Towards a European Roadmap on Research and Innovation in Engineering and Management of Cyber-Physical Systems of Systems

Project Deliverable

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Abstract :

This document, the Report on the second meeting of Working Group 2, provides the minutes of the CPSoS meeting of the Working Group 2: Physically Connected Systems of Systems which took place in Zurich on October, 1st, 2014 and was organized as a public event jointly with STREP DYMASOS (Dynamic Management of Physically Coupled Systems of Systems). An input paper for the discussion is included as an annex of the document, as well as photos from the event.

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Keywords :

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Revision History

The following table describes the main changes done in the document since it was created.

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V1.0	11/10/2014	Creation	Radoslav Paulen (TUDO), Christian Sonntag (TUDO), Benedikt Beisheim (INEOS)
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Acronyms and Definitions

Acronym	Defined as
CPS	Cyber-physical Systems
FP7	7th Framework Programme for Research and Technological Development
IP	Integrating Project
R&D	Research and Development
SoS	Systems of systems
STREP	Specific Targeted Research Project
ToR	Terms of Reference
WG	Working Group

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1. Executive Summary

CPSoS, funded by the EC (FP7 programme), is a 30-months Support Action that provides a forum and an exchange platform for systems-of-systems related communities and ongoing projects, focusing on the challenges posed by the engineering and the operation of technical systems in which computing and communication systems interact with large complex physical systems. Its approach is simultaneously integrative, aiming at bringing together knowledge from different communities, and applications-driven.

The project findings will be summarized in a concise strategic policy document "European research and innovation agenda on Cyber-physical Systems of Systems" supported by a set of in-depth technical papers, presented at a symposium "Cyber-physical Systems of Systems Meeting Societal Challenges".

The second meeting of the Working Group 2: Physically Connected Systems of Systems (chaired by Prof. Sebastian Engell from TU Dortmund, Germany), was held as a public workshop in collaboration with the project DYMASOS which is funded under the same call on October 1st, 2014 at ETH Zurich (Switzerland). It consisted of a joint plenary session and of parallel domain-specific breakout sessions.

An input paper "Analysis of the state of the art and future challenges in the domain of physically connected systems of systems" was developed based on the findings of the kick off meeting of the Working Groups (held in January 2014) and on discussions and interviews with domain experts and practitioners. It was circulated to the participants before the meeting as a basis for the discussions during the meeting.

The discussions were organised around the following main questions:

- What are the main difficulties encountered in the engineering, realization and operation of these systems?
- What are the specific demands and challenges for advanced methods and tools for CPSoS in the areas of electric grids, process industries and smart buildings?
- What are the most important open research questions for CPSoS on short-, medium-, and long-term horizons?

Outcomes:
The discussions provided very useful input for the further elaboration of the document on the state-of-the-art and the future challenges in the domain of physically connected systems of systems, confirming its current content for the most part. Several research challenges were proposed by the CPSoS consortium and by the participants of the workshop. These were discussed and prioritized in terms of time frames of the research development and technological implementation of the solutions in practice. The findings will be discussed with domain experts and within the consortium and will be presented to the European Commission in late 2014.

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2. Meeting overview

The second meeting of the Working Group 2 attracted 39 participants who represented a broad spectrum of domain experts, researchers, developers and industrial practitioners. The meeting was organized jointly with the FP7 STREP DYMASOS in order to discuss the currently pursued research activities in the domain of SoS and to broaden the view on the present challenges. An input paper “Analysis of the state of the art and future challenges in the domain of physically connected systems of systems” was developed based on the findings of the kick off meeting of the Working Groups (held in January 2014) and on the discussions and interviews with domain experts and practitioners performed by Radoslav Paulen (TUDO). It was distributed among the participants prior to the meeting and provided the basis for the discussions during the meeting. The paper is included as an Annex of this report.

The meeting started with a plenary session where the CPSoS project and the definition of the scope of Cyber-physical Systems of Systems and their research challenges as developed by the consortium in consultations with experts outside the project were presented.

In order to stimulate the discussions of the current and future research challenges in the domain of physically coupled systems of systems, the morning plenary session included three talks that were given by the researchers of the DYMASOS project on advanced management methods for CPSoS. Theoretical developments as well as application studies on SoS management were presented.

The afternoon plenary session was focused on the discussion on the state of the art and future developments of engineering tools for physically connected CPSoS. One presentation was contributed by DYMASOS, the other two by external experts, one of them with a background in chemical process management and control and the other one from the DANSE IP on Systems of Systems. The second part of the afternoon was organized as domain-specific breakout sessions on (1) Smart grid and smart buildings, (2) Process Industries, and (3) Tool support for physically coupled Systems of Systems. The parallel discussions were focused on the present challenges and the future research needs in the respective domains. The prioritization of the discussed topics was done based on anonymous voting polls where the participants of the workshop prioritized the research topics according to the time frame of the expected deployment of solutions in practice or their commercial availability.

The final plenary session consisted of presentations of the outcomes of the breakout sessions presenting the prioritized lists of the research topics for the most urgent future developments in the domain of physically connected SoS, a joint discussion on the presented topics and, and an outlook on the next steps.

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3. Morning plenary session: Management Methods for Cyber-physical SoS

The meeting started with the welcome by Sebastian Engell, the Project Coordinator who introduced the CPSoS project to the participants. He gave an overview of the workflow in the project and of the definitions and research challenges for CPSoS. Hand-out slides with a summary of the results from the kick off meeting of WG2 (see Annex) were distributed to the participants.

Three talks were given by the representatives of FP7 STREP DYMASOS in order to stimulate the discussion on the development of methods and tools for engineering and management of cyber-physical systems of systems. The talks were focused on the recent research in DYMASOS and were given on

- “Population-based management of Systems of Systems” by John Lygeros (ETH Zurich)
- “Price-based coordination for resource allocation in an integrated chemical production site” by Goran Stojanovski (TU Dortmund)
- “Coalitional control for electric vehicles charging” by Eduardo F Camacho (Universidad de Sevilla)

John Lygeros presented the recent developments in the WP1 of the DYMASOS project that build upon the population-based methods for coordination of systems of systems using ideas of mean field theory and games theory. An example concerning the coordination of charging of electric vehicles was presented to evidence the usability of the methods. The subsequent discussion addressed the issues of the modeling depth that is required for the correct representation of the system behavior, the stochastic aspect of the load prediction in the power grid and the convergence properties of the presented coordination algorithms.

Goran Stojanovski presented the recent developments in the WP2 of the DYMASOS project that are concerned with price- and market-based methods for the coordination of systems of systems. An example of the coordination needs arising in a petrochemical plant based on a case study provided by an industrial partner of the project highlighted the challenges, and first applications of price-based coordination algorithms were presented. The following discussion concerned aspects of the practical applicability of the presented coordination methods.

Eduardo Camacho presented the recent developments in the WP3 of the DYMASOS project that investigate coordination following the principle of coalitions’ formation and coalitional games theory. An example concerning the coordination of charging of electric vehicles was presented as a case study of usability of the developed methods. Practical aspects of the coalition formation in electric vehicle charging were stressed in the discussion as well as the level of autonomy and the nature of the demands of the users.

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4. Afternoon plenary session: Tools for SoS Engineering

The afternoon plenary session was devoted to the state-of-the-art and current developments of the tools that support the engineering and the management of SoS. Three talks were given on

- "An engineering support platform for large-scale Cyber-physical Systems of Systems" by Christian Sonntag (euTeXoo, DYMASOS)
- "Needs and Tools for Cyber-physical Systems of Systems in the Process Industry" by Cesar de Prada (Universidad de Valladolid)
- "The Danse EU Project: Consistent Integration of Simulation and Formal Analysis in the Design of SoS" by Valerio SENNI (ALES S.r.l.)

Christian Sonntag presented the concept of the engineering support platform that currently is developed in the WP4 of the DYMASOS project. A tool originating from these developments will support the simulation of the coordination of systems of systems supporting co-simulation for integration of models written in different languages. The discussion stressed the need for co-simulation tools and raised concerns about the ability to handle co-simulation of really large-scale systems by the state-of-the-art tools.

Cesar de Prada gave a survey presentation on the state-of-the-art and the future needs of tools used for Cyber-physical engineering and management. The talk was oriented towards the needs arising in the process industry. The main concerns were inconsistencies of the models being used at different levels of the process automation pyramid and the sustainability and deployment of advanced tools for simulation and optimization. Distributed simulation and management strategies were discussed. It was confirmed in the discussion that task of modeling and maintenance of models is a time-consuming one. The further development of methods for distributed optimization was stressed as distributed optimization is currently regarded as a technology that can cope with the increased complexity of optimization problems when a greater modeling depth is employed for the sake of consistency of the models.

Valerio Senni presented the developments of the project DANSE. It was pointed out that DANSE mainly addresses the integration of available tools into a coherent tool chain. The tool chain supports modelling, verification and simulation of hybrid systems and system of systems. In the discussion, it was clarified that verification tools are only available for the discrete part of the systems, hybrid elements are validated based on simulation scenarios.

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5. Parallel breakout sessions

Afterwards, the participants of the meeting split into three groups in order to discuss and to prioritize the research and development challenges in the domains of

- Electric grids and smart buildings (Session moderated by Patrick PANCIATICI from RTE - Réseau de Transport d'Electricité)
- Process Industries (Session moderated by Sebastian ENGELL from TU Dortmund)
- Tool support (Session moderated by Christian SONNTAG from euTeXoo and by Michel Reniers from TU Eindhoven)

5.1. Electric grids and smart buildings

The session was attended by 12 participants, 7 of them coming from industrial and 5 from academic domain. The session was chaired by Patrick Panciatici who described the objective of the session at its opening. He afterwards presented his view on the challenges encountered in the domain of smart grids and power grids. The presented topics included:

- Spatial complexity (from Pan European power grid to active distribution grids)
- Temporal complexity (from decades to milliseconds)
- Stochastic complexity (from failures, weather conditions to grid users' behaviours)
- Aging of grid assets
- Multi-stage decision making under uncertainty (decisions changing the structure of the system, policies or control/protection schemes, the operating points of the system)
- Mixed integer non linear programming, "Convexification" of ACOPF (scalable implementation for large SDP)
- Robust optimization (bi-level programs and semi-infinite programs, chance constraint programming)
- System stability ("Lyapunov like" approach, sum of squares, flatness, ...)
- Distributed (decentralized) controls at substation Level (MPC, setting less protection, ...)
- Massive integration of inverter-based components (synchronization issue, lack of "inertia", ...)
- Requirement for the associated ICT systems (latency, reliability, communication delays)
- Taking advantage of high performance computing.

The presented topics were subsequently discussed. The participants mostly agreed on the relevance of the topics. Radoslav Paulen additionally presented a set of topics that were indicated as key challenges in the domain of smart grids and power grids in the interviews with domain experts and practitioners that he performed in the framework of the CPSoS project. These topics included:

- Modelling and simulation of distributed generation
- Generic and automated building of dynamic models
- Modelling the power system jointly with the communication system
- Simulation of large-scale systems
- Reliable simulation (What depth should be simulated at which level?)
- Demand side management via virtual power plants (subsidies to big consumers; how to do it optimally?)
- Negotiation between market and technical system for the feasibility when planning
- Cultural change of frequency management due to renewables

Additional topics were raised by the participants of the breakout session and discussed subsequently. These included: System integration of active distribution, Data availability and new business models, Better use of measurements (estimation), Cyber-security (privacy), Revision of the communication protocols, Remote control

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of substations, Dynamic reconfiguration and re-engineering while performing a migration from the existing grid to the optimal one, possibilities of synchronization without using GPS and possibilities of establishing DC transmission and distribution.

An anonymous voting poll was conducted at the end of the session in order to prioritize the discussed topics. The prioritization was performed for different time frames based on the expected availability and deployment of the solutions to the research and innovation challenges. The participants prioritized the research topics in short- (less than 4 years), medium- (4 to 8 years), and long-term (more than 8 years) horizons. The participants' votes were distinguished based on the affiliation of the participants in industry or academia. Each participant could cast two votes for each time horizon. The following table summarizes the results (a photo of the voting is present in the Annex of this document):

	Industry		Academia	
Short-term horizon	System Integration of Active Distribution	4 votes	System Integration of Active Distribution	2 votes
	Data availability & new business models	3 votes	Massive Integration of Inverter-based Components	2 votes
	Modelling and Simulation for Distributed Generation	2 votes	Demand Side Management via Virtual Power Plants	1 vote
	System Stability (new concepts)	1 vote	Data availability & new business models	1 vote
	Spatial Complexity	1 vote		
	Distributed (Decentralized) Controls at Substation Level	1 vote		
	Massive Integration of Inverter-based Components	1 vote		
	Better Use of Measurement and Estimation	1 vote		
Medium-term horizon	Requirement for Associated ICT Systems (new control and protection)	3 votes	System Stability (new concepts)	2 votes
	Multi-stage Decision Making under Uncertainty	2 votes	Better Use of Measurement and Estimation	2 votes
	Demand Side Management via Virtual Power Plants	2 votes	Stochastic Complexity	1 vote
	Distributed (Decentralized) Controls at Substation Level	1 vote	Modelling the Power System Jointly with Communication System	1 vote
	Stochastic Complexity	1 vote		
	Massive Integration of Inverter-based Components	1 vote		
	Simulation of large-scale systems	1 vote		
	Negotiation between Market and Technical System for the Feasibility When Planning	1 vote		
	Cultural Change of Frequency Management due to Renewables	1 vote		
	Better Use of Measurement and Estimation	1 vote		
Long-term horizon	Taking Advantage of High Performance Computing	3 votes	Distributed (Decentralized) Controls at Substation Level 2	2 votes
	Cyber-security (privacy)	2 votes	Cyber-security (privacy) 1	1 vote
	Requirement for Associated ICT Systems (latency, reliability, …)	2 votes	System stability 1	1 vote
	Stochastic Complexity	1 vote		
	Aging of Grid Assests	1 vote		
	Mixed Integer Non Linear Programming,	1 vote		

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	"Convexification" of ACOPF			
	Distributed (Decentralized) Controls at Substation Level	1 vote		
	Simulation of large-scale systems	1 vote		

5.2. Process industries

The session was attended by 15 participants, nearly equally distributed among participants from the industrial and the academic domains. The session was chaired by Sebastian Engell who described the objective of the session at its opening and presented the engineering and management challenges in the domain of process industries as identified by the members of the Working Group 2.

- Modeling optimization and simulation tools
- Reduction of the modelling effort
- Model integration, co-simulation
- Distributed management and control
- Handling of faults and abnormal situations
- Using large amounts of data to monitor and improve system operation
- User/operator interaction
- Requirements management over the life cycle
- Holistic model-based design
- Deployment, maintenance, and continuous upgrade / re-engineering
- Dynamic reconfiguration
- Validation and verification

Further he presented a list of topics that originated from the interviews with practitioners in industry performed by TUDO. These concerned the issues of:

- Modelling:
  - How to go quickly from P&ID to high-fidelity simulation of a process? Need to simulate different possible equipment (e.g. pumps) and automation systems (different vendors)
  - How to handle incomplete information in simulation?
  - Exchange of information between models on different levels
  - Doubts on application of co-simulation for large-scale systems
  - Modelling with incomplete or generic information
  - Model building and maintenance is time-consuming; very detailed models needed for control purposes; very hard task for batch plants (hybrid data-based + first-principles models did not penetrate to industry)
  - Information on models -> Limits-aware models
- Full Automation and modelling of human behavior:
  - People and their interaction with the system is the biggest challenge
  - Model the human behavior and decision process; planning is very hard otherwise
  - Building near-autonomous system management because of the demographic changes in Europe
  - People should be taken out of the real-time operation; need to build trust in system and software
  - Decision-support systems (e.g. to support people who decide on the maintenance of equipment)

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- Information systems and systems integration:
    - Big data handling at different levels (SAP(ERP)/MES/APC)
    - Plug-n-play solutions to harmonize the communication across SAP(ERP)/MES/APC, data synchronization
    - Each layer (planning, scheduling, control) uses different model; how to link and integrate these?
    - Integration of different software tools used at different departments (engineering vs. automation and control)
    - Information security – where does the information go (model the flow of information); cyber attacks
    - Integrity, security and trust
- Other topics:
    - Degree of reliability of academic solutions is unknown
    - Need for "non PhD" tools
    - How to control the modules in modular plants; there should be a joint effort of vendors of control systems to develop plug-n-play solutions for those plants.

A collection of topics was discussed further. These included:

- Integrity, security and trust (Lack of understanding in commercial structures, making people aware of benefits, economic benefits for coordinated work in industrial parks)
- Lack and inconsistency of models on higher hierarchical levels, e.g. on the supply chain and production planning layer (possible to build up high level models from lower level models? model simplifications?)
- Standardization (using developed models for several needs)
- Feasibility of set-points provided by high level models is unclear for lower levels
- Supply chain and production should be modelled and optimized simultaneously
- Industrial demand response
- Unmanned operation / remote operations / maintenance
- „Data mining", using historical data for process monitoring, e.g. Baseline calculation from historical data, debottlenecking
- Integration of supply chain, production scheduling, demand planning, and control
- Standardization of model interfaces.

An anonymous voting poll was conducted at the end of the session in order to prioritize the topics discussed. The prioritization was performed for different time horizons based on the expected availability and deployment of the solutions to research challenges. The participants prioritized the research topics in short- (less than 4 years), medium- (4 to 8 years), and long-term (more than 8 years) horizons. The participants' votes were distinguished based on the affiliation of the participants in industry or academia. Each participant cast two votes for each time horizon. The following table summarizes the results (photo of the voting is included in the Annex of this document):

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	Industry		Academia	
Short-term horizon	Modeling optimization and simulation tools	4 votes	Modeling optimization and simulation tools	2 votes
	Standardization of Interfaces	3 votes	Standardization of Interfaces	2 votes
	Dynamic reconfiguration	1 vote	Dynamic reconfiguration	1 vote
	Reduction of the modeling effort	1 vote		
Medium-term horizon	Validation and verification	3 votes	Integration of supply chain, scheduling and control	5 votes
	Integration of supply chain, scheduling and control	2 votes	Modeling optimization and simulation tools	2 votes
	Standardization of Interfaces	1 vote	Standardization of Interfaces	1 vote
	Dynamic reconfiguration	1 vote	Dynamic reconfiguration	1 vote
Long-term horizon	Integration of supply chain, scheduling and control	5 votes	Reduction of the modeling effort	4 votes
	Reduction of the modeling effort	4 votes	Validation and verification	3 votes
	Dynamic reconfiguration	1 vote	Dynamic reconfiguration	2 votes
	Standardization of Interfaces	1 vote		

5.3. Tool support

The breakout session on tool support was attended by 8 participants (1 from industrial domain, 7 from academic domain). The goal of the session was to validate and to prioritize the key challenges in four areas that are seen as crucial for future research and innovation in industrial CPSoS. These areas are “Modeling, Simulation, and Model Management”, “Engineering and Run-time Platforms”, “Model- and Data-based Engineering Tools”, and “Integration and Deployment of Advanced Solutions”. Overall, 16 key challenges were presented, discussed, and prioritized during the breakout session. The challenge of managing the large number of models that arise during the engineering and operation of complex CPSoS received the most votes, followed by challenges such as improving simulation and optimization algorithms, CPSoS developing new management methodologies and tools, CPSoS engineering and runtime frameworks, and providing consistent system integration of advanced solutions. The discussions from this session brought valuable input for the Working Group 3 of CPSoS project and their results will be reported in detail in the Deliverable 2.3 in M13. The following table summarizes the results of prioritization of discussed research topics (photo of the voting is included in the Annex of this document):

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	Industry		Academia	
Short-term horizon	Model Re-use and Predefined and Adaptable Standard Models	1 vote	Model Management	5 votes
	Large-scale, Faithful, Efficient Simulation Algorithms	1 vote	Co-simulation	2 votes
			Large-scale, Faithful, Efficient Simulation Algorithms	2 votes
			Consistent Integration of Data, Engineering, and Operational Artefacts and Tools	2 votes
			Model Re-use and Predefined and Adaptable Standard Models	1 vote
			New CPSoS Engineering Frameworks	1 vote
			Collaborative Engineering and Run-time Environments	1 vote
Medium-term horizon	New CPSoS Engineering Frameworks	1 vote	More Powerful Optimization Algorithms/Tools	4 votes
	More Powerful Optimization Algorithms / Tools	1 vote	New System-wide Management and Coordination Tools	3 votes
			Collaborative Engineering and Run-time Environments	2 votes
			Model Management	1 vote
			Co-simulation	1 vote
			Large-scale, Faithful, Efficient Simulation Algorithms	1 vote
			Stochastic Optimization and Risk Management	1 vote
			Consistent Integration of Data, Engineering, and Operational Artefacts and Tools	1 vote
Long-term horizon	New System-wide Management and Coordination Tools	1 vote	Extending Models with New Aspects (3 votes)	3 votes
	Stochastic Optimization and Risk Management	1 vote	Large-scale Data-based Methods	3 votes
			Stochastic Optimization and Risk Management	2 votes
			Large-scale, Faithful, Efficient Simulation Algorithms	1 vote
			Conceptual Model Alignment	1 vote
			New CPSoS Engineering Frameworks	1 vote
			Collaborative Engineering and Run-time Environments	1 vote
			New System-wide Management and Coordination Tools	1 vote
			Validation and Verification of Large-scale CPSoS	1 vote
			Extending Models with New Aspects	1 vote

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6. Summary of the breakout sessions, Discussion, Next steps and conclusion

The closing session of the meeting was held after the breakout sessions. The results of the discussions during the domain-specific parallel sessions were presented by the chairs (P. Panciatici, S. Engell and M. Reniers) and discussed among the participants. The main research topics put forward in the breakout sessions were summarized as follows:

Smart grids and smart buildings:

- System Integration of Active Distribution (7 votes, short-term horizon)
- Requirement for the Associated ICT Systems (5 votes, industry: medium-term to long-term horizon)
- Massive Integration of Inverter-based Components (4 votes, mostly short-term horizon)
- System Stability (4 votes, predominantly from academia)
- Data availability and new business models (4 votes, short-term horizon)
- Better Use of Measurements (Estimation) (4 votes, medium-term horizon)
- Cyber-security (privacy) (4 votes, long-term horizon)
- Distributed (Decentralized) Controls at Substation Level (4 votes, mostly long-term horizon)

Process industries:

- Integration of supply chain management, scheduling, and control (12 votes, industry: long-term horizon, academia: medium-term horizon)
- Reduction of the modelling effort (9 votes, mostly long-term horizon)
- Modelling, optimization and simulation tools (8 votes, mostly short-term horizon)
- Standardization of interfaces on the higher automation layers (8 votes, mostly short-term horizon)
- Dynamic reconfiguration (6 votes, long-/medium-term horizon)
- Validation and verification of the proper functioning of systems (6 votes, academia: long-term horizon, industry: medium-term horizon)
- Integrity, security and trust (6 votes, short- to medium-term horizon)
- Industrial demand response (5 votes, short- to medium-term horizon)
- Handling of disturbances, faults and abnormal situations (5 votes, medium-term horizon)

Tool support:

- Model Management (6 votes, short-term horizon)
- Large-scale, Faithful, Efficient Simulation Algorithms (5 votes, mostly short-term horizon)
- New System-wide Management and Coordination Tools (5 votes, mostly medium-term horizon)
- More Powerful Optimization Algorithms/Tools (5 votes, medium-term horizon)
- Stochastic Optimization and Risk Management (4 votes, long-term horizon)
- Collaborative Engineering and Run-time Environments (4 votes, mostly medium-term horizon)

After the presentation of the results of the prioritization of the research topics, a subsequent discussion was conducted. Referring to the results of the session on tools, Patrick Panciatici stressed openness of models, transparency of the modelling procedure and tracking of the modelling process. Michel Reniers elaborated the topic mentioning the problem of openness of the data collected over time.

Sebastian Engell concluded the meeting by thanking the participants for their collaboration and for fruitful and focused discussions. He mentioned that the CPSoS consortium will further analyse and process the gathered prioritization results and will synthesize a few research topics that are general and not domain-specific and that could become headlines for the next calls of the EU on research and innovation in the domain of systems of systems.

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7. Annexes

7.1. Input paper

Analysis of the state of the art and future challenges in the domain of physically connected systems of systems

Authors: F. Brancati, V. Havlena, A. Isaksson, E. Kosmatopoulos, S. Kraemer, J. Lygeros, F. Massa Gray, R. Paulen, S. Engell

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A definition of cyber-physical systems of systems, as pursued in the project CPSoS, is that the cyber-physical systems of systems are cyber-physical systems which exhibit the features of systems of systems (SoS) such as:

- Large, often spatially distributed physical systems with complex dynamics
- Distributed control, supervision and management
- Partial autonomy of the subsystems
- Dynamic reconfiguration of the overall system on different time-scales
- Possibility of emerging behaviours
- Continuous evolution of the overall system during its operation.

This document describes the state of the art and future challenges in the domain of physically coupled systems-of-systems covered by Working Group 2 (WG2) of the project CPSoS. This application domain particularly addresses smart grids, smart buildings, energy efficient industrial production, and network management as domain-wide representative examples.

Smart Grids

Power grids represent active electricity distribution systems that are designed and engineered to ensure seamless transport of electrical energy from the place of its production (supply side) to the place of the consumption (demand side). These systems form networks naturally distributed over large areas, such as country or continent, where they encompass multiple nodes of electricity generation and consumption. The operational goals of the grid, mainly on the distribution side, relate first of all to maintaining grid stability while adhering to the grid codes (network specifications) in order to ensure reliable and quality power supply to all consumption entities distributed over the grid. Currently, the electricity distribution systems face vast challenges with the rapidly growing penetration of intermittent renewable energy sources and other distributed sources.

As distributed renewable production is in general, when local generation cannot be used to fully cover local consumption, asynchronous with consumption, different new technical measures are put in place to complement

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standard supply-demand balance techniques consisting of production planning and reserves and to make the system more technically and economically agile in the emerging conditions. These new techniques are demand-side management and distributed energy storage, which both mainly reside on the distribution system level. This has led to the concept of microgrids, which are local interconnections of source, storage, and consumption entities with a single connection to the distribution grid. Microgrids are operated and managed independently from the distribution system operators and can economically optimize their internal power flow and the power exchange profile with the grid based on varying electricity prices, local energy needs, the states of the storage devices and sources availability. They can also be used in principle to stabilize grid voltage conditions, to shorten the energy path to consumers, and to minimize CO_2 content of the distributed energy.

If the microgrid and the distribution grid are, however, not properly interoperated or are not interoperated at all, the distribution and/or transmission system can experience grid codes violation at certain consumption points as well as excessive grid losses through certain distribution paths. With the lack of robust and reliable interoperation concepts, the distribution system operators in current practice act conservatively and prohibit connections of units with production capacity to certain grid points in situations when worst-case static simulations show that grid codes violation might occur. This is especially rigid since all already approved, but even not yet built, distributed production capacities are also considered in these worst-case simulations. Moreover, the electricity grid infrastructure dates from the times of unidirectional power flows and is thus very inflexible in terms of controllability. For example, transformer taps that can adapt the voltage level on the output of the transformer stations are on low-voltage transformer stations only manually controllable in no-load state while they possess significant potential in terms of support for grid codes adherence. Hence that the presented specifications qualify the electricity distribution systems as prototypical case of physically connected systems with spatial physical distribution and management, multi-scale dynamics, partial autonomy of the subsystems, temporal evolution of the system, and possibility of emerging behaviours.

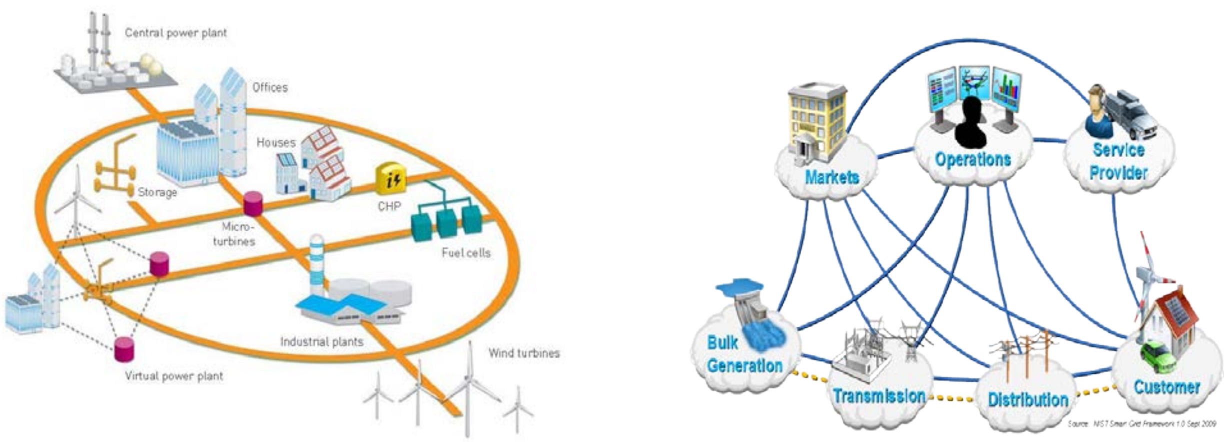

Figure 1. Smart grid conceptual diagrams from the Smart Grids European Technology Program (left) and the NIST Smart Grid Interoperability Panel (right) showing different views on a smart grid.

Smart grids promise a revolutionary advance over today's power grids by enabling two-way flow of both electricity and information, seamless integration of renewable resources at distribution and customer points, widespread use of storage technologies and battery-electric and plug-in-hybrid-electric vehicles, demand response for efficiency and peak reduction, and other technological solutions (see Figure 1). The extended

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electrical power system connects beyond the physical grid itself to consumers at all levels, third-party energy service providers, demand aggregators, electricity markets, and other players. Information integration in terms of measurement, command, and control signals will supplement power flows. Individual systems, complex entities themselves, will retain their ability for autonomous operation, but are coupled via the grid and have to be coordinated.

The operational goals of smart grids are to ensure adherence to grid rules while maximizing the economic benefits of the distribution and transmission grid operation, which include:

- Maximizing the environmental value of energy transfer, taking into account the CO_2 equivalent of the transferred energy,
- Minimizing energy losses in the grid by proper configuration of power flows over grid segments.

Operational constraints are posed on the grid voltage amplitude at all connection points, as requested by grid codes. Furthermore, power flows through individual grid segments and transformer stations are constrained to prevent excessive power dissipation and equipment damage. System-wide possible control actuations are transformer tap changes in transformer stations and capacitor banks switches, both actuated in discrete steps, generator loads and circuit breakers for grid topology reconfiguration.

Drivers of the operational decisions in the electrical grid form a hierarchy. At the upper level, the efficiency, security and sustainability of electrical power generation and transmission are of a concern. On the other hand, at the lower (microgrid) level the focus is given to achievement of the reliability of the network via means of congestion management techniques which include demand side management, (efficient) exploitation of storage capabilities, and flexible electricity generation using conventional sources.
The time-scales on the different levels of the presented hierarchy are largely different; they vary from microseconds to long-term contract management (see Table 1. **Multiscale Time Hierarchy of Power Systems (taken from (Amin & Stringer, 2008)).**). The human-operator actions are usually employed at the time-scale of hours and longer. While achieving the lower-level goals, the preference is given to decisions provided by automated solutions as the system-wide actuation in the distribution grid must provide a safe and fast recovery from possible large disruptive events (e.g. failure of large producers or consumers, certain line breakages, unavailability of certain transformer stations, etc.) to prevent possible outages. The price to pay for guaranteeing safe and fast recoveries is the conservativeness of the actuation.

Table 1. Multiscale Time Hierarchy of Power Systems (taken from (Amin & Stringer, 2008)[1]).

Action/Operation	Time Frame
Wave effects (fast dynamics, lightning-caused overvoltages)	Microseconds to milliseconds
Switching overvoltages	Milliseconds
Fault protection	100 ms or a few cycles
Electromagnetic effects in machine windings	Milliseconds to seconds
Stability	60 cycles or 1 second
Stability augmentation	Seconds

[1] Amin, M., & Stringer, J. (2008). The Electric Power Grid: Today and Tomorrow. *MRS BULLETIN, 33*, 399-407.

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Electromechanical effects of oscillations in motors and generators	Milliseconds to minutes
Tie line load frequency control	1–10 s; ongoing
Economic load dispatch	10 s to 1 hour; ongoing
Thermodynamic changes from boiler control action (slow dynamics)	Seconds to hours
System structure monitoring (what is energized and what is not)	Steady state; ongoing
System state measurement and estimation	Steady state; ongoing
System security monitoring	Steady state; ongoing
Load management, load forecasting, generation forecasting and scheduling	1h to 1 day or longer; ongoing
Maintenance scheduling	Months to 1 year; ongoing
Expansion planning	Years; ongoing
Power plant site selection, design, construction, environmental impact	2–10 years or longer

Although it is believed that the possibility of human interaction on shorter time-scales would result in a better performance in terms of fulfilling the upper-level goals, such interaction is presently not exploited since fast and reliable response of human operators cannot be generally assured. The multi-scale nature of the system dynamics plays crucial role in the way the grid is managed and how its behaviour is forecasted. Tools of static model-based simulation are in use as the simulation models consider the dynamic effects acting on much shorter (or longer) time-scales to be constant.

From the management viewpoint, one of the main features of the smart grid is the inherent stochasticity that originates from the inclusion of renewable energy and from the behaviour of customers. In this respect, the statistical tools for monitoring the network balance are utilized in order to forecast the future evolution of the demand and supply. To deal with the present challenges, several research and innovation projects were launched on modelling, simulation, control and optimization of the electrical grid. Presently, the modelling is commonly done both physics-based and data-based and includes attempts to model the behaviour of the "agents" in the grid. The challenges in simulation include hybrid (continuous-discrete) simulation, simulation of systems with many different time-scales and the coupling between physics and economy as the politically-motivated regulations have a strong influence on the way how grid is operated.

Issues in control of the smart grid include robust and distributed model predictive control and inclusion of new sensors and actuators. In the field of optimization, stochastic optimization (risk management) and discrete decisions are seen as important fields of research. Further challenges in the management of these systems comprise (Amin & Stringer, 2008)[2]:

- low-cost, practical electric and thermal energy storage;
- advanced (post-silicon) power electronics devices (valves) to be embedded into flexible AC and DC transmission and distribution circuit breakers, short-circuit current limiters, and power electronics-based transformers;
- power electronic-based distribution network devices with integrated sensors and communications;
- fail-safe communications that are transparent and integrated into the power system;
- low-cost sensors to monitor system components and to provide the basis for state estimation in real time;
- cost-effective integrated thermal storage (heating and cooling) devices;

[2] Amin, M., & Stringer, J. (2008). The Electric Power Grid: Today and Tomorrow. *MRS BULLETIN, 33*, 399-407.

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- thermal appliances that provide “plug-and-play” capability with distributed generation devices;
- high-efficiency lighting, refrigerators, motors, and cooling;
- enhanced portability through improved storage and power conversion devices

It is worth noting that the idea of smart grids is not limited to electric power but the principles, as well as present challenges, can be transferred to other resource infrastructures such as the ones for natural gas and for water distribution. In smart grids, autonomous/semi-autonomous entities coordinate their operations on an as-needed basis, following selfish goals, while the efficiency and stability of the overall system must be ensured by limited central authority. This is clearly a systems of systems design and management challenge.

Present and future challenges in the domain of smart grids

The smart electricity grids discussed above are only part of the future energy landscape. There is a bidirectional interconnection with other energy carriers, for example the gas network, heat/steam networks, etc. The interconnection needs to be taken into account, when designing next generation electricity grids and optimizing their performance. This is particularly relevant at the level of micro-grids, which can combine electricity generation and consumption with other energy sources, for example combined heat and power.

Market aspects may play a key role in the process. Producers and consumers of electricity, micro-grids, etc. will coordinate with each other to provide smart grid functionality either if forced (by introducing a legal framework), or if the right market mechanism makes it mutually beneficial for them to do so. Figuring out the benefits/costs of different behaviours and fairly allocating them to the different participants will be crucial for the latter approach.

In addition to operational concerns, economic issues of course also arise in long term decisions related to network development, capacity expansion, technology investment, etc.

For all these issues, optimization-based control methods, especially those building on distributed optimization concepts can be central. Dealing with uncertainty (e.g. about future demand and technology, operational uncertainty in the day-ahead markets, etc.) means that links to stochastic programming and randomized optimization should also be investigated.

The challenges in the domain of smart grids further include:

Emergence aspects

- They can be improved by considering the management of renewable energy sources. The forecast of renewable energy production is an enabler here but yet a challenging point.

Governance of smart grids

- Whether smart grid deployments are being driven by legislative and regulatory policies, realizing operational efficiencies, or creating customer value, the motivation and pressure to produce have caused the industry to perform smart grid implementations in fragmented efforts with limited or no stakeholder coordination or agreed-upon standards.

System security monitoring

- Since a smart grid highly relies on ICT infrastructure, then it is exposed at cyber-attacks. Protection against both attacks on control devices (e.g. low voltage grid controller) or on metering devices (e.g. smart meter) is a challenging point.

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Fault management

- It should consider not only the detection, but also the isolation and the recovery from a fault. In particular at LV no mechanisms are actually deployed. Take as reference FDIR (fault detection isolation and restoration) and self-healing approaches.

Generation forecasting

- The management of distributed resources, in particular the renewable ones, is an open issue.

Load management, forecasting, generator scheduling

- Load forecasting is rather standard and transmission grid operators can generally do it quite well. Of interest here is more generator forecasting due to uncertain renewable generation. This dictates a change of paradigm to introduce stochastic effects into generator scheduling, ancillary services, etc. It would also require more wide spread use of stochastic programming, randomized optimization, etc.

Economic load dispatching

- Presumably this means if a certain power consumption is requested (e.g. because a load aggregation provides ancillary services by bidding into the reserves markets) how should the loads participating in the aggregation distribute the request among them. This would require the development of novel distributed optimization and distributed control methods, depending on how many loads participate in the aggregation, the economic relation between them, privacy issues, etc.

Smart buildings

Smart buildings are among high-priority energy management topics in the EU. The building sector consumes around 40% of the energy used in Europe and is responsible for nearly 40% of greenhouse gas emissions. The goal is to establish a reliable and sustainable technology for maintaining green and zero-energy buildings that use all the available sources of energy efficiently and that even actively assist to stabilize the resource and energy networks (e.g. power grid). Adopting a holistic SoS view of the building, its environment, the power grid and its subsystems will offer a substantial improvement in energy savings. In particular, the environment may offer natural resources (e.g., sun light, wind, and water) for cooling, heating and lighting. In addition, the power grid dynamics have a significant impact on the efficiency of the overall operation. An approach based on SoS engineering will bring these systems together to comprehensively take advantage of their individual features.

With the increased focus on energy efficiency, the deployment of renewable energy sources, and the development of smart grid technologies, a growing number of buildings and multi-building facilities (campuses) will become active participants in the market. From the system point of view, such next-generation facilities will be autonomous entities with capabilities to sell or buy electricity to/from the power network and to flexibly shift or reduce electrical loads when needed. The energy system of a building or campus can include any type of local energy generation, distribution, consumption, and storage elements (see Figure 2). Frequently, a central combined heat and power (CHP) plant is a key generation element, and this means that a heat distribution network – and possibly also thermal storage – must be considered in addition to the electricity network. The overall system management can be seen as a complex optimization problem formulated as a balancing between energy generation (supply side) and energy consumption (demand side), which are interconnected by distribution subsystems, such as hot water (HW), chilled water (CHW) and electricity networks.

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The supply side feeds the system with electric power that is generated locally by a variety of distributed generation elements. These can range from complex cogeneration (CHP) units to stand-alone generation units (wind turbines, photovoltaics, etc.) that utilize conventional or renewable sources of energy. Supplies also come from the main electrical power grid, which is operated by the respective system/network operator, and this connection can also serve for selling locally generated excess or green energy back to the main electricity network. In addition to electricity, the supply side includes also boiler plants and chiller plants for heating and cooling the building, which is required to maintain thermal comfort in the interior spaces. Heat is transferred to and from individual rooms or zones through available distribution networks – systems of ducts, pumps and heat exchangers - in which the hot water, chilled water and/or air are used as the three main energy carriers. The demand side aggregates all devices that consume either electrical or thermal energy.

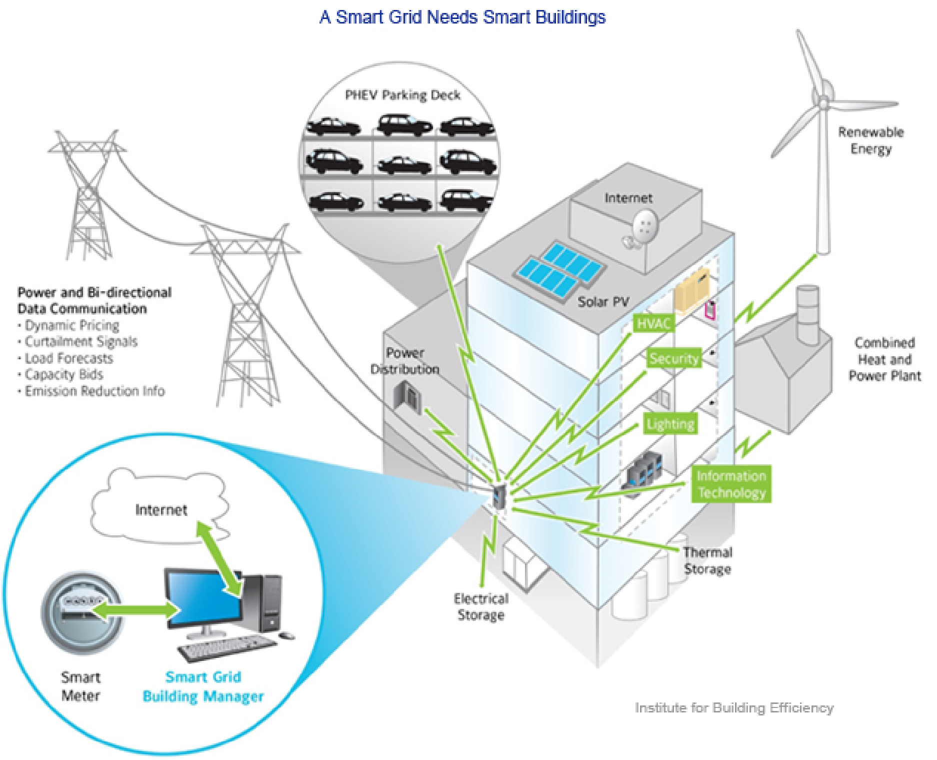

Figure 2. Integration of smart building within smart grids (taken from (Institute for Building Efficiency, 2011) [3]).

Energy storage is an important element that adds more flexibility, but it also increases the operational complexity. Energy storage elements can bring significant advantages particularly when the supply side includes intermittent renewable generation sources. In the future, when electric cars are widely used, their storage capacity could be exploited in a similar way to smoothen energy consumption profiles.

The present state of the art suggests to control and to optimize some of the subsystems independently of the others. Typically, all three, hot-water, chilled-water, and air distribution systems are running in a way to meet the daily demand for heating or cooling inside the building. The flow rates and supply temperatures are maintained around fixed set points, which were specified during the system design. The current standards might apply

[3] Institute for Building Efficiency. (2011, April). *What is a Smart Building?* Retrieved April 2014, from http://www.institutebe.com/smart-grid-smart-building/What-is-a-Smart-Building.aspx

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control schemes employed with rule-based control which commonly defines supply set points using the current ambient temperature, adjusting dynamically after every measurement. Those techniques are, however, unable to dynamically respond to changing conditions, such as forecast of ambient temperature and sunshine intensity, or the daily expectations on number and behaviour of occupants. The majority of today's advanced technologies require an elaborate model of the system to be available. In real-life applications though, these technologies usually turn out to be inapplicable due to absence of such system models, inappropriate modelling assumptions of the present models, computing limitations, complexity trade-offs and simulations' feasibility. Modelling and efficient control of such systems – large-scale systems – demands tedious work of specialized personnel and continuous tuning of the control and modelling parameters due to continuous evolution of real-life CPSoS dynamic behaviour and the subsystem interconnection dependencies.

Boiler and chiller plants are operated in a way to cover the heating and cooling demand whose daily target is specified based on an estimation of the likely demand. When these plants are operated together with other units (CHP), the respective schedules and set points are determined heuristically, exploiting previous operational experience. The same applies to possible interactions with the electricity grid and possible decisions about generating and selling excessive energy.

Given the above shortcomings of the state of the art, there are large opportunities for improvements. Building energy systems should be operated in a predictive/proactive way while considering future demands (day-ahead predictions), weather conditions, and possibly also electricity prices/tariffs and other external parameters. Flow rates and temperatures in water and air distribution systems should be modulated to minimize the operating cost while interior comfort conditions should be kept within a specified comfort range. The ratio between local generation and the purchased electricity should be optimized with respect to dynamic electricity prices, while using various storage mechanisms to accommodate variations.

Present and future challenges in the domain of smart buildings

To overcome the shortcomings of CPSoS inherited from the system nature, modern technologies and methodologies for optimal/efficient control are needed. Such approaches should encompass adaptability, flexibility, stability, and interoperability properties so as to cover all necessary aspects for such purpose.

Recent research has proven adaptive real-time self-learning techniques capable of replacing tedious manual control-parameter retuning and modelling reconfiguration of such complex interconnected subsystems. Modern adaptive mechanisms have to be extended towards the reduction of computational demand and control complexity, the ability to handle thousands of parameters in an efficient manner and, as a consequence, towards the increase of the respective frequency response for real-time control schemes. Self-learning mechanisms can be considered as a concrete basis for future research in order to embed easily, appropriate aspects of adaptive system identification schemes within the control mechanism, so as to directly construct an internal accurate enough model, capable of assessing the effect of control decisions on the real system.

Operating, maintaining and calibrating Cyber-Physical Systems of Systems requires a significant amount of effort which, in many cases, does not guarantee that the CPSoS will operate as it is desired to. The complex interplay of an extremely large number of parameters together with the fact that the system behavior is subject to frequent changes (due to e.g., weather changes, human behavior, incidents or changes in the CPSoS infrastructure) render the transformation of "what the human wants" into "how should the CPSoS control and calibrate the large

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number of parameters so as to do what the human wants" an extremely difficult and complex task. This task becomes significantly more complex when the human operator needs to intervene in the systems in a real-time and dynamic fashion, i.e., "on-the-fly", while the system is in operation. The future research goals should lead towards an integrated, inexpensive, straightforwardly deployable (plug-n-play) application software which will embed conventional cheap infrastructure with a highly intelligent mechanisms for assisting the customers in significantly reducing their energy bills and will enable the human operator to control and adjust CPSoS of high complexity, scale and heterogeneity in a simple yet very efficient manner. More precisely, it should be able to dynamically control all different parameters of systems so as to (i) meet the operator/costumer preferences while (ii) making sure that the overall CPSoS re-adjusts itself so as to optimize the effect of these preferences to the Key Performance Indexes.
In essence, such mechanisms should be able to instruct the customers/operators when and how to operate their energy consuming devices so as to optimally reduce electrical energy bills (while maintaining user comfort, preferences and needs).

There are two basic ingredients necessary to implement a generic Smart Building Efficient Control tool:

- The first of these ingredients is a tool which will be able provide in a plug-n-play, fully-automated manner the optimal decisions towards significantly reducing the energy bills. The attributes of this tool are extremely suitable for the majority of real-life building control applications: in contrast to existing methods and systems, it should not require the involvement of a tedious and effort/time-consuming deployment phase and, most importantly, it is embedded with a very efficient, self-adjusting/self-calibrating mechanism. Such a mechanism adapts in a fully-automatic, quick and effective fashion so as to optimally compensate for the effects of changing weather or grid conditions, changes in the customer's infrastructure as well as for making sure that user preferences, needs and acceptance are optimally satisfied.
- The second of these ingredients is a flexible, hierarchical overlay communication network which will make available the information needed by the intelligent mechanism in a plug-n-play, inter-operable, reliable, efficient and safe manner and, most importantly, without the need for the deployment of a new communication infrastructure. The communication network should provide the necessary interfaces to enable management of edge devices, reliable real-time communications with strict service guarantees as well as providing support for reliable communication of the vital information in unreliable environments (e.g., during periods of network outages or in situations where communication is lost for some time intervals) or rural/remote environments where fixed network infrastructures are not available.

The two basic ingredients mentioned above will be integrated and further enhanced with inter-operability, safety, security as well as user-awareness and human-machine-interaction attributes towards the development of such platform. More precisely, any of the following Smart Building-related Information regarding smart grid functionalities should be used and exploited:

- Real-time information about current as well as future electrical energy tariffs (if variable tariffs are implemented).
- Real-time information concerning local generation and storage information.
- Real-time information concerning local or grid-connected renewable sources status.
- Real-time information concerning distribution network operator requirements.
- In cases of micro-grids, real-time information regarding the status and the needs of all the micro-grid actors.
- Real-time information concerning current voltage and frequency levels.

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Micro-grid connection mode (connected to the grid mode or islanded mode) so as to be able, in the case of islanded mode of operation and in order to prevent blackout, to achieve load balancing in order the available generation added to the power can be extracted from storage devices to meet the demand.

Industrial Systems

Integrated large production complexes in the chemical and in the petrochemical industry are major consumers of energy and raw materials in Europe and a major source of employment and income. They produce virtually all raw materials for convenience products in modern industrial society. The ecological and economic viability of the production depends crucially on the careful management of the orchestra of different units which in many cases are simultaneously producers and consumers of intermediates and carriers of energy (see Figure 3). These sites host a large number of autonomously operated production plants, nowadays often owned by different companies, with complex energy and material stream interconnections among them to ensure operational excellence and competitiveness of the production. The plants belong to competing value chains inside one company or to different owners. Complex networks of carriers of energy and of various chemicals are operated to make the best possible use of energy, materials and intermediates and by-products.

The flexibility of production is limited by many different constraints on individual units which must not be violated in order to prevent, e.g., accelerated equipment degradation or plant trips. Each unit operates most efficiently in terms of economics and energy and resource consumption under specific conditions which often are not compatible with the global state of the production system due to the interconnections and limited resources. The main goal of the site-wide management is to achieve an optimal global performance. The main degree of freedom to achieve this goal lies in ability to vary the production intensity in order to compensate for changing utilities availability and market prices. Essentially each plant operates autonomously, i.e. as an independent agent that tries to reach its production objectives as part of the value chain. Therefore this is an area with an enormous potential for the use of a systems of systems approach leading to better coordination and hence better economic and ecological performance.

The prototypical case study of an integrated chemical production site is a petro-chemical complex (Figure 3) that uses naphtha as a main feedstock. Naphtha is cracked into simpler chemical compounds which are then used to synthetize higher-value products in different subsequent production units. These plants which belong to different business units with their individual economic goals and contractual obligations are interconnected by the networks of steam with different steam pressures, off-gas, electricity, water, compressed air, nitrogen, hydrogen, raw materials, intermediates, and products. The networks that connect the production units usually have only very small buffer capacities so that the mass and energy balances must be met on short horizons.

Along the production chain, several by-products of little economic value are produced. A power plant is employed to burn those waste products that can be incinerated to produce some or most of the electrical power and steam needed by the production plants. Further complexity is added by production plants that feed different steam grades into the headers produced by auxiliary boilers (superheated steam) or by reactor cooling (often saturated steam). Thus, the management of the plants has to take into account continuous degrees of freedom such as the load and the distribution of the flow rates of the different types of fuels to the boilers and discrete degrees of freedom such as switching auxiliary boilers on and off.

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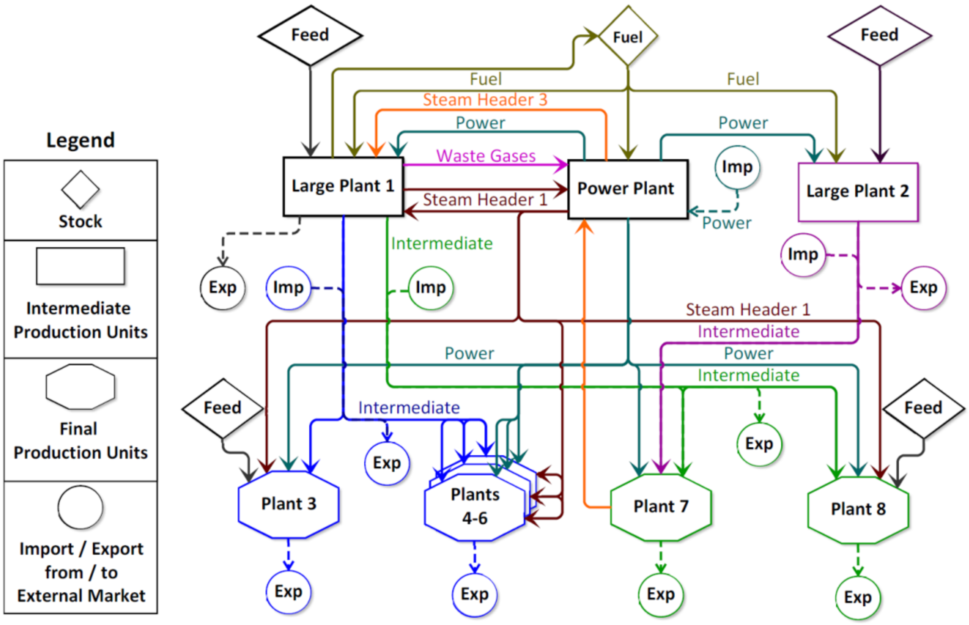

Figure 3. A schematic representation of an integrated chemical production complex.

The steam networks need to be run in a resource-optimal way in order to avoid the loss of energy by, e.g., steam let-down or the loss of production due to steam shortages. The production plants are strongly coupled by flows of material, so their production rates cannot be changed individually. Load reductions of one unit may cause severe restrictions to other units, and in particular the cracker products (intermediates) must be used on the site or fed into pipelines at the contractual rates to avoid severe economic losses. The individual units strive at optimizing their operation economically and ecologically for given production targets and the connections to the other units and to the steam network are constraints in this endeavour.

Characteristic features of integrated production sites are:

- Complex networks of energies and chemicals are operated to enable the proper interaction of integrated production facilities, aiming at wasting as little of the energy, the raw materials, and the intermediate products as possible.
- The balance of the different units for changing throughputs is delicate and requires a careful coordinated operation of all units, as especially gas networks comprise few to no buffer capacities.
- The flexibility of production is limited by many different constraints on individual units which must not be violated in order to prevent accelerated equipment degradation, plant trips or similar events. Therefore, the degrees of freedom to optimize the operation of a complete value chain are limited. The primary degree of freedom is the variation of the production intensity on a real-time frame in order to compensate for e.g. changing utility prices.
- A global optimum is hard to identify and can only be achieved by optimal coordination of individual production units.

The cyber-physical aspect of the industrial systems lies in tight integration of physical plant with computer-based tools such as Enterprise Resource Planning (ERP), Manufacturing Execution System (MES), Supervision, Control & Data Acquisition (SCADA), Distributed Control System (DCS), Human-machine Interfaces (HMIs), Programmable Logic Controllers (PLCs) that interact with the site on different levels and, thus, constitute a hierarchical system,

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so-called automation pyramid. These systems interact with the site on different time scales and, thus, employ conceptually different viewpoints on the site and its parts.
Generally, very simple models are employed for production planning (site-wide and unit-wide) and for prediction of the future plant and market behaviour. The industrial state of the art is the use of static planning tools and network balancing based on meetings between the different operating teams and the use of buffers in the system to smoothen short-term variations. Dynamic variations, such as unplanned shut-downs, forced production reductions, intermittent restrictions on the use of electrical power or steam, and fluctuations of raw material and utility prices, are only addressed on an ad-hoc basis. Rarely an automatic mechanism is installed on site which detects changes in operation conditions and coordinates and adapts production targets of all production plants in real time in order to respond to the disturbances listed above. Site-wide optimization is performed mostly by discussion processes between the managers of the production units. Similarly to the management of electrical grids, the governmental policies, regulations and incentives play a strong role for the decisions taken for site management and these can lead to behaviour which is counterproductive from an energy saving point of view.
Beside the aforementioned dynamic variations that cause violations in the nominal site operation, the inherent uncertainty present in the form of inadequacy of the employed prediction models plays an important role. The maintenance of these models is expensive and is rarely addressed to a sufficient extent. On the one hand, good practice for reducing the effect of such uncertainties is the exploitation of operator training simulators whose usage became well-established in the industry. On the other hand, the models are often not directly available for optimization and further prototypical solutions for handling the uncertainties are currently missing or rarely in use due to the costly maintenance of such solutions.

Present and future challenges in the domain of industrial systems

Two types of engineering approaches exist today for large interconnected industrial systems, green field engineering, during which a complex is built from scratch on a previously not utilized piece of land and brown field engineering. Brown field engineering covers all aspects from adding new plants to existing sites to replacing plants and re-engineering and upgrading plants or simple capacity increases.

If green field engineering is performed by one company or using good site management, the new chemical complex often represents the state of the art in integrated engineering. The challenge lies in offering flexibility in utilities and networks while at the same time providing raw materials and customers to achieve a chemically integrated site. Furthermore, future investments in other chemical plants on the site should be possible using the infrastructure built from the beginning. Optimal structural site planning, using a list of possible plants with varying load profiles and optimal site layout results in complex mixed-integer optimization problems, even if the required plants are known. Adding uncertainty to this optimisation as decisions become more uncertain, the further they are in the future, results in more difficult problems. The solution probably requires either more reserves in utilities and networks or limits the choice of future plants. Additionally, once some plants are built, a future change in the building strategy due to changing markets or legislation may lead to a suboptimal site and plant layout. Combining the methods of structural optimisation with implementation and construction on a future timeline is a challenging problem in green field engineering.

Brown field engineering results in similar challenges. A site and its plants have grown organically or according to the optimal plan of the time and only some spaces and limited utilities, raw materials and logistic options are left. The problem is similar to the green field problem but exhibits more constraints and possible infrastructure

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improvements. The challenge also lies in the tie in with current operational patterns, leading to problems which need to find the engineering and operational optimum at the same time.

In the future we will see tighter integration of the production and electrical systems including connection to the power grid. This is a challenge since most engineers are expert in one of the areas of process and electricals, but few master both. There will also be an increased need to integrate the different levels in the automation hierarchy making, for example, modelling a more difficult task. Automation of automation, i.e. to automatically generate more and more of the control solution and simulation models directly from a CAD description of the system like P&I diagrams, will penetrate among the challenges in industrial systems.

For the management of large interconnected industrial systems, a number of problems have been discussed. Increased focus on energy management will arise in the future as even bigger challenge than nowadays. A more energy efficient process design is often more integrated and as such intrinsically harder to control. The major challenge for an existing chemical site is the optimal medium and long term planning, especially if the production as for example in chemical parks cannot be influenced directly and the profit and losses are not shared. Increased productivity requires tighter integration between the automation layers (ERP, MES, APC, etc.) which is only partly a technical problem, and to a very large degree also a cultural/organizational challenge. Today these automation levels are typically handled by different departments often in different geographical locations using different software tools with limited or no interaction.

The planning problems result in moving horizon scheduling problems of large size without the guarantee that the solution will be applied. The two sides of this challenging coin are the technical implementation of the calculation and the physical implementation of the results in the real world.

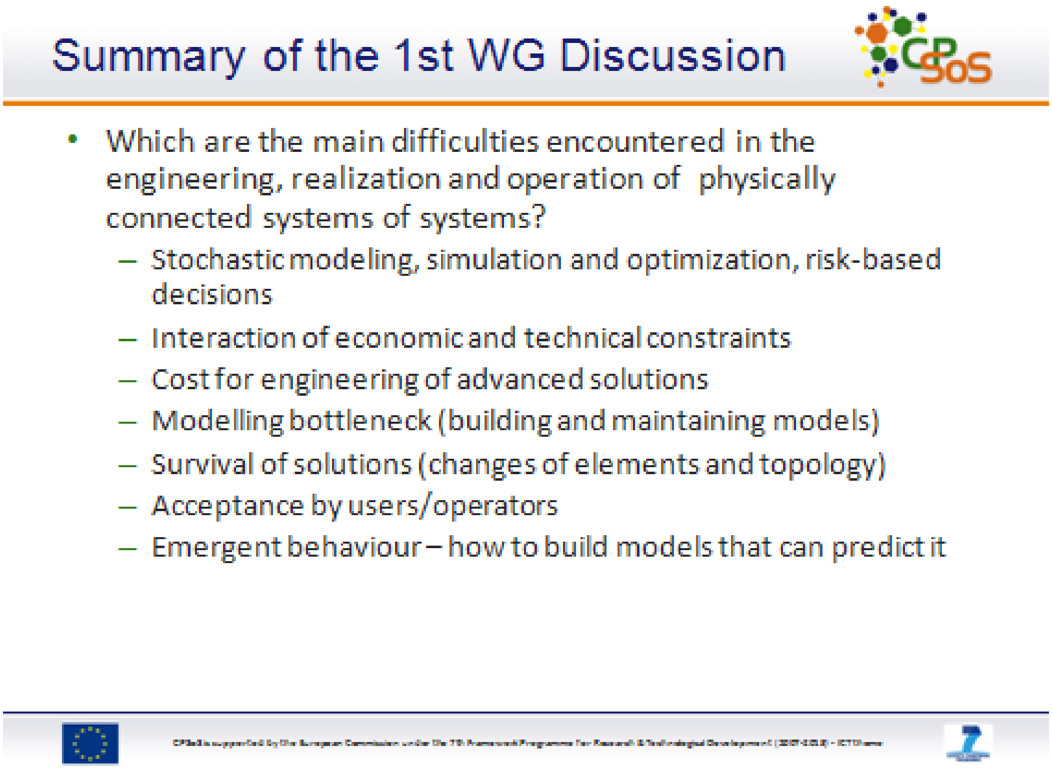
The major challenges for the technical implementation are models and communication. Both can be used but there exists a mixture today of different open and proprietary protocols the configuration of which often takes more time than the implementation of the optimiser. Process models pose problems in two respects: (1) they are often time consuming to develop. Some type of automated modelling must be developed in the future, based on digitally existing process and plant data and (2) they are not re-usable in different applications as some of them are dynamic and black box, some are rigorous physical models, some are rigorous dynamic models but equations are proprietary. If models could be easily and simply created for existing and new plants and communication between the different layers of plant operation was standardised, easy and safe, adding advanced solutions to existing plant management would be relatively easy.

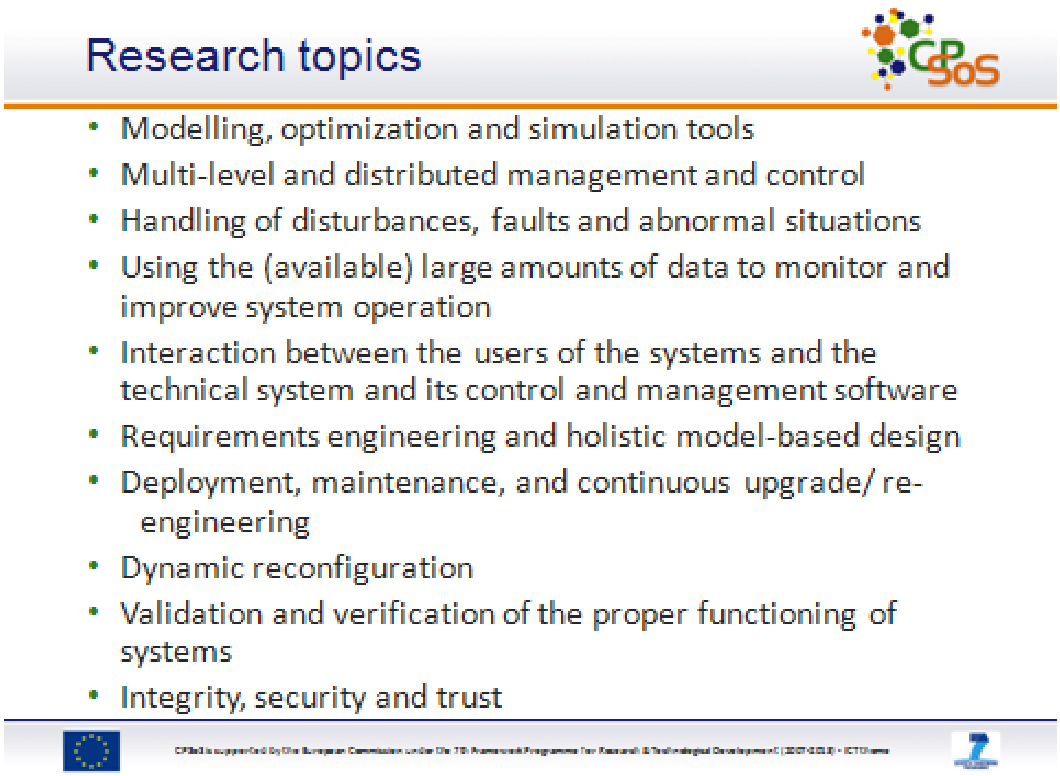
If these global solutions existed, it would still be a challenge to implement the results in the plants on a site. Within one company this is already difficult, on an industrial park with many companies this is close to impossible. One possible way to cover both situations is to influence the price of grids and utilities and create internal exchanges that define the prices according to availability and demand. It needs to be checked and researched, if this approach moves plants towards the global optimum.

A good tool for managers in mergers and acquisitions could be based on these calculations: If a plant is added to or removed from the site or sold and operated by another company, how much does it cost the company overall in site profit to add a plant, to remove a plant or, and this is the most interesting from a systems of systems perspective, to lose the influence on the plant.

This project has received funding from the European Union's Seventh Framework Programme for research, technological development and demonstration under grant agreement No 611115.

7.2. Hand-out with the results of the first meeting of WG2





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7.3. Agenda

Public Workshop „Engineering and Management of Cyber-physical Systems of Systems“

Agenda

10h30- 11h00 **Introduction of the CPSoS project and presentation of a preliminary proposal on priorities in research and innovation areas** *by Prof. Sebastian ENGELL / TU Dortmund*

11h00- 12h30 **Presentations from DYMASOS: Management Methods for Cyber-physical SoS**

- Population based management of Systems of Systems *(John LYGEROS / ETH Zürich)*
- Price based coordination for resource allocation in an integrated chemical production site *(Goran STOJANOVSKI / TU Dortmund)*
- Coalitional control for electric vehicles charging *(Eduardo F CAMACHO / Universidad de Sevilla)*

(23 min presentation + 7 min discussion each)

13h30- 15h00 **Tools for SoS Engineering**

- An engineering support platform for large-scale Cyber-physical Systems of Systems (*Christian SONNTAG / euTeXoo)*
- Needs and Tools for Cyber-physical Systems of Systems in the Process Industry *(Prof Cesar de PRADA / Universidad de Valladolid)*
- The Danse EU Project: Consistent Integration of Simulation and Formal Analysis in the Design of SoS *(Valerio SENNI / ALES S.r.l.)*

15h30- 16h45 **Parallel breakout sessions**

- Future challenges and research needs in Cyber-physical Systems of Systems
- **Sessions:**

  (1) Electric grids and smart buildings *(Moderated by Patrick PANCIATICI / RTE - Réseau de Transport d'Electricité)*

  (2) Process industries *(Moderated by Sebastian ENGELL / TU Dortmund)*

  (3) Tool support *(Moderated by Christian SONNTAG / euTeXoo and Michel Reniers / TU Eindhoven)*

- **Goal:** Discuss the state of the art and challenges for the future, prioritize the future research topics in view of the next calls in Horizon 2020.

17h00- 17h30 **Summary of the breakout sessions** 3 x 5 min reports), ***Discussion, Next steps and conclusion***

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7.4. List of Participants

Members of the CPSoS consortium:

Engell	Sebastian	(TU Dortmund, Germany)
Paulen	Radoslav	(TU Dortmund, Germany)
Reniers	Michel	(TU Eindhoven, Netherlands)
Klessova	Svetlana	(inno, France)
Copigneaux	Bertrand	(inno, France)
Sonntag	Christian	(euTEXoo, TU Dortmund, Germany)

Members of Working Group 2:

Lygeros	John	(ETH Zürich, Switzerland – FP7 Project DYMASOS, Local4Global)
Isaksson	Alf	(ABB, Sweeden)
Brancati	Francesco	(ResilTech SRL, Italy - FP7 Project AMADEOS)
Havlena	Vladimir	(Honeywell, Czech Republic)
Panciatici	Patrick	(RTE - Réseau de Transport d'Electricité, France)

Participants of the workshop:

Hosseini	Alireza	(BASF, Germany)
Pakasin	Goran	(HEP - ODS d.o.o., Croatia)
Bolfek	Martin	(HEP - ODS d.o.o., Croatia)
Habijan	Danijel	(HEP - ODS d.o.o., Croatia)
Beisheim	Benedikt	(INEOS, Germany)
Senni	Valerio	(ALES S.r.l., Italy)
del Real Torres	Alejandro	(IDENER, Spain)
Blanco Polo	Santiago	(AYESA, Spain)
Guidi	Luca	(ENEL, Italy)
Marijan	Sinisa	(KONČAR Electrical Engineering Institute Inc., Croatia),
Sielemann	Michael	(MODELON, Germany)
Lewis	Mark	(NEPIC, United Kingdom)
Schwingenschloegl	Christian	(Siemens, Germany)
Nazari	Shaghayegh	(TU Dortmund, Germany)
Stojanovski	Goran	(TU Dortmund, Germany)
Maxeiner	Lukas	(TU Dortmund, Germany)
Camacho	Eduardo F.	(University of Seville, Spain)
Baotic	Mato	(University of Zagreb, Croatia)
de Prada	Cesar	(University of Valladolid, Spain)
Sanz	Ricardo	(Universidad Politecnica de Madrid, Spain)
Findeisen	Rolf	(Otto-v.-Guericke Univ, Magdeburg, Germany)
Damm	Gilney	(L2S, Supelec, France)
Jost	Michael	(Ruhr-Universität Bochum, Germany)
Jäschke	Johannes	(NTNU Trondheim, Norway)
Koch	Stephan	(ETH Zurich, Switzerland)
Basilio	Gentile	(ETH Zürich, Switzerland)
Grammatico	Sergio	(ETH Zürich, Switzerland)
Kampert	David	(RWTH Aachen, Germany)

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7.5. Photo from the meeting

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7.6. Results of the anonymous voting polls

7.6.1. Breakout session on smart grids and smart buildings

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7.6.2. Breakout session on process industries

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7.6.3. Breakout session on tools support

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