Marquardt, “Neighboring-extremal updates for nonlinear model-predictive control and dynamic real-time optimization”, *Journal of Process Control*, 19, 1277–1288, 2009.

[50] I. Wolf, L. Würth, W. Marquardt, “Rigorous solution vs. fast update: Acceptable computational delay in NMPC”, accepted for the 50th IEEE CDC and the 2011 ECC, Orlando, Florida, USA, 2011 (accepted).

[51] M. Farina and R. Scattolini, “Distributed predictive control: a non-cooperative algorithm with neighbor-to-neighbor communication for linear systems", accepted for publication in *Automatica*, 2011.

Resources

Resources for this work package have been used as planned in the updated description of work.

WP4: Optimization methods for hierarchical and distributed MPC

Objectives

In this work package we will develop well-founded optimization formulations and algorithms for the newly developed methods in the other work packages (in particular, WP3 and WP5). Apart from the classical three optimization problems occurring in all MPC applications — model and parameter identification, on-line moving horizon state estimation, and on-line MPC optimization on the prediction horizon — where the groups participating in this WP have long standing experience, in this work package we will develop new on-line optimization methods for distributed MPC in the case of control systems with limited mutual information.

Progress and achievements

The aim of WP4 is to develop the optimization formulations and algorithms for the methods developed in the other work packages. During the reporting period new advancements have been made in the research directions already explored in the first and the second year of the project and new algorithms have been devised.

Throughout the research project a number of areas of optimization and MPC have been dealt with. Novel optimization methods were developed and investigated in linear as well as nonlinear MPC schemes. First, a distributed version of Han's parallel algorithm for a class of convex programs was investigated. Also convergence to the global optimum, recursive feasibility, and stability results were published. A cooperative distributed linear model predictive control strategy was also introduced based on local communication attaining plant-wide stability. For nonlinear deterministic distributed systems a variant of multiple shooting was thoroughly investigated, having attractable convergence properties and high level of parallelization. In the context of uncertain large-scale systems, a multi-objective model-based predictive control approach was developed for solving a dial-a-ride problem. Several criteria, emulating different dispatchers, are proposed in order to systematize different ways to use the information provided by the dynamic optimal Pareto front. Finally, robust distributed MPC was considered by solving the problem of load scheduling for large-scale irrigation channels. By employing decentralized control, decomposition methods for the schedule were investigated.

Task 4.1: On-line optimization methods for hierarchical and distributed MPC

The first line of research with Task 4.1 involves a distributed version of Han's parallel algorithm for a class of convex programs with convex coupling constraints [2,3]. The distributed algorithm relies on local iterative updates only, instead of system-wide information exchange as in Han's parallel algorithm. Convergence to the global optimum, recursive feasibility, and stability are established using only local communications between the subsystems. In [3] the new algorithm is then applied to an example of coupled spring-mass system with coupled linear constraints. The simulation results demonstrate the convergence and stability properties of the algorithm. In [4] an improved version of the distributed MPC method based on Han's parallel algorithm is proposed and applied to a canal system. The simulation results show that the modifications lead to faster convergence of the method, thus making it more practical in control of water networks.

In [8] a cooperative distributed linear model predictive control strategy applicable to any finite number of subsystems satisfying a stabilizability condition is presented. The control strategy has the following features: hard input constraints are satisfied; terminating the iteration of the distributed controllers prior to convergence retains closed-loop stability; in the limit of iterating to convergence, the control feedback is plant-wide Pareto optimal and equivalent to the centralized control solution; no coordination layer is employed. In [9] a hierarchical distributed MPC scheme is presented. This iterative method aims at reducing the communication between the subsystems. Data is exchanged at each iteration between the neighboring subsystems, while only slower asynchronous communication is required between non-neighboring subsystems. This method is plant-wide stabilizing and does not require iterating until convergence is achieved.

In order to achieve a practical implementation of distributed predictive controllers, routines to be executed in industrial platforms such as PLC, PC-104 based PACs or DSP have been developed at USE. On the PLC platforms, a suite that allows in a user-friendly way to implement explicit predictive control law using standard tools for MATLAB has been developed. A library of functional blocks to implement predictive controllers solving the optimization problem on-line is currently under development. A first predictive controller in absence of constraints has been successfully implemented. The constrained case is in progress. For the PC-104 and DSP platform, a QNX environment has been installed. Efficient quadratic programming solvers based on interior-point methods are under development. These are programmed in ANSI C-Language to ensure the portability between the different platforms. The derived predictive controller for tracking based on the developed QP-solver has been successfully tested in simulation. Specialized algorithms to speed up the control action calculation are currently under investigation.

The group at KUL has developed optimization methods applicable to distributed nonlinear systems [10]. This method may be regarded as generalization Direct Multiple Shooting to the state dimension. It decrease the solution time of optimal control problems by distributing the most time-consuming subtask, simulation and sensitivity calculation, and maintaining a centralized controller. Local convergence theory of Sequential Convex Programming (SCP) directly applies to this variant of multiple shooting, thus depending on the type of Hessian approximation locally quadratic convergence may be achieved. By introducing inexactness in the SQP method [11], considerable CPU-time can be saved, though only locally linear convergence can be attained. In the most extremal case it is possible to totally decouple the centralized controller into local ones, while still reaching convergence.

The solution of convex optimization problems based on interior point methods requires the solution of a set of linear equations that can be efficiently solved using well-known methods as Cholesky decomposition based algorithms. In the case of the optimization problems to be solved for large scale systems, algorithms that do not exploit the structure of the problem may exhibit poor results. In this regard, USE is studying methods which can detect on-line the dominant couplings between the subsystems in order to split the large scale problem into smaller tasks.

Task 4.2: Optimization of uncertain large-scale systems

As a first step towards optimization of uncertain large-scale systems we have developed a line of research whose major objective is to systematize the use of the well-known multi-objective optimization tools, in dynamic environments [5,6,7]. In this context, a multi-objective model-based predictive control approach was developed for solving a dial-a-ride problem, which is inherently a hierarchical system. The dynamic objective function of the logistic part of this problem considers two components that are usually aimed at opposite goals: user and operator costs. When a new call asking for service is received (which is an uncertain process that cannot be predicted well in advance), the method first solves a multi-objective optimization problem, based on a predictive model of the process, providing the Pareto optimal set. Note that from this set just one solution has to be applied to the system. Then, the dispatcher participates in the dynamic routing decisions by expressing his/her preferences in a progressively interactive way, seeking the best trade-off solution at each instant among the Pareto optimal set. The idea of this method is to provide to the dispatcher a more transparent tool for the decisions. Several criteria, emulating different dispatchers, are proposed in order to systematize different ways to use the information provided by the dynamic optimal Pareto front.

We have proposed different criteria to obtain control actions over real-time routing using the dynamic Pareto front. The criteria allow giving priority to a service policy for users, ensuring a minimization of operational costs under each proposed policy. We have evaluated multi-objective model-based predictive control based on a weighted-sum criterion, a goal achievement method, and a fuzzy expert criterion. The service policies were verified approximately on the average of the replications. Under the implemented on-line system it is easier and more transparent for the operator to follow service policies under a multi-objective approach instead of tuning weighting parameters dynamically.

Task 4.3: Optimization methods for robust distributed MPC

In the context of optimization methods for robust distributed MPC we are continuing previous research on the use of mixed-integer linear programming [1], with load scheduling for large-scale irrigation channels as benchmark application.

In large-scale irrigation networks, water is often distributed via open water channels under the power of gravity (i.e. there is no pumping). In practice, channel capacity is limited. This forces farmers to take water by placing orders. Moreover, the time-delay for water to travel from the upstream end to the downstream end of the pool limits the closed-loop bandwidth, which dampens the performance. Hence, the starting and ending of off-takes induce transients (i.e. the water-level drops and rises from set-point). Such a transient response propagates to upstream pools as regulators take corrective actions. In load scheduling, a set of off-takes (requested by farmers) is organized, which ensures that the water level constraints are satisfied, in the face of transients associated with load changes. Moreover, from a farmer's perspective, a preferable solution would involve the smallest possible delay between the requested starting time and the time the load is scheduled. As a result, the scheduling can be expressed as an optimization problem involving minimizing the delay of water delivery subject to constraints. Indeed, the load scheduling sits on the higher level of a two-level control hierarchy. On the lower-level, controllers are designed to ensure stability, robustness, good set-point tracking, and disturbance rejection.

In this research, the problem of load scheduling for large-scale irrigation channels is considered. Based on the analysis of the special structure of open water channels under decentralized control, a decomposition of the scheduling problem is discussed. The solution could be suboptimal compared to an optimal solution, if it exists, to the scheduling problem initially formulated in [1], without considering the structure of the irrigation system. However, such a decomposition scheme avoids computational issues, including memory requirements and computing time, which is significant for large-scale system.

References

[1] J. Alende, Y. Li and M. Cantoni, "A {0,1} linear program for fixed-profile load scheduling and demand management in automated irrigation channels", in *Proceedings of the 48th IEEE CDC*, Shanghai, Dec. 2009.

[2] D. Doan, T. Keviczky, I. Necoara, M. Diehl, and B. De Schutter, "A distributed version of Han's method for DMPC of dynamically coupled systems with coupled constraints", *Proceedings of the 1st IFAC Workshop on Estimation and Control of Networked Systems (NecSys'09)*, Venice, Italy, Sept. 2009.

[3] D. Doan, T. Keviczky, I. Necoara, M. Diehl, and B. De Schutter, "A distributed version of Han's method for DMPC using local communications only", *Control Engineering and Applied Informatics*, vol. 11, no. 3, pp. 6-15, 2009.

[4] D. Doan, T. Keviczky, and B. De Schutter, "An improved distributed version of Han's method for distributed MPC of canal systems", *12th Symposium on Large Scale Systems: Theory and Applications*, Villeneuve

d'Ascq, France, July 2010.
[5] A. Núñez, B. De Schutter, D. Sáez, and C.E. Cortés, “Hierarchical multiobjective model predictive control applied to a dynamic pickup and delivery problem”. *13th International IEEE Annual Conference on Intelligent Transportation Systems*, Madeira Island, Portugal, September 19-22, 2010.
[6] A. Núñez, C.E. Cortés, D. Sáez, M. Gendreau, and B. De Schutter, “Multiobjective model predictive control applied to a dial-a-ride system”, *Proceedings of the 90th Annual Meeting of the Transportation Research Board*, Washington, DC, 19 pp., Jan. 2011. Paper 11-1942.
[7] A. Núñez and B. De Schutter, “Design of a hierarchical model-based predictive controller for an integrated public transport system”. To be submitted.
[8] B.T. Stewart, A.N. Venkat, J.B. Rawlings, S.J. Wright, and G. Pannocchia, “Cooperative distributed model predictive control” *System & Control Letters*, vol. 59, pp. 460-469, 2010.
[9] B.T. Stewart, J.B. Rawlings and S.J. Wright, “Hierarchical cooperative distributed model predictive control”, *Proceedings of the American Control Conference*, Baltimore, 2010.
[10] C. Savorgnan, C. Romani, A. Kozma and M. Diehl, “Multiple Shooting for distributed systems with applications in hydro electricity production”, *Journal of Process Control*, vol. 21, pp. 738-745, 2011
[11] C. Savorgnan, A. Kozma, M. Diehl, “Adjoint-Based Distributed Multiple Shooting for Large-Scale Systems”, *Proceedings of the 18th IFAC World Congress*, vol. 18, 2011

Resources
Resources for this work package have been used as planned in the updated description of work.

WP5: Distributed state estimation algorithms

Objectives

In this work package we will develop new on-line optimization methods for distributed state and variance estimation.

Progress and achievements

As already reported in the HD-MPC annual for Period 1 (M1-12), although the tasks for this work package were scheduled to start from month M16 in the project planning, the research on this work package (in particular on the first task, viz., state estimation) started earlier, during the first year of the project, to allow for the availability of distributed state estimation schemes to be used in conjunction with the distributed state-feedback control laws to be designed in WP3 and WP4.

Task 5.1: State estimation

First, the available methods for estimating the whole state in a large-scale system with Moving Horizon Estimators (MHE) and Kalman-based observers (KF) have been reviewed, see [1] and [2].

Then, MHE distributed estimation algorithms for linear discrete-time systems subject to noise have been developed considering sensor networks made by a set of electronic devices, with sensing and computational capabilities, which coordinate their activity through a communication network, see [3], [4], [5]. Novel state estimation methods have also been developed for large-scale discrete-time constrained linear systems that are partitioned, i.e. represented by coupled subsystems with non-overlapping states, see [6]. Also in this case, focus has been placed on Moving Horizon Estimation (MHE).

A procedure based on the decomposition of a linear process model into a cascade of simpler subsystems and the use of a Kalman filter to individually estimate the states of these subsystems has been described in [7], where both a theoretical comparison and simulation examples have been reported.

The analysis of a special class of nonlinear dynamic systems that can be decomposed into cascaded subsystems, represented as Takagi-Sugeno (TS) fuzzy models has been performed in [8], where it has been proven that the stability of the subsystems implies the stability of the overall system. Applications of such cascaded systems include multi-agent systems, distributed process control, and hierarchical large-scale systems.

Finally, for macroscopic traffic flow models several estimation methods have been investigated, including extended and unscented Kalman filters and particle filters. In particular, in [9] a fuzzy observer has been proposed for the continuous time version of a macroscopic traffic flow model.

During the third year of the project, the distributed estimation algorithms developed the first two years for linear systems were extended to consider also systems with nonlinear dynamics.

First, the DMHE state estimation method for linear systems already described in Deliverable D5.2 and in the papers [3]-[5], has been generalized to nonlinear systems. The goal has been to provide a Nonlinear DMHE (NDMHE) scheme enjoying stability properties. In order to characterize states that can and cannot be recovered by each sensor without communication the notion of MHE detectability has been exploited. Moreover, a consensus-on-estimates penalty term in local MHE problems has been used to let each sensor learn locally MHE undetectable parts of the state from other sensors. The state estimation error dynamics has been derived and it has been shown that when it enjoys incremental input-to-state stability (δ-ISS), stability of the estimation scheme is guaranteed. Unfortunately, checking δ-ISS properties can be hard and requires a global analysis of all estimation errors committed by individual sensors. Therefore, exploiting a small gain property, simple conditions have been provided on the weights associated to communication channels in order to enforce stability of DMHE. An example of application concerning four Van der Pol oscillators has been considered to analyze the performance of the proposed NDMHE algorithm. The results achieved in this framework have been described in Deliverable D5.3 and in [10].

A second stream of research has concerned the extension to the nonlinear case of the partition-based MHE algorithms, named PMHE1, PMHE2 and PMHE3, developed in the first part of the HD-MPC project, see [6]. We recall here that these algorithms have been designed to cope with industrial processes and physical systems composed by a large number of interconnected units (subsystems), each one described by a dynamic model. In the PMHE algorithms, which differ in terms of communication requirements, accuracy and computational complexity, each subsystem solves a reduced-order MHE problem in order to estimate its own states based on the estimate of the other subsystems' states transmitted by its neighbors. During the third year of the project, the results of [6] for linear systems have been extended to the case of nonlinear systems so as to cope with the majority of problems arising in process control, where the nonlinear dynamic phenomena have often to be considered in order to guarantee the accuracy of the solution. The convergence properties of the method have been investigated and sufficient conditions have been given. These conditions turn out to be automatically satisfied when the directed graph describing interconnections among subsystems is acyclic.

The proposed partition-based MHE has then been applied to the problem of estimating the levels and flow rates in the model of three cascade river reaches, which represents a part of the Hydro Power Valley benchmark extensively studied in the HD-MPC project (WP7). In this problem, interconnections between successive reaches are due to the dependence of the input flow rate of the downstream reaches to the level of the final section of the upstream ones, which cannot be measured, but just estimated from the available measures collected along the reach. The results achieved have been extensively described in Deliverable D5.3 and in the paper [11].

Task 5.2: Variance estimation

In the first two years of the project, the currently available techniques for the estimation of the noise co-variances have been reviewed and tested in a number of simulation experiments. This work has been useful for the definition of the main approaches followed so far (Bayesian, maximum likelihood, covariance matching, correlation techniques) and of their main strong and weak characteristics (see also HD-MPC deliverable D5.1).

All the distributed estimation algorithms base on the MHE approach developed in the HD-MPC project require the a-priori knowledge of the co-variances of the noises affecting the system states and outputs, which are generally unknown. This is a serious drawback which could prevent one from achieving satisfactory results, and a particular attention must be placed to the tuning phase. The analysis of the many different approaches proposed in the technical literature to solve the problem of covariance estimation has shown that the so-called correlation approach is probably the most effective and reliable one. Therefore, the algorithms developed by Mehra and the Autocovariance Least Squares (ALS) have been specifically considered. Further tests have proven that the ALS approach is the most effective one, since it outperforms significantly the one proposed by Mehra. Starting from the basic ALS formulation, a novel adaptive algorithm for the on-line estimation of the noise properties has been developed. The co-variances estimates computed with this approach can be used for the adaptive tuning of the weights of the moving horizon estimators. Basically, starting form the output estimation error computed on-line, the algorithm adaptively updates the noise variances, which correspond to the inverse of the weights in the MHE performance index. The method developed has been described in Deliverable D5.3 and has been used in a couple of significant test cases with excellent results, so that it is believed that it can be successfully and widely applied.

References

[1] J. Garcia, J. Espinosa, "On the estimation of the state in a large-scale system using Moving Horizon Observers" *Proceedings of Colombian Conference on Automatic*, Cartagena de Indias, Colombia. April, 2009a.

[2] J. Garcia, J. Espinosa, "Moving Horizon Estimators for Large-Scale Systems", *Journal of Control Engineering and Applied Informatics*, vol. 11, no. 3, pp. 49-56, 2009.

[3] M. Farina, G. Ferrari Trecate, R. Scattolini, "Distributed moving horizon estimation for sensor Networks", *IFAC Workshop on Estimation and Control of Networked Systems*, pp. 126-131, Venice, 2009.

[4] M. Farina, G. Ferrari Trecate, R. Scattolini, "A moving horizon scheme for distributed state estimation", *IEEE Conference on Decision and Control*, pp. 1818-1823, Shanghai, 2009b.

[5] M. Farina, G. Ferrari-Trecate, and R. Scattolini, "Distributed moving horizon estimation for linear constrained systems", *IEEE Transactions on Automatic Control,* vol. 55, no.11, pp. 2462-2475, 2010.

[6] M. Farina, G. Ferrari Trecate, R. Scattolini, "Moving horizon state estimation of large scale constrained partitioned systems", *Automatica*, vol. 46, no. 5, pp. 910-918, 2010.

[7] Zs. Lendek, R. Babuška, and B. De Schutter, "Distributed Kalman filtering for cascaded systems", *Engineering Applications of Artificial Intelligence*, vol. 21, no. 3, pp. 457-469, Apr. 2008.

[8] Zs. Lendek, R. Babuška, and B. De Schutter, "Stability of cascaded fuzzy systems and observers", *IEEE Transactions on Fuzzy Systems*, vol. 17, no. 3, pp. 641-653, June 2009.

[9] Zs. Lendek, R. Babuška, and B. De Schutter, "Fuzzy models and observers for freeway traffic state tracking", *Proc. of the 2010 IEEE American Control Conference*, Baltimore, Maryland, pp. 2278-2283, June-July 2010.

[10] M. Farina, G. Ferrari-Trecate, R. Scattolini, "Distributed moving horizon estimation for nonlinear constrained systems", *International Journal of Robust and Nonlinear Control* (to appear), DOI: 10.1002/rnc.1676.

[11] M. Farina, G. Ferrari-Trecate, C. Romani, R. Scattolini "Moving horizon estimation for distributed nonlinear systems with application to cascade river reaches", *Journal of Process Control*, vol. 21, no. 6, pp. 767-774, 2011.

Resources

The resources for this work package have almost been used as planned in the updated description of work, in the sense that the description of work foresaw 51 person months, while 49.25 funded person months have been realized for this WP; however, additional 8 unfunded person months have been realized within this WP, which brings the total effort to 57.25 person months.

WP6: Hardware and software implementation, and benchmarking

Objectives

The objective of this work package is to analyze hardware and software implementation issues and to use benchmarking as a means for testing the methods developed within the project.

From the point of view of the hardware and software implementation, the work package is also devoted to analyze the advantages and drawbacks of the off-the-shelf solutions, proposing the best choices for implementation.

Progress and achievements

The main achievement of this work package is the preparation (including a complete description, models, and related papers) of six benchmark cases: four-tank system, chemical plant, electric network, heat system and two benchmarks related to WP7 (viz. the hydro-power valley and irrigation channels). The algorithms developed during the Project have been tested on these case studies. The progress for each one of the tasks of WP6 is detailed next.

Task 6.1: Analysis of hardware and software

The objective of this task is the analysis on hardware and software for hierarchical and distributed model predictive control. The software and hardware needed to implement HD-MPC in industrial systems is almost the same of any industrial Distributed Control System (DCS). This task has been focused on the requirements, software and hardware needed for industrial HD-MPC applications and also in those required in HD-MPC based on sensor networks.

On the industrial applications side, a number of commercial industrial control solutions have been considered. These systems are reviewed from the point of view of the requirements of a truly distributed control system. Concerning the communications requirements, the special redundant network topologies used in industrial DCS are reviewed and also the possibility of having different communication systems for those remote locations in which no other means of connecting to the net is available.

Wireless sensor networks have been also analyzed, including some hardware platforms.
Finally, different long distance communication systems have been studied in the task.

The task finished in month M18 and the deliverable D6.1.1: "Report on results of hardware and software analysis" has been produced.

Task 6.2: Development and implementation of a benchmark model guide

The main objective of the Benchmark Model-Guide is to help HD-MPC partners to develop benchmark exercises. The Model-Guide facilitates the proposal and preparation of benchmark exercises and also, it will provide a common format for the description and use of benchmarks.

For each benchmark case, an exhaustive description of its main technological and operational data as well as of the main performance criteria is provided.

The following tools have been developed for this purpose:

- Benchmark Questionnaire: The benchmark developer will be guided with the help of a questionnaire, including an ordered detailed explanation of the elements to be described in the proposal. A detailed description of this tool can be found in Deliverable D6.2.1 and available in HD-MPC Virtual Portal.

- Benchmarks in the Virtual Portal: Benchmark proposers and users find in the virtual-portal all the documentation related to the benchmarking task. (http://www.nyquist.us.es/hdmpcproject/).

Task 6.2 has been finished, the objectives have been achieved, and Deliverable D6.2.1 is available.

Task 6.3 and 6.5: Preparation of benchmarking cases

The objective of this task is the preparation of a collection of real and simulated benchmark cases using the tools developed in the previous subtask.
The consortium decided to prepare four main benchmark cases to be used in the first round of exercises during the first 18 months, one real plant and three simulated systems. These benchmark cases are:

- Four-Tank System
- Electric Network
- Heat System
- Chemical

Two additional benchmark cases were developed during the second half of the project:

- Hydro-power Valley Benchmark
- Irrigation Canal System.

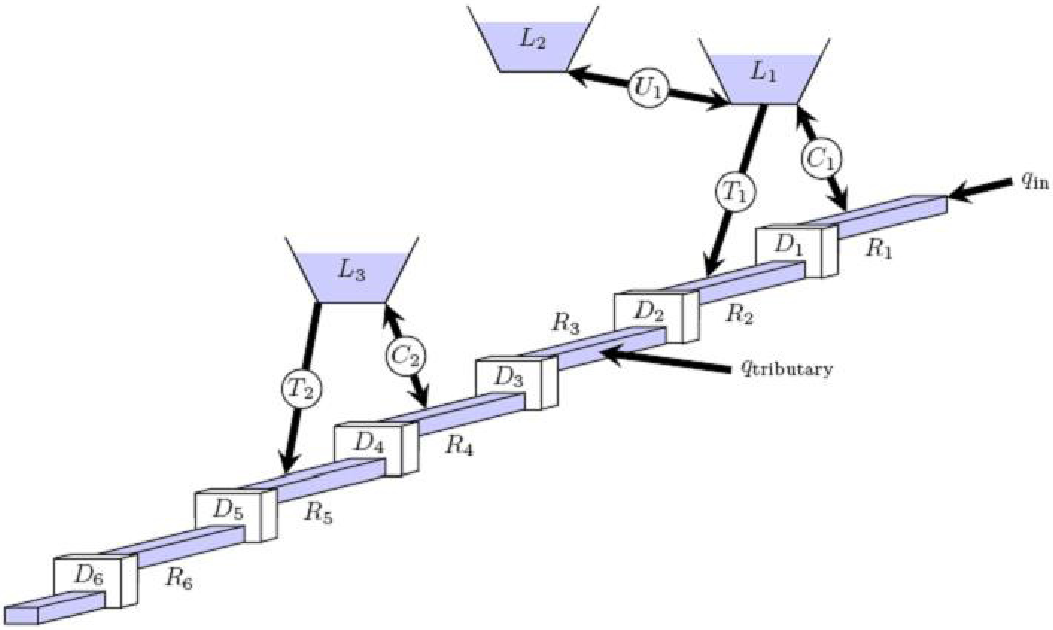
The documentation of these six benchmarks has been prepared, including a complete description of the process and exercises, models, bibliography, etc. All the documentation is available for the interested partners in the HD-MPC virtual portal.

Also, the four-tank system and the hydro-power benchmark were defined by the consortium as public benchmarks, and all the documentation is available to the research community in the public website of the project at http://www.ict-hd-mpc.eu/index.php?page=benchmarks.

Next, a brief description of the two last benchmarks is presented.

Hydro-power valley

The benchmark is a hydro power plant composed by several subsystems connected together. The following figure gives an overview of the system which is composed by 3 lakes (L_1, L_2 and L_3) and a river which is divided in 6 reaches (R_1, R_2, R_3, R_4, R_5 and R_6) which terminate with dams equipped with turbines for power production (D_1, D_2, D_3, D_4, D_5 and D_6). The lakes and the river reaches are connected by a duct (U_1), ducts equipped with a turbine (T_1 and T_2) and ducts equipped with a pump and a turbine (C_1 and C_2) The river is fed by the flows q_{in} and $q_{tributary}$.



Two test scenarios were considered:

- in the first scenario the power output of the system should follow a given reference while keeping the water levels in the lakes and at the dams as constant as possible;
- in the second scenario the system profit should be maximized based on the available information on the hourly electricity price variations.

A complete description of the system, cost functions of the scenarios and models can be found in deliverable D6.5.1 – Chapter 3 and in the Virtual Portal.

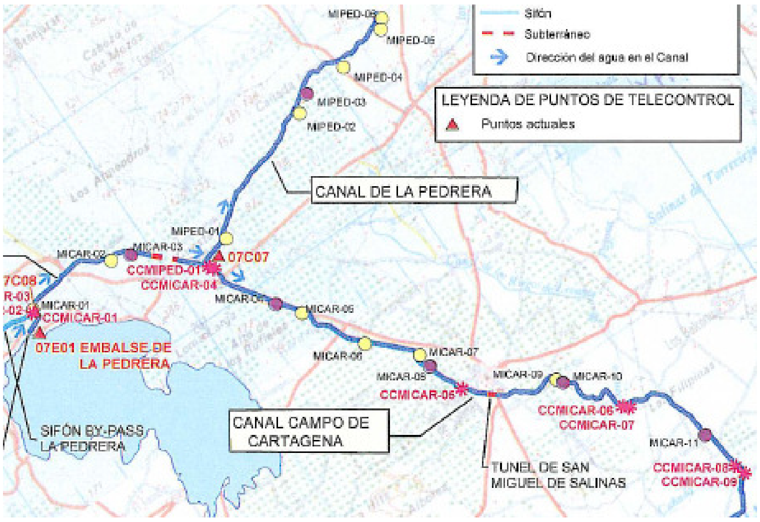
Irrigation Canal Benchmark

The system to be controlled is an open-canal used for water distribution (for irrigation and supply of drinking water), composed of several reaches connected by gates. The target is to control the management of water in order to guarantee flows requested by users (mainly irrigation districts). For this purpose, there are off-take gates at both sides of the canal, where water is taken from the canals for irrigation. The level of the canals must be maintained over a minimum value needed to take water in the off-take points along the channels.

The benchmark is a section of the "postrasvase Tajo-Segura" in Spain. The selected section is a Y-shape canal, a main canal that splits into two canals with a gate placed at the input of each one of them (see the following figure). The length of the canals is:

- Canal de la Pedrera: the total length of this canal is 6.680 km.
- Canal de Cartagena: in our case-study only a part of this canal is used (17.444km).

The total length of the canals is approximately 24 km. The most important elements in the canals are the main gates which regulate the level of water along the canals and the off-take gates, where farmers take water from the canals for irrigation. There are 7 main gates and 17 off-take gates in the selected section,; hence, we have considered that the system is composed of seven subsystems. Each subsystem begins at one of the main gates and ends at the next one.



Task 6.4 and 6.5: Implementation of benchmark exercises

The objective of this task is the implementation of the experiments on the benchmark cases defined in Task 6.3. The main results on the different benchmark cases are:

Four-tank system

Seven different approaches were tested and compared, including two centralized MPC and a decentralized MPC. The tested algorithms were the following:

- Centralized MPC for tracking
- Centralized standard MPC for regulation
- Decentralized MPC for tracking
- Distributed MPC based on a cooperative game
- Sensitivity-Driven Distributed Model Predictive Control
- Feasible-cooperation distributed model predictive controller based on bargaining game theory concepts
- Serial DMPC scheme

The last four ones are distributed MPC algorithms developed by HD-MPC Consortium.

The evaluation and comparison between the different controllers have been performed according to the following indices;

- Controller properties
    - Modeling requirements: the class of models considered by each of the controllers, for instance linear/nonlinear, plant model or subsystem model, etc.
    - Controller objectives: the properties addressed by the tested controllers, for instance optimality, constraint satisfaction, stabilizing design, recursive feasibility, etc.
    - Auxiliary software needed: optimization routines, simulation routines, etc.

- Performance evaluation
    - Performance index: a measure of the performance of the controlled plant.
    - Performance index during the transient: a measure of the performance during the transient to remove the effect of steady offset.

- Settling time: a measure of the velocity of the controlled plant calculated by summing the settling times after all steps in the reference.
- Number of floating point reals transmitted between the controllers per iteration.
- Number of data packets transmitted during a sampling time.

These controllers were based on different models and assumptions and provide a broad view of the different distributed MPC schemes developed within the HD-MPC project. The results obtained show how distributed strategies can improve the results obtained by decentralized strategies using the information shared by the controllers.

This work has been published in the Journal of Process Control (vol. 21, no. 5, June 2011) and it is in the 4th place in the list of the most downloaded papers of the Journal of Process Control in the period April-June 2011 (see www.elsevier.com/locate/jprocont).
A complete description of the algorithms and results can be found in Deliverable D6.4.1 (Chapter 3) and Deliverable D6.5.1.

Another work deals with the problem of the loss of performance of the pair observer-controller, when measurements have a delay due to communication over networks. Here we consider the case where the estimation of the states is carried out using a moving horizon estimator (MHE), the control actions are computed by using a centralized model predictive controller (MPC), and the delay varies randomly and is n times the sampling time. In order to tackle the loss of performance associated with the pair MHE-MPC, an MHE with variable structure is proposed. The resulting pair MHE-MPC was tested using the four tank process as a test bed showing an improvement on the performance.

Heat system

The two-dimensional heat system benchmark has been used to compare various centralized, decentralized and distributed Kalman filters (See deliverable D6.4.1-Chapter 1). The methods that are compared are:

- CKF - Centralized Kalman filter
- PIF - Parallel information filter
- DIF - Decentralized information filter
- DHKF - Decoupled hierarchical Kalman filter
- DFFWA - Distributed Kalman filter with weighted averaging
- DKFCF - Distributed Kalman filter with consensus filters
- DKFBFG - Distributed Kalman filter with bipartite fusion graphs

The obtained results show that, in general, the DKFCF and the DHKF give the smallest errors. Of these two, the DHKF yields more variation than the DKFCF.

Electric power system

A centralized MPC is formulated for the control of generation units of an electric power network. Due to the different time scales of the machines' dynamics, a two levels time-response-based hierarchical structure is proposed. The proposed control structure involves the interaction among the centralized MPC and classical voltage and speed regulators.

Chemical system

Another work performed by UNC studies the application of Infinite Horizon Model predictive Control (MPC) and model reduction by means of Hankel norm to chemical process of interest in the field of control of large, complex and networked systems. In this paper we first described the model of the complete process which is composed by three reactors and three distillation columns. Later, we show the main aspects about model reduction by means of Hankel norm and Infinite Horizon MPC and finally the model obtained through numerical linearization and model reduction is used to design centralized Infinite Horizon Model predictive Control (MPC). This work has been presented in the Conference IEEE LARC & CCAC, Colombia, 2011.

Hydropower Valley

The following approaches have been applied to the proposed benchmark by the HD-MPC consortium.

- Approximate subgradient method.
- Hierarchical MPC controller with RTO (Real-Time Optimizer) coordinator
- Distributed MPC controller with RTO coordinator
- S-DMPC - linear quadratic constrained optimal
- Multiple shooting for distributed system
- Distributed model predictive control based on a cooperative game

The results of these DMPC controllers are reported in Deliverable D7.1.3 (Report that presents the closed-loop validation results for the combined cycle start-up and for the hydro-power valley, including stability and constraints issues), as well as the HD-MPC demonstration of results.

Additionally, a paper using game theory to formulate a distributed model predictive control scheme to control a hydro-power valley has been submitted to 2012 American Control Conference, Montreal, Canada. The proposed control scheme is tested by using a power reference tracking scenario as a test bed.

Irrigation Canal

A hierarchical and distributed model predictive control approach applied to irrigation canal planning from the point of view of risk mitigation has been developed in HD-MPC Project. This approach has been applied successfully to the Irrigation Canal Benchmark. The algorithm presents two levels in optimization. At the lower level, a distributed model predictive controller optimizes the operation by manipulating flows and gate openings in order to follow the water level set-points.

The higher level implements a risk management strategy based on the execution of mitigation actions if risk occurrences are expected. Risk factors such as unexpected changes in demand, failures in operation or maintenance costs are considered in the optimization. Decision variables are mitigation actions which reduce risk impacts that may affect the system. This work shows how model predictive control can be used as a decision tool which takes into account different types of risks affecting the operation of irrigation canals.

A complete description of the algorithm and the results can be found in deliverables D7.3.3 and D6.5.1. Also, this work has been published in the Journal of Process Control (vol. 21, no.5, June 2011).

Task 6.6: Dissemination of benchmarking and results

The objective of this task is to disseminate the benchmarking activity inside and outside the project.

The dissemination activities related to WP6 consist mainly in the publication of documentation in the public HD-MPC website, the use of the Virtual Portal (for consortium internal dissemination and the publication of some papers in Journals and Conference proceedings describing results of any of the benchmark.

- HD-MPC website: http://www.ict-hd-mpc.eu
- Virtual Portal: http://nyquist.us.es/hdmpcproject

External Dissemination

The consortium has defined to the benchmarks as public cases, in such a way that all the documentation is available to the control community to test their distributed approaches and compare them with the results of the HD-MPC consortium approaches. The two public benchmark cases are:

- Four-tank system (Simulated results)
- Hydropower valley

The following information has been uploaded and available in the public HD-MPC website related to each one of the benchmarks:

- Description of the system, including the proposed subsystem decomposition
- Objectives and description of the experiment, including a cost function
- Non-linear model to be used as a simulation model
- Linear model for linear MPC approaches
- Results of different approaches (centralized and decentralized MPC are available for the four tank systems), including experimental results and performance criteria.

Also, the following publications are directly related to benchmark cases:

[1] I. Alvarado, D. Limon, D. Muñoz de la Peña, J.M. Maestre, M.A. Ridao, H. Sheu, W. Marquart, R.R. Negenborn, B. De Schutter, F. Valencia and J. Espinosa, “A comparative analysis of distributed MPC techniques applied to the HD-MPC four-tank benchmark”. *Journal of Process Control*. vol. 21, no. 5, June 2011, pp. 800-815.

[2] C. Savorgnan, C. Romani, A. Kozma and M. Diehl, “Multiple shooting for distributed systems with applications in hydro electricity production”. *Journal of Process Control.* vol. 21, no. 5, June 2011.pp. 738-745

[3] A. Zafra-Cabeza, J.M.Maestre, M.A. Ridao, E.F. Camacho and L. Sanchez, “A hierarchical distributed model predictive control approach to irrigation canals: A risk mitigation perspective”. *Journal of Process Control*. vol. 21, no. 5, June 2011. pp. 787-799.

[4] A. Zafra-Cabeza, J.M. Maestre, M.A. Ridao, E.F. Camacho and L. Sanchez, “Hierarchical Distributed Model Predictive Control: An Irrigation Canal Case Study”. *American Control Conference 2011*. pp. 3172-3177.

[5] C. Savorgnan, A. Kozma, J. Andersson, M. Diehl, “Adjoint-Based Distributed Multiple Shooting for Large-Scale Systems”. *Proceedings of the 18th IFAC World Congress,* 2011.

[6] A. Ferramosca, D. Limon, J.B. Rawlings, E.F. Camacho, “Cooperative Distributed MPC for Tracking”. *Proceedings of the 18th IFAC World Congress*, 2011.

[7] A. Marquez, C. Gomez, and J.Espinosa, “Infinite Horizon MPC and model reduction applied to large scale chemical plant". *IEEE LARC & CCAC*, Colombia, 2011.

[8] F. Valencia, J.D. Lopez, J.A. Patiño, and J.J. Espinosa, “Game theory based distributed model predictive control for an hydro-power valley", *2012 American Control Conference*, Montreal, Canada, June 27-19, 2012 (Submitted).

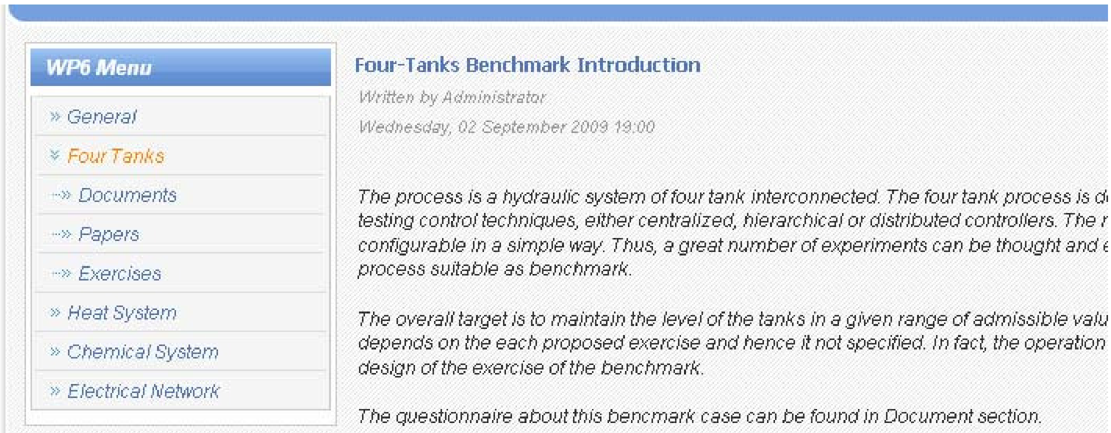
[9] F. Valencia, J.D. Lopez, A. Marquez, and J.J. Espinosa, “Moving horizon estimator for measurement delay compensation in model predictive control schemes", *50th IEEE Conference on Decision and Control and European Control Conference IEEE CDC-ECC*, Orlando, Florida, Dec., 2011.

As already indicated before, it is important to remark that the paper "A comparative analysis of distributed MPC techniques applied to the HD-MPC four-tank benchmark", published in the Journal of Process Control (vol. 21, no. 5, June 2011) is in the 4th place in the list of the most downloaded papers of the journal in the period April-June 2011 (see www.elsevier.com/locate/jprocont).

Internal Dissemination

The objective of the Virtual Portal is to permit the communication among HD-MPC partners and to share experiences, documentation and software in a virtual space. Also, it serves as a document repository and distribution tool among all project participants, ensuring the privacy requirements of contents.

The Virtual Portal includes a section dedicated to WP6, where the consortium participant can find documentation, model guides, models, experiment description, results, etc., about the six benchmark cases used in the project.



Resources

Resources for this work package have been used as planned in the updated description of work.

WP7: Validation and applications on simulated plants

Objectives

The goal of this work package is to apply and to demonstrate the methods and algorithms developed in the other work packages on three applications:

- the start-up of a combined cycle plant (Task 7.1),
- the operations of a hydro power valley (Task 7.2),
- short-term and long-term control of a large-scale water capture system. (Task 7.3)

Progress and achievements

Task 7.1: Application to the start-up of a combined cycle plant

The new constraints on the operational exploitation of the power grid lead to the deployment of Combined Cycle Power Plants that are used to react to grid requirements. Such plants are then frequently started up and shut down and the optimization of these phases is very important. The most critical phase is the start up of the plant because the objective is to reduce the time and the energy required to operationally connect the plant to the grid while minimizing the life-time consumption of the plant.

The aim of Task 7.1 was to assess the potential gains of MPC, and particularly of Hierarchical and Distributed MPC to startup optimization. However the modeling of the plant that is necessary for the implementation of this control is time-consuming because the behavior of the plant is highly non-linear and complex. An additional aim was then to consider the use of models developed during the design phases for the control of the start-up.

Task 7.1.1: Control specification

During the first year the analysis of the process and the start-up procedure has lead to the specification of the control problem and its validation. The structure and the parameters of the test case plant have been fixed and the set of operational constraints and objectives has been specified. The start-up sequence has also been specified with the local objectives and constraints of each phase.

Task 7.1.2: Modeling

During the second year the model of the test case plant has been developed. This model is a simulation model of CCPP with one level of pressure based on a very detailed Modelica model of a combined cycle plant previously developed at the Politecnico di Milano and provided to each project partner. It is written in Modelica and based on the Modelica ThermoPower library. Various components have been parameterized and associated to set up the model. The consistency of the behavior of the plant has been studied by extensive simulation.

As the optimization algorithms developed by the partners of the project require the gradient of the objective function, it has been decided to develop a smooth model of the plant that can be derived from the simulation model. For each used component of the ThermoPower and the Media libraries a smooth version was developed. These new components are based on smooth approximations of the discontinuities and table functions that are included in the original libraries and are fully consistent with the original ones. Simulations have been used to validate the behavior of this new model. These two models have been made available for all partners on the virtual portal of the project.

Based on the Modelica model, a simplified non linear transfer function model of CCPP has been derived too. Specifically, local linear models have been identified at different Gas Turbine load with step responses simulated on the Modelica model. Then, these linear models have been interpolated with membership functions depending on the Gas Turbine load. The non-linear transfer function and the Modelica model have been compared on small and big transients with satisfactory results. Therefore, the interpolated transfer function model has been considered to be sufficiently precise so that it could be used in the next stage of the project [1].

Task 7.1.3: Validation of methods for hierarchical and distributed MPC

First, the open loop optimization of the load profile has been considered. This optimization is a minimal time problem under constraints on stress in the steam turbine and the header of the high pressure superheater.

At the beginning of the third year it appeared that it was not yet possible to use the smooth Modelica model with optimization tools such as DyOs or J-Modelica that were not able to cope with its complexity. However, the simulation of the smooth model is faster (with a factor ten) than the one of the original ThermoPower model, it has then been used for black box optimization of the last phase of the start-up procedure (the increasing load phase).

A novel model-based approach to the optimization of the Gas Turbine (GT) load profile to be used in the start-up phase has been proposed by POLIMI and developed by considering the simplified interpolated model as the reference one. This model is used to compute the optimal load profile during the start-up by assuming that it can be described by a parameterized function, whose parameters are computed by solving a minimum-time optimal control problem subject to the constraints imposed by the plant dynamics and by the maximum peak value of the stress. In order to test the viability of this approach, computed the optimal load profile has been applied to simulate a start-up procedure on the original detailed Modelica simulator, so validating the overall project. This activity, which is based on the cooperation between Politecnico di Milano, EDF, and Supelec, has been extensively described in [1].

The optimization procedure based on the choice of parameterized function in order to convert the continuous optimization problem into a discrete one has been refined during the last year [2]. Various types of parameterized functions have been considered, including polynomial functions, in order to study the trade-off between the complexity of the optimization, mainly linked to the number of parameters that define the polynomial functions, and the start-up time performance. This study demonstrates that the choice of 2nd-order spline functions leads to 30% shorter start-up time than the classical choice of ramps. Some other experiments also demonstrated that the joint optimization of the load and the admission valve profile does not worth the complexity increase.

Some experiments of load optimization with the tool JModelica.org have also been performed on a simpler subsystem. The comparison with the results of black box optimization performed on the same system demonstrates that the results are equivalent but the optimization procedure is much more efficient with JModelica.org. Unfortunately, J-Modelica was not able to take into account the complete model.

In a second phase, a closed loop approach has been considered and MPC of the load profile based on the black box open loop optimization using the smooth model has been implemented.

A centralized MPC has been firstly developed. The criterion is then quadratic and aims at maximizing the load under the stress constraints. The trade-off between the performance, the complexity of the computation and the regularity of the control with respect to the length of the prediction horizon and the type of profile functions has been studied. It shows that the periodic computation of the profile leads to a 49% shorter start-up time than a fixed ramp profile.

In order to make the computation performed at each instant simpler, a hierarchical approach has been implemented in a second stage. At the higher level a minimal time optimization is performed periodically at a long period. The result is used to generate the reference for the lower level, where a quadratic optimization is performed at a shorter period as for the centralized MPC. This approach leads to equivalent start-up time with shorter computation time.

Finally, the distribution of control has been studied. As the algorithms proposed by the project are based on the computation of the gradients, simpler communication based algorithms have been considered. This demonstrated that is very difficult to split the plant because the various subsystems are interacting by mean of steam, the characteristics of which (pressure, flow, enthalpy) are very dependent on each other. Moreover the ability to perform simulations is very sensitive to the profile proposed by the optimization procedure. When the simulation fails no information is returned to the optimization.

To conclude, during this project the control problem of start-up of combined cycle power plant has been specified. A Modelica simulation model has been built and the components to systematically derive a smooth model have been defined. Open Loop optimizations, firstly developed for interpolated transfer function and then applied to Modelica smooth models, and also MPC implementations have demonstrated that important gains can be achieved for the start-up time and the energy consumption. However the available tools are not mature enough to take into account the complexity of the model built for design simulation and to make it possible to use efficient nonlinear optimization algorithm. A first difficulty is related to the use of object oriented capacities of the modeling language that are used in the model. This requires extensions for partners' tool that are at time being under investigation. However even for tools that can handle it, such as JModelica.org, a second difficulty appears. It is related to the complexity of the implicit non-linear system that has to be solved. The developers of the JModelica.org tool are not partners of this project but interactions with them have been set up to solve the problem in the future.

A simple hierarchical approach has been proposed and implemented to make the optimization computation simpler and evaluate what could be done with such approaches. However there is no theoretical guaranty about optimality or stability of this solution. In order to implement more theoretically based hierarchical approaches such as the ones proposed in this project it is necessary to include some considerations about robustness with respect to the lower level. It is then necessary to apply min-max approaches to be able to take into account some variations of parameters in the simulations used for optimization what is quite impossible at the moment. The approaches based on invariant set computations are also impossible to implement with this type of models.

Finally, one specific aspects of this type of process is that they are difficult to simulate. During the optimization process it happens that the simulation fails. The implicit constraints defined by these limits on simulation are difficult to make explicit but are very important to help the optimization procedure.

Task 7.2: Application to the operation of a hydro power valley

Hydro Power Valleys are also a kind of power plant for which Hierarchical and Distributed Model Predictive Control approaches are pertinent. Each plant is then equipped with local controllers and the coordination is often done by the operator who imposes flow or level set-points. In this task the use of HD-MPC methods to optimally coordinate the power plants of one valley is investigated.

Task 7.2.1: Control specification

In the first year of the project, EDF has selected a case study that contains high head and cascade run-of-river power plants. The system consists of 9 subsystems that are interconnected. Three objectives functions have been defined so far that correspond to different goals (maximization of the power produced, minimization of the power regulation error, distributed regulation problem). The constraints on the actuator and on the state have been defined as well as the tests to check the robustness of the solution. A method to coordinate the global and local optimization has been proposed.

Due to confidentiality reason, an exhaustive description and of the model for the case study was not possible and a Public Benchmark has been developed and made available from the HD-MPC portal. This new plant contains 6 reaches and 3 lakes. The Public Benchmark contains also the different constraints and the objective function to minimize. In subtasks 7.2.1 to 7.2.3 of Task 7.2 we have focused on the EDF case study as defined in the initial Description of Work. The case of the Public Benchmark has been treated in a separate subtask 7.2.4 that has been added during the last year of the project in the updated Description of Work of 08/06/2011.

Task 7.2.2: Modeling

During the second year of the project, models have been developed in order to simulate and to optimize the control of the whole valley. First, a detailed model based on 1D Saint-Venant equations has been developed using the Mascaret and Scicos software. This model integrates a precise geometry of the reaches and uses a finite difference scheme to solve the Saint-Venant equations. A simulation platform has been set up for final validation. This platform is made up of the Mascaret-Scicos model, Matlab and an OPC data server. The Mascaret model was however found too complex to be used for control design. To this end, a non-linear model has been developed in cooperation with the HD-MPC project partners.

A Simulink model of the Hydro Power Valley (HPV) has been developed by POLIMI. The parameters have been tuned to fit the SciCos/Mascaret model as much as possible. The reach models are derived from the Saint-Venant equations with a spatial discretization. The model has been used to design a centralized MPC, so that to allow for fair comparisons of the performance provide by distributed MPC algorithms developed in the project. The equations developed for the Case Study have been reused for the HPV Public Benchmark.

Task 7.2.3: Validation of methods for hierarchical and distributed MPC

Many of the distributed MPC algorithms developed inside the HD-MPC project have been derived under the main assumption that the system state is known. As a matter of fact, this hypothesis is generally not realistic, and this is in particular true in the case of the HPV, where most of the states coincide with the levels and the flows at different sections of the reaches.

For these reasons, in any realistic application of the distributed control algorithms it is mandatory to use a state observer, which must be distributed itself to guarantee the distributed nature of the overall control project. Therefore, the distributed state estimation algorithm previously developed in WP5 for linear systems and described in [3] has been extended to the case of partitioned systems with nonlinear dynamics in [4]. The proposed partition-based MHE has been applied to the problem of estimating the levels and flow rates in the model of three cascade river reaches. Interconnections between successive reaches are due to the dependence of the input flow rate of the downstream reaches to the level of the final section of the upstream ones, which cannot be measured, but just estimated from the available measures collected along the reach. The results achieved, which are also extensively described in [4] show that the proposed approach allows one to estimate the system's state in a distributed way with a high level of accuracy.

A HD-MPC solution has been developed for the Case Study during the project.

A first approach applied in [5] and analogue to the approach adopted for the CCPP Case Study was to optimize directly the objective functions with intensive non linear simulations done. SNOPT and KNITRO have been used with the Tomlab interface. The advantages of this approach are that it is straightforward and handles all nonlinearities. The drawback is that the convergence is not guarantied and can be very slow.

A solution based on linear model has been developed in the last year and is described in the deliverable D.7.3.3. This formulation leads to a linear constrained Quadratic Problem which can efficiently be solved by existing solver like SNOPT available with Tomlab. Tests with the nonlinear simulation model show good performance even in case of disturbance and model error.

To conclude, during the project the problem of controlling an HPV with an HD-MPC approach has been addressed. A case study made of 4 rivers reaches and 5 lakes has been proposed. The solution proposed for this case study consists of two layers. The upper level computes the power and level references for the lower level and the lower level consists of local MPC controllers that follow the references in spite of the perturbations. An aggregation of the local state estimators has been developed too to give a state of the whole valley required for the upper level. The proposed solution has been tested in simulation against perturbations and model errors and seems to be robust. A lot of work has been done to find a solution and little has been done to assess the interest of this approach. In fact, it is difficult to assess its value in our case for several reasons. First, there is no other upper level controls to compare with (the optimization is generally done by the operator). Second, it is difficult to replay a transient because there are a lot of operating conditions that are not recorded. However, it seems that the solution developed in the HD-MPC project has the potential value to help the operator in his daily tasks and it is worthwhile to go from the case study to a real application. An intermediary stage would be to keep the operator in the loop and to validate the references proposed by the upper level, before leaving the loops in automatic modes. The implementation of the local controllers will probably be more difficult to do in a real plant, because local PLC does not always accept MPC controllers. Further refined tests will certainly be needed to convince the operator before an industrialization of the solution on a real plant.

Task 7.2.4: Demonstration of HD-MPC results

HPV optimization has been chosen by the partners as a main problem to be addressed in the last year of the project. Due to confidential reason, a Public Benchmark has been developed and put on the HD-MPC portal. This benchmark consists of 6 reaches and 3 lakes. Equations initially developed for the case study have been used for the Public Benchmark. The project focused on the tracking problem and aimed at an economical assessment too. The description of the Public Benchmark is available from the HD-MPC portal.

Five different control approaches have been implemented for the public benchmark:

- RWTH has implemented an S-DMPC controller for the HPV. Further, a two-layer architecture on the HPV has been envisaged. This consists of a slow controller solving a rigorous nonlinear optimal control problem, while the fast distributed controller tracks the references on a faster time-scale.

- KUL has developed a nonlinear model based optimal control with L1 (power tracking) and L2 (state tracking) terms. Two methods have been implemented for which a convergence analysis has been carried out:
    - an exact SQP method based on Distributed Multiple Shooting
    - an inexact SQP method using adjoint-based distributed multiple shooting.
- TUD has implemented a solution for the power reference tracking with the following characteristics:
    - Use of a reduced order linearized, discrete-time model.
    - Cost function: 1-norm term for power tracking, 2-norm term for state penalty).
    - Use of a double-flow model to deal with the discontinuities of the combined pump and turbine.
    - Horizon length $N = 10$.
    - Simulation time: 48 steps (1 day).

  The algorithm has a distributed nature, aiming to solve the centralized problem at each time step (we let the algorithm runs till convergence, so basically the centralized MPC problem is solved).
- USE and TUD proposed a distributed MPC solution based on agent negotiation.
- UNC made a hierarchical solution with a coordinator that solves an infinite horizon MPC with zone control and local controllers solving an infinite horizon MPC control problem for each subsystem.

A power tracking scenario has been used to test the algorithms: the power output of the system should follow a given reference while keeping the water levels in the lakes and at the dams as constant as possible.
Economic indexes have been defined to compare the different approaches. Also the performance with constraints and communication requirements of the distributed approaches have been considered. The best results are obtained with the Distributed Multiple Shooting approach, with a nearly perfect tracking and a negligible economic cost. Good results are also obtained with the Fast Gradient-based DMPC approach and with the hierarchical infinite horizon MPC approach.

Task 7.3: Short-term and long-term control of a large-scale water capture system

Task 7.3.1: Modeling for hierarchical and distributed MPC

During the first and the second years of the project, the following actions have been performed jointly by INOCSA and USE:

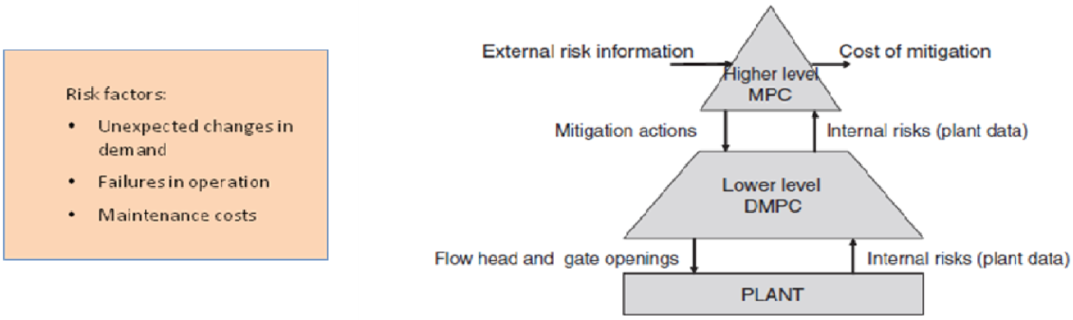
- Detailed study of the management that is being performed, the current control techniques and the elements which constitute the "Canales del Bajo Guadalquivir" (South of Spain) and the "Canales del Postrasvase Tajo-Segura" (South- East of Spain).
- Formulation of the general HD-MPC problem applied to these kinds of canals and the related constraints.
- Development of a simulation platform in SIC to test distributed controllers in the field of Water Capture System applications. This work is closely related to the Irrigation Canals benchmark of WP6, which was decided to be a part of the Postrasvase Tajo-Segura (see section regarding WP6). The advantage of SIC is an easy integration with MATLAB, then the controller can be developed using this tool. A SIC model of the benchmark was produced during the second year.
- Also the "Canales del Bajo Guadalquivir" were modeled in HEC-RAS.

During the third year of the HD-MPC project, USE has developed multivariable control models of the "Canales del Postrasvase Tajo-Segura" oriented both to upstream and downstream control. The models have been obtained using identification methodologies with the simulation tool SIC, using techniques such as least squares and also the linear parametric model and process model of the System Identification Tools of MATLAB.
The models obtained are in general of first and second order with delays.

Task 7.3.2: Predictive management of water resources

During the project, a hierarchical and distributed MPC algorithm has been developed to be applied to the benchmark regarding Irrigation Canals (IC).

Two levels of hierarchy are defined in this algorithm: In the upper level, risk management is used to optimize the Irrigation Canal operation in order to consider the process uncertainties. A centralized MPC is used in the optimization, and it determines the optimal water levels of reaches taking into account the benefits and costs associated to IC. In the lower level, a DMPC based on game theory drives the IC to the given set points.



This approach has been published in [6] and [7].

The HD-MPC deliverable D.7.3.3 presents all the results obtained during the execution of the project HD-MPC regarding the modeling and control of Irrigation Canals (IC), including results and conclusions of the tests developed with the IC benchmark.

References

[1] F. Casella, M. Farina, F. Righetti, R. Scattolini, D. Faille, F. Davelaar, A. Tica, H. Guéguen, and D. Dumur, "An optimization procedure of the start-up of combined cycle power plants", *Proceedings of the 18th IFAC World Congress*, Milan, Italy, 2011.

[2] A. Tica, H. Guéguen, D. Dumur, D. Faille, F. Davelaar, "Optimization of the combined cycle power plants start-up", *Proceedings of the 54th ISA Power Industry Symposium 2011 (POWID 2011)*, Charlotte, NC, USA, 2011.

[3] M. Farina, G. Ferrari-Trecate, and R. Scattolini, "Moving horizon state estimation of large-scale constrained partitioned systems", *Automatica*, vol. 46, no. 5, pp. 910-918, 2010.

[4] M. Farina, G. Ferrari-Trecate, C. Romani, and R. Scattolini, "Moving horizon estimation for distributed nonlinear systems with application to cascade river reaches", *Journal of Process Control*, vol. 21, no. 6, pp. 767-774, 2011.

[5] F. Petrone, Model Predictive Control of a Hydro Power Valley, MSc thesis, Politecnico di Milano, 2010.

[6] A. Zafra-Cabeza, J.M. Maestre, M.A. Ridao, E. F. Camacho, and L. Sánchez, "A hierarchical distributed model predictive approach to irrigation canals: a risk mitigation perspective", *Journal of Process Control*, vol 21, no. 5, pp. 787-799, June 2011.

[7] A. Zafra-Cabeza, J.M. Maestre, M.A. Ridao, E. F. Camacho, and L. Sánchez, "A hierarchical distributed model predictive control: an irrigation canal case-study", *Proceedings of the 2011 American Control Conference*, pp 3172-3177, 2011.

Resources
Resources for this work package have been used as planned in the updated description of work.

WP8: Dissemination

Objectives

The goal of this work package is to publicize the results of the project towards a broad audience including academia, industry, and other interested parties. This will be done via various channels, including press releases, a web site, papers and special issues in international journal papers, papers and special sessions at international conferences, scientific presentations, demonstrations, open-source software releases, technical reports, a publicly available database of benchmark problems, and the organization of an international workshop.

The project undertakes to establish a web site supported by the project partners, to provide a unified view of the project; a copy thereof will be included in the Dissemination Package.

The project will also actively participate in the concertation activities organized at ICT Programme level relating to the area of Wireless Sensor Networks and Cooperating Objects, involving ongoing FP6 and FP7 projects in this area, with the objective of providing input towards common activities and receiving feedback, contributing advice and guidance and receiving information relating to ICT programme implementation, standards, policy and regulatory activities, national or international initiatives, etc.

Progress and achievements

The main achievement of this work package for the reporting period are the publication a special issue of the *Journal of Process Control* on HD-MPC and the organization of two successful HD-MPC workshops, viz. the HD-MPC Industrial Workshop in Leuven, Belgium on June 24, 2011 and the final HD-MPC Workshop in Milano, Italy on August 28, 2011. Moreover, two special sessions on HD-MPC have been organized for the IFAC World Congress 2011 in Milano, Italy. In addition, the public website of the project (http://www.ict-hd-mpc.eu) and the Virtual Portal[9] (http://www.nyquist.us.es/hdmpcproject/) set up as part of Tasks 8.1 and 1.4 have been updated and are being maintained.

Task 8.1: Setting up a web site

A web site has been set up for the project by Bart De Schutter and Moritz Diehl. The web site, which can be found at the address http://www.ict-hd-mpc.eu, contains several sections to illustrate the project and the results achieved.

In addition to the project web site, a Virtual Portal has been set up by Miguel Ridao (see the activities reported for WP1), which can be found at http://www.nyquist.us.es/hdmpcproject/.

Task 8.2: Organizing special sessions at conferences or special issues of journals

Bart De Schutter and Riccardo Scattolini have organized as guest editors a special issue of the *Journal of Process* Control on “Hierarchical and Distributed Model Predictive Control” (vol. 21, no. 5, June 2011).

In addition, the following events have taken place

- Tamás Keviczky and Rudy Negenborn have organized an invited session on “Optimization Methods for Hierarchical and Distributed Model Predictive Control” at the 14th Belgian-French-German Conference on Optimization, Leuven, Belgium, September 14-18, 2009.

[9] This Virtual Portal contains all the data related to the work packages and other tools to improve the communication between the partners.

- Bart De Schutter, Rudy Negenborn, and Moritz Diehl have organized an invited session on “Hierarchical and Distributed Model Predictive Control" at the 2010 American Control Conference (ACC 2010), Baltimore, Maryland, USA, June 30-July 2, 2010.
- Bart De Schutter and Alfredo Nunez have organized two invited sessions on “Hierarchical and Distributed Model Predictive Control” at the 18th IFAC World Congress, Milan, Italy, August 28 – September 2, 2011

Task 8.3: HD-MPC workshop

Moritz Diehl and Riccardo Scattolini have organized the HD-MPC workshop on “Hierarchical and Distributed Model Predictive Control, Algorithms and Applications” on August 28, 2011 in Milan, Italy as a pre-congress workshop for the 18th IFAC World Congress, Milan, Italy.

The workshop presented the advances of the HD-MPC project in the field of hierarchical and distributed control and estimation for large-scale complex networked systems. Two main streams of HD-MPC research were covered. The first one refers to distributed optimization techniques for the solution of a centralized MPC problem. In this case, the goal is to decompose the optimization problem into a number of smaller and more easily tractable ones. In this framework, primal and dual approaches were considered. The second approach relies on the solution of a number of local control problems with information exchange among them. In this case, the control algorithm itself, rather than its numerical solution, is distributed. Convergence properties of the methods can be achieved by resorting to robust MPC algorithms, where the uncertainties are related to the mutual influences among the subsystems. In the same way, it was shown how to construct hierarchical control methods, where the hierarchical structure stems either from a structural decomposition of the system under control, or from its multi-level and multi time scale description.

A number of examples were discussed to witness the potentialities of the methods. In particular, reference was made to spatially distributed systems, such as irrigation channels and water networks. A complex application dealt with the control of a hydroelectric power valley, with five reservoirs, three river reaches and a number of additional plants (ducts, turbines, generators, dams). The design of a hierarchical control scheme for Combined Cycle Power Plants was also discussed.

For detailed information we refer to deliverable D8.3.1 (“Proceedings of the international HD-MPC workshop”) and to the HD-MPC website, in the topic “Events”.

Task 8.4: Industrial short courses

- Tamás Keviczky has co-organized (in cooperation with Siep Weiland and Mircea Lazar from Eindhoven University of Technology, Eindhoven, The Netherlands) the DISC Summer school on “Distributed Control and Estimation”, Noordwijkerhout, The Netherlands, June 2-5, 2009. This summer school was aimed at research students and staff members of DISC, as well as other researchers and engineers (including people from industry) engaged in the systems and control area.
- Moritz Diehl, Boris Houska, and Hans Joachim Ferreau organized an industrial course on “Automatic Control and Dynamic Optimization” on July 14-15, 2011 in Leuven, Belgium. The course covered several aspects of MPC for its application to real world scenarios.
- Moritz Diehl, Alfredo Núñez, Attila Kozma, Carlo Savorgnan, and Holger Scheu organized the international HD-MPC industrial workshop in Leuven, Belgium on June 24, 2011. This workshop consisted of three sessions:
    - Session 1 – Theory of Hierarchical and Distributed MPC
        - Carlos Bordons: Introduction to MPC

    - Bart De Schutter: Distributed and hierarchical MPC: Main concepts and challenges
- Session 2 – Methods and Software for Hierarchical and Distributed MPC
    - Moritz Diehl: Algorithms for nonlinear MPC of large scale systems
    - Holger Scheu: Dynamic real-time optimization
    - Riccardo Scattolini: Distributed predictive control and simplified implementations
- Session 3 – Industrial Application of Hierarchical and Distributed MPC
    - Laura Sánchez: HD-MPC approach to irrigation channels
    - Damien Faille: Optimization of combined cycle plants and hydro-power valleys
    - Carlo Savorgnan: Hydro Power Valley demo

More information can be found at the workshop website: http://www.kuleuven.be/optec/hdmpc-ind-ws

Resources

Resources for this work package have been used as planned in the description of work.

4. Deliverables and milestones tables

Deliverables (excluding the periodic and final reports)

Please list all the deliverables due in this reporting period, as indicated in Annex I of the Grant Agreement.
Deliverables that are of a nature other than written "reports", such as "prototypes", "demonstrators" or "others", should also be accompanied by a short report, so that the European Commission has a record of their existence.
If a deliverable has been cancelled or regrouped with another one, please indicate this in the column "Comments".
If a new deliverable is proposed, please indicate this in the column "Comments".

*This table is **cumulative**, that is, it should always show **all deliverables from the beginning of the project**.*

TABLE 1. DELIVERABLES[10]

Del. no.	Deliverable name	WP no.	Lead beneficiary	Nature	Dissemination level	Delivery date from Annex I (proj month)	Delivered Yes/No	Actual / Forecast delivery date	Comments
1.1	Report on the requirements for the virtual portal (D1.4.1)	1	TUD	R	PP	3	Yes	01-03-2009	
8.1	Report on the set-up of a web site including downloads of reports, presentations, open-source software and a database of benchmark problems (D8.1.1)	8	KUL	R	PU	3	Yes	01-03-2009	
2.1	Report on literature	2	POLIMI	R	PP	6	Yes	01-04-2009	

[10] For Security Projects the template for the deliverables list in Annex A1 has to be used.

	survey and preliminary definition of the selected methods for the definition of system decomposition and hierarchical control architectures (D2.1)								
4.1	Report of literature survey, analysis, and comparison of on-line optimization methods for hierarchical and distributed MPC (D4.1.1)	4	KUL	R	PU	6	Yes	28-08-2009	
4.2	Report of literature survey and analysis of optimization methods for MPC of uncertain large-scale systems (D4.2.1)	4	KUL	R	PU	9	Yes	21-09-2009	
6.1	Model guide and web-based computer tool for benchmarking (D6.2.1)	6	USE	R,O	PU	9	Yes	05-06-2009	
1.2	First annual progress report (D1.2.1)	1	TUD	R	RE	12	Yes	04-10-2009	
2.2	Report on the final assessment of the methods for the definition of the control architecture and preliminary report on extended algorithms coping with structural	2	POLIMI	R	PP	12	Yes	31-08-2009	

	constraints, changes, and multi-level models (D2.2)								
3.1	Report on literature survey on hierarchical and distributed nonlinear MPC, including analysis and comparison, and description of the resulting methodological framework (D3.1.1)	3	RWTH	R	PU	12	Yes	29-09-2009	
3.2	Report on readily available methods for simple toy problems (D3.1.2)	3	RWTH	R	PU	12	Yes	01-10-2009	
3.3	Report on literature survey and analysis of (optimization) methods for robust distributed MPC (D3.2.1)	3&4	RWTH	R	PU	12	Yes	28-08-2009	
4.3	Overview, toolbox and tutorial manual of existing state-of-the-art distributed optimization algorithms (D4.1.2)	4	KUL	R	PU	12	Yes	01-08-2009	
6.2	Documentation for benchmark cases (D6.3.1)	6	USE	R	PU	12	Yes	24-09-2009	This deliverable consists of 2 parts. Part I describes the four tank system and Part II describes the other three benchmark cases, viz., the chemical benchmark case, the electric power system, and the heat system.

7.1a	Report that defines the control specification for the combined cycle start-up (D7.1.1)	7	EDF	R	PU	12	Yes	03-09-2009	
7.1b	Report that defines the control specification for the hydro-power valley(D7.2.1)	7	EDF	R	PU	12	Yes	03-09-2009	
7.2	Report on meteorological forecasting models (D7.3.1)	7	EDF	R	PU	12	Yes	03-09-2009	
3.4	Report on assessment of existing coordination mechanisms for simple case studies, and on possible options for improving and extending these coordination mechanisms (D3.3.1)	3	RWTH	R	PU	15	Yes	01-12-2009	
2.3	Final report on the results regarding multi-level models and architectures for hierarchical and distributed MPC (D2.3)	2	POLIMI	R	PU	18	Yes	28-02-2010	
3.5	Report of literature survey and analysis regarding timing and delay issues (D3.4.1)	3	RWTH	R	PU	18	Yes	01-03-2010	
6.3	Report on results of hardware and	6	USE	R	PU	18	Yes	01-03-2010	

	software analysis (D6.1.1)								
6.4	Report on implementation for selected benchmarks (D6.4.1)	6	USE	R	PU	18	Yes	01-03-2010	
8.2	Report on or proceedings of special session at an international conference (D8.2.1)	8	KUL	R	PU	18	Yes	20-02-2010	
1.3	Second annual progress report (D1.2.2)	1	TUD	R	RE	24	Yes	01-09-2010 (scientific part)	The scientific part was delivered on 01-09-2010
1.4	Report on knowledge management, links with potential users of results, and future perspectives (D1.3.1)	1	TUD	R	RE	24	Yes	27-08-2010	
3.6	Report on new methods for complex control problems (nonlinear, dynamic, constrained) (D3.1.3)	3	RWTH	R	PU	24	Yes	27-08-2010	
3.7	Report on newly developed methods for hierarchical and distributed robust nonlinear dynamic MPC (D3.2.2)	3	RWTH	R	PU	24	Yes	27-08-2010	
3.8	Report on newly developed coordination mechanisms for hierarchical and distributed MPC (D3.3.2)	3	RWTH	R	PU	24	Yes	27-08-2010	

4.4	Report on redefinition of optimality criteria and generation of optimal solutions, and on analysis of sensitivity, scalability of solutions and computing cost (D4.2.2)	4	KUL	R	PU	24	Yes	26-08-2010	
5.1	Report on the state of the art in distributed state and variance estimation, and on preliminary results on disturbance modeling for distributed systems (D5.1)	5	POLIMI	R	PU	24	Yes	26-08-2010	
7.3a	Report that presents the model and open-loop simulation results for the combined cycle start-up (D7.1.2)	7	EDF	R	PU	24	Yes	28-08-2010	
7.3b	Report that presents the model and open-loop simulation results for the hydro-power valley (D7.2.2)	7	EDF	R	PU	24	Yes	28-08-2010	
7.4	Report on models of hydraulic transport systems (D7.3.2)	7	EDF	R	PU	24	Yes	01-09-2010	
8.3	Report on the organization of an industrial short	8	KUL	R	PU	24	Yes	26-08-2010	

	course (D8.4.1)								
3.9	Report on implementation of timing and delay related approaches to simple case studies (D3.4.2)	3	RWTH	R	PU	27	Yes	30-11-2010	
3.10	Report on extensive assessment of the developed coordination mechanisms, including case studies (D3.3.3)	3	RWTH	R	PU	30	Yes	01-03-2011	
4.5	Report on new algorithms with guaranteed convergence to an optimum of the global system, at a high rate of convergence, and with intelligent hot-starting (D4.1.3)	4	KUL	R	PU	30	Yes	01-03-2011	
5.2	Intermediate report on new methods for distributed state and covariance estimation for large-scale interconnected systems (D5.2)	5	POLIMI	R	PP	30	Yes	01-03-2011	
3.13	Software tool with different methods and variants for different problem classes (D3.1.4-software)	3	RWTH	D	RE	33	Yes	01-06-2011	This software can be downloaded from the HD-MPC Virtual Portal in the item “Deliverables”, subitem “WP3”.
4.6	Report on new	4	KUL	R	PU	33	Yes	01-06-2011	

	stochastic optimization methods for robust distributed MPC (D4.3.1)								
8.4	(Report on) special issue of an international journal (D8.2.2)	8	KUL	R	PU	33	Yes	14-05-2011	
3.11	Reports on the evaluation results, including economical potential and suggestions for real-life applications (D3.1.4)	3	RWTH	R	PU	36	Yes	31-08-2011	
3.12	Reports and publications on the evaluation results, impact on the economics and operability of distributed processes (D3.2.3)	3	RWTH	R	PU	36	Yes	01-09-2011	
5.3	Final report on new methods for distributed state and covariance estimation (D5.3)	5	POLIMI	R	PU	36	Yes	11-07-2011	
6.5	Final report on maintenance of benchmark service and dissemination results (D6.5.1/D6.6.1)	6	US	R	PU	36	Yes	01-09-2011	
7.6	Report on optimization of distribution of water (D7.3.3)	7	EDF	R	PU	36	Yes	01-09-2011	
8.5	Proceedings of the international HD-	8	KUL	R	PU	36	Yes	31-08-2011	

	MPC workshop (D8.3.1)								
7.5a	Report that presents the closed-loop validation results for the combined cycle start-up (D7.1.3)	7	EDF	R	PU	38	Yes	01-11-2011	
7.5b	Report that presents the closed-loop validation results for the hydro-power valley, including stability and constraints issues, as well as the HD-MPC demonstration of results (D7.2.3)	7	EDF	R	PU	38	Yes	01-11-201	This deliverable consists of 2 parts. Part I describes the work on the hydro-power valley and Part II describes HD-MPC demonstration of results using the public hydro-power benchmark.
1.5	Third annual progress report/Final report (D1.2.3)	1	TUD	R	RE	40	Yes	08-11-2011 (scientific part)	The scientific part was delivered on 08-11-2011

Milestones

Please complete this table if milestones are specified in Annex I of the Grant Agreement.
Milestones will be assessed against the specific criteria and performance indicators as defined in Annex I.

Note: Milestones for the current reporting period (M25-40) are indicated in bold italics.

TABLE 2. MILESTONES							
Milestone no.	**Milestone name**	**Work package no**	**Lead beneficiary**	**Delivery date from Annex I**	**Achieved Yes/No**	**Actual / Forecast achievement date**	**Comments**
M1.1.1	Kick-off meeting of the project	1	TUD	1	Yes	03-09-2009	See minutes of the kick-off meeting
M1.1.2	Installation of the steering committee	1	TUD	1	Yes	03-09-2009	See minutes of the kick-off meeting
M1.1.3	First annual meeting	1	TUD	12	Yes	09-09-2009	See minutes of the meeting
M1.1.4	Second annual meeting	1	TUD	18	Yes	03-09-2010	See minutes of the meeting
M1.1.5	***Third annual meeting***	***1***	***TUD***	***40***	***Yes***	***23-06-2011***	***See minutes of the meeting***
M1.4.1	Definition of the requirements for the virtual portal	1	TUD	3	Yes	01-03-2009	See Deliverable D1.4.1

M1.4.2	Implementation and opening of the virtual portal	1	TUD	6	Yes	01-05-2009	See Virtual Portal at http://www.nyquist.us.es/hdmpcproject/
M2.1	Analysis of the available methods for system decomposition	2	POLIMI	3	Yes	01-03-2009	See Deliverable D2.1
M2.2	Definition of decomposition procedures for distributed estimation and control	2	POLIMI	9	Yes	01-06-2009	See Deliverable 2.2
M2.3	New algorithms for the definition of multi-level models and architectures suitable for hierarchical and distributed MPC	2	POLIMI	15	Yes	01-12-2009	See Deliverable 2.3
M3.1.1	Analysis of existing methods for hierarchical and distributed nonlinear MPC, and simple own methods implemented and shared with partners	3	RWTH	12	Yes	01-09-2009	See Deliverable D3.1.1 and D3.1.2

M3.1.2	Methods developed for hierarchical and distributed MPC for complex control problems	3	RWTH	24	Yes	01-08-2010	See Deliverable D3.1.3
M3.1.3	***Evaluation of the results completed***	***3***	***RWTH***	***36***	***Yes***	***31-08-2011***	***See Deliverable D3.1.4***
M3.2.1	Analysis of existing (optimization) methods for robust distributed MPC	3 & 4	RWTH	12	Yes	01-09-2009	See Deliverable D3.2.1
M3.2.2	***Methods developed for decentralized robust nonlinear dynamic MPC problems***	***3***	***RWTH***	***27***	***Yes***	***27-08-2011***	***See Deliverable D3.2.2***
M3.2.3	***Validation and evaluation of robust methods***	***3***	***RWTH***	***36***	***Yes***	***01-09-2011***	***See Deliverable D3.2.3***
M3.3.1	Newly developed coordination mechanisms for hierarchical and distributed MPC	3	RWTH	24	Yes	01-09-2010	See Deliverable D3.3.1 and D3.3.2

M3.3.2	***Extensive assessment of the developed coordination mechanisms completed, including case studies***	***3***	***RWTH***	***30***	***Yes***	***01-03-2011***	***See Deliverable D3.3.3***
M3.4.1	Assessment of existing methods to deal with timing and delay issues, and identification of most appropriate methods including options and ways to extend them	3	RWTH	18	Yes	01-03-2010	See Deliverable D3.4.1
M3.4.2	***New methods for dealing with timing and delay issues in hierarchical and distributed MPC***	***3***	***RWTH***	***27***	***Yes***	***01-12-2010***	***See Deliverable D3.4.2***
M4.1.1	Analysis of suboptimality of existing algorithms	4	KUL	9	Yes	01-06-2009	See Deliverable D4.1.1

M4.1.2	***Development of new methods with guaranteed convergence and high rate of convergence (with an emphasis on increased optimality, speed of convergence, efficiency, and on-line applicability)***	***4***	***KUL***	***30***	***Yes***	***01-03-2011***	***See Deliverable 4.1.3***
M4.2.1	Choice of appropriate tools for optimization of uncertain large-scale systems, and redefinition of the optimality criteria	4	KUL	12	Yes	01-09-2009	See Deliverable D4.2.1
M4.3.1	***New stochastic optimization methods for robust distributed MPC***	***4***	***KUL***	***33***	***Yes***	***01-06-2011***	***See Deliverable D4.3.1***
M5.1	Analysis of the available methods for distributed state and variance estimation	5	POLIMI	21	Yes	01-06-2010	See Deliverable D5.1

M5.2	***Definition of new algorithms for distributed state estimation and of new methods for the choice of the number and location of integrating disturbances***	***5***	***POLIMI***	***27***	***Yes***	***01-12-2010***	***See Deliverable D5.2***
M5.3	***New methods for distributed variance estimation***	***5***	***POLIMI***	***33***	***Yes***	***01-06-2011***	***See Deliverable D5.3***
M6.1.1	Selection of the best choices for hardware and software	6	USE	18	Yes	01-03-2010	See Deliverable D6.1.1
M6.2.1	Distribution of the model guide and opening of the web-tool	6	USE	9	Yes	01-06-2009	See Deliverable D6.2.1
M6.4.1	Selection of the benchmark proposals	6	USE	15	Yes	1-12-2009	See HD-MPC Virtual Portal and Deliverable 6.4.1
M6.6.1	***Results of benchmark proposals shared with partners and other interested parties***	***6***	***USE***	***36***	***Yes***	***01-09-2011***	***See the HD-MPC Virtual Portal, Deliverable D6.5.1/D6.6.1, and published conference and journal papers, in particular:*** ***I. Alvarado, D. Limon, D. Muñoz de la Peña, J.M. Maestre, M.A. Ridao, H. Scheu, W. Marquardt, R.R. Negenborn, B. De Schutter, F. Valencia, J. Espinosa, "A comparative analysis of distributed MPC techniques applied to the HD-MPC four-tank benchmark",*** **Journal of Process Control,** ***vol. 21, no. 5, pp. 800-815, June 2011***

M7.1.1/M7.2.1	Control specification for the combined cycle start-up and for the hydro-power valley available	7	EDF	12	Yes	01-08-2009	See Deliverables D7.1.1 and D7.2.1
M7.1.2/M7.2.2	Model and open-loop simulation results for the combined cycle start-up and for the hydro-power valley available	7	EDF	24	Yes	01-08-2010	See Deliverables D7.1.2 and D7.2.2
M7.1.3/M7.2.3	***Closed-loop validation results for the combined cycle start-up and for the hydro-power valley available, including stability and constraints issues, as well as the HD-MPC demonstration of results***	***7***	***EDF***	***40***	***Yes***	***01-11-2011***	***See Deliverables D7.1.3 and D7.2.3 (Part I & Part II)***
M7.3.1	Meteorological forecasting model	7	EDF	12	Yes	01-08-2009	See Deliverable D7.3.1

M7.3.2	Predictive model of hydraulic transport systems	7	EDF	24	Yes	01-08-2010	See Deliverable D7.3.2
M7.3.3	***Methods and/or tools to optimize the distribution of water***	***7***	***EDF***	***36***	***Yes***	***01-09-2011***	***See Deliverable D7.3.3***
M8.1.1	Opening of a web site including downloads of reports, presentations, open-source software and a database of benchmark problems	8	KUL	6	Yes	01-04-2009	See the HD-MPC web site at http://www.ict-hd-mpc.eu
M8.2.1	Organization of special session at an international conference	8	KUL	15	Yes	01-12-2009	See Deliverable D8.2.1 and the on-line program of the BFG'09 conference at www.cs.kuleuven.be/conference/bfg09/ as well as the on-line program of the ACC 2010 conference at http://css.paperplaza.net/conferences/conferences/2010ACC/program
M8.2.2	***Organization of special issue of an international journal***	***8***	***KUL***	***27***	***Yes***	***01-12-2010***	***See Deliverable D8.2.2 and the Special Issue of the*** **Journal of Process Control,** ***vol. 21, no. 5, June 2011***

M8.3.1	***Organization of an HD-MPC international workshop and publication the workshop proceedings***	***8***	***KUL***	***36***	***Yes***	***01-09-2011***	***See Deliverable D8.3.1 and the web page*** ***http://www.ict-hd-mpc.eu/index.php?page=ifac_workshop***
M8.3.2	***Communication of the project results to the scientific community***	***8***	***KUL***	***36***	***Yes***	***01-09-2011***	***Conference and journal paper , conference presentations, HD-MPC workshop*** ***See http://www.ict-hd-mpc.eu/index.php?page=publications and the list of publications and presentations in Section 5 below***
M8.4.1	Communication of the project results to industry by organizing industrial short courses	8	KUL	24	Yes	01-09-2010 (for the DISC Summer School and the PAO lecture as well as the preparation of the Leuven course, which will actually take place in February 2011)	See Deliverable D8.4.1

5. Project management

Consortium management tasks and achievements

The management of the HD-MPC consortium is the subject of Task 1.1 (Management) and Task 1.2 (Monitoring and reporting) of WP1. More specifically, Task 1.1 (Management) includes the establishment of a steering committee (with one member per participant), the organization of the kick-off meeting, the annual project meetings, and the regular work package meetings (at least twice a year). Task 1.2 (Monitoring and reporting) includes regular monitoring of the progress within the work packages, managing the annual report, etc.

During the kick-off meeting of the project on September 3, 2008 in Leuven, Belgium the steering committee has been installation with the following members:

- Bart De Schutter (TUD),
- Wolfgang Marquardt (RWTH),
- Riccardo Scattolini (POLIMI),
- Miguel Ridao (USE),
- Javier Arbáizar (INOCSA),
- Jairo Espinosa (UNC),
- Damien Faille (EDF),
- Hervé Guéguen (SUPELEC),
- Moritz Diehl (KUL).

In the mean time Arbáizar has left INOCSA. His role within the steering committee has been taken over by Laura Sánchez Mora (INOCSA).

During the reporting period the progress of the project and the work packages were monitored during the HD-MPC meetings in Delft, The Netherlands (September 2-3, 2010), Chatou, France (February 3-4, 2011), and Leuven, Belgium (June 23, 2011). In addition, we have organized two HD-MPC workshops, viz. the HD-MPC Industrial Workshop in Leuven, Belgium in June 2011 and the final HD-MPC Workshop in Milano, Italy in August 2011.

In view of the fact that most HD-MPC participants are involved in almost all work packages and in order to actively stimulate coordination and cross-fertilization between work packages, we have opted to let the work package meetings coincide and to organize joint HD-MPC-wide meetings, instead of organizing separate work package meetings. We aimed at organizing at least two of these joint meetings per year; with the annual meetings included, we had 2 such meetings in the first reporting period (in Milan and Rennes) and 3 in the second reporting period (in Aachen, Seville, and Delft), and three more in the current reporting period (in Rennes, Chatou, and Leuven), as well as two HD-MPC workshops (in Leuven and Milan). In addition, for some dedicated, specialized topics, separate work package meetings were of course still possible. An example of the latter is the WP7 web meeting on modeling and optimization of the combined cycle start-up that took place on December 14, 2009, the meeting on models that took place in Aachen on February 10, 2010, and the meeting on robust HD-MPC that take place in Brussels on October 27, 2010. The minutes of all these meetings can be found on the HD-MPC Virtual Portal.

In order to allow for additional interaction between the HD-MPC participants outside the meetings and visits, the Virtual Portal provides a place to exchange published and submitted papers as well as reports on the latest research, models, and software. Moreover, two mailing lists have been installed to allow for an easy and fast communication within the consortium and within the steering committee.

The HD-MPC project also included a cooperation partner from the US, viz. the group of Prof. Jim Rawlings at the University of Wisconsin-Madison (UWM). For this partner there was no EU funding foreseen for personnel and equipment, but we did allocate a travel budget for UWM within the part of the project budget managed by the coordinator, which allowed UWM researchers to visit the other participating groups and to attend various HD-MPC meetings and workshops. During the course of the project UWM researchers have visited several of the HD-MPC groups. In particular, Brett Stewart (UWM) visited TU Delft for a 3-month period in May-June 2009; during that period he also visited KUL and RWTH Aachen. Moreover, Prof. Jim Rawlings (UWM) visited TU Delft and KUL in June 2009, and he also gave the opening lecture of the final HD-MPC workshop in Milan, Italy.

Problems which have occurred and how they were solved or envisaged solutions;

In the current reporting period the project has been running smoothly and we have not encountered any problems.

During the review meeting in October 2010 and in the subsequent review report the reviewers identified the following main issues:

- improve the involvement of industrial partners and show the usefulness of HD-MPC methods in real-world scenario,
- start using one platform only for simulations and implementations, or in general get more focus,
- the interactions between partners can still be improved further,
- the deliverables are too long and do not provide insight.

We have addressed these issues as follows in the current reporting period:

- To increase the involvement of industrial partners and to show the usefulness of HD-MPC methods in real-world scenario, we have decided to demonstrate and compare several HD-MPC methods on the hydro-power valley benchmark. This has been added as a *new Task 7.2.4: "Demonstration of HD-MPC results"* in WP7.
  The aim of this demonstration is to show the usefulness and potential benefits of one or more of the methods developed within the framework of the HD-MPC project for industry. To this aim we will test one or more of the HD-MPC methods on the hydro-power valley benchmark, compare them with the currently used control method(s), and assess advantages and disadvantages as well as performance gains.
  Based on (earlier) discussions within the HD-MPC project regarding the suitability of the various WP7 applications for an in-depth assessment of HD-MPC methods as well as regarding confidentiality issues, the choice is made to use the public version of the WP7 hydro-power valley (HPV) benchmark for this assessment and to take an approach that is similar to the joint four-tanks study published in the Special Issue on HD-MPC of *Journal of Process Control* (vol. 21, no. 5, June 2011, pp. 800–815).
  This assessment is coordinated by USE and the results have been reported in Deliverable 7.2.3, Part II.

- As for starting to use one platform only for simulations and implementations, we already replied to the reviewers that this was not a feasible nor efficient option, since each of the methods developed by the partners requires underlying toolboxes and supporting software developed for the partner's specific platform that cannot easily and without much additional effort be ported to another platform. A much more efficient solution is to use interfaces towards the various platforms: in particular, for the HD-MPC demonstration of results using the public hydropower we addressed the issue by writing the model in one programming language and by providing interfaces to the various platforms used by the different partners.

- To increase the focus we decided to primarily use public HPV benchmark for case studies and illustration purpose, and we introduced the extra Task 7.2.4 on HD-MPC demonstration of results as a common benchmark for comparing and assessing various HD-MPC approaches (see 1st item of this list). Moreover, we asked and obtained permission to months and to drop Task 4.2 ("Optimization of uncertain large-scale systems") so as to be able to concentrate our efforts on the other tasks.
- The intensive work on the common HPV benchmark and the joint activities such as the Special Issue on HD-MPC of the Journal of Process Control, as well as the HD-MPC Industrial Workshop in Leuven and the Final HD-MPC Workshop in Milan also helped to even further increase the interaction between partners. In addition, we actively stimulated further exchanges of researchers (see list below).
  In the current reporting period the interaction with the industrial partners was increased significantly through the intensified focus on the three applications of WP7 and on the HD-MPC demonstration of results.
- In order to address the comment regarding the length of the deliverables and the lack of insight, we choose not to adopt the suggestion by the reviewers to move (submitted) papers to appendix or to leave them out altogether due to the following reasons: almost our deliverables are public, it is not allowed to put published papers (as is) on a public website, submitted papers are not available to the public, and deliverables should in principle not only be useful for reviewers but also for outside parties. Instead, we decided to make increase the length of the executive summaries and more importantly to add one chapter called "Synopsis of the report" to each new deliverable. This first chapter of about 5-10 pages that summarizes main results of subsequent chapters and it puts new results in perspective to earlier results, and relates them to results of other WPs/deliverables, including relevance for applications, and to HD-MPC overall objectives. The synopsis chapter also allows reviewers to get a good and accurate impression of the contents and relevance of the results reported in the subsequent chapters without having to read all those subsequent chapters in a very detailed way.

During the first and the second reporting period the following issues and solutions arose:

At the end of the first reporting period we had reported two problems: one was related to the timely hiring of the researchers, in particular for the KUL team. Since September 2009 the KUL team has a Ph.D. student who works full-time on the project, which has addressed the hiring problem and which has also allowed us to execute the research program of the project as scheduled. The second problem was related to the timely delivery of the deliverables for months 3, 6, and 9. For month 12 all deliverables were approximately delivered on time. To streamline the process of producing the deliverables, we have since month 12 of the project opted to explicitly appoint one partner for each deliverable to take care of the editing and coordination of that deliverable. This has resulted in a timely delivery of all the deliverables for the second *and the current reporting period.*

During the review meeting in October 2009 and in the subsequent review report the reviewers identified the following main issues:

- the communication and interaction between the groups should be improved,

- the interaction with other related STREP projects could be increased,
- the quality of some deliverables should have been better,
- more focus is required,
- how about the continuation of the work beyond the current project.

We have addressed these issues as follows in the second reporting period *as well as in the current reporting period*:

- To increase the level of communication and interaction between the HD-MPC groups we have stimulated more joint activities (including joint deliverables, joint posters, joint papers, …) as well as more exchanges of researchers and students. We have also taken more time for discussions at the HD-MPC meetings and we have set up three dedicated meetings on WP7 topics (the web meeting in December 2009, the model meeting in Aachen in February 2010, and the robust HD-MPC meeting in October 2010 in Brussels). In the second and the current reporting period also much more joint work has been performed for the deliverables. In particular, for the special issue of the *Journal of Process Control* we have written a joint paper with several groups in which the theoretical methods developed by those groups were applied to the real-life four-tank set-up at the University of Seville. In the current reporting period we have also applied and compared 5 different HD-MPC methods to the public hydro-power benchmark. This has generated a very intensive interaction between all HD-MPC partners.
- In order to establish stronger links with related EU projects we have invited them for the special sessions we have organized for ACC 2010 and for the IFAC World Congress 2011, as well as for the special issue on HD-MPC of *Journal of Process Control*. For these special sessions and for the special issue about 40% of the contributions are now coming from other STREPs and other EU projects including WIDE, FeedNetBack, EMBOCON, HYCON, and HYCON2.
- The process for producing deliverables of high quality has been streamlined with explicit responsibles assigned for each deliverable as well as one or two HD-MPC reviewers (different from the authors), where the first final draft of each deliverable should be available for internal review well ahead of the deadline (at least one month) so that there is enough time for a proper review and for adequately taking the comments and suggestions of the reviewer into account.
- To increase the focus within the project we have decided to primarily consider the following joint case studies within the more fundamental work packages WP3–5:
    - water networks (hydro-power valley and irrigation network),
    - combined cycle plants.

  These are simplified versions of the WP7 applications and they will be included as such within WP6.
- To ensure the continuation of the research program beyond the current project we have started some local/national projects, including cooperation with companies on HD-MPC related work (see deliverable D1.3.1: "Report on knowledge management, links with potential users of results, and future perspectives"). Moreover, we applied for one follow-up STREP project and we still intend to apply for two or more follow-up STREP projects for HD-MPC.

  TUD is participating in the newly approved COST action TU1102 "Towards autonomic road transport support systems" (2012-2015), which is related to HD-MPC. TUD and US are participating in the European 7th Framework Network of Excellence "Highly-complex and networked control systems (HYCON2)" (2010-2014).

  In addition, several related projects at the national level have been approved such as the BSIK NGI[11] projects "Sustainable mobility with cooperative vehicle-infrastructure systems" (2010-2012) and "Model-based predictive control for intelligent micro-transportation systems" (2010-

[11] BSIK-NGI is a research program funded by the Dutch government in the field of Next Generation Infrastructures.

2012) and “Model-based predictive control for intelligent water management – Towards real-life implementation” (2010-2012).

Changes in the consortium, if any;

No changes took place in the composition of the consortium

List of project meetings, dates and venues;

The following joint meetings involving several partners have taken place (the minutes of these meetings can be found on the Virtual Portal):

- September 3, 2008: Kick-off meeting in Leuven, Belgium
- March 5-6, 2009: HD-MPC meeting in Milano, Italy
- May 29, 2009: WP7 meeting on Modeling and Control of Water Systems, Chatou, France
- September 9-10, 2009: HD-MPC meeting in Rennes, France
- December 14, 2009: web meeting on the combined cycle start-up
- February 10, 2010: meeting on models in Aachen, Germany
- February 11-12, 2010: HD-MPC meeting in Aachen, Germany
- June 1-2, 2010: HD-MPC meeting in Seville, Spain
- September 2-3, 2010: HD-MPC meeting in Delft, The Netherlands
- October 27, 2010: meeting on robust HD-MPC in Brussels, Belgium
- February 3-4, 2011: HD-MPC meeting in Chatou, France
- June 23, 2011: HD-MPC meeting in Leuven, Belgium
- June 24, 2011: HD-MPC industrial workshop in Leuven, Belgium
- August 28, 2011: final HD-MPC Workshop in Milano, Italy

In addition, there were also some meetings with a smaller number of participants:

- November 20, 2008: Joint meeting USE-INOCSA on modeling software for water canals, Madrid, Spain
- April 7, 2009: Joint meeting USE-INOCSA to prepare the WP7 meeting in Chatou (May 29, 2009), Seville, Spain
- May 13, 2009: Joint meeting USE-INOCSA on WP7, Madrid, Spain
- June 30, 2009: Joint meeting USE-INOCSA on WP7, Madrid, Spain
- March 18, 2010: meeting of INOCSA and USE with the managers of the 'Canales del Bajo Guadalquivir' about the HD-MPC project; including a visit to the 'Canales del Bajo Guadalquivir' (WP7), and definition of the control and management of the 'Canales del Bajo Guadalquivir'
- April 6, 8, and 28, 2010: meeting between USE and INOCSA in Seville about the irrigation canal benchmark (WP6) and WP7.
- May 4, 2010: meeting between USE and INOCSA in Madrid on the irrigation canal benchmark
- May 26-27, 2010: meeting between USE-INOCSA in Seville to work on the irrigation canal benchmark
- August 19, 2010: meeting between EDF and KUL on the connection between the controller and the HPV simulator
- February 2, 2011 and April 13, 2011: visits of the INOCSA and USE teams to the 'Canales del Bajo Guadalquivir' (Sevilla); meetings with the person in charge of the management of water for irrigation (J. Bellido) in order to show him some results.

In addition, the teams of SUPELEC and EDF also regularly met with each other about the power plant model. There were also some exchanges of the SUPELEC team with Holger Scheu (RWTH) about smooth models for optimization. In the current reporting period the team members from INOCSA and USE met about once a week to discuss the work on the irrigation canals.

Project planning and status;

Taking into account the approved extension of the project with 4 months for working out the HD-MPC demonstration of results (see also the updated Description of Work of 08/06/2011), the project has been running according to the schedule and – apart from some delays in the first reporting period – all the deliverables and milestones planned for the second and the current reporting period have been realized in time.

Impact of possible deviations from the planned milestones and deliverables, if any;
All the deliverables and milestones planned for the reporting period have been realized.

Any changes to the legal status of any of the beneficiaries, in particular non-profit public bodies, secondary and higher education establishments, research organizations and SMEs;
There have not been any changes in the legal status of the participants.

Development of the Project web site;
A public web site has been set up for the project. The web site can be found at the address http://www.ict-hd-mpc.eu, and it contains several sections to illustrate the project and to publicize the results we have achieved.
A password-protected private Intranet/Virtual Port for HD-MPC participants only has also been set up at http://www.nyquist.us.es/hdmpcproject/. This Virtual Portal is also accessible to the reviewers and the commission.
More details on the web site and the Virtual Portal can be found in the section above that reports on WP1 as well as in the deliverables D1.4.1 and D8.1.1.

Use of foreground and dissemination activities during this period (if applicable).

The work performed within HD-MPC has been published[12] in the following international journal papers and book chapters:

Journal papers (published during the current reporting period)

- I. Alvarado, D. Limon, D. Muñoz de la Peña, J.M. Maestre, M.A. Ridao, H. Scheu, W. Marquardt, R.R. Negenborn, B. De Schutter, F. Valencia, J. Espinosa, "A comparative analysis of distributed MPC techniques applied to the HD-MPC four-tank benchmark", *Journal of Process Control*, vol. 21, no. 5, pp. 800-815, June 2011.
- L.D. Baskar, B. De Schutter, Z. Papp, and J. Hellendoorn, "Traffic control and intelligent vehicle highway systems: A survey", *IET Intelligent Transport Systems*, vol. 5, no. 1, Mar. 2011.
- B. De Schutter and R. Scattolini, "Introduction to the special issue on hierarchical and distributed model predictive control", *Journal of Process Control*, vol. 21, no. 5, pp. 683-684, June 2011.
- M.D. Doan, T. Keviczky, and B. De Schutter, "An iterative scheme for distributed model predictive control using Fenchel's duality", *Journal of Process Control*, vol. 21, no. 5, pp. 746-755, June 2011.

[12] We only list published papers here. In addition, some submitted and accepted papers are listed in the WP progress descriptions in Section 3 above.

- M. Farina, G. Ferrari-Trecate, and R. Scattolini, "Distributed moving horizon estimation for linear constrained systems", *IEEE Transactions on Automatic Control*, vol. 55, no. 11, pp. 2462-2475, Nov. 2010.
- M. Farina, G. Ferrari-Trecate, C. Romani, and R. Scattolini, "Moving horizon estimation for distributed nonlinear systems with application to cascade river reaches", *Journal of Process Control*, vol. 21, no. 5, pp. 767-774, June 2011.
- A. Ferramosca, D. Limon, I. Alvarado, T. Alamo, F. Castaño, and E.F. Camacho, "Optimal MPC for tracking of constrained linear systems", *International Journal of Systems Science*, vol. 42, no. 8, pp. 1265-1276, 2011.
- M. Houwing, R.R. Negenborn, and B. De Schutter, "Demand response with micro-CHP systems", *Proceedings of the IEEE*, vol. 99, no. 1, pp. 200-213, Jan. 2011.
- Zs. Lendek, R. Babuška, and B. De Schutter, "Sequential stability analysis and observer design for distributed TS fuzzy systems", *Fuzzy Sets and Systems*, vol. 174, no. 1, pp. 1-30, July 2011.
- Y. Li and B. De Schutter, "Stability and performance analysis of an irrigation channel with distributed control", *Control Engineering Practice*, vol. 19, no. 10, pp. 1147-1156, Oct. 2011.
- S. Lin, B. De Schutter, Y. Xi, and H. Hellendoorn, "Fast model predictive control for urban road networks via MILP", *IEEE Transactions on Intelligent Transportation Systems*, vol. 12, no. 3, pp. 846-856, Sept. 2011.
- J.M. Maestre, D. Muñoz de la Peña, E.F. Camacho, and T. Alamo, "Distributed model predictive control based on agent negotiation", *Journal of Process Control*, vol. 21, no. 5, pp. 685-697, June 2011.
- D.R. Ramirez , T. Alamo, and E.F. Camacho, "Computational burden reduction in min–max MPC", *Journal of the Franklin Institute*, vol. 348, no. 9, pp. 2430-2447, Nov. 2011.
- C. Savorgnan, C. Romani, A. Kozma, and M. Diehl, "Multiple shooting for distributed systems with applications in hydro electricity production", *Journal of Process Control*, vol. 21, no. 5, pp. 738-745, June 2011.
- H. Scheu and W. Marquardt, "Sensitivity-based coordination in distributed model predictive control", *Journal of Process Control*, vol. 21, no. 5, pp. 715-728, June 2011.
- K. Staňková, G.J. Olsder, and B. De Schutter, "On European electricity market liberalization: A game-theoretic approach", *INFOR: Information Systems and Operational Research*, vol. 48, no. 4, pp. 267-280, Nov. 2010.
- A.N. Tarău, B. De Schutter, and J. Hellendoorn, "Hierarchical route control in DCV-based baggage handling systems", *International Journal of Services Operations and Informatics*, vol. 6, no. 1/2, pp. 5-29, Jan. 2011.
- A.N. Tarău, B. De Schutter, and J. Hellendoorn, "Predictive route choice control for automated baggage handling systems using mixed-integer linear programming", *Transportation Research Part C,* vol. 19, no. 3, pp. 424-439, June 2011.
- A. Zafra-Cabeza, J.M. Maestre, M.A. Ridao, E.F. Camacho, and L. Sánchez, "A hierarchical distributed model predictive control approach to irrigation canals: A risk mitigation perspective", *Journal of Process Control*, vol. 21, no. 5, pp. 787-799, June 2011.

Journal papers (published during the first and second reporting period)

- D. Doan, T. Keviczky, I. Necoara, M. Diehl, and B. De Schutter, "A distributed version of Han's method for DMPC using local communications only", *Journal of Control Engineering and Applied Informatics*, vol. 11, no. 3, pp. 6-15, 2009.
- M. Farina, G. Ferrari-Trecate, and R. Scattolini, "Moving horizon state estimation of large-scale constrained partitioned systems", *Automatica*, vol. 46, no. 5, pp. 910-918, 2010.
- J. Garcia and J.J. Espinosa, "Moving horizon estimators for large-scale systems", *Journal of Control Engineering and Applied Informatics*, vol. 11, no. 3, pp. 49-56, Sept. 2009.

- D. Limon, I. Alvarado, T. Alamo, and E.F. Camacho, “Robust tube-based MPC for tracking of constrained linear systems with additive disturbances”, *Journal of Process Control*, vol. 20, pp. 248–260, 2010.
- Z. Lukszo, M.P.C. Weijnen, R.R. Negenborn, and B. De Schutter, “Tackling challenges in infrastructure operation and control: Cross-sectoral learning for process and infrastructure engineers”, *International Journal of Critical Infrastructures*, vol. 5, no. 4, pp. 308-322, 2009.
- J.M. Maestre, D. Muñoz de la Peña, and E.F. Camacho, “Distributed MPC based on a cooperative game”, *Optimal Control Applications and Methods*, 2010.
- R.R. Negenborn, S. Leirens, B. De Schutter, and J. Hellendoorn, “Supervisory nonlinear MPC for emergency voltage control using pattern search”, *Control Engineering Practice*, vol. 7, no. 7, pp. 841-848, July 2009.
- R.R. Negenborn, P.-J. van Overloop, T. Keviczky, and B. De Schutter, “Distributed model predictive control of irrigation canals”, *Networks and Heterogeneous Media*, vol. 4, no. 2, pp. 359-380, June 2009.
- B. Picasso, D. De Vito, R. Scattolini, and P. Colaneri, “An MPC approach to the design of two-layer hierarchical control systems”, *Automatica*, vol. 46, no. 5, pp. 823-831, 2010.
- R. Scattolini, “Architectures for distributed and hierarchical model predictive control – a review”, *Journal of Process Control*, vol. 19, pp. 723-731, 2009.
- A.N. Tarău, B. De Schutter, and J. Hellendoorn, “Model-based control for throughput optimization of automated flats sorting machines”, *Control Engineering Practice*, vol. 17, no. 6, pp. 733-739, June 2009.
- A.N. Tarău, B. De Schutter, and J. Hellendoorn, “Route choice control of automated baggage handling systems”, *Transportation Research Record*, no. 2106, pp. 76-82, 2009.
- A.N. Tarău, B. De Schutter, and J. Hellendoorn, “Centralized, decentralized, and distributed model predictive control for route choice in automated baggage handling systems”, *Journal of Control Engineering and Applied Informatics*, vol. 11, no. 3, pp. 24-31, 2009.
- A.N. Tarău, B. De Schutter, and H. Hellendoorn, “Model-based control for route choice in automated baggage handling systems”, *IEEE Transactions on Systems, Man, and Cybernetics, Part C: Applications and Reviews*, vol. 40, no. 3, pp. 341-351, May 2010.

Book chapters (published during the current reporting period)

- R.R. Negenborn, G. Hug-Glanzmann, B. De Schutter, and G. Andersson, “A novel coordination strategy for multi-agent control using overlapping subnetworks with application to power systems”, in *Efficient Modeling and Control of Large-Scale Systems* (J. Mohammadpour and K.M. Grigoriadis, eds.), New York, New York: Springer, ISBN 978-1-4419-5756-6, pp. 251-278, 2010.

Book chapters (published during the first and second reporting period)

- M. Arnold, R.R. Negenborn, G. Andersson, and B. De Schutter, “Distributed predictive control for energy hub coordination in coupled electricity and gas networks”, Chapter 10 in *Intelligent Infrastructures* (R.R. Negenborn, Z. Lukszo, and H. Hellendoorn, eds.), vol. 42 of *Intelligent Systems, Control and Automation: Science and Engineering*, Springer, pp. 235-273, 2010.
- B. De Schutter, H. Hellendoorn, A. Hegyi, M. van den Berg, and S.K. Zegeye, “Model-based control of intelligent traffic networks”, Chapter 11 in *Intelligent Infrastructures* (R.R. Negenborn, Z. Lukszo, and H. Hellendoorn, Eds.), vol. 42 of *Intelligent Systems, Control and Automation: Science and Engineering*, Springer, pp. 277-310, 2010.
- D. Limon, A. Ferramosca, I. Alvarado, T. Alamo, and E.F. Camacho, “MPC for tracking of constrained nonlinear systems”, in *Nonlinear Model Predictive Control. Towards New*

Challenging Applications (L. Magni, D.M. Raimondo, and F. Allgöwer, Eds.), vol. 384 of *Lecture Notes in Control and Information Sciences*, 2009.
- L. Magni and R. Scattolini, "An overview of nonlinear Model Predictive Control", in *Automotive Model Predictive Control: Models, Methods and Applications* (L. Del Re, F. Allgower, L. Glielmo, C. Guardiona, and I. Kolmanvski, Eds.), vol. 402 of *Lecture Notes in Control and Information Science*, Springer, pp. 107-117, 2010.
- B. Picasso, C. Romani, R. Scattolini, "Hierarchical model predictive control of Wiener models", *Nonlinear Model Predictive Control* (L. Magni, D.M. Raimondo, F. Allgower eds.), vol. 384 in *Lecture Notes in Control and Information Sciences*, pp. 139-152, Springer, 2009.
- P.-J. van Overloop, R.R. Negenborn, B. De Schutter, and N.C. van de Giesen, "Predictive control for national water flow optimization in The Netherlands", Chapter 17 in *Intelligent Infrastructures* (R.R. Negenborn, Z. Lukszo, and H. Hellendoorn, eds.), vol. 42 of *Intelligent Systems, Control and Automation: Science and Engineering*, Springer, pp. 439-461, 2010.

Moreover, the work performed within HD-MPC has been published[13] in the following international conference papers:

International conference papers (published during the current reporting period)

- G. Bajracharya, T. Koltunowicz, R.R. Negenborn, D. Djairam, B. De Schutter, and J.J. Smit, "Optimization of transformer loading based on hot-spot temperature using a predictive health model", *Proceedings of the 2010 International Conference on Condition Monitoring and Diagnosis*, Tokyo, Japan, pp. 914-917, Sept. 2010.
- L.D. Baskar, B. De Schutter, and J. Hellendoorn, "Hierarchical model-based predictive control for intelligent vehicle highway systems: Regional controllers", *Proceedings of the 13th International IEEE Conference on Intelligent Transportation Systems (ITSC 2010)*, Madeira Island, Portugal, pp. 249-254, Sept. 2010.
- A. Cabañas, L. Sánchez, M.A. Ridao and L. Garrote, "Plataforma para el control y similación en la gestión de sistemas de canales", *XXXI Jornadas de Automática*, Jaén, Spain, Sept. 2010.
- F. Casella, M. Farina, F. Righetti, R. Scattolini, D. Faille, F. Davelaar, A. Tica, H. Gueguen, and D. Dumur, "An optimization procedure of the start-up of combined cycle power plants", *Proceedings of the 18th IFAC World Congress*, Milan, Italy, Aug.-Sept. 2011.
- L. Cortes, C. Portilla, A. Marquez, and J.Espinosa, "Centralized and decentralized LQR for a two reactors chain and flash system", *Proceedings of the IEEE IX Latin American Robotics Symposium and the IEEE Colombian Conference on Automatic Control*, Bogota, Colombia, Oct. 2011.
- M.D. Doan, T. Keviczky, and B. De Schutter, "A dual decomposition-based optimization method with guaranteed primal feasibility for hierarchical MPC problems", *Proceedings of the 18th IFAC World Congress*, Milan, Italy, pp. 392-397, Aug.-Sept. 2011.
- M.D. Doan, T. Keviczky, and B. De Schutter, "A distributed optimization-based approach for hierarchical MPC of large-scale systems with coupled dynamics and constraints", *Proceedings of the 50th IEEE Conference on Decision and Control and European Control Conference*, Orlando, Florida, Dec. 2011.
- M. Farina, G. Ferrari-Trecate, and R. Scattolini, "Distributed moving horizon estimation for nonlinear constrained systems", *Proceedings of the 8th IFAC Symposium on Nonlinear Control Systems*, Bologna, Italy, pp. 909-914, Sept. 2010.

[13] We only list published papers here. In addition, some submitted and accepted papers are listed in the WP progress descriptions in Section 3 above.

- M. Farina and R. Scattolini, "Distributed non-cooperative MPC with neighbor-to-neighbor communication", *Proceedings of the 18th IFAC World Congress*, Milan, Italy, Aug.-Sept. 2011.
- M. Farina and R. Scattolini, "An output feedback distributed predictive control algorithm", *Proceedings of the 50th IEEE Conference on Decision and Control and European Control Conference*, Orlando, Florida, Dec. 2011.
- A. Ferramosca, D. Limon, J.B. Rawlings, and E.F. Camacho, "Cooperative distributed MPC for tracking". *Proceedings of the 18th IFAC World Congress*, Milan, Italy, pp 1584-1589, Aug.-Sept. 2011.
- Z. Hidayat, R. Babuška, B. De Schutter, and A. Núñez, "Decentralized Kalman filter comparison for distributed-parameter systems: A case study for a 1D heat conduction process", *Proceedings of the 16th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA'2011)*, Toulouse, France, 8 pp., Sept. 2011.
- Z. Hidayat, R. Babuška, B. De Schutter, and A. Núñez, "Observers for linear distributed-parameter systems: A survey", *Proceedings of the 2011 IEEE International Symposium on Robotic and Sensors Environments (ROSE 2011)*, Montreal, Canada, pp. 166-171, Sept. 2011.
- Zs. Lendek, R. Babuška, and B. De Schutter, "Stability analysis and observer design for string-connected TS systems", *Proceedings of the 18th IFAC World Congress*, Milan, Italy, pp. 12795-12800, Aug.-Sept. 2011.
- Y. Li and B. De Schutter, "Performance analysis of irrigation channels with distributed control", *Proceedings of the 2010 IEEE International Conference on Control Applications*, Yokohama, Japan, pp. 2148-2153, Sept. 2010.
- Y. Li, J. Alende, M. Cantoni, and B. De Schutter, "Decomposition of a fixed-profile load scheduling method for large-scale irrigation channels", *Proceedings of the 2010 IEEE International Conference on Control Applications*, Yokohama, Japan, pp. 2166-2171, Sept. 2010.
- Y. Li and B. De Schutter, "Control of a string of identical pools using non-identical feedback controllers", *Proceedings of the 49th IEEE Conference on Decision and Control*, Atlanta, Georgia, pp. 120-125, Dec. 2010.
- Y. Li and B. De Schutter, "Fixed-profile load scheduling for large-scale irrigation channels", *Proceedings of the 18th IFAC World Congress*, Milan, Italy, pp. 1570-1576, Aug.-Sept. 2011.
- D. Limon, I. Alvarado, A. Ferramosca, T. Alamo, and E.F. Camacho, "Enhanced robust NMPC based on nominal predictions", *Proceedings of the 8th IFAC Symposium on Nonlinear Control Systems*, Bologna, Italy, Sept. 2010.
- D. Limon, M. Pomar, J. E. Normey-Rico, T. L. M. Santos, and E.F. Camacho, "Robust design of dead-time compensator controllers for constrained non-linear systems", *Proceedings of the 50th IEEE Conference on Decision and Control and European Control Conference*, Orlando, Florida, Dec. 2011.
- S. Lin, B. De Schutter, S.K. Zegeye, H. Hellendoorn, and Y. Xi, "Integrated urban traffic control for the reduction of travel delays and emissions", *Proceedings of the 13th International IEEE Conference on Intelligent Transportation Systems (ITSC 2010)*, Madeira Island, Portugal, pp. 677-682, Sept. 2010.
- S. Lin, B. De Schutter, A. Hegyi, J. Hellendoorn, and Y. Xi, "On a spatiotemporally discrete urban traffic model", *Proceedings of the 18th IFAC World Congress*, Milan, Italy, pp. 10697-10702, Aug.-Sept. 2011.
- A. Marquez, C. Gomez, P.A. Deossa, and J.J. Espinosa, "Infinite horizon MPC and model reduction applied to large scale chemical plant", *Proceedings of the IEEE IX Latin American Robotics Symposium and the IEEE Colombian Conference on Automatic Control*, Bogota, Colombia, Oct. 2011.

- P. Mc Namara, R.R. Negenborn, B. De Schutter, and G. Lightbody, "Coordination of a multiple link HVDC system using local communications based distributed model predictive control", *Proceedings of the 18th IFAC World Congress*, Milan, Italy, pp. 1558-1563, Aug.-Sept. 2011.
- R.R. Negenborn, P.-J. van Overloop, and B. De Schutter, "Coordination of local controllers in large-scale water systems", *Proceedings of the 9th International Conference on Hydroinformatics (HIC 2010)*, Tianjin, China, pp. 2178-2185, Sept. 2010.
- A. Núñez, B. De Schutter, D. Sáez, and C.E. Cortés, "Hierarchical multiobjective model predictive control applied to a dynamic pickup and delivery problem", *Proceedings of the 13th International IEEE Conference on Intelligent Transportation Systems (ITSC 2010)*, Madeira Island, Portugal, pp. 1553-1558, Sept. 2010.
- A. Núñez, C.E. Cortés, D. Sáez, M. Gendreau, and B. De Schutter, "Multiobjective model predictive control applied to a dial-a-ride system", *Proceedings of the 90th Annual Meeting of the Transportation Research Board*, Washington, DC, 19 pp., Jan. 2011. Paper 11-1942.
- A. Núñez, D. Sáez, I. Skrjanc, and B. De Schutter, "A new method for hybrid-fuzzy identification", *Proceedings of the 18th IFAC World Congress*, Milan, Italy, pp. 15013-15018, Aug.-Sept. 2011.
- B. Picasso, D. Desiderio, and R. Scattolini, "Robustness analysis of nominal model predictive control for nonlinear discrete-time systems", *Proceedings of the 8th IFAC Symposium on Nonlinear Control Systems*, pp. 214-219, Bologna, Italy, Sept. 2010.
- B. Picasso, D. Desiderio, and R. Scattolini, "Inherent robustness of nonlinear discrete-time systems", *Proceedings of the 18th IFAC World Congress*, Milan, Italy, Aug.-Sept. 2011.
- B. Picasso and D. Limon, "On the stability in discrete-time discontinuous systems", *Proceedings of the 18th IFAC World Congress*, Milan, Italy, Aug.-Sept. 2011.
- S. Roshany-Yamchi, R.R. Negenborn, M. Cychowski, B. De Schutter, J. Connell, and K. Delaney, "Distributed model predictive control and estimation of large-scale multi-rate systems", *Proceedings of the 18th IFAC World Congress*, Milan, Italy, pp. 416-422, Aug.-Sept. 2011.
- C. Savorgnan, A. Kozma, J. Andersson, and M. Diehl, "Adjoint-based distributed multiple shooting for large-scale systems", *Proceedings of the 18th IFAC World Congress*, Milan, Italy, Aug.-Sept. 2011.
- H. Scheu and W. Marquardt, "Distributed model-predictive control driven by simultaneous derivation of prices and resources", *Proceedings of the 18th IFAC World Congress*, Milan, Italy, pp. 398-403, Aug.-Sept. 2011.
- K. Staňková and B. De Schutter, "First steps towards finding a solution of a dynamic investor-bank game", *Proceedings of the 2010 IEEE International Conference on Control Applications, Yokohama*, Japan, pp. 2065-2070, Sept. 2010.
- K. Staňková and B. De Schutter, "Stackelberg equilibria for discrete-time dynamic games - Part I: Deterministic games", *Proceedings of the 2011 IEEE International Conference on Networking, Sensing and Control*, Delft, The Netherlands, pp. 249-254, Apr. 2011.
- K. Staňková and B. De Schutter, "Stackelberg equilibria for discrete-time dynamic games - Part II: Stochastic games with deterministic information structure", *Proceedings of the 2011 IEEE International Conference on Networking, Sensing and Control*, Delft, The Netherlands, pp. 255-260, Apr. 2011.
- A.N. Tarău, B. De Schutter, and J. Hellendoorn, "Predictive control for baggage handling systems using mixed integer linear programming", *Proceedings of the 5th IFAC International Conference on Management and Control of Production Logistics (MCPL 2010)*, Coimbra, Portugal, 6 pp., Sept. 2010. Paper 4.
- A. Tica, H. Guéguen, D. Dumur, D. Faille, and F. Davelaar, "Optimization of the combined cycle power plants start-up", *Proceedings of the 54th ISA Power Industry Symposium (POWID 2011)*, Charlotte, North Carolina, June 2011.

- H. van Ekeren, R.R. Negenborn, P.-J. van Overloop, and B. De Schutter, "Hybrid model predictive control using time-instant optimization for the Rhine-Meuse Delta", *Proceedings of the 2011 IEEE International Conference on Networking, Sensing and Control*, Delft, The Netherlands, pp. 216-221, Apr. 2011.
- F. Valencia, J.D. Lopez, A. Marquez, and J.J. Espinosa, "Moving horizon estimator for measurement delay compensation in model predictive control schemes", *Proceedings of the 50th IEEE Conference on Decision and Control and European Control Conference*, Orlando, Florida, Dec. 2011.
- F. Valencia, J.J. Espinosa, B. De Schutter, and K. Stanková, "Feasible-cooperation distributed model predictive control scheme based on game theory", *Proceedings of the 18th IFAC World Congress*, Milan, Italy, pp. 386-391, Aug.-Sept. 2011.
- P.-J. van Overloop, R.R. Negenborn, S.V. Weijs, W. Malda, M.R. Bruggers, and B. De Schutter, "Linking water and energy objectives in lowland areas through the application of model predictive control", *Proceedings of the 2010 IEEE International Conference on Control Applications*, Yokohama, Japan, pp. 1887-1891, Sept. 2010.
- P.-J. van Overloop, R.R. Negenborn, D. Schwanenberg, and B. De Schutter, "Towards integrating water prediction and control technology", *Proceedings of the 2011 IEEE International Conference on Networking, Sensing and Control*, Delft, The Netherlands, pp. 80-85, Apr. 2011.
- I. Wolf, L. Würth, and W. Marquardt, "Rigorous solution vs. fast update: Acceptable computational delay in NMPC", *Proceedings of the 50th IEEE Conference on Decision and Control and European Control Conference*, Orlando, Florida, Dec. 2011.
- A. Zafra-Cabeza, J.M. Maestre, M.A. Ridao, E. F. Camacho, and L. Sánchez, "A hierarchical distributed model predictive control: An irrigation canal case-study", *Proceedings of the 2011 American Control Conference*, San Francisco, California, pp. 3172-3177, June-July 2011.

International conference papers (published during the first and second reporting period)

- M. Arnold, R.R. Negenborn, G. Andersson, and B. De Schutter, "Distributed control applied to combined electricity and natural gas infrastructures", *Proceedings of the International Conference on Infrastructure Systems 2008: Building Networks for a Brighter Future*, Rotterdam, The Netherlands, Nov. 2008. Paper 172.
- M. Arnold, R.R. Negenborn, G. Andersson, and B. De Schutter, "Model-based predictive control applied to multi-carrier energy systems", *Proceedings of the 2009 IEEE PES General Meeting*, Calgary, Canada, July 2009. Paper 09GM1452.
- M. Arnold, R.R. Negenborn, G. Andersson, and B. De Schutter, "Multi-area predictive control for combined electricity and natural gas systems", *Proceedings of the European Control Conference 2009*, Budapest, Hungary, pp. 1408-1413, Aug. 2009.
- G. Bajracharya, T. Koltunowicz, R.R. Negenborn, Z. Papp, D. Djairam, B. De Schutter, and J.J. Smit, "Optimization of maintenance for power system equipment using a predictive health model", *Proceedings of the 2009 IEEE Bucharest Power Tech Conference*, Bucharest, Romania, June-July 2009. Paper 563.
- L.D. Baskar, B. De Schutter, and H. Hellendoorn, "Dynamic speed limits and on-ramp metering for IVHS using model predictive control", *Proceedings of the 11th International IEEE Conference on Intelligent Transportation Systems (ITSC 2008)*, Beijing, China, pp. 821-826, Oct. 2008.
- L.D. Baskar, B. De Schutter, J. Hellendoorn, and A. Tarău, "Traffic management for intelligent vehicle highway systems using model-based predictive control", *Proceedings of the 88th*

Annual Meeting of the Transportation Research Board, Washington, DC, Jan. 2009. Paper 09-2107.

- L.D. Baskar, B. De Schutter, and H. Hellendoorn, "Optimal routing for intelligent vehicle highway systems using mixed integer linear programming", *Proceedings of the 12th IFAC Symposium on Transportation Systems*, Redondo Beach, California, pp. 569-575, Sept. 2009.
- L.D. Baskar, B. De Schutter, and J. Hellendoorn, "Optimal routing for intelligent vehicle highway systems using a macroscopic traffic flow model", *Proceedings of the 12th International IEEE Conference on Intelligent Transportation Systems (ITSC 2009)*, St. Louis, Missouri, pp. 576-581, Oct. 2009.
- A. Cabañas, L. Sánchez, M.A. Ridao and L. Garrote, "Plataforma para el control y similación en la gestión de sistemas de canales", *XXXI Jornadas de Automática*, Jaén, Spain, Sept. 2010.
- D. De Vito, B. Picasso, and R. Scattolini, "On the design of reconfigurable two-layer hierarchical control systems with MPC", *Proceedings of the 2010 American Control Conference*, Baltimore, Maryland, June-July 2010.
- D. Doan, T. Keviczky, I. Necoara, M. Diehl, and B. De Schutter, "A distributed version of Han's method for DMPC of dynamically coupled systems with coupled constraints", *Proceedings of the 1st IFAC Workshop on Estimation and Control of Networked Systems (NecSys 2009)*, Venice, Italy, pp. 240-245, Sept. 2009.
- M.D. Doan, T. Keviczky, and B. De Schutter, "An improved distributed version of Han's method for DMPC of canal systems", *Proceedings of the 12th IFAC Symposium on Large Scale Systems: Theory and Applications*, Villeneuve d'Ascq, France, 6 pp., July 2010.
- D. Faille and F. Davelaar, "Model based start-up optimization of a combined cycle power plant", in *Proceedings of the IFAC Symposium on Power Plants and Power Systems Control (IFAC PP&PSC 2009*, Tampere Hall, Finland, July 2009
- M. Farina, G. Ferrari Trecate, R. Scattolini, "Distributed moving horizon estimation for sensor networks", *Proceedings of the IFAC Workshop on Estimation and Control of Networked Systems (NecSys'09)*, pp. 126-131, Venice, Italy, 2009.
- M. Farina, G. Ferrari Trecate, and R. Scattolini, "A moving horizon scheme for distributed state estimation", *IEEE Conference on Decision and Control*, pp. 1818-1823, Shanghai, China, 2009.
- M. Farina, G. Ferrari-Trecate, and R. Scattolini, "State estimation for large-scale partitioned systems: a moving horizon approach", *Proceedings of the 2010 American Control Conference*, Baltimore, Maryland, June-July 2010.
- L. Galbusera, G. Ferrari Trecate, and R. Scattolini, "A hybrid model predictive control scheme for multi-agent containment and distributed sensing", *IEEE Conference on Decision and Control,* pp. 7006-7011, Shanghai, China, 2009.
- M. Houwing, R.R. Negenborn, M.D. Ilič, and B. De Schutter, "Model predictive control of fuel cell micro cogeneration systems", *Proceedings of the 2009 IEEE International Conference on Networking, Sensing and Control*, Okayama, Japan, pp. 708-713, Mar. 2009.
- S. Leirens, C. Zamora, R.R. Negenborn, and B. De Schutter, "Coordination in urban water supply networks using distributed model predictive control", *Proceedings of the 2010 American Control Conference*, Baltimore, Maryland, pp. 3957-3962, June-July 2010.
- Zs. Lendek, R. Babuška, and B. De Schutter, "Fuzzy models and observers for freeway traffic state tracking", *Proceedings of the 2010 American Control Conference*, Baltimore, Maryland, pp. 2278-2283, June-July 2010.
- Y. Li and B. De Schutter, "Offtake feedforward compensator design for an irrigation channel with distributed control", *Proceedings of the 2010 American Control Conference*, Baltimore, Maryland, pp. 3747-3752, June-July 2010.
- S. Lin, B. De Schutter, Y. Xi, and H. Hellendoorn, "Study on fast model predictive controllers for large urban traffic networks", *Proceedings of the 12th International IEEE Conference on Intelligent Transportation Systems (ITSC 2009)*, St. Louis, Missouri, pp. 691-696, Oct. 2009.

- S. Lin, B. De Schutter, Y. Xi, and H. Hellendoorn, “An efficient model-based method for coordinated control of urban traffic networks”, *Proceedings of the 2010 IEEE International Conference on Networking, Sensing and Control*, Chicago, Illinois, p. 8-13, Apr. 2010.
- S. Lin, B. De Schutter, Y. Xi, and H. Hellendoorn, “Model predictive control for urban traffic networks via MILP”, *Proceedings of the 2010 American Control Conference*, Baltimore, Maryland, pp. 2272-2277, June-July 2010.
- J.M. Maestre, D. Muñoz de la Peña, and E.F. Camacho, “Distributed MPC based on a cooperative game”, *Joint 48th IEEE Conference on Decision and Control and 28th Chinese Control Conference*, Shanghai, China, 2009.
- J.M. Maestre, D. Muñoz de la Peña, and E.F. Camacho, “Distributed MPC: a supply chain case study”, *Joint 48th IEEE Conference on Decision and Control and 28th Chinese Control Conference*, Shanghai, China, 2009.
- A. Marquez, J.J. Espinosa, and D. Odloak, “IHMPC and POD to the control of a non-isothermal tubular reactor”, *Proceedings of the 9th International Symposium on Dynamics and Control of Process Systems (DYCOPS 2010)*, Leuven, Belgium, pp. 431-436, July 2010.
- I. Necoara, C. Savorgnan, Q. Tran Dinh, J. Suykens, and M. Diehl, “Distributed nonlinear optimal control using sequential convex programming and smoothing techniques”, *Proceedings of the 48th IEEE Conference on Decision and Control (CDC 2009)*, Shanghai, China, pp. 543-548, Dec. 2009.
- R.R. Negenborn and B. De Schutter, “A distributed model predictive control approach for the control of irrigation canals”, *Proceedings of the International Conference on Infrastructure Systems 2008: Building Networks for a Brighter Future*, Rotterdam, The Netherlands, Nov. 2008. Paper 152.
- R.R. Negenborn, M. Houwing, B. De Schutter, and J. Hellendoorn, “Model predictive control for residential energy resources using a mixed-logical dynamic model”, *Proceedings of the 2009 IEEE International Conference on Networking, Sensing and Control*, Okayama, Japan, pp. 702-707, Mar. 2009.
- R.R. Negenborn, P.-J. van Overloop, and B. De Schutter, “Coordinated distributed model predictive reach control of irrigation canals”, *Proceedings of the European Control Conference 2009*, Budapest, Hungary, pp. 1420-1425, Aug. 2009.
- R.R. Negenborn, A. Sahin, Z. Lukszo, B. De Schutter, and M. Morari, “A non-iterative cascaded predictive control approach for control of irrigation canals”, *Proceedings of the 2009 IEEE International Conference on Systems, Man, and Cybernetics*, San Antonio, Texas, pp. 3652-3657, Oct. 2009.
- B. Picasso, C. Romani, R. Scattolini, “On the design of hierarchical control systems with MPC”, *Proceedings of the European Control Conference 2009*, Budapest, Hungary, 2009.
- H. Scheu, J. Busch, and W. Marquardt, “Nonlinear distributed dynamic optimization based on first order sensitivities”, Proceedings of the 2010 American Control Conference, Baltimore, USA, pp. 1574-1579, June 30-July 2, 2010.
- T.L.M. Santos, J.E. Normey-Rico, D. Limon, “Explicit input-delay compensation for robustness improvement in MPC”, *9th IFAC Workshop on Time Delay Systems (TDS2010)*, Prague, Czech Republic, 2010.
- T.L.M. Santos, D. Limon, T. Alamo, and J.E. Normey-Rico, “Robust tube based MPC for constrained systems with dead-time”, *UKACC International Conference on Control*, Coventry, UK, 2010.
- A.N. Tarău, B. De Schutter, and J. Hellendoorn, “Route choice control of automated baggage handling systems”, *Proceedings of the 88th Annual Meeting of the Transportation Research Board*, Washington, DC, Jan. 2009. Paper 09-0432.

- A. Tarău, B. De Schutter, and H. Hellendoorn, "Centralized versus decentralized route choice control in DCV-based baggage handling systems", *Proceedings of the 2009 IEEE International Conference on Networking, Sensing and Control*, Okayama, Japan, pp. 334-339, Mar. 2009.
- A.N. Tarău, B. De Schutter, and H. Hellendoorn, "Receding horizon approaches for route choice control of automated baggage handling systems", *Proceedings of the European Control Conference 2009*, Budapest, Hungary, pp. 2978-2983, Aug. 2009.
- A.N. Tarău, B. De Schutter, and J. Hellendoorn, "Decentralized route choice control of automated baggage handling systems", *Proceedings of the 12th IFAC Symposium on Transportation Systems*, Redondo Beach, California, pp. 70-75, Sept. 2009.
- A.N. Tarău, B. De Schutter, and J. Hellendoorn, "Predictive route choice control of destination coded vehicles with mixed integer linear programming optimization", *Proceedings of the 12th IFAC Symposium on Transportation Systems*, Redondo Beach, California, pp. 64-69, Sept. 2009.
- A.N. Tarău, B. De Schutter, and H. Hellendoorn, "Hierarchical route choice control for baggage handling systems", *Proceedings of the 12th International IEEE Conference on Intelligent Transportation Systems (ITSC 2009)*, St. Louis, Missouri, pp. 679-684, Oct. 2009.
- A.N. Tarău, B. De Schutter, and J. Hellendoorn, "DCV route control in baggage handling systems using a hierarchical control architecture and mixed integer linear programming", *Proceedings of the 3rd International Conference on Information Systems, Logistics and Supply Chain (ILS 2010)*, Casablanca, Morocco, 12 pp., Apr. 2010.
- M. van den Berg, B. De Schutter, A. Hegyi, and H. Hellendoorn, "Day-to-day route choice control in traffic networks with time-varying demand profiles", *Proceedings of the European Control Conference 2009*, Budapest, Hungary, pp. 1776-1781, Aug. 2009.
- R.T. van Katwijk, B. De Schutter, and J. Hellendoorn, "Multi-agent coordination of traffic-control instruments", *Proceedings of the International Conference on Infrastructure Systems 2008: Building Networks for a Brighter Future*, Rotterdam, The Netherlands, Nov. 2008. Paper 141.
- R.T. van Katwijk, B. De Schutter, and J. Hellendoorn, "Multi-agent control of traffic networks: Algorithm and case study", *Proceedings of the 12th International IEEE Conference on Intelligent Transportation Systems (ITSC 2009)*, St. Louis, Missouri, pp. 316-321, Oct. 2009.

In addition to the above conferences, the work performed within the HD-MPC project has been presented at the following symposia, workshops, and seminars:

Symposia, workshops, and seminars (during the current reporting period)

- At the final HD-MPC workshop in Milan, Italy, August 28, 2011 the following presentations were given:
    - Jim Rawlings: An overview of distributed MPC
    - Moritz Diehl, Attila Kozma, and Carlo Savorgnan: Hierarchical and distributed optimization methods
    - Marcello Farina, Bruno Picasso, and Riccardo Scattolini: Design of hierarchical and distributed MPC control systems with robustness tools
    - Pepe Maestre, Daniel Limón, and David Muñoz de la Peña: Distributed MPC based on game theory
    - Wolfgang Marquardt and Holger Scheu: Distributed model predictive control by primal decomposition
    - Bart De Schutter: Hierarchical MPC with applications in transportation and infrastructure networks

- Damien Faille and Frans Davelaar: Hierarchical and distributed control of a hydro power valley
- Adrian Tica, Hervé Guéguen, Didier Dumur, Damien Faille, and Frans Davelaar: Application to start-up of combined-cycle power plant
- Laura Sánchez and Miguel Ridao: Distributed control of irrigation canals

- At the HD-MPC industrial workshop, Leuven, Belgium, June 24, 2011 the following presentations were given:
  - Carlos Bordons: Introduction to MPC
  - Bart De Schutter: Distributed and hierarchical MPC: Main concepts and challenges
  - Moritz Diehl: Algorithms for nonlinear MPC of large scale systems
  - Holger Scheu: Dynamic real-time optimization
  - Riccardo Scattolini: Distributed predictive control and simplified implementations
  - Laura Sanchez: HD-MPC approach to irrigation channels
  - Damien Faille: Optimization of combined cycle plants and hydro-power valleys
  - Carlo Savorgnan: Hydro Power Valley demo
- On November 1, 2010 Bart De Schutter gave a presentation on "Hierarchical MPC for intelligent vehicle-highway systems" in the Optimization and Applications Seminar series, organized jointly by ETH Zürich and the University of Zürich, Zürich, Switzerland.
- Bart De Schutter gave a presentation on "Reinforcement learning & Multi-level multi-agent MPC for large-scale infrastructures", on July 18, 2011 at VITO, Mol, Belgium.
- Riccardo Scattolini gave a presentation on "Architectures for distributed and hierarchical MPC", *Tutorial on Model Predictive Control*, organized by Lalo Magni, IFAC World Congress 2011, Milan, Italy.
- Moritz Diehl gave a presentation on "Distributed multiple shooting for nonlinear model predictive control of river systems for hydro power generation", at the 25th IFIP TC 7 Conference on System Modeling and Optimization, Berlin, Germany, Sept. 12-16, 2011.
- During the NWO Workshop on Application of Operations Research in Urban Transport, Delft, The Netherlands, Sept. 26-29, 2011, Bart De Schutter gave a presentation on "Model-based predictive control for large-scale urban traffic networks".

Symposia, workshops, and seminars (during the first and the second reporting period)

- Riccardo Scattolini has attended the workshop on "Automotive Model Predictive Control: Models, Methods and Applications", held in Linz on February 2009, with the scope to find potential applications of hierarchical and distributed MPC in the automotive field. He also gave the invited talk: "An overview of Nonlinear Model Predictive Control".
- Riccardo Scattolini attended the workshop on "Optimization Based Control and State Estimation for Decentralized and Networked Systems", University of Magdeburg, June 1-2, 2009, where he gave the invited talk: "Distributed State Estimation with Moving Horizon Observers"
- Jenifer Zaráte Flóres gave a presentation on "Hydro power valley control: Decomposition/Coordination methods" at the 14th Belgian-French-German Conference on Optimization, Leuven, Belgium, September 14-18, 2009
- Bart De Schutter and Rudy Negenborn gave a presentation on "Distributed model predictive control for water infrastructures", *LCCC Workshop on Multi-agent Coordination and Estimation*, Lund, Sweden, February 5-6, 2010.
- Moritz Diehl discussed "Inexact SCP methods for hierarchical optimization of decomposable systems." Presentation at the *LCCC Workshop on Distributed Model Predictive Control and Supply Chains,* Lund University, Lund, Sweden, May 19-21, 2010.

- Carlo Savorgnan talked about “Distributed nonlinear MPC with applications in hydroelectricity production.” Seminar at the Lund University, Lund, Sweden, May 25, 2010.
- Adrian Tica, Hervé Guéguen, and Didier Dumur presented a poster on “Design optimisation and validation of start-up sequences for power plants”, IETR doctoral student workshop, Université de Rennes, Rennes, France, June 16, 2010 (poster in French).

Several HD-MPC researchers participated in the LCCC Workshops on Multi-agent Coordination and Estimation and on Distributed Model Predictive Control and Supply Chains organized by Prof. A. Rantzer of Lund University. At these workshops also several researchers from other ongoing EU projects were present (including WIDE, FeedNetBack, EMBOCON, HYCON, and HYCON2), with whom we have interacted intensively during these workshops.

In order to connect with other ongoing FP7 projects, we have also (re)presented HD-MPC at several events organized by or on behalf of the European Commission:
- Bart De Schutter has given a presentation on HD-MPC at the Concertation Meeting on Control of Large-Scale Systems (CLaSS), Brussels, Belgium, October 20, 2008
- Bart De Schutter gave a presentation on “Distributed Control for Power Networks” at the Concertation Meeting on Monitoring and Control for Energy Efficiency, Brussels, Belgium, October 21, 2008.
- Bart De Schutter gave a talk in “Distributed control of power networks” at the Final Workshop of the Network of Excellence HYCON, Brussels, Belgium, March 3, 2009
- Bart De Schutter gave a presentation on “Multi-agent control of traffic networks” at the ESF Exploratory Workshop on Foundations of Autonomic Computing for Traffic Management Systems, Durham, UK, April 14-16, 2010.
- At the special session on EU projects organized by dr. Pereira at CPS Week, April 12-16, 2010 in Stockholm, Sweden, the HD-MPC project was present with three posters:
    - general overview poster of the HD-MPC project,
    - poster on the fundamental results obtained within HD-MPC, in particular robust hierarchical MPC, distributed optimization, and a new coordination method,
    - poster on the application to the start-up of the combined cycle power plant.
- Riccardo Scattolini and Bart De Schutter participated in the EU Workshop on Monitoring and Control for Full Water-Cycle Management co-organized with HD-MPC and EUCLID, Brussels, Belgium, June 18, 2010. There, Bart De Schutter gave a presentation on “Distributed model predictive control for water systems”.

There have also been some visits and exchanges of researchers between the participating groups:
- Jairo Espinosa (UNC) has visited the KUL team on September 4, 2008.
- Jairo Espinosa (UNC) has visited the group at RWTH on March 9, 2009 and the KUL group on March 10, 2009.
- Brett Stewart (UWM) has visited TU Delft for a 3-month period in May-June 2009. While at TU Delft he worked on the topic “Distributed cooperative model predictive control”. On June 17 he gave a presentation on “Cooperative, Distributed Model Predictive Control for Systems with Coupled Input Constraints”.
- Jim Rawlings (UWM) and Brett Stewart (UWM) have visited KUL in June 2009.
- Brett Stewart (UWM) has visited RWTH Aachen on June 15, 2009. This visits included a lively and intense discussion on Distributed MPC.
- Jim Rawlings (UWM) has visited TU Delft on June 22, 2009. He also gave a presentation on the past, present, and future of MPC entitled “Optimal dynamic operation of chemical processes: assessment of the last 20 years and current research opportunities”.

- In the week June 22-26, 2009, Marcello Farina visited the research groups in Louvain and Delft, giving the seminar: “Distributed State Estimation with Moving Horizon Observers”.
- Jairo Espinosa (UNC) has visited the KUL team on September 11, 14, and 15, 2009.
- Antonio Ferramosca (USE) has visited the UWM team for a 6-month period from August 2009 to February 2010.
- Jairo Espinosa (UNC) has visited the KUL team on September 11, 14, and 15, 2009.
- Carlo Romani (POLIMI) visited the KUL team from September 11, 2009 to February 14, 2010. He followed the optimization course taught by Moritz Diehl and worked on modelling and distributed control of a hydro-power valley.
- Daniele Balzaretti (MSc student at POLIMI) visited TUD from November 2009 to May 2010 to develop his MSc thesis on distributed state estimation.
- Francesco Petrone (MSc student at POLIMI) visited EDF from February 1, 2010 to March 26, 2010 and from June 1, 2010 to June 30, 2010 to develop his MSc thesis on modeling and control of a hydro-power valley.
- Fabio Righetti (MSc student at POLIMI) visited EDF from March 1, 2010 to March 31, 2010 and from June 1, 2010 to June 30, 2010) to develop his MSc thesis on modeling and control of a combined cycle power plant.
- Dang Doan (TUD) has visited the partner group at KUL on March 16, 2010 to discuss about his research and to meet with prof. Stephen Boyd (Stanford, USA).
- Felipe Valencia Arroyave (UNC) has visited TUD from March 22, 2010 to August 31, 2010 to work on a feasible-cooperation distributed model predictive control scheme based on game theory.
- During April and June 2010 the team at SUPELEC had several exchanges with Fabio Righetti (POLIMI) about the power plant model simulation.
- Rudy Negenborn (TUD) and Yuping Li (TUD) have visited the INOCSA and USE teams in the week of May 10-14, 2010.
- Alfredo Núñez (TUD) visited US from February 7 to February 9, 2011.
- Attila Kozma (KUL) spent February 2011 at RWTH in Aachen.
- Since September 2011 Alejandro Marquez (UNC) is visiting RWTH for a period of 6 months.
- Pepe Maestre, PhD student at US until April 2011, is a postdoc at TUD since May 2011.

6. Explanation of the use of the resources

See the financial part of this report as well as the cumulative quarterly management report for Quarter 5 of Period 3.

7. Financial statements – Form C and Summary financial report

See the financial part of this report.

8. Certificates

See the financial part of this report.