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Robust Self-Scheduling of Operational Processes for Industrial Demand Response Aggregators

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***Abstract*—This paper proposes a novel structure for Industrial Demand Response Aggregators (IDRA) to provide operational flexibility for the power system. A robust self-scheduling approach is formulated for the first time to optimize different sub-processes of the whole production line of heavy industries. The new approach satisfies the customer order with the lowest energy cost. Numerical studies are implemented on 8 integrated cement factories, from Khorasan Regional Electric Company (KREC), in the east of Iran. The results show that the integrated model of heavy industries provides guaranteed flexibility to the system when a power shortage occurs or system reliability is jeopardized.**

***Index Terms*— Demand response aggregator; cement plant; heavy industry; production line; robust scheduling.**

I. INTRODUCTION

IN the last few years, the Iran Power Grid (IPG) has been experiencing high peak hours during hot summer days, especially at midday hours. The main reason for the increased peak demand is the cooling systems of residential and commercial consumers. Studying the behavior of the Load Duration Curve (LDC), the peak level violates the safety margin of the IPG for 100 to 120 hours annually, all in summer days. Making huge investments in installing new generation capacity cannot be an economic decision for policymakers. In order to overcome the problem, there are some kinds of heavy industries whose consumption behavior have structural flexibility inherently.

In this way, if the operation scheduling of the industries is optimized and integrated, adequate flexibility can be provided for the power system to prevent huge investments.

Traditionally, the heavy industries were subject to energy management for decades. Among heavy industries, cement manufacturing [1], Aluminium production [2], steel powder manufacturing [3], pulp and paper industry [4], oxygen generation [5] and oil refinery [6] have attracted many attentions for Demand Response Programs (DRP).

In the Iran's industrial sector, according to the report of Iran Energy Efficiency Organization (IEEO) [7], the 84 cement plants, with total cement capacity of 85 Mt/year, consume more than 4 % of total generated electrical energy which equals to 11 % of total electrical energy consumed in the industrial part. Therefore, the cement industries consume about 7500 Million kWh energy annually with the energy intensity 110 kWh/t.

Considering the above-mentioned facts, the cement industries can provide high potential for DRPs to reduce/eliminate the need for more expensive alternative forms of flexibility, e.g. fast-run generation units and energy storages. In this way, a comprehensive self-scheduling system is needed to schedule operation of the factories based on the signals received from the power system operator while the daily production satisfies the ordered value.

Cement plants are sites that, through a variety of techniques, process quarried raw materials into cement [8]. There are different technologies to produce various kinds of cement. Generally, in spite of the kinds of technology, four main process routes are normally used for the production of cement as (1) Dry (2) semi-dry (3) semi-wet and (4) wet processes. From viewpoint of energy management, a cement plant can be divided into four main sub-processes as (1) Crushing (2) kiln feed preparation (3) clinker production and (4) finish grinding [9].

During the last decades, some research studies in the field of energy management in cement industries have been published. First of all, in 1977, a comprehensive report on the international experiences about load management in industries was prepared at California States [10]. Later in 1997, Lafarge's Whitehall, a cement company at Pennsylvania, made a contract for power curtailment optimizing energy consumption during on-peak hours [11]. Although there were some other studies in cement industries in the last decades of the 20th century, barely any

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distinguished research with mathematical structure of self-scheduling is seen.

Due to the early recession in 2000, especially in developed countries, some cement-field researchers decided to investigate cost-effective energy consumption technologies in cement industries in terms of thermal and electrical energies. An in-depth analysis of US cement industries was carried out in the first year of the decade [12]. By constructing an energy conservation supply curve, they found a total cost-effective energy saving of 11 % of energy use and a saving of 5 % of total carbon dioxide emissions. In [13], energy-efficiency opportunities are investigated in China's cement plants. Regarding the electrical energy, the results showed that the total technical electricity-saving potential is 40 % of total electricity use in the 16 understudied cement plants. Although the other same studies were carried out in other countries, e.g. in Malaysia [14] and Cyprus [15] , the common feature is that the most studies aimed to investigate the potentials of energy saving for both fuel-based and electricity-based processes without considering the role of industry in the local power system or fuelling network.

In recent years, by the advent of DRPs, many policymakers of the industrial sector have investigated new ways to increase the flexibility of production lines. In this way, on one hand, they take the advantage of cost-effective operation strategies, and on the other hand, they reduce the needs of the power system for more expensive alternative forms of flexibility like costly fast-run power plants or storage systems. In this regard, a self-scheduling for a cement plant participating in the electricity market is proposed in [16] to reach a compromise between risk and profit. In this paper, the fuzzy α-cuts is used to model a range of decision-making with different production strategies. Ref. [17] proposes an industrial DRP for a cement industry located in China to improve wind penetration and provide ancillary service for the power system. In [18], a potential of load shifting for a cement plant in South Africa is investigated to reduce evening peak load and save electrical cost. The results showed that by six-hour load shifting on the raw mill, a 2% reduction in an electricity bill is achieved without adversely affecting production. Ref. [19] proposes a coordination method based on model predictive control for cement crushing to provide regulation and ancillary services for the power system. The distinguishing feature of the paper is to provide a solution to the problem that the current electricity market cannot fully utilize the demands with fast switching capabilities due to their granularity restrictions. To sum up, Figure 1 describes the main features of research studies in the cement factories from 1980 until now. In addition, from viewpoint of cement industries, the needs for future power systems with high penetration of renewable energies are stated.

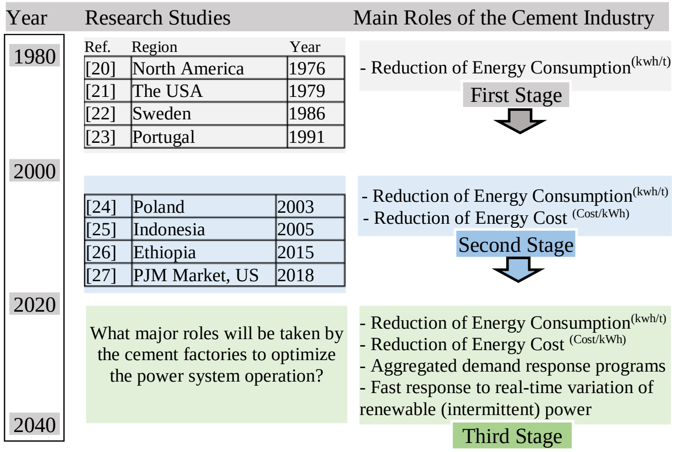
The common feature of the studies in the literature is that the researchers have focused on segregated industries without investigating the opportunities for participation in a deregulated environment of the power system. Moreover, barely any mathematical formulation for the production line of the heavy industries to give the industrial policymakers a chance of reducing energy cost or receiving financial incentives is seen. Against the background, this paper proposes a mathematical structure for an Industrial Demand Response Aggregator (IDRA) participating in electricity market to procure the required energy on one side and optimize the consumption behavior of the whole production line of cement plants, on the other side. Based on the abovementioned facts, the contributions of the proposed approach can be stated as follows:

(1) Formulating a mathematical framework for the whole production line of a cement plant to lower the energy cost.

(2) Proposing a robust-based self-scheduling for industrial processes to provide a guaranteed flexibility for the power system.

(3) Integrating the potential of flexible industrial sub-processes to respond to the power system signals (DRPs) through a proposed IDRA.

The remainder of the paper is organized as follows: in section II, the structure of IDRAs is illustrated. In section III, the whole production line of modern cement plants is formulated mathematically. The coordination mechanism between the IPG and the IDRAs is stated in section IV. Finally, the simulation results and discussion are described in section V.



Ref.	Region	Year
[20]	North America	1976
[21]	The USA	1979
[22]	Sweden	1986
[23]	Portugal	1991

[24]	Poland	2003
[25]	Indonesia	2005
[26]	Ethiopia	2015
[27]	PJM Market, US	2018

Fig. 1. Trends of research studies for cement industries

II. INDUSTRIAL DEMAND RESPONSE AGGREGATOR

The model in Eq.(1) comprises an industrial demand response aggregator and a set of heavy industries $\rho = \{1,2,\dots,\Theta\}$. The IDRA participates in the electricity market, on behalf of the industries, to procure the required energy from the day-ahead electricity market $\Pi_t^{DA} \in \mathbb{R}_+$ and bilateral contracts $\Pi_t^{BC} \in \mathbb{R}_+$with electricity price $\lambda_t^{DA} \in \mathbb{R}_+$and $\lambda_t^{BC} \in \mathbb{R}_+$, respectively for time slot $t\epsilon\{\tau,\dots,\tau+\tau_T\}$. In addition, each industry has thermal-self generation facilities $\gamma = \{1,2,\dots,H\}$ with cost function $C^{\gamma}(\Pi_t^{SG})\colon \mathbb{R}_+ \to \mathbb{R}_+$, where C^{γ} is the cost function of generating Π_t^{SG} units of energy. The additional cost imposed to the industry ρ due to load reduction request of the power system for sub-process $\kappa = \{1,2,\dots,\mathrm{K}\}$ is described as $\Upsilon_{t,\rho}^{\kappa} \in \mathbb{R}_+$. The imposed cost includes start-up cost $\varpi_{t,\rho}^{\kappa} \in \mathbb{R}_+$ with decision binary variable $\mu_{t,\rho}^{\kappa} \in \{0,1\}$ and shut-down cost $\vartheta_{t,\rho}^{\kappa} \in \mathbb{R}_+$ with decision binary variable $\nu_{t,\rho}^{\kappa} \in \{0,1\}$,while $\mu_{t,\rho}^{\kappa} + \nu_{t,\rho}^{\kappa} \leq 1$. The produced volume of cement $\emptyset_t^{\rho} \in \mathbb{R}_+$ must satisfy the ordered value by the customers $\emptyset_o^{\rho} \in \mathbb{R}_+$. Given the demand profiles of each industry $\Pi_t^{\rho} = [\Pi_{\tau}^{\rho},\dots,\Pi_{\tau+\tau_T}^{\rho}]$, the IDRA aims to minimize total energy cost of the aggregated industries for the time horizon τ_T by solving the following objective function:

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$$\min_{\begin{pmatrix}\Pi_t^{DA},\Pi_t^{BC}\\ \Pi_t^{\rho},\Pi_t^{SG}\end{pmatrix}}\left[\begin{array}{l}\sum_{t=\tau}^{\tau+\tau_N}\lambda_t^{DA}\Pi_t^{DA}+\sum_{t=\tau}^{\tau+\tau_N}\sum_{\beta=1}^{\mathrm{B}}\lambda_{\beta,t}^{BC}\Pi_{\beta,t}^{BC}\\ +\sum_{t=\tau}^{\tau+\tau_N}\sum_{\gamma=1}^{\mathrm{H}}\sum_{\rho=1}^{\Theta}C_{\rho}^{\gamma}(\Pi_t^{SG})+\sum_{t=\tau}^{\tau+\tau_N}\sum_{\rho=1}^{\Theta}\sum_{\kappa=1}^{\mathrm{K}}\Upsilon_{t,\rho}^{\kappa}\end{array}\right] \tag{1}$$

Subject to:

$$\forall \mathrm{t}\in\mathrm{T},\forall\rho\in\{\Theta\},\forall\kappa\in\mathrm{K}:\quad \Upsilon_{t,\rho}^{\kappa}=\left(\varpi_{t,\rho}^{\kappa}\times\mu_{t,\rho}^{\kappa}\right)+\left(\vartheta_{t,\rho}^{\kappa}\times\nu_{t,\rho}^{\kappa}\right) \tag{2}$$

$$\forall \mathrm{t}\in\mathrm{T}:\quad \Pi_t^{DA}+\sum_{\beta=1}^{B}\Pi_{\beta,t}^{BC}=\sum_{\rho=1}^{\Theta}\Pi_t^{\rho}-\sum_{\gamma=1}^{\mathrm{H}}\sum_{\rho=1}^{\Theta}\Pi_t^{SG,\rho,\gamma} \tag{3}$$

$$\forall\rho\in\{\Theta\}:\quad \sum_{t=\tau}^{\tau+\tau_N}\phi_t^{\rho}=\phi_o^{\rho} \tag{4}$$

where (2) describes the imposed cost of demand response, i.e. start-up and shut-down costs, (3) states the power balance of the IDRA, and (4) restricts the cement production to the ordered value during the understudied time horizon.

In the deregulated environment of electricity market with uncertain day-ahead electricity price, the IDRA aims to determine the optimal operation strategies based on the worst-case realization of the wholesale market price. Therefore, to achieve the aim, the IDRA optimizes the min-max structure as follows:

$$\min_{\begin{pmatrix}\Pi_t^{DA},\Pi_t^{BC}\\ \Pi_t^{\rho},\Pi_t^{SG}\end{pmatrix}}\left[\begin{array}{l}\max\left(\sum_{t=\tau}^{\tau+\tau_N}\lambda_t^{DA}\Pi_t^{DA}\right)+\sum_{t=\tau}^{\tau+\tau_N}\sum_{\beta=1}^{\mathrm{B}}\lambda_{\beta,t}^{BC}\Pi_{\beta,t}^{BC}\\ +\sum_{t=\tau}^{\tau+\tau_N}\sum_{\gamma=1}^{\mathrm{H}}\sum_{\rho=1}^{\Theta}C_{\rho}^{\gamma}(\Pi_t^{SG})+\sum_{t=\tau}^{\tau+\tau_N}\sum_{\rho=1}^{\Theta}\sum_{\kappa=1}^{\mathrm{K}}\Upsilon_{t,\rho}^{\kappa}\end{array}\right] \tag{5}$$

To solve the problem, by using the duality theorem, the primal min-max problem is converted to a dual robust mixed-integer quadratic program (R-MIQP) as follows:

$$\min_{\begin{pmatrix}\Pi_t^{DA},\Pi_t^{BC},\Pi_t^{\rho}\\ \Pi_t^{SG},\xi_t,\psi\end{pmatrix}}\left[\begin{array}{l}\sum_{t=\tau}^{\tau+\tau_N}\lambda_t^{DA}\Pi_t^{DA}+\sum_{t=\tau}^{\tau+\tau_N}\sum_{\beta=1}^{\mathrm{B}}\lambda_{\beta,t}^{BC}\Pi_{\beta,t}^{BC}+\sum_{t=\tau}^{\tau+\tau_N}\sum_{\gamma=1}^{\mathrm{H}}\sum_{\rho=1}^{\Theta}C_{\rho}^{\gamma}(\Pi_t^{SG})\\ +\sum_{t=\tau}^{\tau+\tau_N}\sum_{\rho=1}^{\Theta}\sum_{\kappa=1}^{\mathrm{K}}\Upsilon_{t,\rho}^{\kappa}+\sum_{t=\tau}^{\tau+\tau_N}\xi_t+\Gamma\psi\end{array}\right] \tag{6}$$

Subject to:

Constraints (2)-(4)

$$\forall t\in T,\forall\xi_t\geq 0,\forall\psi\geq 0:\quad \xi_t+\psi\geq(\lambda_t^{DA}\times\Pi_t^{\rho}) \tag{7}$$

where the symbols $\xi_t\in\mathbb{R}_+$ and $\psi\in\mathbb{R}_+$ indicate the dual variables of the corresponding constraints in the duality theorem. The wholesale price λ_t^{DA} takes values in the interval $[\bar{\lambda}_t^{DA}$-$\hat{\lambda}_t^{DA}, \bar{\lambda}_t^{DA}$+$\hat{\lambda}_t^{DA}]$ where $\bar{\lambda}_t^{DA}$ is the nominal value for the price and $\hat{\lambda}_t^{DA}$ is the maximum allowed deviation from the nominal value. Furthermore, the total deviation in the horizon is bounded so that the price cannot take an extreme value in more than $\Gamma\in\mathbb{N}_+$ time periods. This results in the following deterministic set Ω for the uncertain price sequence:

$$\Omega=\left\{\lambda_t^{DA}\in\mathbb{R}_+,\quad \forall t:\lambda_t^{DA}\in\left[\bar{\lambda}_t^{DA}-\lambda_t^{DA},\bar{\lambda}_t^{DA}+\lambda_t^{DA}\right],\sum_{t=\tau}^{\tau+\tau_N}\left|\frac{\lambda_t^{DA}-\bar{\lambda}_t^{DA}}{\lambda_t^{DA}}\right|\leq\Gamma\right\} \tag{8}$$

As mentioned above, the aim of IDRA is to determine the optimal operation strategies of the contracted industries based on the worst-case realization of the wholesale market price. In addition, to study the impacts of wholesale market price uncertainty on the operation strategies, an uncertainty set is determined by set Ω (8). To determine the optimal operation strategies, under different intervals of worst-case realization of the wholesale market price uncertainty, an iterative procedure is considered. In this procedure, the uncertainty set, including lower and upper limits of the market price, is portioned into Q subintervals to evaluate the impacts of each subinterval on operation strategies. The procedure iterates until the whole interval of the market price uncertainty set is covered. Finally, by running the iterative procedure, the robust operation strategies are determined receiving the full response of the heavy industries for all subintervals of the wholesale price uncertainty. The proposed algorithm can be stated by following simple steps:

Step 1: Construct wholesale market price uncertainty set as $\Omega=[\lambda^{\min}, \lambda^{\max}] = [\bar{\lambda}_t^{DA}$-$\hat{\lambda}_t^{DA}, \bar{\lambda}_t^{DA}$+$\hat{\lambda}_t^{DA}]$.

Step 2: Break down the uncertainty set Ω to Q subintervals, subject to:

$$\Omega(q)=\left\{\lambda_t^{DA}\in\mathbb{R}_+,\quad \begin{array}{l}\forall t:\lambda_t^{DA}\in\left[\lambda^{\min},\lambda^{\min}+\gamma^q\right]\\ \forall q=1,\ldots,Q:\quad \gamma^q=q\times\dfrac{\left|\lambda^{\max}-\lambda^{\min}\right|}{Q}\end{array}\right\}$$

Note that the q={1,…,Q} is a counter index for the robust iterative procedure.

Step 3: Determine robust operation strategies for each subinterval of Ω(q) by using R-MIQP (6).

Step 4: Increase the counter index q to cover all the subintervals of the uncertainty set Ω(q). If q<Q go back to step 2, otherwise stop the algorithm.

III. PRODUCTION LINE OF A MODERN CEMENT PLANT

The whole production line of a modern cement plant can be modeled through four sub-processes as (1) Crushing (C) (2) Kiln Feed Preparation (KFP) (3) Clinker Production (CP) and (4) Finish Grinding (FG). There is a storage between every two sub-processes to store the output production. It can provide flexibility to the power system through shutting down the process when a power shortage occurs in the electricity network. Therefore, the mathematical structure of the production line of a modern cement factory is described as the following matrix space:

$$\Pi_t^{\rho}=\sum_{\kappa=1}^{\mathrm{K}}\Pi_t^{\rho,\kappa} \tag{9}$$

$$\left[\Pi_t^{\rho,\kappa}\right]=\left[\Pi_t^{\rho,\kappa}\right]\times\left[\bar{\phi}_t^{\rho,\kappa}\right] \tag{10}$$

$$\left[\bar{\phi}_t^{\rho,\kappa}\right]=\left[\eta_t^{\rho,\kappa}\right]\times\left[\underline{\phi}_t^{\rho,(\kappa-1)}\right] \tag{11}$$

$$\left[SoS_t^{\rho,\kappa}\right]=\left[SoS_{t-1}^{\rho,\kappa}\right]+\left[\bar{\phi}_t^{\rho,\kappa}\right]-\left[\underline{\phi}_t^{\rho,\kappa}\right] \tag{12}$$

where $\tilde{\Pi}_t^{\rho,\kappa}\in\mathbb{R}_+$ is the rated electricity consumption of sub-process κ (MWh/ton); $\bar{\phi}_t^{\rho,\kappa}\in\mathbb{R}_+$ is the output production of sub-process κ (ton/h); $\underline{\phi}_t^{\rho,\kappa}\in\mathbb{R}_+$ is the rate of output from storage κ to sub-process $\kappa+1$; $\underline{\phi}_t^{\rho,(\kappa-1)}\in\mathbb{R}_+$ is the rate of supply from storage $\kappa-1$ to the sub-process κ; $\eta_t^{\rho,\kappa}$ is the ratio of output weight to input weight and $SoS_t^{\rho,\kappa}$ is the State of Storage for siloes (ton).

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Equation (9) describes the total electric energy consumption of the cement plants as a summation of $K \in \mathbb{N}_+$ sub-processes, (10) illustrates the electric energy consumption of sub-process κ as a function of rated electric consumption and output production, (11) shows the relation of the output and input weight for each sub-process κ, and (12) illustrates the State of Storage for siloes as a function of previous SoS, input and output production. Note that, according to (11), weight losing/gaining in sub-process κ occurs due to some chemical/physical changes, e.g. water vaporizing or gypsum added to cement clinker.

The proposed model of the production line is bounded by the following equalities and inequalities:

$$\sum_{t=\tau}^{\tau+\tau_N} \underline{\phi}_t^{\rho,(\kappa=\mathrm{K})} = \phi_o^\rho \tag{13}$$

$$\overline{\phi}_{\min}^{\rho,\kappa} \le \overline{\phi}_t^{\rho,\kappa} \le \overline{\phi}_{\max}^{\rho,\kappa} \tag{14}$$

$$\underline{\phi}_{\min}^{\rho,\kappa} \le \underline{\phi}_t^{\rho,\kappa} \le \underline{\phi}_{\max}^{\rho,\kappa} \tag{15}$$

$$SoS_{\min}^{\rho,\kappa} \le SoS_t^{\rho,\kappa} \le SoS_{\max}^{\rho,\kappa} \tag{16}$$

where (13) guarantees that the production level satisfies the customer ordered value, (14) restricts the production level of each sub-process to a lower $\overline{\Phi}_{min}^{\rho,\kappa}$ and upper $\overline{\Phi}_{max}^{\rho,\kappa}$ bound; (15) limits the flow of output from the previous storage to the next sub-process; finally the capacity of storage is bounded to lower $SoS_{min}^{\rho,\kappa}$ and upper $SoS_{max}^{\rho,\kappa}$ capacities through (16). To clarify the proposed mathematical model, Figure 2 describes the schematic diagram for the whole production line of the cement manufacturing plant.

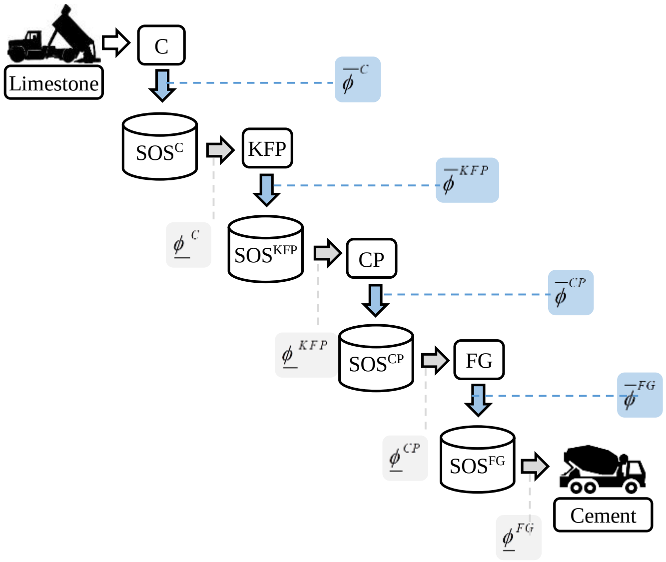

Fig. 2. Manufacturing processes of a modern cement plant

IV. COORDINATION MECHANISM

In the suggested approach, the Iran Grid Management Company (IGMC) is responsible for maintaining the reliability of the Iran Power Grid (IPG) on one side and providing a competitive environment for large consumers to procure their electrical energy from electricity market on the other side. In this way, the DRPs, including price-based or incentive-based programs, are scheduled by the IGMC. On the other hand, the IDRA plays an intermediary role between heavy industries and the IGMC. The IDRA negotiates with the contracted heavy industries to exchange some information about the operation during the next 24 hours. The IDRA receives the information from industries mainly as followings:

(1) Minor/daily maintenance programs
(2) Crew constraints
(3) Daily/weekly ordered value
(4) Cost data of self-generation facilities

Against, the IDRA provides information to the industries as followings:

(1) Electricity price for day-ahead market and bilateral contract
(2) DRPs scheduled by the IGMC

The flow of information between different participants is depicted in Figure 3. Collecting the abovementioned information, the IDRA determines the optimized operation for the contracted industries during the next 24 hours. In order to clarify the problem, the coordination mechanism between IGMC, IDRA and the industries are described step-by-step in Figure 4.

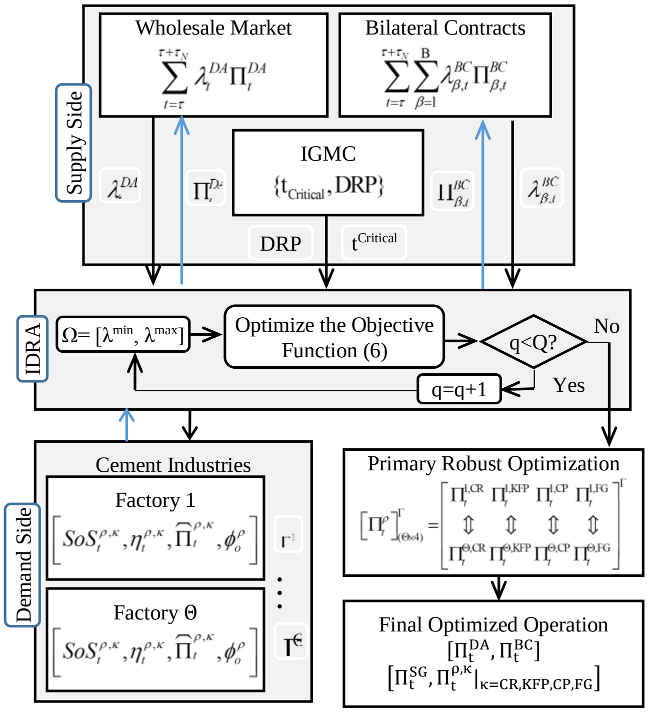

Fig. 3. The flow of information in the proposed approach

V. NUMERICAL STUDIES

In this section, the numerical studies are presented. First of all, the input data about the test electricity market and contracted industries are described. Afterward, the simulation results are illustrated and discussed.

A. INPUT DATA

In this paper, the aim is to optimize the operation of cement industries in the IPG during a hot day (24 hours) of summer when the power network experiences serious power shortage during two peak hours as follows:

(1) Day peak hour due to the high electrical demand for residential and commercial cooling systems.

(2) Night peak hour due to the high demand for residential and commercial lighting systems.

Considering the input parameter data, the R-MIQP problem (6) is solved for 25 iterations (Q=25) to produce required data for obtaining the robust strategies. The value of Q depends on the size of the uncertainty set Ω. The simulations have been done using different input data values and the best results based on robust strategies.

Algorithm 1: Demand Response Aggregator for Cement Plants
"TOU: Time of Use, CPP: Critical Peak Pricing, ED: Extreme Day"

```
1:   The IDRA receives:
       - The ordered cement for each plant $\sum_{t=1}^{\tau+\tau_N} \emptyset_t^{\rho}$ over next $\tau_N$ hours.
       - The price of day-ahead and bilateral contracts $(\lambda_t^{BC}, \lambda_t^{DA}) \in \mathbb{R}_+$.
       - The cost data of self-generation facilities $C^{\gamma}(\Pi_t^{SG}): \mathbb{R}_+ \rightarrow \mathbb{R}_+$.
       - The crew constraints and maintenance scheduling of the industries.
       - The DRPs.
2:   The IDRA makes a decision about how to participate in the day-ahead
     market with electricity price uncertainty $\lambda_t^{DA} \in \Omega$ as followings:
2-1:   Construct wholesale market price uncertainty set $\Omega = [\lambda^{\min}, \lambda^{\max}] = [\bar{\lambda}_t^{DA} - \hat{\lambda}_t^{DA}, \bar{\lambda}_t^{DA} + \hat{\lambda}_t^{DA}]$.
2-2:   **While** q<Q **do**:
2-3:     Break down the uncertainty set Ω to Q subintervals, subject to:
         $$\Omega(q) = \left\{ \lambda_t^M \in \mathbb{R}, \begin{array}{l} \forall t : \lambda_t^M \in \left[\lambda^{\min}, \lambda^{\min} + \gamma^q\right] \\ \forall q = 1,\ldots,Q : \quad \gamma^q = q \times \frac{\left|\lambda^{\max} - \lambda^{\min}\right|}{Q} \end{array} \right\}$$
2-4:     Update q→q+1.
3:   Receive signal from IGMC containing the hours of load reduction in
     the form of TOU, CPP or ED-CPP.
4:   For each subinterval, Ω(q), computes the operation schedule of cement
     plants (Eq. (6)) in the worst case realization of wholesale price as:
     $$\left[\Pi_t^{\rho}\right]_{(\Theta\times 4)}^{\Gamma} = \begin{bmatrix} \Pi_t^{1,CR} & \Pi_t^{1,KFP} & \Pi_t^{1,CP} & \Pi_t^{1,FG} \\ \Updownarrow & \Updownarrow & \Updownarrow & \Updownarrow \\ \Pi_t^{\Theta,CR} & \Pi_t^{\Theta,KFP} & \Pi_t^{\Theta,CP} & \Pi_t^{\Theta,FG} \end{bmatrix}^{\Gamma}$$
5:     **End while**
6:   The cement plants finalize their operational schedule according to their
     risk-bearing capacity to choose robustness level Γ.
7:   The IDRA aggregates the final robust operation schedule over $\tau_N$ hours
     to participate in the electricity market.
8:   The IDRA finds the best-recovered solution to the electricity market
     $[\Pi_t^{DA}, \Pi_t^{BC}]$ and to cement plants $\left[\Pi_t^{SG}, \Pi_t^{\rho,\kappa}|_{\kappa=CR,KFP,CP,FG}\right]$ such that
     $\sum_{t=1}^{\tau+\tau_N} \emptyset_t^{\rho} = \emptyset_o^{\rho}$.
```

Fig. 4. The algorithm of coordination mechanism

The IPG supplies 84 cement plants all over the country. Figure 5 describes the classification of the 84 cement factories (N=84) into 10 clusters (M=10) by using the *k*-means clustering approach. Each cluster of factories is managed by a local IDRA. The main reason for the classification is that the number of cement factories is high; therefore, a centralized IDRA may fail to consider all the technical/economic constraints of the contracted industries. Note that *k*-means evaluates the factories based on their location, (x,y)=(longitude, latitude), and finds a centroid, i.e. local IDRA, for the factories classified in the cluster. In this paper, the problem is to determine the operation of contracted industries for the North East IDRA (NE-IDRA). The NE-IDRA has a contract with 13 cement factories located in the northeast of Iran. Scheduling the industries operation, 5 cement plants are out of service; consequently, the NE-IDRA has agreed a contract with 8 cement plants to optimize their operation. Table 1 describes the technical characteristics of a main cement plant (CF-1).

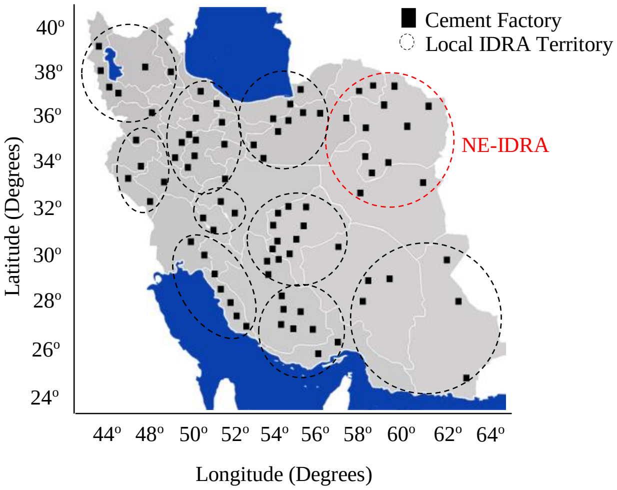

Fig. 5. The 84 cement plants in the IPG with associated IDRA

The data of electricity price belong to the Iran Electricity Market in June 2017. Figure 6 describes the robustness region of day-ahead market price uncertainty. The price gap between lower and upper market price is portioned into 25 subintervals (Q=25).

Table 1. Technical characteristics of a cement factory (CF-1)

Plants ID	Sub-process	C	KFP	CP	FG
CF-1	$\Pi_{\text{Rated}}^{\rho}$ (kW)	2200	11000	11550	11220
	$\tilde{\Pi}_t^{\rho}$ (kWh/t)	1.5	31	23	37
	$[\bar{\phi}_{min}^{\rho}, \bar{\phi}_{max}^{\rho}]$(t/h)	0-880	0-330	121-137.5	0-220
	η^{ρ}	1	1.2	0.6	1.04
	$SoS_{\max}^{\rho}$ (t)	2400	1400	1800	5000

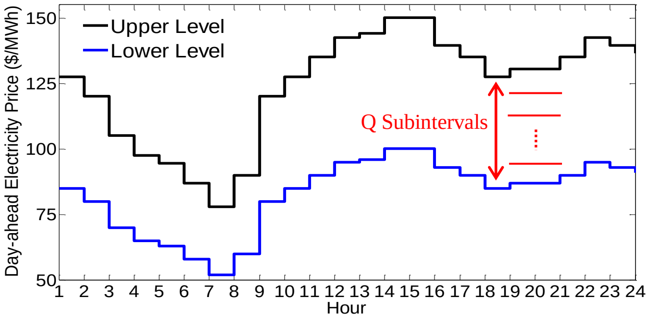

Fig. 6. Robustness region of the day-ahead market price

As mentioned above, the IPG has been experiencing two peak hours during a day in the summer. Figure 7 shows the two peak hours, i.e. 12-16 and 21-23, during a hot summer day in the IPG. The IGMC uses the price-based DRP to notice the industries about the load reduction in these two periods. In fact, the electricity price contains important notices about the request of load reduction.

In the wholesale market, 4 different bilateral contracts are considered in this study: one contract spanning all periods (24 hours), and three contracts for valley, shoulder and peak hours individually. Table 2 describes the characteristics of each bilateral agreement. Note that the contract decisions should be made at the beginning of the day.

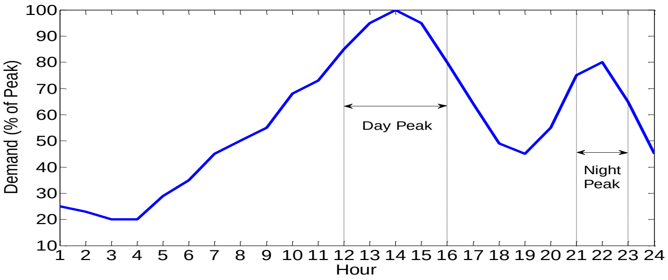

Fig. 7. Peak hours in a daily load profile of the IPG

Table 2. Data of bilateral contracts

Contract No.	Usage Period (Hour)	$P^{C,Max}$ (MW)	$P^{C,Min}$ (MW)	$\lambda^{C,R}$ ($/MWh)
1	24 (Whole day)	24	8	70
2	1-8 (valley)	20	4	50
3	9-11, 17-20, 23-24 (shoulder)	28	12	65
4	12-16, 21-22 (peak)	24	9.6	85

In the bilateral contracts data, the third and fourth columns describe the upper and lower levels of contracts, respectively. The fifth column shows the reference price of bilateral contracts. It is worth mentioning that the final price of energy in the contracts equals to the average value of a reference price associated with the contract ($\lambda^{C,R}$) and the pool price in each period t spanned by the contract (λ^{DA}).

B. RESULTS AND DISCUSSIONS

The suggested approach is formulated as an R-MIQP problem which is solved using the CONOPT 3 solver in GAMS 24.1.2 software (www.gams.com/dd/docs/solvers/cplex.pdf) linked with MATLAB 8.4 on an Intel Pentium CPU at 2 GHz and 4 GB of RAM.

Figure 8 illustrates the optimized operation of the cement plant CF-1. In this figure, the operation of the whole production line is depicted in four different subfigures. As the graph reveals, the operations of the C and KFP are scheduled mainly in the valley and shoulder periods. The output productions of these two sub-processes are stored in the siloes to be used by the other sub-process, i.e. CP and FG, during the peak hours of the day. As mentioned in the previous sections, the operation of the CP must be continuous without any interruption. For this reason, the CP is continuously on during the 24 hours. However, the CP' consumption is scheduled near the lower level during peak hours. Following the similar pattern, the energy-intensive operations of the FG are scheduled mainly in the shoulder hours. The FG is the final process before cement shipping. Based on the FG operation, the cement shipment is moved mainly outside of peak hours. Therefore, it provides a potential flexibility to rail or truck shipping. Finally, regarding the total consumption of cement factory, the major consumptions of the plant are operated in the valley and shoulder hours. As a result, it can provide a golden opportunity to the IPG to prevent power shortage during the hot days of summer.

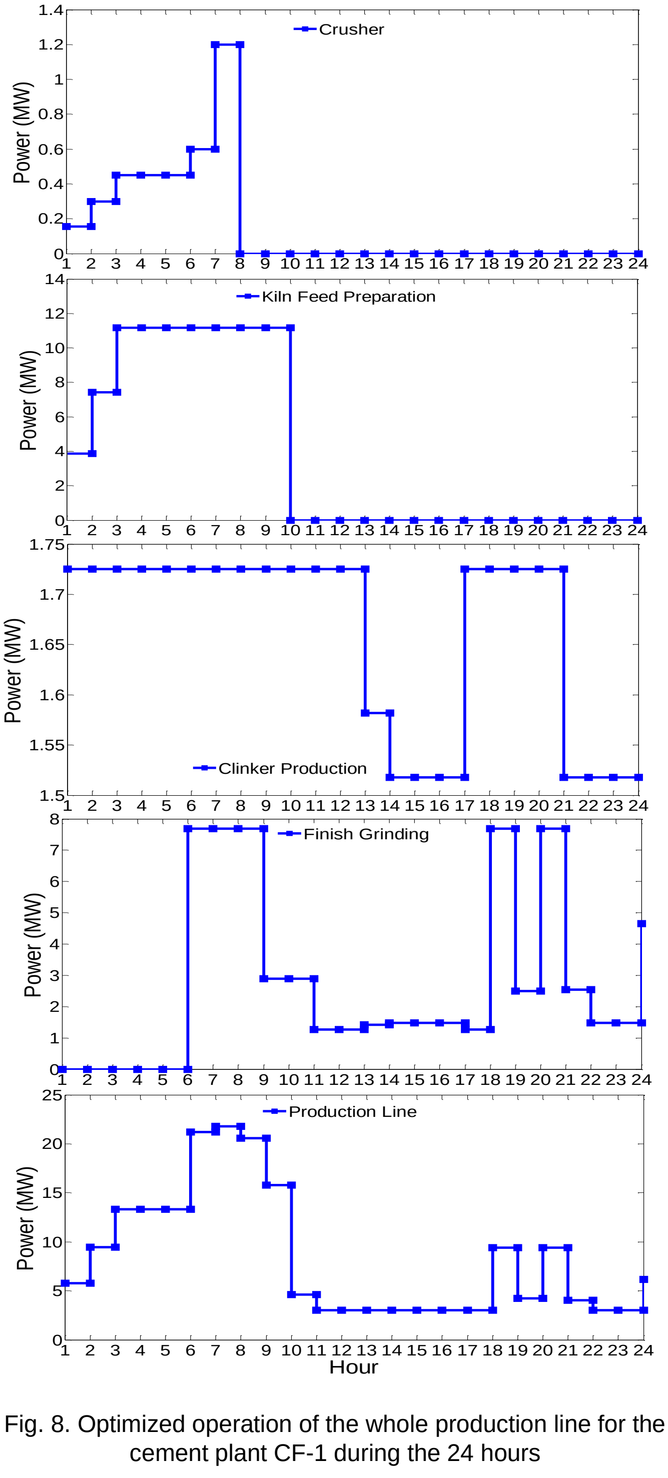

Fig. 8. Optimized operation of the whole production line for the cement plant CF-1 during the 24 hours

In order to show the role of storage capacity in providing flexibility to the power system, the electric energy consumption of the whole production line for cement plant CF-1 is depicted in Figure 9. In this figure, the storage capacity of siloes

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decreases from 100% (9a) to 50% (9b) and 25% (9c), respectively. As the graphs reveal, by decreasing the storage capacity, the flexibility of the cement plant to optimize the consumption pattern decreases noticeably. In fact, when the storage capacity of siloes is designed properly, the primary sub-processes, i.e. C and KFP, can be run completely during the valley periods and then final sub-process, i.e. CP and FG, use the stored material during the peak hours of the day.

In contrast, in a cement plant with low storage capacity, all the sub-processes, including primary and final ones, must be run simultaneously to prevent from interrupting the cement production. In this situation, the operations of plants move to peak hours and the potential of the industries to participate in the DRPs decreases. For this reason, in some cases, the NE-IDRA provides governmental supportive plans for the cement factories to increase the storage capacity of the siloes. In this situation, the cement industries can respond effectively to the request of the IGMC to decrease the consumption level when a power shortage occurs or system reliability is jeopardized.

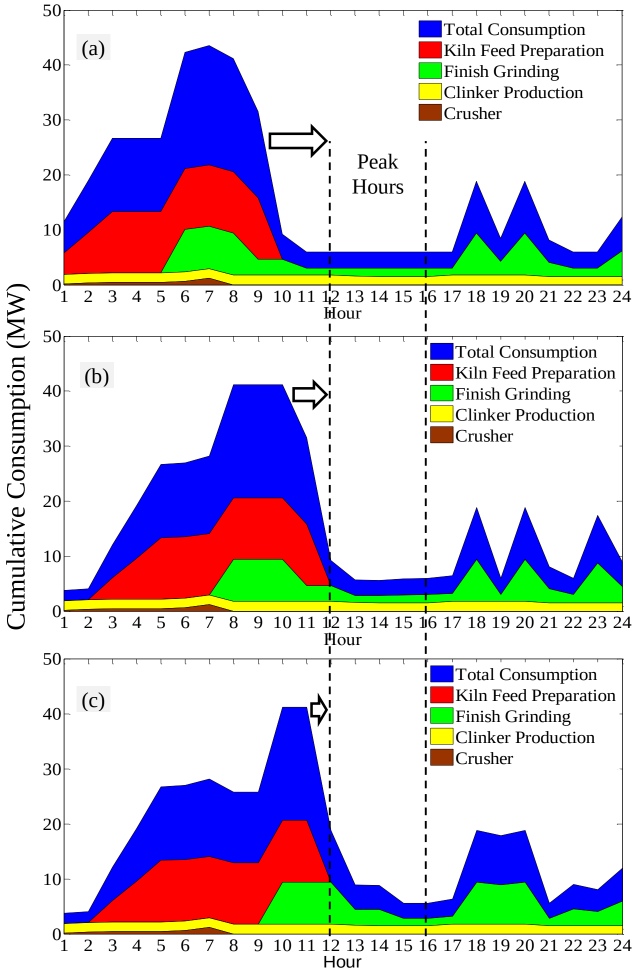

Fig. 9. The role of storage capacity in providing flexibility to the power system, (a) 100 (b) 50 and (c) 25 % of storage capacity

Figure 10 illustrates the daily load profile of the 8 cement factories. In this figure, the total consumption of the 8 aggregated cement industries is compared with the 8 segregated factories. Based on the graph, using the aggregated cement plants, the NE-IDRA can provide power flexibility to the power system during the peak hours. In contrast, in the traditional system with segregated industries, total consumption of the industries is high during the peak hours. In this way, the industries operation is scheduled without considering the pool electricity price and DRP notices received from the IGMC. Therefore, the IDRA prevent power shortage during peak hours.

Figure 11 describes the robust decisions of the cement plant CF-1 in the electricity market. Based on the graph, by increasing the robustness level, the industry prefers to procure less energy from the day-ahead market with price uncertainty. Adversely, the procurement from bilateral contracts increases with increasing the robustness level. In fact, when a more robust strategy is implemented, the decision makers prefer to procure more energy from resources with less uncertainty. In addition, the industries rely heavily on their self-generation facilities when a more robust strategy is chosen.

Based on figure 10, aggregating the cement plants through the NE-IDRA, an average of around 60 MW power is reduced during day peak hours, i.e. 12-16, in comparison with the segregated plants. Regarding the severe power shortage in the IPG during the summer peak hours, the aggregated industries provide 60 MW power flexibility to the IPG. Considering an investment cost 600×10^3 \$/MW for a gas turbine power plants with lifetime 30 years, an annual cost saving of 12×10^5 \$/year is obtained and prevents a huge investment in installing fast-run generation units.

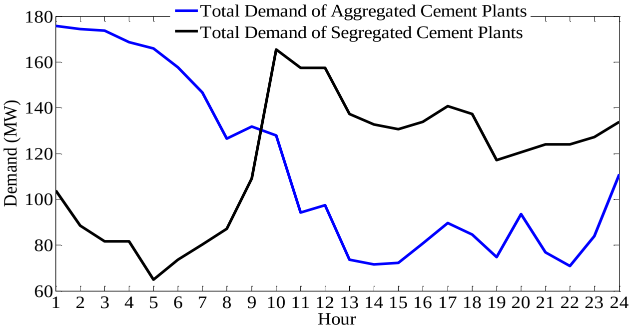

Fig. 10. Total demand of aggregated cement industries in comparison with the segregated plants

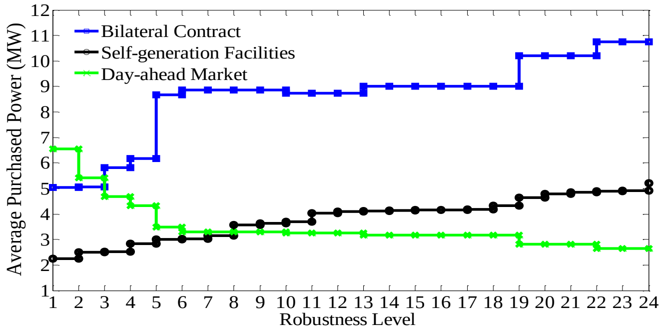

Fig. 11. Robust procurement strategies for the cement plant CF-1

From the industries' viewpoint, aggregating the cement plants result in a considerable reduction in the electricity bills. Figure 12 compares the total electricity bills of the 8 cement plants considering propitious (lower uncertainty) and pernicious (upper uncertainty) facets of the pool electricity

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price. Regarding the bar graph, aggregating the cement plants, the total electricity bill is dropped from 240528 to 216412 $ and from 360792 to 324618 $ for propitious and pernicious facets, respectively. All in all, the maximum energy cost reduction can be from 360792 to 216412 $, an approximately 40% reduction.

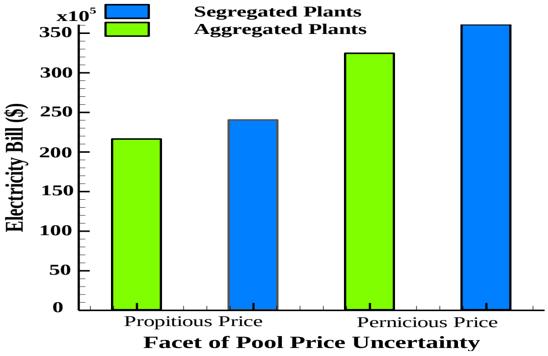

Fig. 12. Electricity bills of the cement plants for different scenarios

VI. CONCLUSION

This paper proposed a novel robust-based self-scheduling approach for integrated heavy industries to provide functional flexibility to power system during high peak hours. Increasing the power system flexibility and decreasing the energy cost of industries were the two main features of the suggested approach.

Aggregating the cement factories, the local Industrial Demand Response Aggregators were able to optimize the operation of the contracted industries when a power shortage occurs or system reliability is jeopardized. Simulation results showed that the storage capacities of the cement factories play a crucial role in providing flexibility to the power system.

Although the proposed IDRA optimized the operation of the cement plants, integration of other heavy industries, e.g. metal plants, can be an innovative idea for future researches. Besides, coordination of responsive plans between residential and industrial demand response aggregators attracts many attentions in this regards. The suggested ideas are under study in the local IDRAs to provide functional flexibility to the IPG during hot days of summer.

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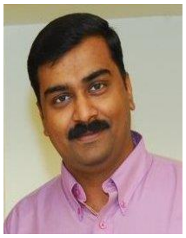

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