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

Research Challenges in Cyber-physical Systems of Systems

Sebastian Engell
Process Dynamics and Operations Group
Department of Biochemical and Chemical Engineering
TU Dortmund
Germany

DYMASOS – Dynamic Management of Physically Coupled Systems of Systems

Support Action CPSoS

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

Project Overview

- 33 month Support Action
- Focus on Systems of Systems where large complex physical systems interact with computing and communication systems – Cyber-physical SoS

Goal:

Define a European research and innovation agenda on Cyber-physical Systems of Systems

Consortium

- TU Dortmund
  - Sebastian Engell
  - Christian Sonntag
  - Radoslav Paulen
- Haydn Consulting
  - Haydn Thompson
- TU Eindhoven
  - Michel Reniers
  - Wan Fokking
- Inno TSD
  - Svetlana Klessova
  - Bertrand Copigneaux

Analysis of the State of the Art

Kick off of 3 Working Groups (25 members)

Analysis of relevant programmes

38 intervie

ns

the art – reports

3 public meetings with 100+ participants

CPSoS State of th art document and initial roadmap

MAJOR INDUSTRIES AND 17 SMEs INVOLVED

Jan 2014 | June 2014 | Dec 2014

Outline

- Examples of cyber-physical systems of systems
- Properties of cyber-physical systems of systems
- Research challenges:
  - Distributed / coordinated management
  - Support for engineering and re-engineering
  - Cognitive cyber-physical systems – make use of “big data”
- Medium-term research and innovation priorities
- Summary

Examples of cyber-physical systems of systems

- **Electrical distribution grid**
  - Large-scale system
  - Transition from centralized to local generation
  - Increasing variability of the generation
  - Transition from hierarchical to distributed management

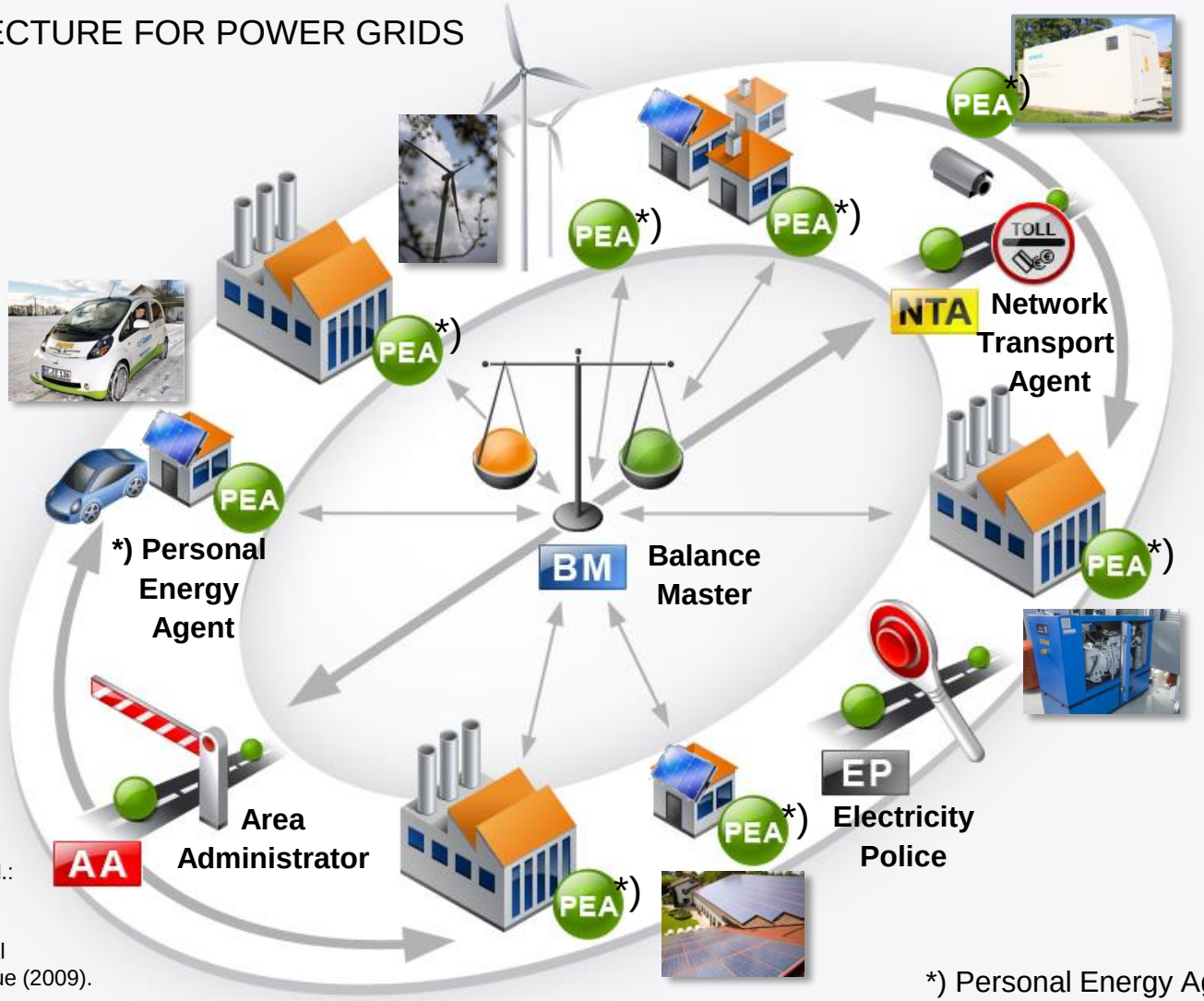
Self-Organizing Energy Automation Systems coordinating smart components within the grid

SIEMENS

MULTI-AGENT ARCHITECTURE FOR POWER GRIDS (SCHEMATIC)

Design Principles:

- Smart components.
- Use plug and play for engineering.
- Coordination of local algorithms whenever necessary



Böse, C.; Hoffmann, C; Kern, C.; Metzger M.: *New Principles of Operating Electrical Distribution Networks with a high Degree of Decentralized Generation,* 20th International Conference on Electricity Distribution, Prague (2009).

*) Personal Energy Agent

unrestricted © Siemens AG 2014. All rights reserved

Examples of cyber-physical systems of systems

- Electrical distribution grid

- **Electrical vehicle charging**
  - Home charging
  - Charging points
  - **Different agents in action:**
    - Network operators
    - Electricity marketers
    - Parking owners
    - Car owners

Examples of cyber-physical systems of systems

- Electrical distribution grid

- **Electrical vehicle charging**
  - Home charging
  - Charging points
  - Goals:
    - Meet customer demands
    - Guarantee power network stability
    - Make best use of green energy, minimize carbon footprint

Examples of cyber-physical systems of systems

- Electrical distribution grid
- Electrical vehicle charging

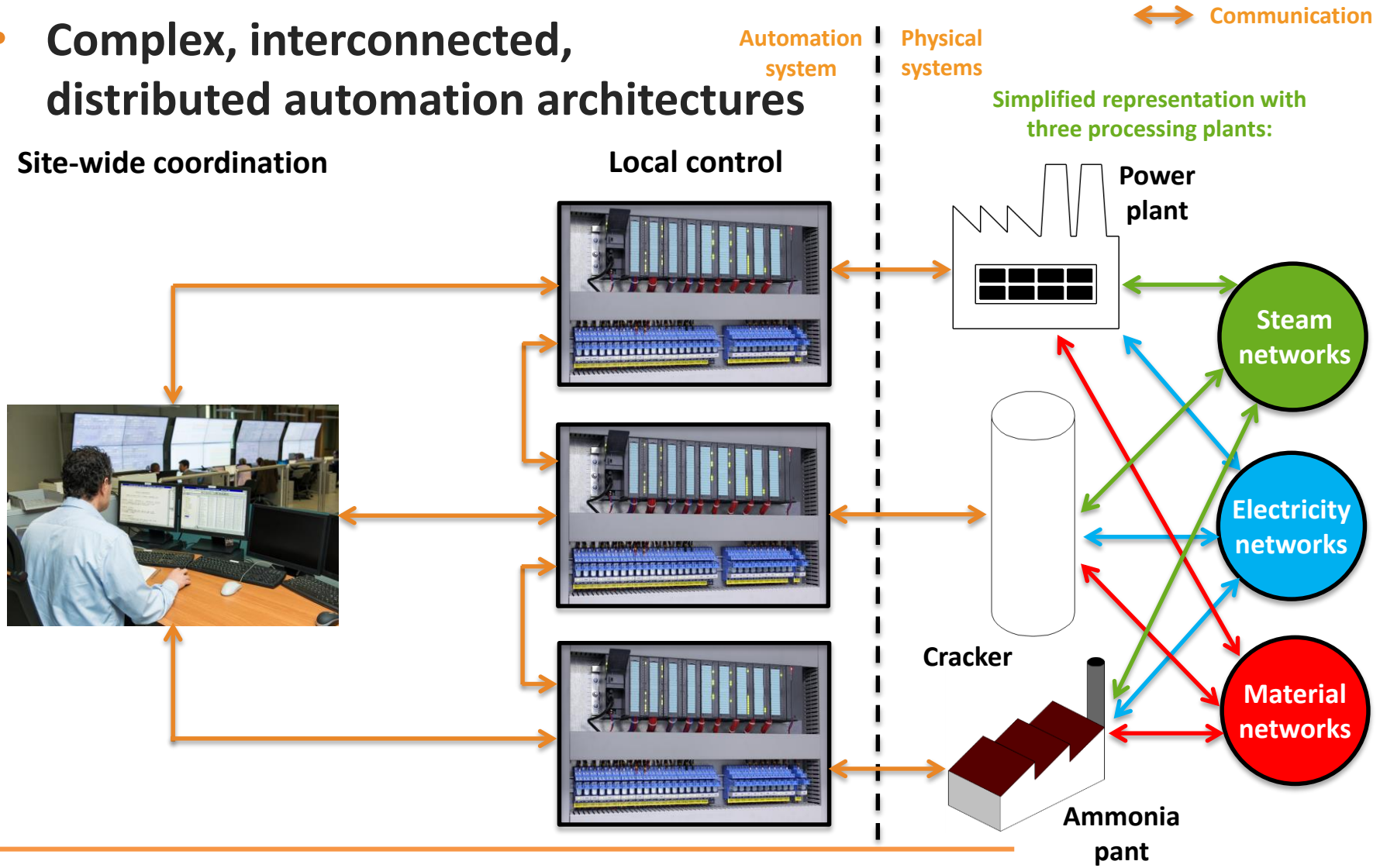
- **Chemical production sites**
  - Large distributed computer controlled installations
  - Plants coupled by various networks for steam, gas, intermediates

Example: INEOS Cologne plant

- **Production site of INEOS in Cologne, Germany**
  - More than **16 plants**
  - **Thousands of sensors**
  - **Thousands of actuators**
  - **Several hundred tons of raw materials** processed per hour
  - **Several hundred tons of steam** per hour
  - Plants connected by **internal networks**
    - Electricity
    - Fuel gas
    - Steam (at different pressures)
    - Nitrogen
    - Intermediates

Integrated chemical production site: Automation

- Complex, interconnected, distributed automation architectures



Examples of cyber-physical systems of systems

- Electrical distribution grid
- Electrical vehicle charging

- **Chemical production sites**
  - Large distributed computer controlled installations
  - Plants coupled by various networks for steam, gas, intermediates
  - Individual business goals of the plants
  - Goal:
    - Reduction of energy consumption and environmental impact
    - Minimize total operating cost

Cyber-physical Systems of Systems

- Key elements of the socio-technical infrastructure
- Providing essential services to the citizens
- Backbone of the industrial infrastructure
- Vulnerable
- Difficult to engineer and to operate
- Good engineering and efficient management is crucial for
  - Energy and resource efficiency
  - Economic competitiveness of the industries
  - Quality of life
- The main potential is on the system level, not on subsystem control and optimization

Characteristics: Physical System Elements

- *Significant* number of *interacting* components that are (partially) physically coupled and together fulfill a certain function, provide a service, or generate products.
- The components can provide services independently but the performance of the overall system depends on the “orchestration” of the components.
- After a removal of some components, the overall system can still fulfill its function, with reduced performance.

Characteristics: Control and Management

- Not performed in a completely centralized or top-down manner with one “authority” providing all the necessary control signals but with distributed decision power
- Structures vary from a (multi-layered) hierarchy to a fully decentralized structure where only technical constraints, economic incentives and human interactions connect the subsystems.
- Partial autonomy of the control and management systems of the components
  - Disturbances can be handled (to some extent) locally
  - Subsystems can exhibit “selfish” behaviour with local goals, and preferences.
  - Autonomy can result from human users or supervisors taking or influencing the local decisions.
- The “managerial element” of the components goes beyond classical decentralized control.

Dynamic Reconfiguration and Evolution

- Addition, modification, replacement or removal of components on different time scales
- Changes of the connectivity and the mode of operation
  - Components may come and go (like in air traffic control)
  - Reaction to faults
  - Changes of system structures and management strategies following changes of demands, supplies or regulations.
- Systems operate and are continuously improved and modified over long periods of time.
  - The infrastructure “lives” for 30 or more years, and new functionalities or improved performance have to be realized with only limited changes.
  - Management and control software has long periods of service, while the computing hardware base and the communication infrastructure change much more rapidly.
- Engineering is re-engineering and takes place at run time.

Characteristics: Emerging Behaviour

- Occurrence of pattern formation, self-organization, oscillations and instabilities on the system level
- Not always anticipated in the design
- Many emerging phenomena are not intended in technical systems
- Simple feedback phenomena and design flaws should not be mixed up with emerging behaviour.

Enabling Technologies

- Communication technologies, standardized protocols, Internet of Things
- Computing technologies, high-performance and distributed computing, multicore and mixed-criticality computing, low power processing / energy harvesting for ubiquitous installation
- Sensors, including energy harvesting
- Management and analysis of huge amounts of data (“big data”).
- Human-machine interfaces, e.g. head up displays, display glasses, polymer electronics and organic LEDs
- Security of distributed/ cloud computing and of communication systems
- Systems and control theory and technology
- …

Research and Innovation Challenges

- **Distributed management of cyber-physical systems of systems**
- **Engineering support for the design-operation continuum of cyber-physical systems of systems**
- **Cognitive CPSoS** with innovative use of the large amounts of data that are collected in CPSoS

Distributed Management of Cyber-physical Systems of Systems

- Decision structures and system architectures
- Self-organization, structure formation, and emergent behaviour in technical systems of systems
- Real-time monitoring, exception handling, fault detection and mitigation of faults and degradation
- Adaptation and integration of new components
- Humans in the loop and collaborative decision making
- Trust in large distributed systems

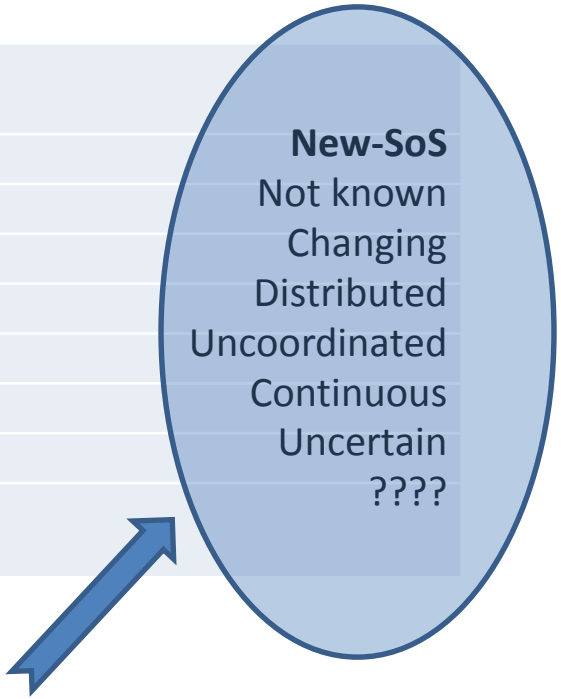
Engineering support for the design-operation continuum of cyber-physical systems of systems

Challenges

- CPSoS are continuously evolving which softens, or even completely removes, the traditional separation between the engineering/design phases and the operational stages
- The high degree of heterogeneity and partial autonomy of CPSoS requires new, fully integrated approaches for their design, validation, and operation
- CPSoS are highly flexible and thus subject to frequent, dynamic reconfiguration, which must be supported by design support tools to enable efficient engineering
- Failures, abnormal states, and unexpected/emerging behaviours are the norm in CPSoS
- CPSoS are socio-technical systems in which machines and humans interact closely

Cyber Physical SoS

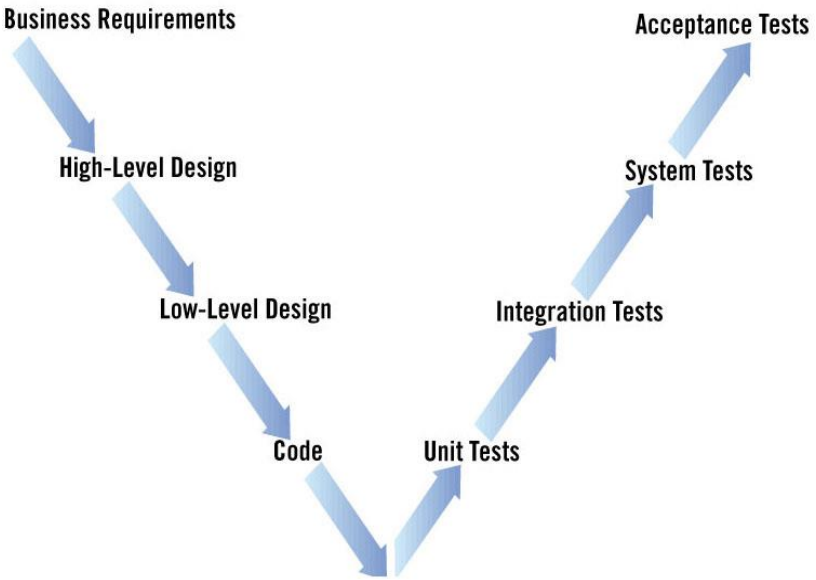
Characteristic	Old-Classic	New-SoS
Scope of System	Fixed (known)	Not known
Specification	Fixed	Changing
Control	Central	Distributed
Evolution	Version controlled	Uncoordinated
Testing	Test phases	Continuous
Technology	Given and fixed	Uncertain
System development	Process model	????



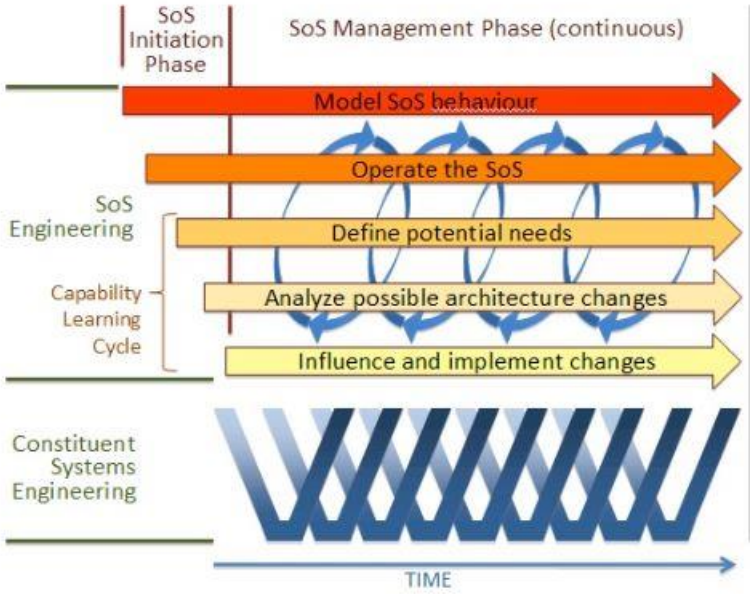
No good model, dynamic evolving, mixed criticality systems – certification!

CPSoS is supported by the European Commission under the 7th Framework Programme for Research & Technological Development (2007-2013) - ICT theme

Development Cycle for CPSoS



Traditional

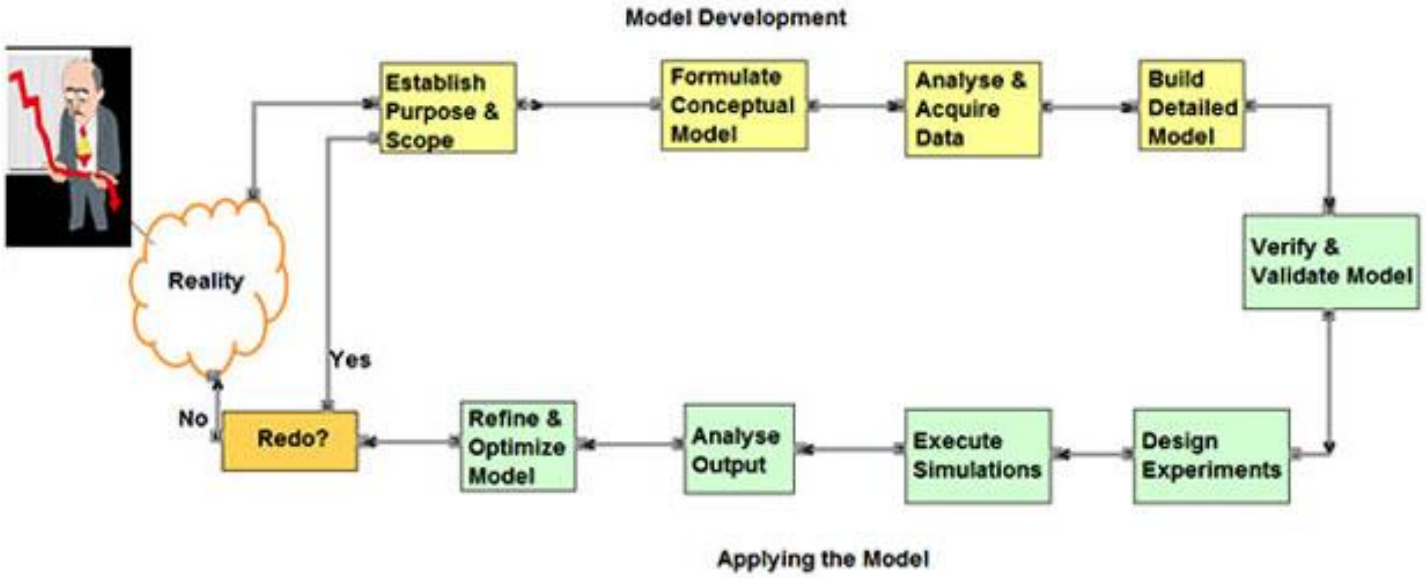


Iterative Approach (DANSE)

CPSoS are never finished!

CPSoS is supported by the European Commission under the 7th Framework Programme for Research & Technological Development (2007-2013) - ICT theme

Key Research Challenges



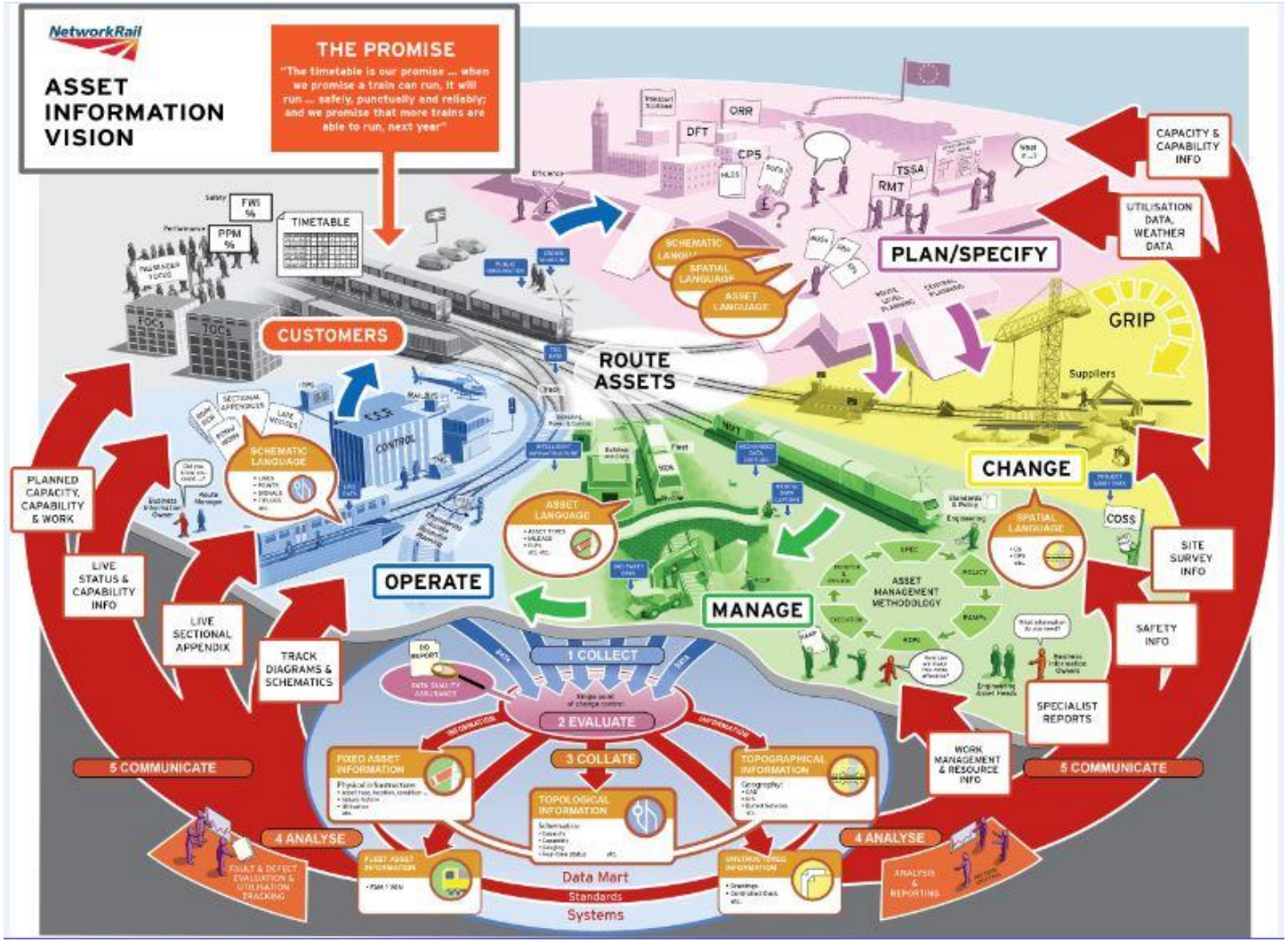
- Integrated engineering of CPSoS over their full life-cycle
- Modelling, simulation, and optimization of CPSoS
- Establishing system-wide and key properties of CPSoS

Cognitive Cyber-physical Systems

Cyber-physical Systems of Systems

- Large, distributed and extremely complex presenting a myriad of operational challenges
- Need for improved **situational awareness**, however, gaining an overview of the entire SoS is inherently complicated by the presence of decentralized management and control
- The introduction of **cognitive features** to aid both operators and users of complex Cyber-physical systems of systems is seen as a key requirement for the future to reduce the complexity management burden from increased interconnectivity and the data deluge presented by increasing levels of data acquisition
- Requires research in a number of supporting areas to allow **vertical integration** from the sensor level to supporting algorithms for information extraction, decision support, automated and self-learning control, dynamic reconfiguration features and consideration of the **sociotechnical interactions with operators and users**

Complexity of a Rail Network

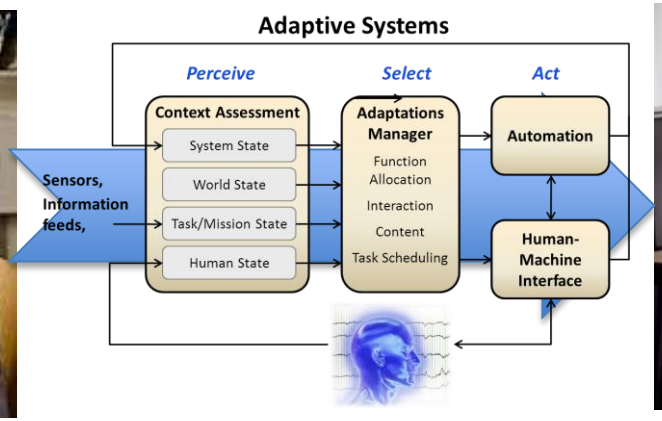


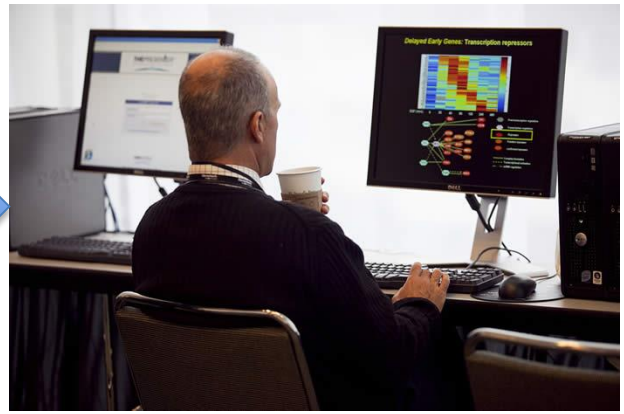
Key Research Challenges

- Situational awareness in large distributed systems with decentralized management and control
- Handling large amounts of data in real time to monitor the system performance and to detect faults and degradation
- Learning good operation patterns from past examples, auto-reconfiguration and adaptation
- Analysis of user behaviour and detection of needs and anomalies

Future Cognitive CPS

Before





After

- The end result of combining real world, real-time information for decision support with autonomous control and learning features will be *Cognitive Cyber-Physical Systems of Systems*
- These will support both users and operators, providing:
  - situational awareness
  - automated features to manage complexity

  that will allow them to meet the challenges of the future

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

Medium-term Research and Innovation Priorities in Cyber-physical Systems of Systems

www.cpsos.eu

Medium-term research priorities (1)

Methodological:

- System integration and dynamic reconfiguration
- Robust distributed system-wide control and optimization
- Resilience in systems of systems
- Overcoming the modelling bottleneck
- Humans in the loop
- Towards cognitive systems: data-based system operation

Medium-term research priorities (2)

Application-driven:

- Integration of control, scheduling, planning and demand-side management
- New ICT infrastructures for adaptable, resilient, and reconfigurable manufacturing processes
- Development and exploitation of ICT to support multi-disciplinary, multi-objective optimization of operations in dynamic, 24/7 systems
- Safe, secure and trusted autonomous operations for systems with humans in the loop

System integration and dynamic reconfiguration

- Dynamic requirements engineering
- Plug-and-play integration and live removal of components
- Configuration control
- Incremental live validation of modifications to the system
- Integrated engineering over the full life-cycle
- Reference architectures, open platforms and easy-to-test interfaces for integration, semantic integration to simplify the interactions of existing systems as well as the deployment of new systems
- Standardization

Robust distributed system-wide control and optimization

- Coordination mechanisms for systems with autonomously managed units
- Understanding how the management and control structure (centralized, hierarchical, distributed, clustered) influences system performance and robustness
- Dealing with uncertainty, neglected couplings, stochastic effects, user interactions
- Combining model-based and data-based optimization
- Involvement of humans

Resilience in systems of systems

- Strategies for system-wide fault detection and mitigation
- Integrated cross-layer handling or disturbances and break-downs
- Advanced integrated monitoring of the state of the system and triggering of preventive maintenance to improve long-term performance

Overcoming the modelling bottleneck

- Faster model development and better model reuse, automated modelling
- Model maintenance and adaptation
- Collaborative environments for model exchange between competing companies, trust in models from others
- Integration of legacy system models
- Combination of models of different depth and different formalisms in system-wide models of CPSoS, co-simulation, hierarchical modeling, appropriate levels of abstraction
- Meta-modelling and model management to ensure model consistency
- Modelling over the full life cycle of the system
- Combination of model- and data-based optimization
- Economic / socio-technical modelling

Human in the loop

- Filtering and appropriate presentation of information to human users and operators for the acceptance of advanced computer-based solutions
- Investigation of the human capacity of attention and of measures to provide motivation for sufficient attention and consistent decision making
- Analysis of the cognitive models of system operatorsMonitoring of the actions of the users and anticipating their behaviours and their situation awareness
- Social phenomena (dynamics of user groups)
- Combination of the capabilities of humans and algorithms in real-time monitoring and decision making (collaborative decision making and control, e.g. autonomous cars)

Towards cognitive systems: Data-based system operation

- On-line data stream analysis to monitor the system performance, to detect faults and degradation, and to identify characteristic situations
- Combination of (semi-)rigorous and data-based models
- Data-based prediction and its use for control and optimization
- Visualization of the results of online data analysis
- Automatic reconfiguration and adaptation, learning good operation patterns from past examples
- Trust in data

Manufacturing Systems

- New ICT infrastructures for adaptable, resilient, and reconfigurable manufacturing processes
  - Seamless and low-effort reconfiguration of manufacturing systems for fast adaptation to changing customer demands
  - Self-adaptation of production machines and robots
  - Semantic system integration of decentralized manufacturing systems across the complete value chain
- Data and information visualization for decision support in manufacturing
  - Automatic extraction of crucial indicators from large amounts of data
  - New HMI paradigms for responsive data visualization to maximize the real-time situational awareness of human operators

Transportation and Logistics

- Development and exploitation of ICT to support multi-disciplinary, multi-objective optimization of operations in complex, dynamic, 24/7 systems
  - Improve capacity, efficiency and reduce cost
  - Maintain continuous operation and provide resilience to disruption and failures
  - Reduce emissions

- Safe, secure and trusted autonomous operations for systems with humans in the loop
  - What systems should be made autonomous and what should be left to the human operator?
  - Homogeneous HMIs
  - Societal acceptance, trust, privacy
  - Liability

Summary

- Definition of cyber-physical systems of systems
- Examples of cyber-physical systems of systems
- Research challenges:
  - Distributed management
  - Support for engineering and re-engineering
  - Cognitive cyber-physical systems – make use of “big data”
- Examples of ongoing research
- Medium-term research priorities
- **Cyber-physical systems of systems are an extremely relevant and challenging area of research**
- **Next EU ICT Call:**
  Smart Cyber-physical Systems - Science of system integration

Thank you very much for your attention!

www.cpsos.eu