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Article

Demand Response Programs Design and Use Considering Intensive Penetration of Distributed Generation

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Abstract: Further improvements in demand response programs implementation are needed in order to take full advantage of this resource, namely for the participation in energy and reserve market products, requiring adequate aggregation and remuneration of small size resources. The present paper focuses on SPIDER, a demand response simulation that has been improved in order to simulate demand response, including realistic power system simulation. For illustration of the simulator's capabilities, the present paper is proposes a methodology focusing on the aggregation of consumers and generators, providing adequate tolls for the demand response program's adoption by evolved players. The methodology proposed in the present paper focuses on a Virtual Power Player that manages and aggregates the available demand response and distributed generation resources in order to satisfy the required electrical energy demand and reserve. The aggregation of resources is addressed by the use of clustering algorithms, and operation costs for the VPP are minimized. The presented case study is based on a set of 32 consumers and 66 distributed generation units, running on 180 distinct operation scenarios.

Keywords: clustering; demand response; distributed generation; Virtual Power Player

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1. Introduction

Demand Response (DR) is related to the modification of the electricity consumption pattern by end-use customers, in response to incentives or price signals, for economic or technical reasons when scheduled or called by the network or market operator. It has been largely explored in order to take full advantage of the power system's operation [1]. Several issues related to the operation of electricity markets, as the case of market power done by some players can be reduced by the adequate modeling and use of DR, as proposed and explained in [2].

The integration of DR resources can be fully addressed if the available Distributed Generation (DG) resources are also considered. DG and DR can be put together through the implementation of smart grids [3]. In fact, the full integration of DR also requires the participation of small size resources in electricity markets' DR programs, which are usually oriented to large size resources [4]. Adequate DR resources aggregation approaches are therefore necessary [5]. In fact, as DR, DG, and storage units, for example, can influence the demand, adequate scheduling of these resources is needed. The work in [6] proposes a joint scheduling optimization model for storage, DR, and DG (focusing on wind generation) minimizing total costs.

Virtual Power Players (VPP) aim to aggregate small size energy resources, including DG and DR, making participation in electricity markets products intended for the participation of large players possible. A VPP can also own and operate part of a distribution network and other energy resources as storage units and electric vehicles. The resource management by a VPP can be done minimizing the operation costs or increasing resource revenues [7].

The large integration of DG and DR resources brings several challenges related to the intermittence and unpredictability of these resources' availability. In this context, adequate attention is needed for the provision of reserves in the operation of power systems, in order to maintain increased levels of operation security [8]. A VPP is able to manage the available resources in order to achieve the reserve needs in the operated network and also for participation in electricity markets [9].

The aggregation of DG and DR resources with similar characteristics can be performed using clustering tools [10]. Several groups (clusters) of resources can be defined, aiming for the capture of common characteristics that better characterize the resources in a specific context [11].

The present paper includes a methodology that has been developed in order to support the VPP network operation. The VPP aggregates distributed DR and DG resources and the energy purchased to electricity suppliers, in order to fulfil its electricity needs. The VPP operation costs are minimized. The electricity needs are a result of energy and determined reserve requirements. It is also possible to define an amount of electricity to be used in order to participate in electricity markets.

Once obtained, a set of defined operation scenarios addressing the uncertainty on the main variables of the referred optimization problem clustering tools are applied in order define resource groups adequate for the operation of the network. This aggregation is done separately for DG and for DR resources, addressing the scheduled amounts of power for energy and for reserve. In this way, an alternative to the traditional aggregation of resources by type is obtained.

The present paper also focuses on the simulation of DR programs and events. In fact, the implementation of DR brings a diversity of programs, players, and approaches, which should adequately be addressed in both the economic and the technical standpoints.

In [4,12], some of the authors of the present paper published some work related to DemSi, a DR simulator. In the present paper, we present SPIDER – Simulation Platform for the Integration of DEmand Response. Departing from the experience obtained with the implementation and use of DemSi, several improvements and structural changes have been made, which are reflected in the SPIDER platform.

After this introductory section, Section 2 presents the decision support system that serves as base for the SPIDER operation, and the SPIDER itself. Then, Section 3 explains the proposed resources aggregation methodology in its two phases. Then, Section 4 presents the case study and the obtained results. Section 5 presents the main conclusions.

2. Decision Support System

The work presented in this paper focuses on a methodology for the DG and DR resources aggregation and also on the SPIDER platform which has been developed by the authors in order to support decision making concerning a diversity of players acting in the context of DR programs, according to Figure 1.

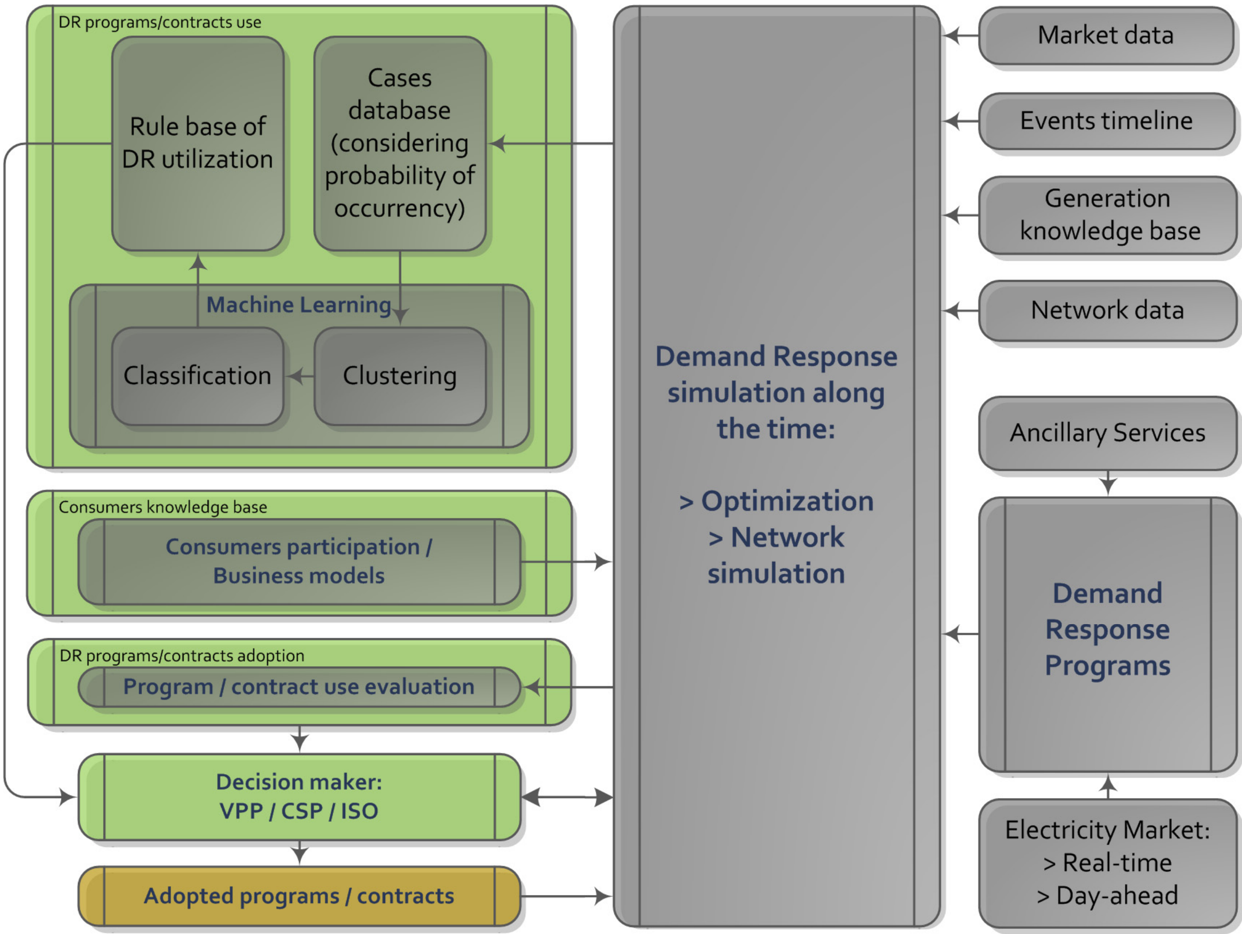

Figure 1. Decision support system.

As already stated, the decision support provided by the SPIDER platform departs from previous work on DemSi. Similarly to DemSi, SPIDER has important capabilities in what concerns the DR programs use. This section presents the SPIDER and its improvements.

Two main sub-modules are included, concerning the contracts use and the contracts adoption. For program adoption, decision support considerers DR programs and contract evaluation. The modules of the system depicted in Figure 1 in grey color are the ones concerning the demand response programs use and the power system simulation. Those modules include the optimization, including both deterministic and heuristic methods, of the different players' behavior in order to support their decision concerning the DR program's use and adoption.

The modules depicted in green constitute the ones regarding the decision-support for the DR program's adoption. An adequate study of the DR program's adoption has need of a large amount of data to be analyzed. Concerning the treatment of such a large amount of data, SPIDER enables one to study and determine the data-mining techniques adequate for the consumers' participation in the DR program's classification. With a large diversity of consumers acting in DR programs, with different types (domestic, commerce, industry, services, *etc*.), different peak consumption power, different daily load demand profile, and with different goals/awareness in the scope of that program, selecting the most appropriate classification techniques is required.

Concerning the diversity of DR programs, despite several improvements and changes needed for the full integration of DR programs, one can find a diversity of real implementations, namely at the level of electricity markets in United States [13]. DR programs can be classified according several aspects with the service type usually as the main characteristic. It can be energy, capacity, regulation, and reserve. Additionally, DR programs can be classified according to the Primary driver (economic or reliability), the trigger logic (operational, price, system frequency), minimum eligible resource size, minimum reduction, and minimum sustainable response period, among others.

According to the current implementations, one can refer to the fact that in the capacity service type only the reliability primary driver is used. Generally, consumers are not mandated to enroll in the DR programs, but once enrolled, the required response when the trigger is activated is always verified except in some cases of energy service type. Additional characteristics of DR programs can include the possibility of aggregation of resources, the DR event times (advance notification, ramp period, sustained response period, *etc*), and metering and performance evaluation issues.

Several designed and proposed DR models were implemented in DemSi, combining the use of GAMS [14] optimization software and of MATLAB [15], which has been used to program some of the models. The other models have been programmed in GAMS. PSCAD [16] was used in DemSi for the electrical network simulation. Those DR models have been adapted in order to be included in SPIDER.

SPIDER is an important tool for DR programs and models of analysis and validation, both in what concerns the business and economic aspects and the technical validation of their impacts in the network. SPIDER considers the players involved in the DR actions and the results can be analyzed from each specific player's point of view. This includes five types of players: electricity consumers, electricity retailers (suppliers), distribution network operator (DNO), Curtailment Service Providers (CSPs), and VPPs.

Simulink [15] is used as the basis platform for network simulation. The used network can be chosen by a set of networks already available. As an alternative, the user may introduce a new network from scratch. SPIDER also provides the user with functionalities that allow modifying already existing networks. The diagram of Figure 2 shows the interactions between software and the network, and the consumers'/producers' data as well as the available DR programs.

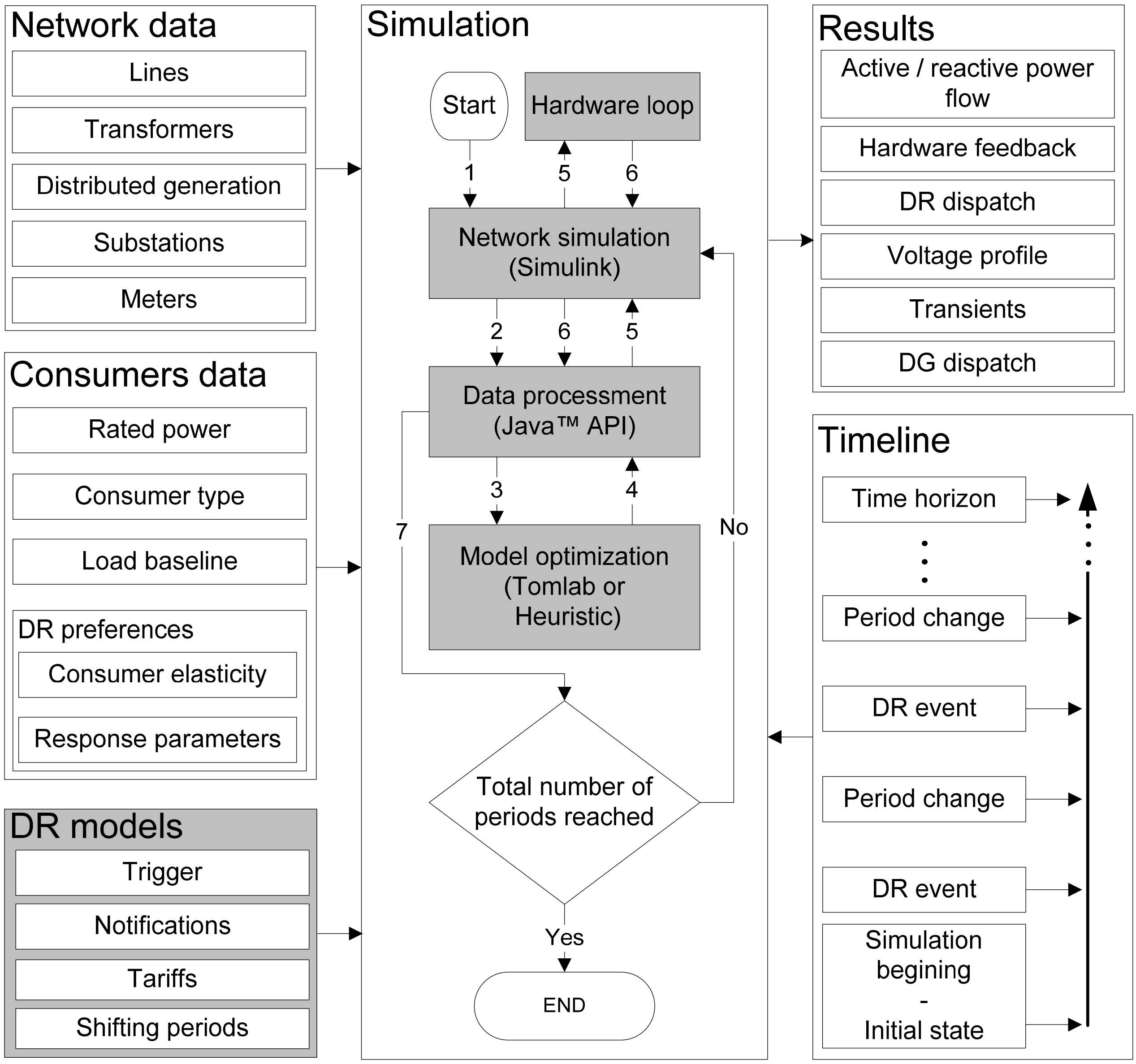

Figure 2. SPIDER simulation platform.

Consumers can be characterized individually or in an aggregated basis. The simulation requires knowledge about load data and about the contracts between clients and their electricity suppliers. These contracts may include flexibility clauses that allow the network operator to reduce or cut the load of specific clients and circuits. On the other hand, the response of each client to the used tariff scheme is also characterized, allowing the analysis of the impact of alternative DR schemes.

According to Figure 2, the simulation of a scenario requires information concerning network characterization, consumers' profiles, and DR programs models. The gray blocks in Figure 2 are the ones that do not change when the conditions of simulation (models, network, *etc.*) change.

The simulation timeline is composed by a sequence of periods with a single event or multiple events occurring over time. In the beginning of the simulation, all the variable parameters, including the system voltage, are defined according to the considered initial state. Every change in the system causes instability in the simulation, and therefore some simulation time is given for the system to be in a stable state. The loads and generators' actual status are also implemented in the respective hardware, with the possibility of obtaining real behavior on the loop. After this stabilization time, the network state is saved and the first DR event is simulated. A stabilization period succeeds the DR event trigger; after this, the new state of the system, seen as the results of the event, is saved. This sequence is repeated for the number of periods of the simulation. After saving the results of an event, the network state for the next period is charged.

During the simulation, different software tools are used to communicate and transfer data among them. The simulation starts in Simulink and every time a new network state needs to be charged and/or saved this is done using the JAVA API connection to save/use data to/from Microsoft Excel datasheets for example. The optimization (resources schedule) can be deterministic (performed in TOMLAB), or heuristic (Using PSO implemented in MATLAB for example). The sequence of software data transferences is represented by numbers in the middle block of Figure 2.

In a summarized way, the main differences between DemSi and SPIDER are related to the following aspects concerning hardware, software, and the resulting skills:

- Use of Simulink as the main simulation basis software, instead of PSCAD;
- Integration of hardware loads and generators, which was not possible in DemSi. This is enabled by the OPAL-RT [17] platform which includes digital and analog input and output cards and also the communications by Ethernet;
- Control of the simulation by using a JAVA™ Application Programming Interface (API), instead of MATLAB. This makes possible the integration of further sources of data and simulation and also interaction with the user;
- Real-time simulation capabilities enabled by the OPAL-RT platform. This feature was not available in DemSi. In the past, the simulation used to take long simulation time;
- Use of TOMLAB instead of GAMS for obtaining the deterministic solutions for optimization problems. Has TOMLAB is naturally integrated in MATLAB. The robustness of the software connections has been improved. Also, the optimization times became for adequate for the real-time simulation of the power system.

3. Resources Aggregation Methodology

The present paper includes a resources optimization and aggregation methodology which has been developed in the context of SPIDER, in the scope of a VPP operation. The developed methodology can be divided into two distinct main phases—the resources scheduling, and the resources aggregation—according to Figure 3. In the first phase, given the inputs of the DG and DR resources power and prices parameters, the optimal scheduling of the resources considering the energy end reserve needs is performed.

In the second phase, the aggregation of the resources is performed according to the scheduled operation scenarios. The resources are aggregated regarding a specified number of clusters desired to be implemented in the DR program's definition. The aggregation is performed for DG and for DR resources separately, and comparing the obtained clusters in three aggregation approaches—energy schedule, reserve schedule, and global resource schedule including energy and reserve. It is then possible for the VPP to discuss the best approach to be implemented in the remuneration of DR programs and DG aggregation. The clusters computation is based on MATLAB Cluster function [15].

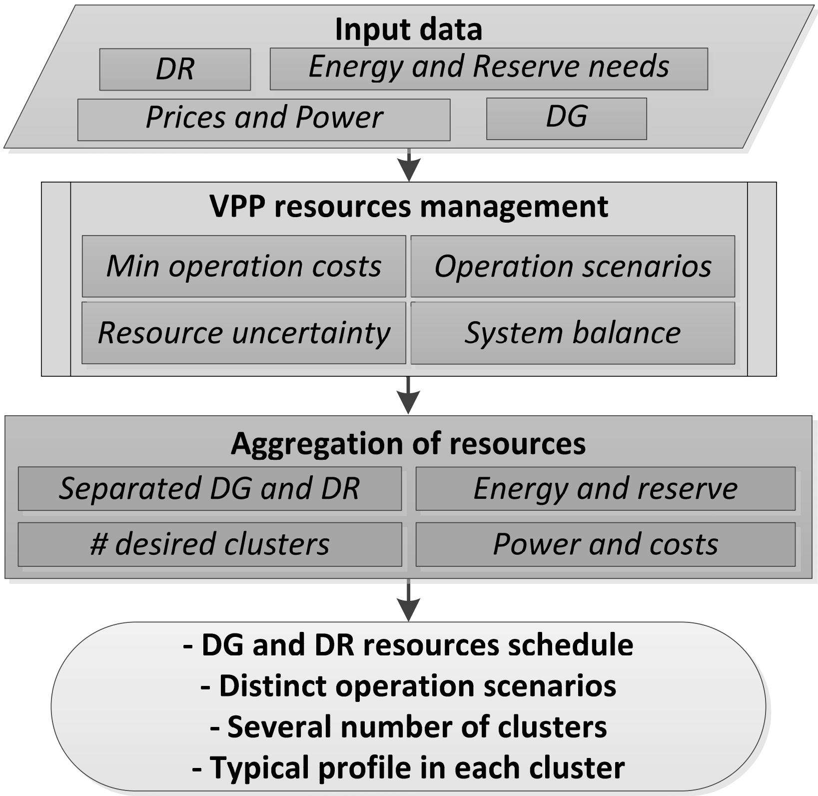

Figure 3. Diagram of the proposed resources aggregation methodology.

The proposed methodology is innovative and contributes to the following aspects in the resource scheduling and aggregation field:

- Several types of DG resources, competing with DR and electricity suppliers, for energy and reserve provision;
- A VPP managing a distribution network, obtaining the energy and reserve to fulfill its needs and determining the remuneration to be given to each resource or resources cluster;
- Remuneration of the DG and DR resources according their characteristics instead of the remuneration by resource type (consumer type and DG unit technology).

The related literature lacks remuneration of the DG and DR resources according to its operation scenarios in each VPP network and according to other characteristics like resource size, *etc*.

The implemented optimization problem has been adapted from the work developed in [9]. In order to focus on innovative aspects of the work, only the most relevant aspects of the formulation are presented here. The objective function, as in Equation (1), leads to the minimization of the costs considering the bids for energy (e) and reserve (r) products, made by suppliers, generators, and DR. All the bids are made with quadratic cost functions. In the present paper, the suppliers' terms in the objective function are not included in order to focus on DG and DR.

When the schedule of the resources is performed, it is not possible to know about the effective use of the determined required power for reserve; therefore, the probability of the use of the reserve is included. The binary variables are due to the fact that the fixed costs only have to be considered when the resource is actually used. The linear costs related to the non-contracted load shed and to the excess generated power are also included.

$$
\begin{aligned}
&\text{Minimize } OC = \\
&\left[\begin{array}{l}
\sum_{g=1}^{Ng}\left[\begin{array}{l}
X_{Gen(g)} \times Ca^{e}_{Gen(g)} + P^{e}_{Gen(g)} \times Cb^{e}_{Gen(g)} + {P^{e}_{Gen(g)}}^{2} \times Cc^{e}_{Gen(g)} \\
+ X_{Gen(g)} \times Ca^{r}_{Gen(g)} + \left[P^{r}_{Gen(g)} \times Cb^{r}_{Gen(g)} + {P^{r}_{Gen(g)}}^{2} \times Cc^{r}_{Gen(g)}\right] \times pr
\end{array}\right] \\
+ \sum_{c=1}^{Nc}\left[\begin{array}{l}
X_{Red(c)} \times Ca^{e}_{Red(c)} + P^{e}_{Red(c)} \times Cb^{e}_{Red(c)} + {P^{e}_{Red(c)}}^{2} \times Cc^{e}_{Red(c)} \\
+ X_{Red(c)} \times Ca^{r}_{Red(c)} + \left[P^{r}_{Red(c)} \times Cb^{r}_{Red(c)} + {P^{r}_{Red(c)}}^{2} \times Cc^{r}_{Red(c)}\right] \times pr
\end{array}\right]
\end{array}\right]
\end{aligned}
\quad (1)
$$

The first constraint of the model is the balance equation, presented in Equation (2), this time also including the Suppliers.

$$
\sum_{sp=1}^{Nsp} P^{e}_{Sup(sp)} + \sum_{g=1}^{Ng} P^{e}_{Gen(g)} + \sum_{c=1}^{Nc} P^{e}_{Red(c)} = \sum_{c=1}^{Nc} P_{Load(c)} \quad (2)
$$

The remaining constraints of the formulation are:

- The maximum capacity limit of generation of each resource for energy and for the reserve;
- The sum of energy and reserve provided by the resource must not exceed the upper limit of the resource capacity;
- The balance of each consumer's power;
- The balance of all the resources providing reserve, which need to guarantee the required power for this product.

The optimization model has been implemented and solved using TOMLAB, which is a commercial optimization tool running on MATLAB [15]. In this way, the results of the resources scheduling and of the aggregation of the resources can support the DG and DR implementation by the VPP.

4. Case Study

The present section shows the results obtained in the implemented 32 consumers' and 66 DG units' scenario, explained in Sub-Section 4.1. After that, it is divided in three Sub-Sections, providing details on the resources scheduling (Sub-Section 4.2), on the aggregation of DR (Sub-Section 4.3), and on the aggregation of DG resources (Sub-Section 4.4).

4.1. Scenario Data

The implemented case study in which VPP operation costs are minimized is described in this section. It has been adapted from [9], namely in what concerns the resources characterization for the aiming schedule. It concerns a 33 bus distribution network with large penetration of DG of several types as well as several consumer types.

In the case study, all the generators are offering the total available or installed capacity (a total of 2663 kW by DG and 5500 kW from suppliers). As shown in Table 1, 70% of this capacity is offered to the energy product. The remaining 30% regards the participation in the reserve product.

Table 1. Generators' characteristics and bid prices.

Type of generator	*Number of units*	*Total (kW)*	*Energy (m.u./kWh)*	*Reserve (m.u./kWh)*
Photovoltaic	32	558	0.15	0.165
Cogeneration (CHP)	15	740	0.001062	0.001168
Fuel cell	8	235	0.098	0.1078
Hydro	2	70	0.042	0.0462
Wind	5	700	0.071	0.0781
Biomass	3	350	0.086	0.0946
Waste to energy (MSW)	1	10	0.056	0.0616
Supplier 1	1	1200	0.23	0.286
Supplier 2	1	800	0.24	0.264
Supplier 3	1	900	0.25	0.275
Supplier 4	1	1800	0.26	0.253
Supplier 5	1	800	0.27	0.297

The bid price of generators is considered equal for all the generators of the same type, for energy and reserve products. In this paper, only the linear component of the price due to space constraints is presented. Full details are available in [9].

From the consumer resources side, the aggregated consumption is 5332 kW. The types of consumer are: Domestic—DM; Small Commerce—SC; Medium Commerce—MC; Large Commerce—LC; Medium Industrial—MI; and Large Industrial—LI.

The consumers' participation limit in DR is equal to 40% of the consumer consumption. This capacity is divided into two parts: 60% for the participation in the energy, and 40% for the reserve. Table 2 presents the consumer prices and the division by buses. These values were considered equal for the consumers of the same type. Again, only the linear component of the price is presented due to space constraints. Full details are in [9].

Table 2. Consumers' characteristics and bid prices.

Type of consumer	**Buses**	**Energy**	**Reserve**
		(m.u./kWh)	
DM	5, 8, 9, 10, 11, 12, 14, 15, 16, 25, 26, 27, 32	0.20	0.21
SC	2, 3, 4, 17, 22	0.16	0.18
MC	1, 13, 18, 19, 20, 21, 28, 29, 30	0.19	0.20
LC	6, 7, 31	0.18	0.19
IN	23, 24	0.14	0.07

After the resources scheduling, the proposed methodology focuses on the clusters definition. According to the variation in important parameters, 180 operation scenarios were implemented. Further details are given in Section IV.

4.2. Energy Resources Scheduling

As the main first phase of the proposed methodology, the scheduling of the DG and DR resources to provide energy and reserve is obtained. One can see in Figure 4c how the implemented 180 operation scenarios are obtained. It regards the variation of the generation price (from 50% to 200%), of the required reserve amount (from 25% to 200%), and of the probability of using the reserve (*pr*, from 0 to 1). In the case of DG contribution to energy production (reserve is not shown due to space constraints), one large DG unit has been deleted in order to have clear detail on the illustration. It can be seen that in the case of energy production, the schedule of DG and DR have slight variations along the different operation scenarios. In the case of the reserve, the resources schedule is largely depending on the input parameters, namely the required amount of reserve.

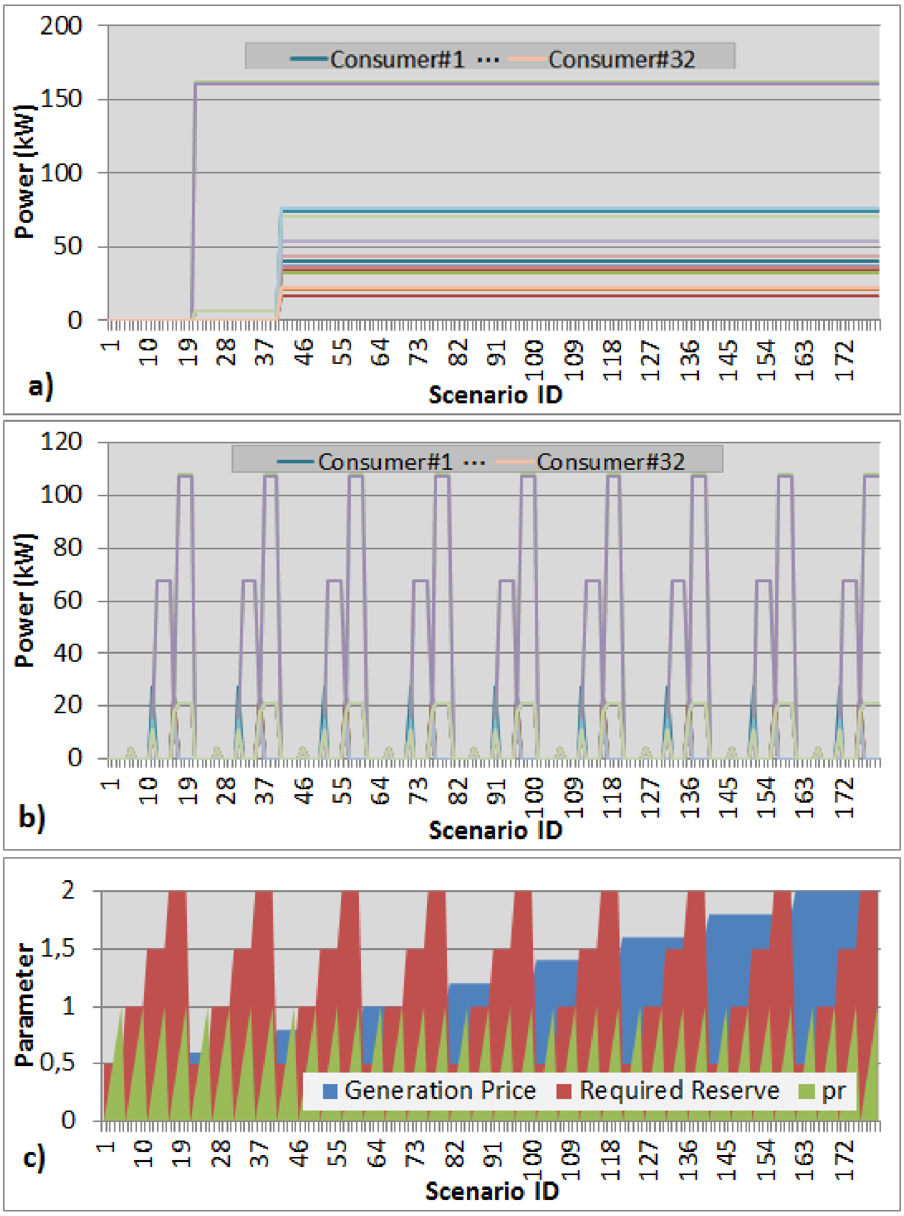

Figure 4. *Cont.*

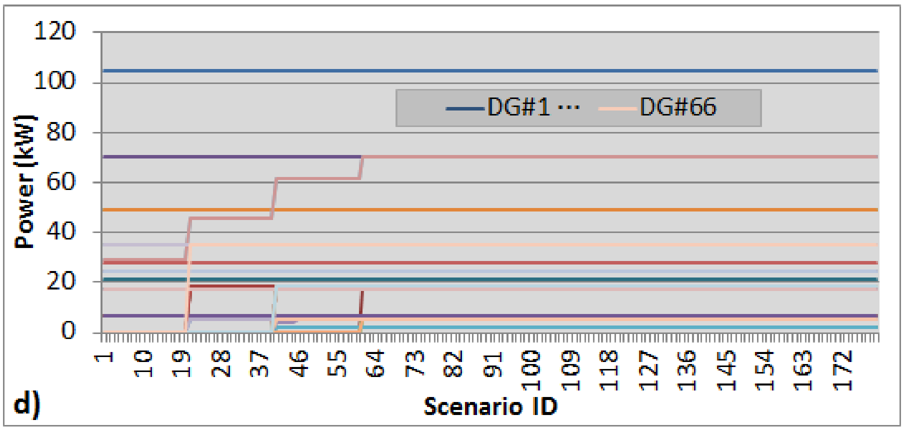

Figure 4. Resources scheduling in each scenario: (**a**) Each of the 32 DR resources in energy production; (**b**) Each of the 32 DR resources in reserve production; (**d**) Each of 66 DG resources in energy production. Scenario parameters variation (**c**); generation price, required reserve, reserve use probability—*pr*.

In what affects the VPP operation costs in each scenario, Figure 5 shows its variation concerning the different values of required reserve amounts, and generation price variation.

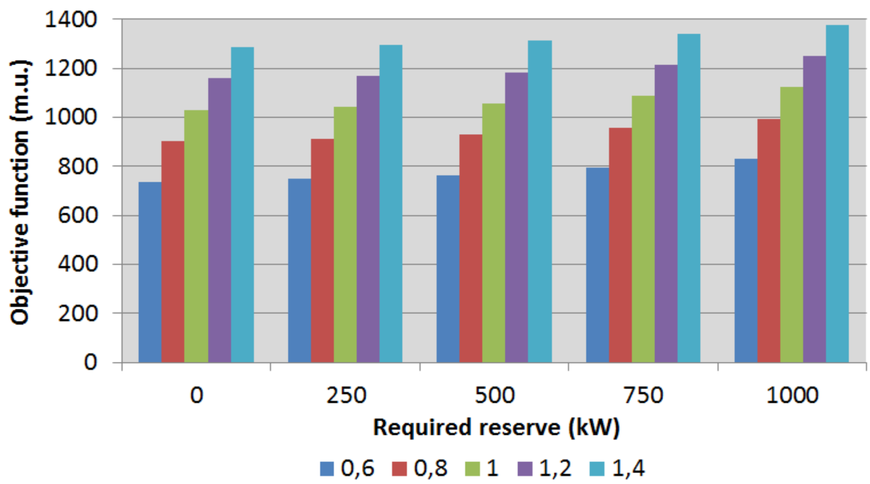

Figure 5. VPP operation in each scenario.

As seen in Figure 5, the required amount of reserve has a slight impact on the operation costs. The larger impact is given to the increase on the generation price.

4.3. DR Resources Aggregation

The DR resources used in the case study are classified according to its consumer type (a total of 6 consumers types are used). In fact, one of the motivations of the proposed methodology is to provide VPP with the ability of defining remuneration tariffs different from the traditional remuneration by type. The aggregation of the DR resources has been performed according to the proposed methodology with specifying in this case a total number of clusters equal to four. Also as proposed, the results of the aggregation are obtained from the resources schedule of the energy product, reserve product, and the two of these simultaneously (global). Figure 6 presents the 32 consumers in aggregation.

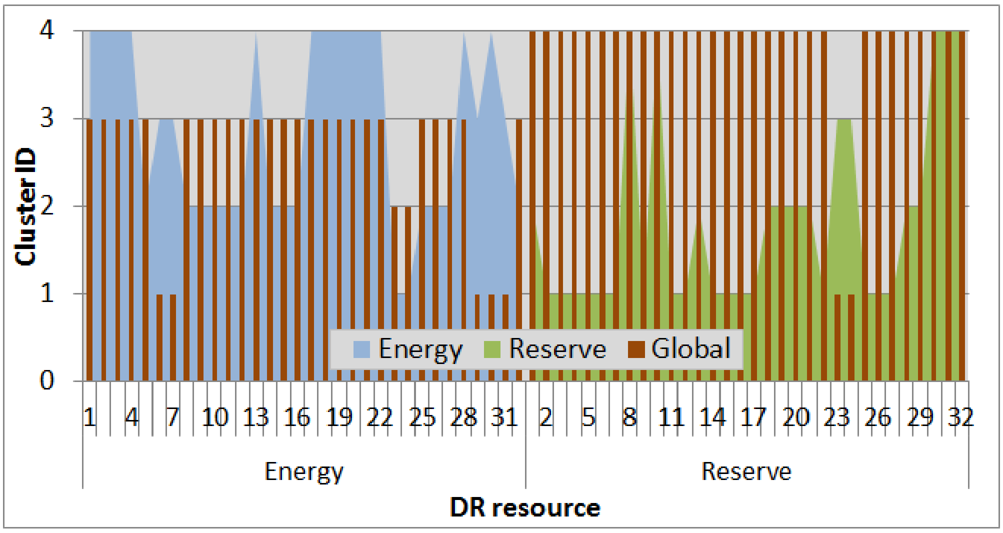

Figure 6. DR resources cluster comparison.

It can be seen the DR participation, in the Energy product, and in the reserve product. It can be seen that while in the energy product the Cluster 1 is the one with less resources, in the reserve product the cluster with less resources is Cluster 4. In the global approach, Cluster 2 is the one with less resources.

This shows that several distinct aggregation results can be obtained depending on the way we consider the operation scenarios. It is interesting to see that in the global approach the same consumer can belong to distinct clusters in the energy and in the reserve participation.

Giving the focus now to the obtained cluster profiles along the operation scenarios, Figure 7 addresses, sequentially from top to bottom, the clusters representative profile (centroid) for global, energy, and reserve approaches. Each line represents a kind of average resource schedule between the resources that belong to the specific cluster. More detailed information about the specific resources aggregated to each cluster can be seen in Figure 8 for Cluster 4 in the energy product approach. It can be seen that, when comparing the energy and the reserve approaches, the energy one has more stable profiles. This means that the aggregated resources are scheduled and remunerated with slight differences between the implemented operation scenarios.

In the case of the reserve approach, all the cluster centroids are more depending on the scenario, namely due to the reserve probability of use variation. In this case, one can see three clusters with small size resources aggregated. The fourth cluster, Cluster 3, aggregates the remaining more distinct resources and scenarios.

In what concerns the global approach, one can see that there are two clusters (Cluster 2 and Cluster 3) aggregating resources with stable profiles. The clustering algorithm aggregated the remaining resource profiles in two clusters, one for low size consumers (Cluster 4) and another for medium size consumers (Cluster 1).

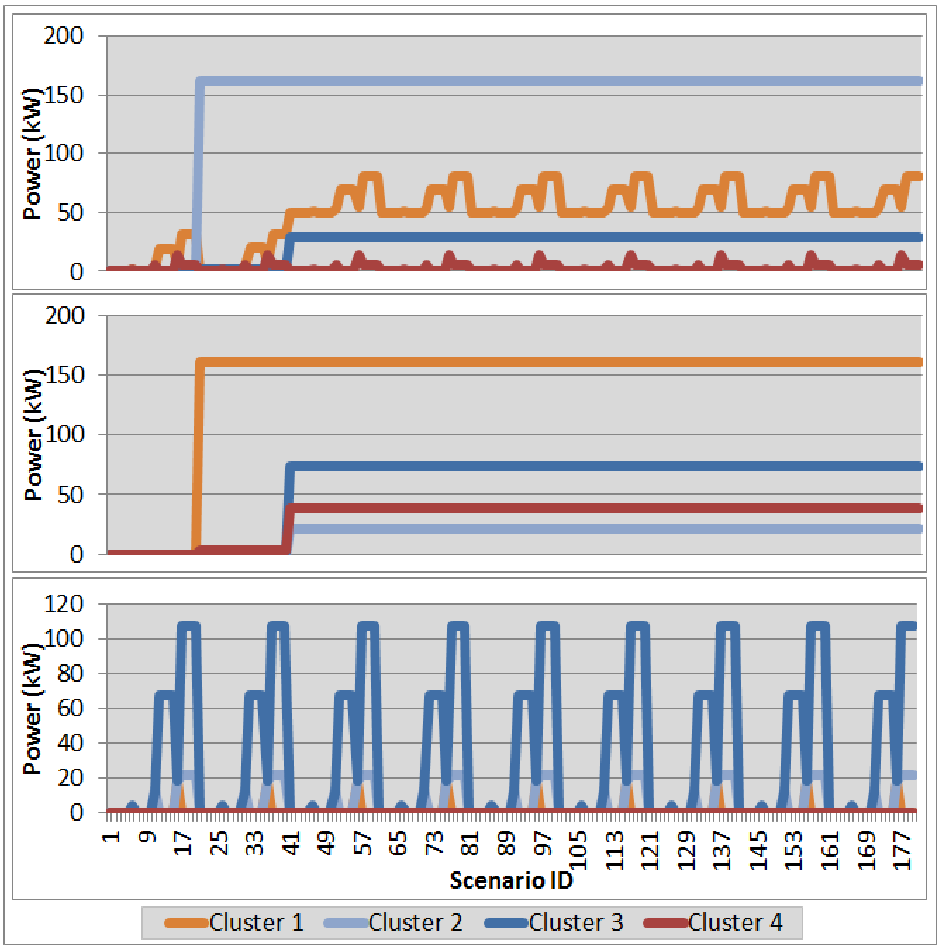

Figure 7. Cluster representative profiles.

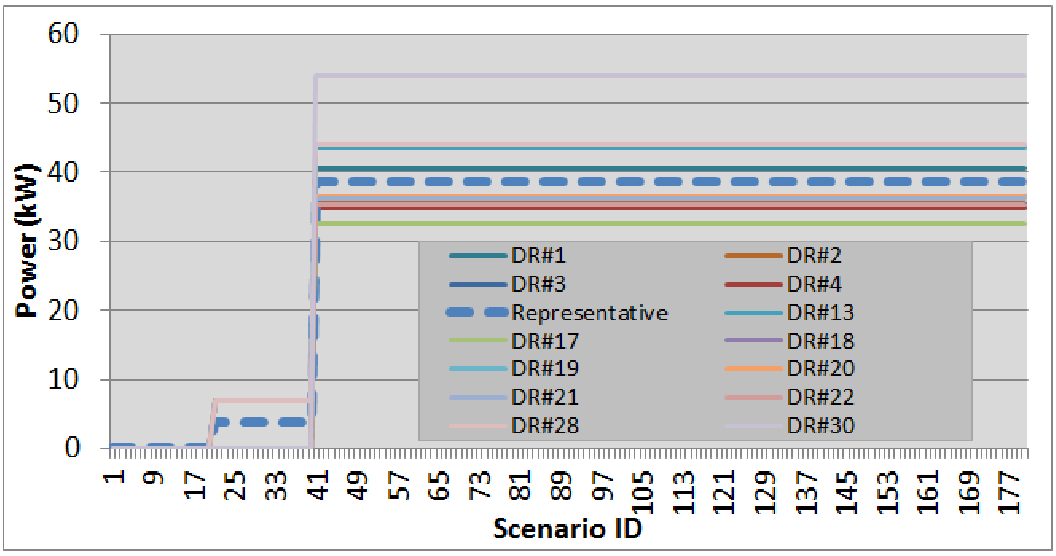

Figure 8. Resources profiles in Cluster 4, in the energy approach.

Associated with each obtained cluster representative profile, we have the profiles of each resource that is aggregated to the cluster. Due to space limitations, Cluster 4 in the energy product approach has been selected to illustrate the cluster constitution in Figure 8. It can be seen how the clustering algorithm defined the representative cluster profile along the operation scenarios, represented with a dashed line.

4.4. Results for the Event Occurring in Period 12

The results concerning the DG resources segregation are presented in this sub-section. In the case of DR resources aggregation, the number of clusters equal to 4 was considered in order to provide adequate deep analysis on the aggregation of the resources per clusters, *etc*.

In the case of the DG, the same three approaches are considered (energy, reserve, and global). However, in order to make a comparison of the obtained clusters with the traditional grouping by DG type, the number of desired clusters was defined equal to 7.

Table 3 focuses on the resources aggregated to each one of the 7 clusters, in each scheduled resources aggregation approach, and on the type of resources aggregation. In the case of the global approach, the total number of resources is 132 (66 × 2) since the 66 DG units are aggregated in the energy and in the reserve provision schedule simultaneously. In the last column of Table 3, one can see the number of resources in each DG type. Once the aggregation approaches are implemented, it can be seen that the aggregation of resources in the energy provision schedule is closer to the consumer types than in the other approaches.

Table 3. DG resources aggregation.

Cluster ID	***Global***	***Energy***	***Reserve***	***Type***	
1	34	1	13	2	Hydro
2	35	9	1	5	Wind
3	32	25	12	32	PV
4	1	1	11	1	MSW
5	12	4	3	3	Biomass
6	16	14	21	15	CHP
7	2	12	5	8	Fuel cell
Total	132	66	66	66	-

It is not possible to establish a connection between a specific cluster obtained and a DG type. However one can see, for example, that the group with higher number of resources has 25 units and the PV units are 32. In the case of the global approach a DG unit can sometimes belong to a certain cluster in the energy schedule and to other different clusters in the reserve schedule approach.

It can be seen that, from both the DR and DG scheduling aggregation the resulting resources aggregation is very dependent on the scheduling approach (energy, reserve, or global) and on the specific operation scenarios that are implemented in the energy resources scheduling phase to provide energy and reserve. In this way, each VPP, in each set of operation scenarios, should perform the implementation of the proposed methodology.

5. Conclusions

The presented work addressed the use of DG and DR by a VPP in order to fulfil the energy and the reserve needs in the operation of a distribution network, minimizing the operation costs. Several operation scenarios were implemented and the DG and DR energy resources schedule was obtained for each scenario. Using a clustering algorithm, the resources were aggregated in several clusters, making it possible for the VOPP to aggregate the resources according to the operation scenarios and according to the resources characteristics, avoiding the use of traditional grouping by resource type.

The paper also presented and discussed the implementation of SPIDER, a decision support system and simulation platform for DR integration. It is capable of providing improved simulation skills in the case of real-time simulation, including the validation of technical and economic DR models.

In this way, the VPP is able to define the operation scenarios that are more relevant in each context and to impose a certain number of clusters according to the number of DR programs and DG tariffs that are desired and possible to implement. The integration of the proposed methodology in SPIDER raises the scientific contribution of the work presented in the paper.

Acknowledgments

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Conflicts of Interest

The authors declare no conflict of interest.

Nomenclature

c	Consumer index
$Ca^{e}_{Gen(g)}$	Generator g fixed cost, for the energy product [m.u./h]
$Ca^{e}_{Red(c)}$	Consumer c reduction fixed cost, for the energy product [m.u./h]
$Ca^{r}_{Gen(g)}$	Generator g fixed cost, for the reserve product [m.u./h]
$Ca^{r}_{Red(c)}$	Consumer c reduction fixed cost, for the reserve product [m.u./h]
$Cb^{e}_{Gen(g)}$	Generator g linear cost, for the energy product [m.u./kWh]
$Cb^{e}_{Red(c)}$	Consumer c reduction linear cost, for the energy product [m.u./kWh]
$Cb^{r}_{Gen(g)}$	Generator g linear cost, for the reserve product [m.u./kWh]
$Cb^{r}_{Red(c)}$	Consumer c reduction linear cost, for the reserve product [m.u./kWh]
$Cc^{e}_{Gen(g)}$	Generator g quadratic cost, for the energy product [m.u./kWh^2]
$Cc^{e}_{Red(c)}$	Consumer c reduction quadratic cost, for the energy product [m.u./kWh^2]
$Cc^{r}_{Gen(g)}$	Generator g quadratic cost, for the reserve product [m.u./kWh^2]
$Cc^{r}_{Red(c)}$	Consumer c reduction quadratic cost, for the reserve product [m.u./kWh^2]
g	Generation index
Ng	Total number of generators
Nsp	Total number of suppliers
$P^{e}_{Gen(g)}$	Generator g scheduled power, for the energy product [kW]
$P^{e}_{Red(c)}$	Consumer c scheduled load reduction, for the energy product [kW]

$P^{e}_{Supplier(sp)}$	Supplier *sp* scheduled power, for the energy product [kW]
$P_{Load(c)}$	Initial power of load demand [kW]
pr	Reserve use probability
$P^{r}_{Gen(g)}$	Generator *g* scheduled power in the reserve product [kW]
$P^{r}_{Red(c)}$	Consumer *c* scheduled reduction power for the reserve product [kW]
sp	Supplier index
$X_{Gen(g)}$	Binary variable related to the use of generator *g*
$X_{Red(c)}$	Binary variable related to the use of DR reduction c

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