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Energy flexibility scheduling optimization considering aggregated and non-aggregated industrial electrical loads#

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ABSTRACT

In the modern energy sector, energy flexibility is highly essential. Participation in demand response programs is open to different power customers, with the greatest potential for some high-consumption industrial firms. This paper proposes a novel optimization model to maximize the profit obtained by marketing energy flexibility in a generic manner which is applicable for different industries. Two particular strengths of this model are its inclusion of dependencies between loads and load aggregation. We investigate the model's performance in two use cases: one with dependent loads and another with aggregated loads. Results demonstrate that the proposed model can achieve its objectives in different use cases, giving exceptional usage for industrial flexibility cases.

Keywords: industrial flexibility optimization, aggregated loads flexibility, generic flexibility data format

NONMENCLATURE

Indices and Sets	
F	Set for Load
M_f	Set for measures of load f
T	Set for time
f	Index for loads
m	Index for measures
t	Index for time
$D_{start-start-after}$/ $D_{start-start-before}$	Set for dependencies that one load should start after/before the start of another one
$D_{exclusion\_after}$/ $D_{exclusion\_before}$	Set for dependencies that one load should not start after/before the start of another one
Parameters	
$e_{f,m,i}$	Power for measure m of load f at step i
$\lvert e_{f,m} \rvert$	Time length of measure m of load f
DT_f	Regeneration time of load f
p_t	Electricity price at time t
c_f	Load activation constant cost
$validity_{f,t}$	Times that load f can start
$Usage_{f,min}$	Minimum permissible number of usages for load f
$Usage_{f,max}$	Maximum permissible number of usages for load f
Variables	
$x_{f,t}$	Load activation binary variable equal two 1 if load f is activated at t and 0 otherwise
$y_{f,m,t}$	Measure activation binary variable equal two 1 if measure m of load f is activated at t and 0 otherwise
Abbreviations	
EFDM	Energy Flexibility Data Model
inf	Infinity

1. INTRODUCTION

The rising electrification of the industrial sector impacts the electricity grid [1]. A common issue is grid congestion, which is solvable via network and infrastructure expansion. We can also mitigate congestion and other challenges by using energy flexibility on the demand side and active consumer engagement in balancing and wholesale markets [2]. Industries utilize a substantial quantity of energy in general and electricity in particular [3]. As a result, the industrial sector offers enormous potential for capturing existing energy flexibility and using it to solve such issues. Industries who desire to offer their energy flexibility face obstacles due to the complexity of energy markets. The difficulty results from the variety of options and substantial price fluctuation in markets. These hinder the evaluation of revenue potentials and the decision to invest in energy flexibility. Decision making tools are significantly important for tackling this issue [4].

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This study proposes a novel optimization model that determines when and in what quantity industry can offer flexibility in electricity markets and maximize profit. The decision-making process for energy flexibility marketing can employ the optimization model. For the description of energy flexibilities and associated parameters, the optimization model employs a generic data model [5].

Compared to other optimization models in this domain, our model is novel in its allowance for dependencies between flexible loads. In many industries, there is a link between different machines which creates dependency between the operation of machines. Prior research, for example [6] and [7], often do not consider machine dependencies. Others, such as [8] and [9], use the material flow of an industrial process (e.g. in chemical plants) to create dependencies. However, this approach limits the model's generalizability. The proposed model in this paper directly takes machine dependencies into account and creates a generic model.

A second contribution of this model is the use of complex aggregated loads for flexibility. There are many opportunities for aggregators with industrial loads to combine different loads into complex aggregated loads and optimize flexibility [10]. The novel mathematical formulation here can optimize flexibility for both aggregated and non-aggregated loads.

2. OPTIMISATION MODEL

2.1 Inputs and Outputs

The optimization model requires two inputs. The first input is the electricity market price. The second input is information about the industrial company's prospective energy flexibility. We used the energy flexibility data model (EFDM) [5] to describe the energy flexibility. The EFDM defines three classes to describe energy flexibility potential: flexible loads, storages, and dependencies.

Following this data model's specification allows for a more generic modeling of energy flexibility. As indicated in Fig. 1, we consider flexible loads and dependencies as possible inputs of the EFDM in this paper.

The output of the optimization model consists also of two parts. The first output indicates the calculated schedule and the flexible load measures with their parameters, such as power deviation amount or activation time. The second output is the potential profit from offering and selling the energy flexibility based on the results of the optimization model and the calculated schedule.

Industrial companies can describe their flexibilities based on the EFDM [5]. The EFDM uses key figures (represented in *Table 1*) to describe key characteristics of loads. Moreover, it can describe the relationships

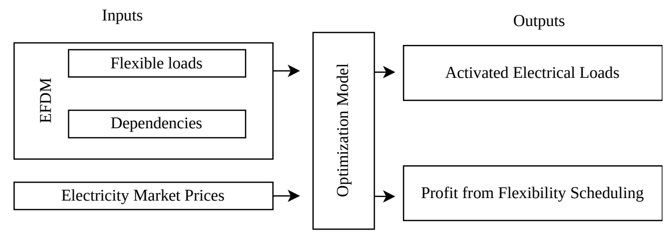

Fig. 1 - Inputs and outputs of the optimization model

Table 1 - Key figures of the EFDM used for optimization

Key figures	*Description*
Power state	Load deviations from normal operation point
Holding duration	The length of the operation for load per usage
Usage number	The total permissible number of usages for each load during optimization period
Validity	The interval that using flexible load is allowed for energy flexibility purposes
Activation gradient	The rate power changes during activation
Deactivation gradient	The rate power changes during deactivation
Regeneration duration	The time length that a load should not be activated after its deactivation
Costs	The cost of using flexible load, excluding the costs of electricity

between different loads using the dependency concept, which demonstrates the necessity of activation (or deactivation) of one load after (before) another load.

To use the inputs from the EFDM for the optimization model, we transform the inputs such that they can be used in the model. Key figures such as validity, usage number, and holding duration can be imported directly from the EFDM for the optimization. One of the important concepts in the optimization model is the measure. The measure describes specific characteristics that one load can have based on the key figures of the EFDM for that specific load. The next

Table 2 - Example for one load

Load	*Power state*	*Holding duration*	*Activation gradient*	*Deactivation gradient*
L1	*1 MW*	*[2,3] hours*	*inf*	*inf*

Table 3 - Possible measures of flexible load L1 prepared for optimization model

Measures of L1	$\|e_{f,m}\|$	$e_{f,m,i}$
Measure1	*2*	$e_{1,1,1}=1,\ e_{1,1,2}=1$
Measure2	*3*	$e_{1,2,1}=1,\ e_{1,2,2}=1,\ e_{1,2,3}=1$

example clarifies how to transform information in the EFDM for one load in a format that the optimization model can use.

Based on the information in Table 2, there are two options for *L1* to participate in the market. *L1* can be activated, and then remains active for 2 hours (measure 1) or 3 hours (measure 2), and then be deactivated as presented in Table 3.

2.2 Mathematical Model

The objective function of this paper is to maximize the profit gained by offering energy flexibility to the market:

$$max \sum_{f\in F}\sum_{m\in M_f}\sum_{t\in T} y_{f,m,t}\left(-c_f+\sum_{i=1}^{|e_{f,m}|} e_{f,m,i} * p_{t+i-1}\right). \quad (1)$$

In the objective function, the binary variable $y_{f,m,t}$ indicates if the optimization activates measure *m* of load *f* at time *t*. If so, we multiply this binary variable by the net profit gained by market participation. Equation (2) restricts the number of activations of each load. Equation (3) relates the activation time of each measure and each load. Each load can have several measures. Regarding equation (3), the optimization allows the activation of at most one measure of each load at each time. To restrict the periods that we can use each load for energy flexibility, we have proposed equation (4). Therefore, these equations are

$$Usage_{f,min} \le \sum_{t\in T} x_{f,t} \le Usage_{f,max} \quad \forall\ f\in F\ , \quad (2)$$

$$x_{f,t} = \sum_{m\in M_f} y_{f,m,t} \quad \forall\ f\in F\ ,\forall\ t\in T\ , \quad (3)$$

and

$$x_{f,t} \le validity_{f,t} \quad \forall\ f\in F\ ,t\in T. \quad (4)$$

After activation of each measure, the optimization forces the deactivation of the flexible load before the end of optimization period (*T)* considering regeneration time (DT_f) and the length of that measure ($|e_{f,m}|$):

$$y_{f,m,t} \times \left(t + |e_{f,m}| + DT_f - 1\right) \le T \quad \forall\ f\in F\ ,\forall\ m\in M_f\ ,\forall\ t\in T\ . \quad (5)$$

After its deactivation and during the regeneration time, the optimization does not allow the activation of flexible load. Therefore, after the activation of one measure ($y_{f,m,t}$) of flexible load *f*, the optimization cannot activate that flexible load again until $|e_{f,m}|$ time steps and regeneration time DT_f have passed. As presented in equation (6), if measure *m* of load *f* activates at *t*, load *f* cannot start until this measure is deactivated after $|e_{f,m}|$ time steps and regeneration time (DT_f) of load f has passed:

$$\sum_{h=2}^{|e_{f,m}|+DT_f} x_{f,t+h-1} \le \left(1-y_{f,m,t}\right)\times\left(|e_{f,m}| + DT_f - 1\right) \quad \forall\ f\in F\ ,\forall\ m\in M_f\ ,\forall\ t\in T. \quad (6)$$

We consider dependencies between different loads using 4 equations. First, the activation of one load may force the activation of another load; we formulate this dependency in equations (7) and (8). Equation (7) describes that load *j* should start *a* to *b* time steps after the activation of load *i.* If load f_i is activated at *t*, $x_{f_i,t}$ will be equal to 1. Therefore, $x_{f_j,t}$ must be equal to 1 from *a* to *b* time steps after *t*. The same approach can describe equation (8), where the activation of load *i* necessitates the activation of load *j* in the previous time steps. These equations are

$$x_{f_i,t} \le \sum_{h=a}^{b} x_{f_j,t+h} \quad \forall\ f_i\ and\ f_j \in D_{start-start-after}\quad (i\ne j), t\in T \quad (7)$$

and

$$x_{f_i,t} \le \sum_{h=a}^{b} x_{f_j,t-h} \quad \forall\ f_i\ and\ f_j \in D_{start-start-before}\quad (i\ne j), t\in T\ . \quad (8)$$

Second, we formulate the exclusion of one load due to the activation of another load in equations (9) and (10). These equations formulate the exclusion of load *i* from *a* to *b* steps after or before the activation of load *j* , respectively. Here, if load f_i is activated at *t,* $x_{f_i,t}$ will be equal to 1, and all $x_{f_j,t}$ must be zero from *a* to *b* time steps after *t*. Likewise, equation (10) excludes one load before the activation of another. Thus, these equations are

$$\sum_{h=a}^{b} x_{f_j,t+h} \le (1- x_{f_i,t})\times(b-a+1) \quad \forall\ f_i\ and\ f_j \in D_{exclusion\_after}\quad (i\ne j), t\in T \quad (9)$$

and

$$\sum_{h=a}^{b} x_{f_j,t-h} \le (1- x_{f_i,t})\times(b-a+1) \quad \forall\ f_i\ and\ f_j \in D_{exclusion\_before}\quad (i\ne j), t\in T\ . \quad (10)$$

3. CASE STUDY AND RESULTS

We demonstrate the capabilities of the proposed model in two cases. In the first case, we consider several flexible loads and dependencies. In the second case, we use aggregated loads and assess the model's ability to optimally schedule them. For all cases, we use synthetic data of flexible loads as input. For electricity prices, we use EPEX Day-ahead auction results from the market region Germany-Luxembourg.

The first case uses data from 1 day (07/10/2020) and the second case uses data from 1 week (05/10/2020 – 11/10/2020) [11]. We used Gurobi solver [11] with a Intel i7-9750H processor and 32 GB RAM for the simulations using the Python programming language. The simulation time was less than one second for all cases.

3.1 Case I

In Case I, we consider four different flexible loads with different characteristics such as holding duration, power state, activation/deactivation gradient, number of usages, validity period, and activation cost (Table 4). The load deviation type indicates if the flexible load will decrease (*load decrease* type) or increase (*load increase* type) during the energy flexibility provision. Moreover, the loads have dependencies between each other as presented in Table 5.

Fig. 2 illustrates the results of Case I. The first flexible load *L1* decreases its power consumption between 17:00-22:00. Although this period is not the highest price period, it gets activated because the model considers the validity restriction of *L1* which prevents its activation between 8:00-13:00 during the highest price period. Moreover, the optimization selects the 3-hours period as holding duration for *L1* to obtain the highest possible profit. The second flexible load of the *decrease* type reduces its power consumption three times, as per its maximum usage number. The optimization does not use *L2* during the period between 10:00-12:00. Rather, the optimization selects 11:00-13:00 for activating *L2* to satisfy a 1-hour regeneration period of *L2*. Due to the dependency between *L1* and *L3*, the optimization activates *L3* three hours after the activation of *L1* to satisfy the dependency between them.

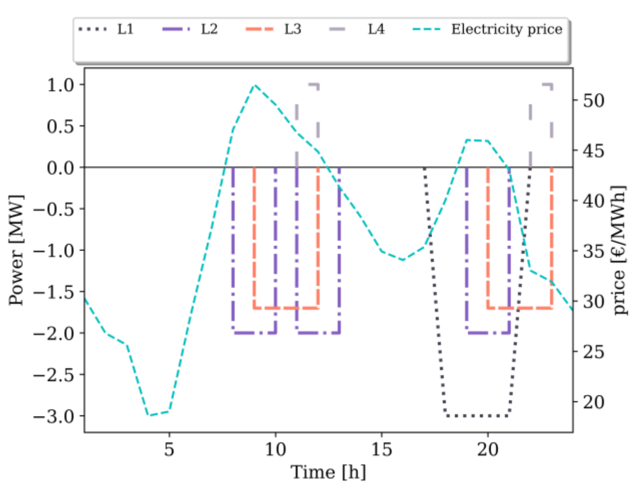

Fig. 2 - Results of Case I

Table 4 - Characteristics of flexible loads considered in Cases I

Key Figure	*Units*	*L1*	*L2*	*L3*	*L4*
Load deviation type	-	decrease	decrease	decrease	increase
Power state	MW	[3,3]	[2,2]	[1.7, 1.7]	[1,1]
Activation gradient	MW/h	3	inf	inf	inf
Deactivation-gradient	MW/h	3	inf	inf	inf
Validity restriction	time	1-12	-	-	-
Activation cost	Euro	0	0	0	0
Holding duration	h	[1,3]	[1,2]	[2,3]	[1,3]
Regeneration time	h	0	1	2	0
Usage Number	-	[0,1]	[0,3]	[0,2]	[0,2]

Table 5 - Dependencies between loads in Case I

Trigger load	*Dependent load*	*Dependency type*
L1	L3	L3 must start 3 hours after the activation of L1
L3	L4	L4 must start 1 to 2 hours after the activation of L3

L3 uses another activation during the peak price hours to gain more profit. Furthermore, the optimization activates *L4* of load type *increase* twice although increasing power reduces the profit while the electricity price is positive. The existing dependency between *L3* and *L4* necessitates the activation of *L4* 1-2 hours after *L3*. Thus, the optimization requires the consideration of high-price periods for *L3* and low-price periods of *L4*. Thus, *L4* is active 2 hours after *L3* to match low-price periods.

3.2 Case II

In this case, we evaluate the functionality of our model for aggregated loads. We assume here that *L1* and *L2* result from the aggregation of other flexible loads, and both are the load *decrease* type. The proposed model can use these aggregated loads for energy flexibility optimization purposes. *L1* and *L2* are aggregated flexibilities used as inputs to the model, as depicted in Fig. 3. The minimum usage number of both flexible loads is 0. The maximum usage number of the flexible loads *L1* and *L2* are 6 and 10, respectively.

Fig. 4 illustrates the results of Case II. The activation of both aggregated loads *L1* and *L2* are coinciding with the high price hours, in order to maximize the profit gained. In each activation of *L1*, aggregated load *L1* decreases by 1 MW. After one hour, it decreases by 2.5 MW and remains unchanged for 1 hour. Then it decreases by 2 MW for an hour and deactivates afterwards. The same logic explains the power changes for *L2* in each activation. The optimization activates *L1* and *L2* respectively 10 and 6 times, which are the highest possible usage numbers for these aggregated loads.

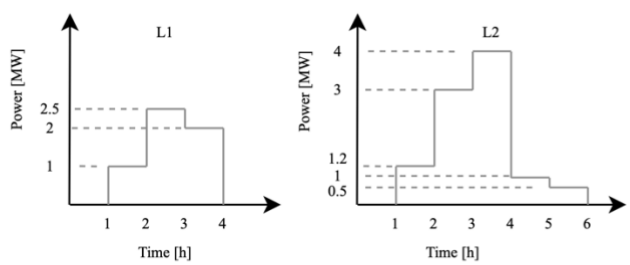

Fig. 3 - Aggregated flexibilities used as input for Case II

4. DISCUSSIONS

We tested our model for two different cases to demonstrate the capabilities of the model in calculating a schedule for energy flexibilities. The proposed model had the intended performance. The evaluations indicated the ability of the model to capture the potential flexibilities for simple and complex EFDMs. The proposed model can consider different power states for loads, regeneration time, activation/deactivation gradients, various holding durations, and between-load dependencies for both aggregated and non-aggregated electrical loads, which is neglected in other models. Using aggregated loads can reduce the computational burden significantly, since the number of binary variables in the problem decreases when using aggregated loads.

The concept of measure used here adds potential to this model. Since only one measure of each load is allowed for activation at each time, we can define various measures for aggregated loads, and the optimization will choose the most profitable one based on electricity prices. For instance, *L1* in Fig. 5 has three different measures (red, blue, and grey lines) and *L1* can follow only one of the measures in each activation period.

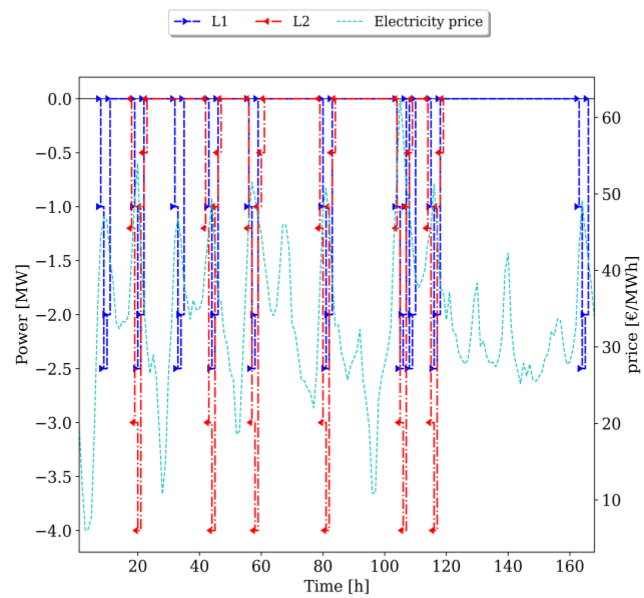

Fig. 4 - Results of Case II

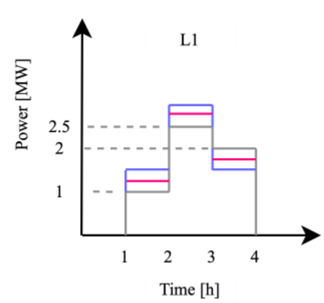

Fig. 5 - Different measures of aggregated load L1

The proposed model also does not require the information about baseline power consumption or material flow in industrial processes for the optimization. This is particularly valuable since some industries avoid sharing this information.

Although we proposed the model for the industrial sector in this paper, it is applicable for other energy sector users such as electric vehicles and residential buildings, due to the generic format of the required data as input.

This model and the evaluated cases have some limitations. We acknowledge especially that due to the unavailability of real data, our cases relied on synthetic data instead. Moreover, the calculation time of the problem increases as the optimization periods and number of loads increase.

5. CONCLUSIONS

In this study, we proposed an optimization model based on a generic data format to calculate the optimal energy flexibility scheduling for industrial loads. We evaluated the model in different simple and complex use cases including aggregated and non-aggregated loads, and results indicated the model's capability to handle different cases and maximize profit from energy flexibility provision. In future research, we will consider adding energy storage systems to the model for flexibility purposes. We will also consider using heuristic methods to reduce the calculation time.

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