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A Framework for Simulation, Optimization and Information Management of Physically-Coupled Systems of Systems

David Kampert * **Shaghayegh Nazari** ** **Christian Sonntag** **,*** **Ulrich Epple** * **Sebastian Engell** **

* *Chair of Process Control Engineering, RWTH Aachen University, Aachen, Germany (e-mail: {kampert, epple}@plt.rwth-aachen.de)*
** *Chair of Process Dynamics and Operations, TU Dortmund University, Dortmund, Germany (e-mail: {shaghayegh.nazari, sebastian.engell}@bci.tu-dortmund.de)*
*** *euTeXoo GmbH, Dortmund, Germany (e-mail: christian@eutexoo.de)*

Abstract: The paper deals with the optimization of the operation of so-called systems of systems, i.e. large systems where the subsystems possess some autonomy but the system as a whole has to be operated optimally. Specifically, the focus is on systems of systems that are physically coupled, e.g. electric grids or production plants that are coupled by flows of matter and energy. Besides the development of suitable distributed optimization methods for reducing operational costs, the method's validation, integration and log-term use in real installations is a major challenge. To ensure maintainability and adaptability of the optimized management, the information exchange between the system and the optimization methods has to be addressed. A concept for an information exchange platform was developed as part of the European project DYMASOS. Requirements for the platform and validation scenarios are derived from industrial case studies.

Keywords: Systems of Systems, Production Systems, Systems Management, Systems Engineering, Distributed Optimization, Co-Simulation.

1. INTRODUCTION AND MOTIVATION

The term "system of systems" (SoS) is attributed to systems in which each constituent system is an autonomous and operational unit of its own, but all these units provide services or generate or distribute products in a coordinated fashion. The operation of an SoS can potentially be vastly improved on the coordination level.

The term itself stems from the military domain, but it has been applied in many other domains and several definitions of "system of systems" have been proposed. The definitions agree to the extent that the following characteristics are met by an SoS (cf. Luzeaux (2013a)):

- The constituent systems have operational and managerial independence.
- The definition and the configuration of the global system are evolutionary in nature.
- There may be emergent behavior in the global system.
- The constituent systems are geographically distributed.

While the original definition given by Maier (1998) refers to systems that are exclusively coupled by the exchange of information, the DYMASOS[⋆] project (DYnamic Management of physically coupled Systems Of Systems) specifically addresses SoS that are coupled by flows of matter or energy (see DYMASOS Project (2013)). Geographic distribution and the exchange of other resources are not considered as key features in this case.

The case studies considered in the project are taken from the chemical industry and from the sector of electrical power grids. The goal of DYMASOS is the development and validation of new methods for optimized coordination of physically coupled SoS (with respect to operational costs). Two major challenges exist: The first and obvious challenge is the development of suitable coordination methods. Different coordination methods are investigated for this purpose: population control (Parise et al. (2014)), marked-based coordination (Stojanovski et al. (2015)) and coalitional control (Muros Ponce et al. (2014)). The second challenge concerns the validation and the integration of the coordination methods into real-world systems. Both validation and information management are crucial for the long-term application of coordination methods in an industrial environment. In particular, large systems undergo continuous modifications which have to be taken into account in the coordination system in an automated fashion. Otherwise, the effort for updates may soon become prohibitive since a vast number of mutually dependent aspects regarding hardware, software, protocols, data formats, networks, security and privacy require consideration.

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Selberg and Austin (2008) have demonstrated the need for sustainable concepts by stating that

(1) the complexity of the SoS framework should not grow as constituent systems are added, removed, or replaced, and
(2) the constituent systems should not need to be reengineered as other constituent systems are added, removed, or replaced.

A management concept that takes these aspects into account will produce lesser costs on the long term than a solution that is custom-made for the current technical configuration. The development of corresponding engineering tools is thus a discrete task and deserves special attention.

The industrial case study providers of DYMASOS have already identified the potential of SoS-level coordination strategies. Corresponding software systems exist and are in use; but these systems are custom-made for specific tasks in specific technological environments. Considering the above-mentioned goals, the needed software should allow to connect different simulation models with different coordination strategies and different real-world control and automation systems. Currently, there is no solution available that possesses these features without extensive case-specific adaptations. On the other hand, scientific publications on SoS are either considering particular case studies or very abstract aspects like SoS terminology or classification. Thus, this paper presents the basic ideas of the required flexible software for SoS management. For the considered kinds of physically coupled SoS, a generic approach seems possible. The focus of the paper is on the required concepts, not on software architecture.

The following section provides an overview of the specific application domain: large chemical plants. Section 3 discusses the simulation, optimization and validation framework that is used to test the coordination strategies in a simulated SoS. This framework will also be the basis for quantitative evaluation of the case studies. Section 4 introduces the concept of the platform for information exchange. Finally, Section 5 gives an outlook on the integration and evaluation of the platform.

2. CASE STUDY AND SOLUTION CONCEPTS

For the purpose of this paper, the case study regarding chemical plants is the most relevant one among the case studies of DYMASOS. Each plant on a production site constitutes a system that is managed as a unit on its own. The SoS topology is determined by the pipe connections that are used for the exchange of materials (e.g. ethylene, propylene) or energy (steam on several pressure levels), which is essential information to simulate the overall SoS. Optimizing the operation of the SoS consists of finding a trade-off between the goals of each individual plant and the need to balance the exchanged streams.

The plants constitute an SoS that has a structure which only rarely changes and has slow dynamics. Mathematical models of the production processes exist (on different levels of detail) and simulations are available. The challenge on the level of the SoS, i.e. the production site, is that each plant plans its production individually but the global profitability and resource efficiency is ultimately the matter of interest.

The approach to the coordination of the plants which is pursued in DYMASOS is to introduce an artificial market where the streams are traded. The prices on this market, e.g. the price for the consumption of 5 bar steam, are adapted by a central coordinator according to the current demands so that the networks are balanced. The production planning of the plants takes these prices into account and optimizes the local cost. This procedure is iterated and prices are adapted until an equilibrium is found, using the alternating direction method of multipliers (Gabay and Mercier (1976)), see Stojanovski et al. (2015).

Before the coordination approach can be applied in a real-world environment, it needs to be carefully tested and analyzed. For this purpose, i.e. the validation of the distributed optimization and coordination mechanism, a framework is under development.

3. SIMULATION, OPTIMIZATION AND VALIDATION FRAMEWORK

The idea of the framework is to separate the optimization and coordination algorithms from the models and to provide standard interfaces to connect models of different levels of detail to the optimization algorithms in a structured and modular fashion.

The proposed simulation, optimization and validation framework (in short SOV framework) is based on the object-oriented and freely available modeling language *Modelica* which is specifically designed for heterogeneous modeling. It includes libraries from a large number of different domains such as mechanics, electronics, control, etc., which makes it a proper choice for the implementation of a generic platform. Modelica is equation-based, which is beneficial since the considered SoS, e.g. electrical grids, are often undirected networks.

As shown in Figure 1, each subsystem is represented using one of the four model components. The management algorithms consist of communicating *local management and control algorithms* and an optional global *coordination algorithm*. In model-based approaches, the management algorithms can access an abstract model of the subsystem, called the *design model*, and determine a locally optimal solution with respect to a *local problem formulation*. The set of *validation models* are detailed subsystem models which accurately represent the physical SoS.

The SOV framework provides standardized interfaces for the implementation of the interconnections shown in Figure 1 between model components (i.e. design and validation models) as well as management components (i.e. management and coordination algorithms). The interfaces support time-driven (synchronous) as well as event-driven communication between the components. Time-continuous communication is additionally supported by the interface between the validation models and the management components.

In large-scale SoS, the manual interconnection of the components is a tedious and error-prone task. Therefore, the framework proposes the use of a Modelica model generator