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Adaptive pricing for optimal resource allocation in industrial production sites ⋆

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Abstract: In large integrated production sites, an optimal allocation of the shared resources among different possibly competing production plants is key to a resource and energy efficient operation of the overall site. Typically, a large integrated production site can be regarded as a physically coupled system of systems (SoS), since it comprises many different physically linked production plants with a certain degree of autonomy in respect to the individual operating conditions where the plants tend to pursue their own economic goals and interests. In order to improve the overall operation of the production site, a centralized optimization for the shared resource allocation within the site is favored. However, a centralized solution cannot always be realized due to various technical or managerial reasons. One of the reasons is the limited amount of information about the individual subsystems that a central site management can access, because the subsystems want to preserve a high level of confidentiality. In this contribution, we present the application of price-based coordination (subgradient-based price updates and the Alternating Direction Method of Multipliers, ADMM) to the case study of the integrated petrochemical production site of INEOS in Köln. We discuss the requirements of the price-based coordination for industrial applicability in the case of limited sharing of information. In a simulation study, we show how the central site management uses price incentives to steer the individual productions plants towards a site-optimal operation and thus is able to react to changing conditions such as capacity changes.

Keywords: Resource allocation; Distribution networks; Price-based coordination; Industrial production systems; Communication protocols; Systems of systems (SoS);

1. INTRODUCTION

Large industrial production sites (or industrial clusters) are examples of complex physically coupled systems of systems (SoS), since the sites are typically composed of many different production plants, which can be regarded as subsystems (Engell et al., 2015). The subsystems have a certain degree of autonomy to optimize their individual profit and pursue their own (confidential) business goals. The individual plants are coupled by shared resource networks, through which streams of material or energy are exchanged. Common examples are steam on different pressure levels, electricity, and intermediate product streams.

Because of the physical coupling, the aggregate of the individual optima is not necessarily the site optimum. In order to optimally operate the overall production site in terms of energy and resource efficiency, the shared resource networks have to be balanced, because of limited storage and buffer capacities. Therefore, a central optimization of the shared resource distribution is favorable. Although appealing, a centralized optimization is often not feasible in practical applications due to various technical and managerial reasons. A centralized optimization can be limited by the problem size and computational burden, it needs to be reformulated in case of a topology change if subsystems are added to or taken out of the system, and it is prone to missing information about the subsystems. The latter case holds true in the situation in which the different subsystems are operated by different business units or companies that are not interested in providing access neither to the model equations and economic evaluation of their production plants, nor to individual constraints. This is a common situation in large-scale technical systems, e. g., traffic systems or distribution grids.

The limitation of scarce information on the subsystems can be overcome by applying distributed coordination techniques, which are able to recover the overall optimum under certain conditions. There are different distributed strategies, which mainly differ in the degree of autonomy that is

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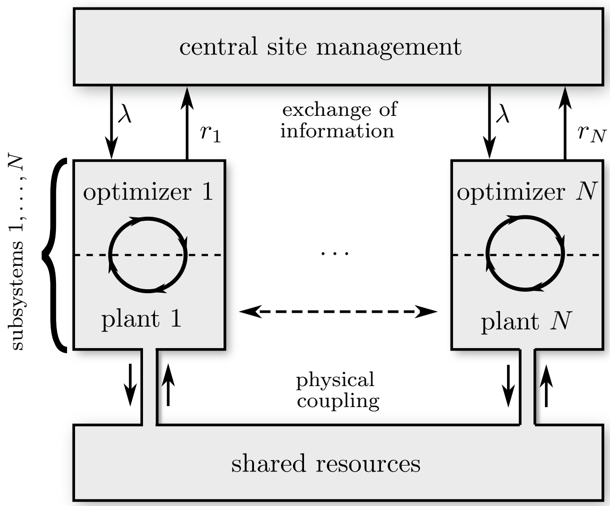

Fig. 1. Exemplary management structure of an industrial production site with N individually optimized production plants that are physically coupled by shared resources where information exchange is restricted prices λ and shared resource utilization r_i.

present in the constituent subsystems, in the mathematical formulation of the subsystems local management, and in the way the communication between the subsystems within the SoS is realized. Different coordination strategies can be derived from game theory (Grammatico et al., 2015), coalitional control (Fele et al., 2014), or market theory (Jose and Ungar, 2000). Consider a management structure of a production site as illustrated in Fig. 1 with a central site management and N subsystems that are physically coupled by shared resources. Every subsystem i consists of a plant i that is optimized by an optimizer i, which has full knowledge of the plant. The information exchange between the central site management and the individual subsystems is restricted to sharing prices for resources λ and shared resource utilization r_i of every plant. Price-based coordination techniques from market theory match the depicted management structure well and are therefore suitable to be applied to existing production sites.

Price-based coordination mechanisms rely on the assumption that the subsystems are sensitive to price incentives that are announced by a coordinating entity (an auctioneer) within a given market and that there is one price for which there is an equilibrium of the market (Walker, 1987). The objective of distributed price-based algorithms is to find this equilibrium price by iteratively adjusting the prices until the market is balanced. There are different possibilities to realize the updates of the prices. A trade-off exists between, on the one hand, the rate of convergence and thus the number of iterations, and, on the other hand, the amount of shared information and the modifications of the individual optimization problems.

In this context two major coordination approaches are applicable. We compare subgradient-based price updates with the Alternating Direction Method of Multipliers (ADMM), where in addition to the price signals the coordinator broadcasts references to the individual subsystems (Boyd et al., 2011). We apply the two distributed coordination methods to an extended version of the industrial case study of INEOS in Köln described in Wenzel et al. (2016), in which four different resources are shared among nine production plants (see Fig. 2).

The rest of the paper is structured as follows. We first give an overview about the mathematical formulation of the resource-constrained site-wide optimization problem and present the employed price-based coordination schemes. Afterwards, the case study is described and simulation results are provided for a realistic scenario of demand and capacity changes in the production site. Finally, we draw conclusions, discuss the limitations, and give an outlook on future research directions.

2. MATHEMATICAL PROBLEM FORMULATION

Here we assume that the resource constrained optimization problem of a production site with N individual subsystems can be formulated as a QP of the following form

$$\min_{u_i \in \mathcal{U}_i, \forall i} \quad \frac{1}{2} \sum_{i=1}^{N} u_i^T P_i u_i + q_i^T u_i + q_{0,i} \tag{1a}$$

$$\text{s. t.} \quad \sum_{i=1}^{N} r_i(u_i) + \phi_{r,i} = 0, \tag{1b}$$

where we assume that the matrices $P_i \in \mathbb{R}^{n_{u,i} \times n_{u,i}}$ are positive definite ($P_i \succ 0$) and that they result from soft constraints that reflect certain production targets. The linear terms of the objective function represent the economic cost function of a subsystem, i. e., the costs for raw materials and the revenue due to the sale of product streams. Further, the individual subsystems are constrained by linear inequalities and lower and upper bounds on the inputs $u_i \in \mathbb{R}^{n_{u,i}}$, $u_i \in \mathcal{U}_i$. The inputs can be, e. g., inflowing streams of mass and energy. The vector $r_i(u_i) \in \mathbb{R}^{n_r}$ contains the shared resources that are exchanged via the networks and $\phi_{r,i} \in \mathbb{R}^{n_r}$ is a constant offset. The sum over all r_i and $\phi_{r,i}$ is referred to as a complicating constraint and has to be zero in order to balance the networks. The vectors r_i are computed as

$$r_i(u_i) = C_{r,i} u_i, \tag{2}$$

where $C_{r,i} \in \mathbb{R}^{n_r \times n_{u,i}}$ is the mapping matrix for every subsystem that links inputs and shared resources. Note that produced amounts are added with negative signs, consumed amounts with positive signs. If a plant is not involved in production or consumption of a shared resource, the respective entry in r_i is set to zero.

3. PRICE-BASED COORDINATION

Price-based coordination is a distributed optimization mechanism to solve the resource constrained optimization problem in (1) by iteratively changing prices for the shared resources that are exchanged between the subsystems. The idea for the distributed algorithm is based on a Walrasian auction in which a central auctioneer (coordinator) and N agents (subsystems) take part (Walker, 1987). The coordinator evaluates the imbalance between demand and supply of the traded goods (shared resources) and repetitively adjusts the prices for the goods until the equilibrium price of the market λ^* is found. This process is referred to as tatônnement of exchange. At the equilibrium price the demand matches the supply.