SCHEDULING OF FLEXIBLE ELECTRICITY PRODUCTION AND CONSUMPTION IN A FUTURE ENERGY DATA MANAGEMENT SYSTEM: PROBLEM FORMULATION

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ABSTRACT

Rapidly changing electricity markets call for innovative solutions to support balancing of energy production and consumption, and utilize the increasing amount of energy from renewable sources. MIRABEL is a future energy data management system based on flexible offers (flex-offers) for energy production and consumption. One of its core functionalities is scheduling of aggregated flex-offers to minimize the costs of the balance responsible party. This paper presents a formulation of this scheduling problem in terms of decision variables, constraints and the objective function, and discusses the problem characteristics.

1 INTRODUCTION

Electrical energy markets are rapidly changing. Their deregulation is redefining the roles and activities of the involved parties. In addition, the urgency of environmental sustainability calls for reduction of carbon emissions and higher utilization of renewable energy sources (RES). However, RES, like solar panels and windmills, make it hard for electricity distributors to include their production into daily schedules because of their dependence on external factors, such as weather conditions. Finally, smart metering is being increasingly adopted in electricity consumption. Under these conditions, new solutions are sought to support flexibility on electricity markets, ensure reliable supply, and balance the costs and benefits of the involved parties.

In striving for these goals, information and communication technology (ICT) is of crucial importance. An ICT system to serve the needs of a deregulated electricity market and enable the integration of a higher rate of energy from distributed and renewable sources into the electricity grid is being developed in the European Seventh Framework Programme project MIRABEL (Micro-Request-Based Aggregation, Forecasting and Scheduling of Energy Demand, Supply and Distribution) [1]. The project proposes a conceptual and infrastructural approach to supply and demand side management where electricity producers and consumers issue flexible offers (termed *flex-offers*), indicating flexibilities in start time and energy amount. These flex-offers are then processed by the MIRABEL system to balance electricity supply and demand.

As electricity market regulations vary across the countries, a common platform was identified first to build upon in MIRABEL. For this purpose the Harmonized Electricity Market Role Model [2] defined by the European Network of Transmission System Operators for Electricity (ENTSO-E) and cooperating institutions was selected. Despite still being refined, the model provides a coherent view of the electricity markets in Europe, represented by roles, domains, and their interactions. In this model, the elementary role is *party connected to the grid* that contracts for the right to produce or consume electricity at a metering point. Types of this party are producers and consumers, sometimes denoted by a common term *prosumers*. A collection of metering points (related to prosumers) for imbalance settlement is a domain called *balance group*. The role providing balance responsibility and financial security for a balance group is *balance responsible party* (BRP).

Balance group is the basic domain where the MIRABEL system will be applied. To assist the BRP in equalizing the inflows and outflows of electricity at the balance group endpoints, i.e., producers, consumers and connections to the external network, the system provides:

- handling of the novel concept of flex-offers for electricity production and consumption,
- forecasting of electricity production and consumption,
- aggregation of flex-offers on a regional level, scheduling of electricity production and consumption based on aggregated flex-offers, and disaggregation of the scheduled flex-offers for the purpose of their contracting,
- a distributed, decentralized and scalable computer infrastructure to handle the data load from the prosumers.

The overall MIRABEL architecture and functionalities are described in [3]. This paper focuses on the flex-offer scheduling problem as faced in this system. It presents a formal definition of the scheduling problem, upgrading its draft version given in [4].

The paper is further organized as follows. First, the concepts needed to formulate the problem are explained. Next, the scheduling problem is formulated as an optimization problem in terms of decision variables, constraints and the objective function. The paper then discusses the characteristics that make the problem highly specific and complex. It concludes with a summary of the presented work.

2 CONCEPT DESCRIPTION

2.1 Time intervals

In the MIRABEL scheduling problem, time is discretized into intervals (usually 15 minutes long). Each such interval is called a *time step interval*, and every time related concept is defined as a multiple of time step intervals. *Scheduling interval* is the interval for which scheduling needs to be performed and is also a multiple of time step intervals.

2.2 Mismatch and imbalance prices

For each time step interval, a *mismatch* amount is given. Mismatch represents the difference between all produced and consumed energy that is forecast for the corresponding time interval. Mismatch is positive when forecasts imply more produced than consumed energy, and negative when the consumed energy is forecast to exceed the produced energy. Mismatch is merely a prediction of imbalances that are about to happen in reality when the time in question has passed and the producers and consumers of energy will adhere (or not) to the forecast behavior. The BRP has to pay penalties for any imbalance. Their price is called the *imbalance price*.

2.3 Flex-offers

A *flex-offer* represents an offer of a consumer to buy energy from the BRP or an offer of a producer to sell energy to the BRP. Each flex-offer is defined with:

– start time flexibilities,

– energy intervals, where each interval is defined with its duration, price, and energy flexibilities, and

– total energy constraint.

The start time flexibilities denote on which time step intervals the execution of the flex-offer can start. For example, the production flex-offer from Figure 1 can start on four time step intervals, while the consumption flex-offer can start from the second to the eleventh time step interval. This means that the consumption flex-offer has greater time flexibility than the production one. The flex-offer's energy intervals are shown as boxes in Figure 1 (the production flex-offer has four energy intervals, while the consumption flex-offer two). Each energy interval has its duration expressed in multiples of time-step intervals, a price per energy amount and flexibilities, i.e., the minimum and maximum energy that can be assigned to the flex-offer for that energy interval (indicated with arrows in Figure 1). The energy of production flex-offers is regarded as positive, and the energy of consumption flex-offers as negative.

2.4 Market energy and prices

The mismatch that remains after all flex-offers have been scheduled can sometimes be bought (negative mismatch) or sold (positive mismatch) on the *energy market* at a price called the *market price*.

3 PROBLEM FORMULATION

The MIRABEL scheduling problem is defined with:

– the scheduling interval,

– mismatch and imbalance prices, which are given for every time step interval in the scheduling interval,

– market prices, which are given for some time step intervals in the scheduling interval, and

– (aggregated) flex-offers with all their defining information.

The task is to fix time and energy flexibilities of all given flex-offers and establish the amount of energy to be bought (sold) on the market so that all constraints are satisfied and the cost for the BRP is minimized.

In the continuation of this section, the problem is formally defined in terms of decision variables, constraints and the objective function, using the notation from Table 1.

Table 1: *Notation used in the problem formulation.*

Variable	Meaning
n	number of flex-offers
m	number of time step intervals in the scheduling interval
E^i_{I}	remaining mismatch amount for time step interval i
$p^i_{\mathrm{I+}}$, $p^i_{\mathrm{I-}}$	price of positive/negative imbalance for time step interval i
E^i_{M}	market energy amount for time step interval i
$p^i_{\mathrm{M+}}$, $p^i_{\mathrm{M-}}$	price of energy that can be sold/bought on the market for time step interval i
s_k	schedule for the k-th flex-offer
t_k	start time of the k-th flex-offer
E^j_k	energy amount of the j-th energy interval of the k-th flex-offer
p^j_k	price of the j-th energy interval of the k-th flex-offer

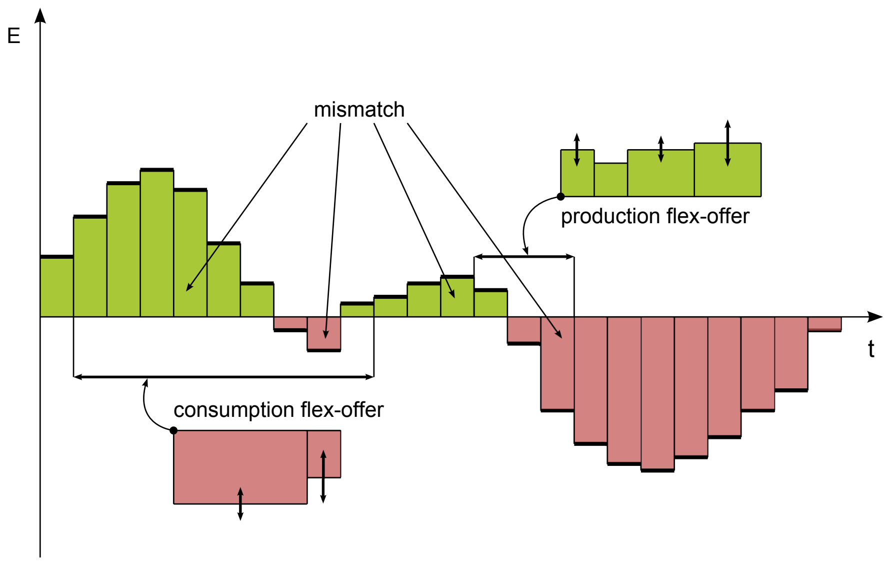

Figure 1: *An example of mismatch and two flex-offers (one production and one consumption).*

3.1 Decision variables

The decision variables of the scheduling problem are represented with the pair (S, M), where S is a vector of flex-offer schedules, and M is a vector of market energy amounts:

$$S = \begin{bmatrix} s_1 \\ s_2 \\ \vdots \\ s_n \end{bmatrix}, \; M = \begin{bmatrix} E_{\mathrm{M}}^1 \\ E_{\mathrm{M}}^2 \\ \vdots \\ E_{\mathrm{M}}^m \end{bmatrix},$$

where the notation from Table 1 is used. Each flex-offer schedule s_k is defined with the flex-offer start time t_k and energy amounts for each energy interval of the flex-offer:

$$s_k = (t_k, E_k^1, E_k^2, \ldots, E_k^{n_k}),$$

where n_k is the number of energy intervals of the k-th flex-offer. The pair (S, M) of flex-offer schedules and market energy amounts is a solution to the scheduling problem.

3.2 Constraints

Flex-offer flexibilities are in fact constraints on flex-offer schedules. Each flex-offer schedule $s_k = (t_k, E_k^1, E_k^2, \ldots, E_k^{n_k})$ is subject to the following constraints:

$$t_k \in \left[\underline{t_k}, \overline{t_k}\right],$$

where $\underline{t_k}$ and $\overline{t_k}$ are the earliest and latest start times for t_k, and

$$E_k^j \in \left[\underline{E_k^j}, \overline{E_k^j}\right] \text{ for all } j = 1, \ldots, n_k,$$

where $\underline{E_k^j}$ and $\overline{E_k^j}$ are the minimum and maximum energy amounts for E_k^j. In addition to providing time and energy flexibilities, a prosumer may provide a total energy constraint that determines the sum of energy that needs to be produced (or consumed) in the entire flex-offer over all its energy intervals:

$$\sum_{j=1}^{n_k} E_k^j \in \left[\underline{E_k}, \overline{E_k}\right],$$

where $\underline{E_k}$ and $\overline{E_k}$ are the minimum and maximum total energy constraint amounts for the k-th flex-offer.

Any of the specified constraint intervals can degenerate into a point, leaving no flexibility. For example, the production flex-offer from Figure 1 has no flexibility in the second energy interval.

Market prices that are part of the given problem instance can have an arbitrary form. For any time step interval i, the following combinations are possible:

- only the price $p_{\mathrm{I}+}^i$ for selling energy on the market is defined,
- only the price $p_{\mathrm{I}-}^i$ for buying energy on the market is defined,
- both prices $p_{\mathrm{I}+}^i$ and $p_{\mathrm{I}-}^i$ are defined, or
- none of the prices is defined.

The vector of market energy amounts is constrained according to the defined prices:

$$E_{\mathrm{M}}^i \in \begin{cases} \mathbb{R}_0^+ & \text{if only } p_{\mathrm{I}+}^i \text{ is defined,} \\ \mathbb{R}_0^- & \text{if only } p_{\mathrm{I}-}^i \text{ is defined,} \\ \mathbb{R} & \text{if both prices are defined,} \\ \{0\} & \text{if none of the prices is defined.} \end{cases}$$

This means, for example, that if only the price $p_{\mathrm{I}+}^i$ for selling energy on the market is defined, the market energy amount for interval i must not be negative, since it is not possible to buy energy on the market.

A schedule is considered feasible if its start time is fixed within the given flexibilities, the energy amounts are fixed within the given flexibilities, and all the energy constraints are satisfied. A market energy amount is considered feasible if it is set according to its constraints. A *solution is feasible* if all of its schedules and market energy amounts are feasible.

3.3 Objective function

The objective of the scheduling problem is minimization of cost for the BRP. The cost for the BRP c of a solution (S, M) consists of the cost of remaining negative imbalances $c_{\mathrm{I-}}$, the cost of remaining positive imbalances $c_{\mathrm{I+}}$, the cost of flex-offers c_{FO} and the cost of the energy bought on the market $c_{\mathrm{M-}}$ minus the profit from the energy sold on the market $c_{\mathrm{M+}}$:

$$\begin{aligned} c(S,M) &= \underbrace{\sum_{\substack{i=1\\ E_{\mathrm{I}}^i<0}}^{m} p_{\mathrm{I-}}^i \left|E_{\mathrm{I}}^i\right|}_{c_{\mathrm{I-}}} + \underbrace{\sum_{\substack{i=1\\ E_{\mathrm{I}}^i>0}}^{m} p_{\mathrm{I+}}^i E_{\mathrm{I}}^i}_{c_{\mathrm{I+}}} + \underbrace{\sum_{k=1}^{n}\left(\sum_{j=1}^{n_k} p_k^j E_k^j\right)}_{c_{\mathrm{FO}}} \\ &+ \underbrace{\sum_{\substack{i=1\\ E_{\mathrm{M}}^i<0}}^{m} p_{\mathrm{M-}}^i \left|E_{\mathrm{M}}^i\right|}_{c_{\mathrm{M-}}} - \underbrace{\sum_{\substack{i=1\\ E_{\mathrm{M}}^i>0}}^{m} p_{\mathrm{M+}}^i E_{\mathrm{M}}^i}_{c_{\mathrm{M+}}}, \end{aligned}$$

where the notation from Table 1 is used. Note that while buying energy from the market increases the cost for the BRP, selling energy decreases it (hence minus in the formula above). Similarly, the BRP must buy the energy produced by the production flex-offers (which increases the total cost), while the energy consumed by the consumption flex-offers represents profit for the BRP and decreases the total cost. This is expressed by the sign of the energy amount E_k^j.

If there are more solutions that minimize the cost c, the one which results in the smallest amount of remaining mismatch is preferred.

The decision variables t_k denoting start times of flex-offers are present in the calculation of the objective function only implicitly. They influence the amounts of remaining mismatch and market energy amounts, i.e., E_{I}^i and E_{M}^i values, and therefore indirectly affect the total sum of costs for the BRP.

In short, the presented scheduling problem consists of finding a feasible solution (S, M) which minimizes the cost function $c(S, M)$.

4 DISCUSSION

The scheduling problem formulated in this work differs from the scheduling problems treated in the literature either in the context of production systems (e.g., [5]) or energy sector (e.g., [6]). Unlike the usually scheduled activities, flex-offers are structured, consisting of several energy intervals, each interval with its own properties. Regarding the decision variables, in addition to start time, flex-offer scheduling involves determining energy amount for each energy interval of every flex-offer, and the market energy amounts. This substantially increases the problem complexity in terms of the number of candidate solutions. Finally, the objective function is not related to a time measure, but is rather a composed cost function.

These characteristics and the expected large number of flex-offers to be processed make the MIRABEL scheduling problem non-standard and highly complex. Known scheduling heuristics are therefore very unlikely to be directly applicable. The approach followed in solving this problem will therefore be metaheuristic algorithms, possibly hybridized with local optimization.

5 CONCLUSION

Scheduling of electricity production and consumption based on prosumer flex-offers was formulated as an optimization problem. This formulation is a prerequisite for implementing suitable optimization algorithms. Solving the problem will be a functionality of the MIRABEL energy data management system that is currently under development.

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REFERENCES

[1] MIRABEL Project. Available from `http://www.mirabel-project.eu/`, retrieved on September 10, 2011.

[2] European Transmission System Operators. The Harmonized Electricity Market Role Model, version 2009-01. Available from `http://www.scribd.com/doc/48492720/Role-Model-v2009-01`, retrieved on September 6, 2011.

[3] Z. Marinšek, G. Černe, H. Berthold, C. Nychtis, F. J. Rumph, M. Konsman, H. Frey, L. Šikšnys, T. B. Pedersen, D. Kaulakiene, B. Filipič, M. Böhm. D1.2 Final role model and process specification. Technical report, MIRACLE Consortium, December 2010.

[4] T. Tušar, E. Dovgan, B. Filipič, A. Savinov. D5.3 Initial draft of the scheduling and negotiation framework. Technical report, MIRACLE Consortium, May 2011.

[5] M. L. Pinedo. *Scheduling: Theory, Algorithms, and Systems*. Third edition. Springer, New York, 2008.

[6] H. Y. Yamin. Review on methods of generation scheduling in electric power systems. *Electric Power Systems Research*, Vol. 69, No. 2–3, pp. 227–248, 2004.