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Real-Time Flexibility Market Participation of Thermostatically Controlled Loads

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Abstract— **The objective of this paper is to demonstrate the feasibility of using the aggregated flexibility of thermostatically controlled loads (TCLs) to provide balancing and congestion management services to system operators through the participation in a real-time flexibility market. To this aim, a TCL aggregation model that employs a bottom-up approach based on physical end-use load models has been developed. A direct load control (DLC) scheme is considered, where the control variable is the thermostat temperature setpoint. This temperature can be manipulated between the upper and lower limits set by end-users, who receive an economic compensation in exchange for the loss of comfort. As output a set of flexibility bids to be sent to the market are obtained. To demonstrate the applicability of the proposed aggregation model and estimate the overall flexibility potential from TCLs, a large-scale case study, based on a future power system in Spain has been considered.**

Index Terms-- **ancillary services, aggregator, demand response, load management, thermostatically controlled loads.**

I. INTRODUCTION

The increasing share of intermittent renewable energy sources (RES) in the European power systems results in higher need for flexibility resources providing ancillary services (AS) to compensate for the power fluctuations. In this context, new opportunities are emerging for distributed energy resources (DERs) – distributed generation, storage and controllable demand – connected to distribution networks to take part in the real-time operation of transmission and distribution networks by providing flexibility to the system operators. However, the effective integration of large amounts of small-scale DERs into the AS provision is a challenge that requires adaptation of current market mechanisms as well as development of new and efficient tools for aggregators of flexibility resources to take part in them.

The objective of this paper is to assess the potential of using the aggregated flexibility from thermostatic loads (commonly called thermostatically controlled loads (TCLs) [2][10]) to provide balancing and congestion management services to system operations through the participation in a novel real-time flexibility market called "Integrated Reserve Market" [6],[7]. This novel market, which was defined within the SmartNet EU project [1], procures balancing service, through currently existing manual Frequency Restoration Reserve (mFFR) and Replacement Reserve (RR) products, while, at the same time, solves predicted congestions for next time steps and avoids creating new grid congestions. This "Integrated Reserve Market" is explained in detail in [7].

To this aim, a TCL aggregation model has been developed. The model estimates the aggregated flexibility of a group of TCLs (heat pumps and/or air-conditioning systems with inverter technology that allow electronic control of thermostat temperature) which are subscribed to a direct load control (DLC) program where the control variable is the temperature setpoint. The aggregator is allowed to modify the temperature setpoint of the thermostat between the upper and lower limits agreed with TCL owners. In exchange for this loss of comfort, end-users receive an economic compensation which depends on the discomfort level achieved in relation or the baseline temperature. The model employs a bottom-up approach, based on physical end-use load models, where the individual flexibility of each TCL is estimated via a second-order equivalent thermal parameter (ETP) describing the dynamics of the house [4],[5]. The output obtained is a set of flexibility bids to be sent to the market, which include the aggregated flexibility and the related cost. Detailed description of this algorithm was provided in [2]. This paper extends the aforementioned work by applying the aggregation model to a large-scale case study with the twofold objective of demonstrating the applicability of the model in the "Integrated Reserve Market" and estimating the overall potential contribution of the demand flexibility from TCLs to solve power system imbalance.

The paper is divided into four main sections. Section I is the introduction. Section II describes the aggregation model developed for the aggregation of TCLs. Section II shows the results of a case study. Section IV summaries the main conclusions drawn from the study.

II. AGGREGATION MODEL FOR TCLS

The objective of the developed aggregation model is to create flexibility bids for the participation of an aggregator of TCLs into the "Integrated Reserve Market" [2],[6],[7]. This market is called after intraday markets to solve imbalances and

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congestions caused by forecasting errors on renewable generation and demand. It is organized as an electricity exchange where the traded quantities within each market session are flexibility bids obtained by modifying the planned schedule/commitment on previous markets (baseline). Each flexibility bid is defined by a power profile which specifies, for each time-step of the market period, the price requested for the offered extra supply or consumption of energy. The market horizon is usually from 15 minutes to 1 hour depending on market requirements.

This section includes a short overview of the developed aggregation model. Detailed description can be found in [2]. Algorithm 1 in Appendix A summarizes the main steps of the iterative process developed to generate the flexibility bids. The aggregation algorithm employs an iterative approach to estimate a set of flexibility profiles which corresponds to possible control strategies that the aggregator can apply over the TCLs in its portfolio. Possible control strategies are defined by the combination of two variables: temperature setpoint, and duration of the control action. The setpoints for each TCL are defined as a function of their given temperature control limits ($T_{sp\_min}^{k}$ and $T_{sp\_max}^{k}$) that are divided according to given pre-defined equal-sized temperature intervals (N_{sp}^{prof}). Also, the duration of the control action of the IRM (N_{ts}^{prof}) can vary from a single time-step to the total number of time-steps in the market horizon (N_{ts}^{tot}). The model is based on a bottom-up approach consisting of aggregating, in each set of bids, the simulated individual flexibility profiles and their related costs for all TCLs (N_{TCL}). In each set, all bids have the same type of control action (temperature intervals and control duration). Each of them will constitute a final bid that the aggregator will send to the market.

The temperature setpoint ($T_{sp}^{s,k}$) is finally set to the baseline temperature ($T_{bc}^{t,k}$) beyond the duration of the control profile (D_{prof}^{n}), which includes also the rebound period, because the control is returned to the device which tries to restore its initial conditions. The baseline power consumption is an input data, and it will normally correspond to the comfort temperature setpoint ($T_{bc}^{t,k}$). The superscripts used in the formulation are as follows: *k* refers to each TCL up to N_{TCL}, *s* refers to the fixed temperature intervals up to N_{sp}^{prof}, *n* refers to the duration of the control up to N_{ts}^{prof}, and *t* refers to the time-step up to N_{ts}^{tot}.

$P_{flex}^{t,s,k}$ is the estimated individual power flexibility of the TCL *k* at time-step *t* that is calculated as the difference between the baseline power consumption ($P_{bc}^{t,k}$) and the actual power consumption ($P_{ctl}^{t,s,k}$) required to attain the considered control temperature setpoint ($T_{sp}^{s,k}$). The latter is calculated via the second-order thermal parameter model (ETP) described in [2].

$c_{flex}^{t,s,k}$ is the individual flexibility cost for activating the estimated flexibility, expressed in [€/kWh] that is calculated according to (1) as a function of the discomfort level achieved by the end-user (the deviation of the internal temperature ($T_{int}^{t,s,k}$) from the baseline temperature due to the application of the control action); and the parameter δ^{k} [€/(kWh·ºC)] defining the user's sensitivity to temperature discomfort [2].

$$c_{flex}^{t,s,k} = \delta^{k} \left| T_{int}^{t,s,k} - T_{bc}^{t,k} \right| \qquad (1)$$

δ^{k} is a subjective parameter measuring the benefit to be obtained for a unit of temperature deviation. In a practical system, this parameter should be agreed in advance between the user and the aggregator. A practical way to estimate it will be to assume that at the maximum discomfort level, the end-user will be willing to receive the money that it should have paid for maintaining the temperature comfort level according to (2) where $\lambda^{t,elect}$ can be the electricity price in *t* [€/kWh] and T_{disc}^{k} is the maximum discomfort temperature for end-user *k*:

$$\delta^{k} = \frac{\lambda^{t,elect}}{\left| T_{disc}^{k} - T_{bc}^{t,k} \right|} \qquad (2)$$

The calculated individual flexibility and cost profiles are added to create the aggregated flexibility profiles that represent the bids that will be delivered to the market [8]. These flexibility profiles include both, the flexibility and the rebound period.

The bids are delivered to the "Integrated Reserve Market" as complex bids including the following constraints: 1) "non-curtailable bids" (indivisible bids) meaning that the market operator can either accept or reject the total energy quantity offered. 2) "accept all time steps or none" to ensure that a bid is accepted for all time-steps considered in the bid or that it is not accepted at all, 3) "exclusive choice constraint" to indicate that only a single bid can be accepted among the set of bids as they correspond to different control actions over the same set of TCLs and, therefore, they are mutually exclusive.

After the market clearing process, the aggregator has to perform the disaggregation process that consists of transforming the market results into individual temperature setpoints to the delivered to the TCLs to achieve the committed flexibility profile. As the aggregated flexibility bids are calculated by horizontal summation of individual flexibility bids, and the aggregator knows at the bid creation time the mapping between the individual flexibility bids and the applied control actions, the disaggregation process is straightforward.

III. CASE STUDY AND RESULTS

The case study has been conducted based on a real power system in Spain in a future scenario, to check the applicability of the aggregation model and demonstrate that flexible demand from TCLs is capable of providing substantial value to the system through the participation in the Integrated Reserve market devoted to solving system imbalances and congestions.

The case study is divided into three main parts. In the first one, the results of the "Integrated Reserve Market" for a particular distribution network are presented. The objective of this analysis is to assess the contribution of the TCL flexibility to solve power system imbalance and avoid congestions for a sample distribution network. The second part focuses on estimating the overall potential of the contribution of the demand flexibility from TCLs to solve power system imbalance at the entire power system level. Finally, the third part of the study performs a computational scalability analysis to check the applicability of the developed aggregation algorithm to the considered real-time market. For the simulations, the market platform developed by the SmartNet project has been used

[1],[8]. Simulations have been performed using the Amazon cloud computing service (c4.4xlarge instance type) characterized by an equivalent 16 virtual CPU with 2.9 GHz per CPU and 30 GB of RAM.

A. Input data

The considered power system represents the Spanish Transmission system to which 396 Medium Voltage (MV) representative distribution network are connected. The case study is focused on a future spring scenario. For the definition of the scenario, projections on DER penetration and location on the distribution network as well as load and demand forecasts have been carried out based on ENTSO-E vision for year 2030 [3],[9]. Based on this, a total of 124,539 controllable heat pumps connected to the distribution networks and managed by the TCL aggregators are considered. These TCL devices have nominal powers ranging from 2 to 3 kW and coefficients of performance (COP) of 3 Wt/We (note however that for the considered case, in springtime, the maximum power consumption will be around 800 We). It is assumed that the TCL aggregators have agreed four different types of DLC contracts with end-users, which are characterized by different temperature control margins. Table I shows the characteristics of each of them and the number of TCLs involved. For the case study, it is assumed that the baseline temperature is the comfort temperature setpoint. It is assumed that the "Integrated Reserve Market" is called every hour with a time resolution of 15 minutes. The market is cleared every hour per distribution network [6].

TABLE I. INFORMATION OF DLC CONTRACTS

Nº	**Temperature Control Margins**			**TCLs involved**	
	Minimum setpoint $T^k_{sp\_min}$ ***[ºC]***	***Comfort setpoint*** T^k_{sp} ***[ºC]***	***Maximum setpoint*** $T^k_{sp\_max}$ ***[ºC]***	***Number***	***%***
1	18	22	24	12,454	10
2	21	22	23	49,816	40
3	20	23	26	24,908	20
4	17	20	23	37,362	30

The ETP parameters that characterize building envelopes of the TCLs are presented in Table II, being C^k_{int} the thermal capacity of the internal mass, C^k_{env} the thermal capacity of the envelope mass, R^k_{int} the heat transfer resistance between the internal mass and the envelope, R^k_{env} the heat transfer resistance between the envelope mass and the exterior and R^k_{ext} the heat transfer resistance between the internal mass and the exterior. These are normally distributed with mean values according to [10] and relative standard deviation of 15%.

TABLE II. ETP SIMULATION PARAMETERS

Parameter	**Value**	**Units**
C_{int}	$N(11.49)\cdot 10^6$	J/ºC
C_{env}	$N(25.92)\cdot 10^6$	J/ºC
$1/R_{int}$	N(332,49.8)	W/ºC
$1/R_{env}$	N(4491,673.7)	W/ºC
$1/R_{ext}$	N(20, 3)	W/ºC

B. Results and discussion

1) Case study 1: Sample distribution network simulation

For the first part of the study, a particular MV distribution network with nominal voltage of 22kV and located in the north-western region of Spain is considered. The TCL aggregator is responsible for scheduling a cluster of 360 domestic heat pumps connected to this network whose baseline, minimum and maximum temperatures are 22ºC, 21ºC and 23ºC for all of them respectively. The forecasted outdoor temperature in the considered area is taken from a typical spring day having an average value of 15.7 ºC. Fig. 1 shows the power system regulation needs for the considered day that the DSO needs to solve with the "Integrated Reserve Market".

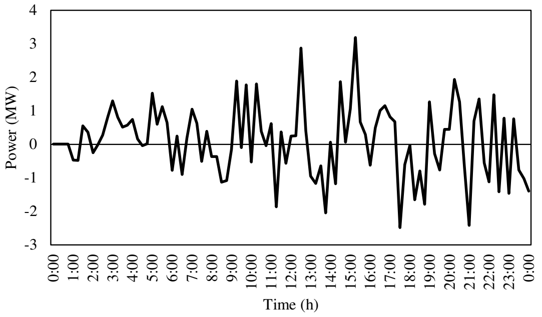

Figure 1. Power system regulation needs of the considered network

Based on the information presented in section III.A, the iterative process presented in Algorithm 1 is run by the aggregator to generate the aggregated flexibility bids for each market period. Fig. 2 shows the maximum amount of flexibility bid by the TCL aggregator in each direction for all market sessions of the considered day and the finally accepted quantities as output of the market clearing processes. According to the normal convection, upward bids consist of an increase of generation or a decrease of consumption; and on the opposite, downward bids consist of a decrease of generation or an increase of consumption.

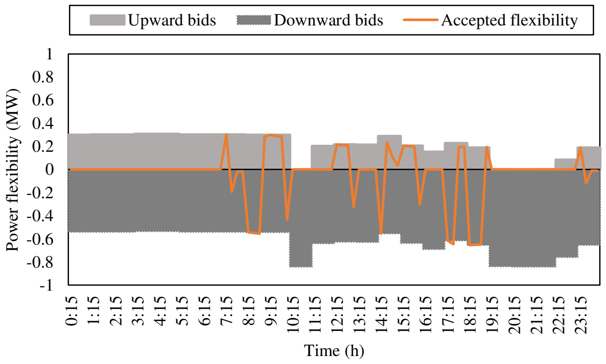

Figure 2. Maximum upward and downward amount of flexibility bid by the TCL aggregator for the whole day and accepted quantities

The final contribution of TCLs flexibility to solve power regulation needs along the day for the considered network is shown in Fig. 3 (starting at 7:15 which is the first time-step where TCL flexibility is accepted). For this particular distribution network, the participation of the TCLs in the "Integrated Reserve Market" contributes to solve the 8.22 % of the upward system regulation needs and the 18.82 % of the downward system regulation needs.

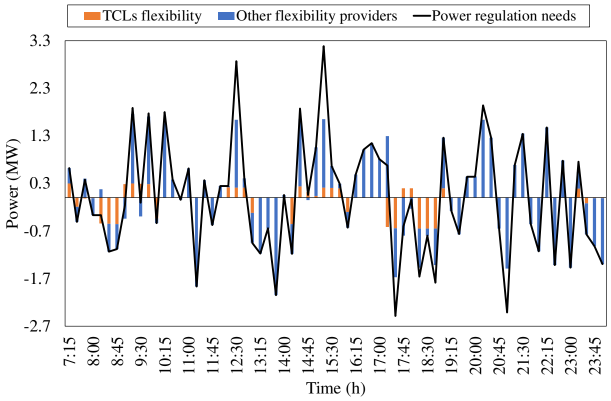

Figure 3. Accepted flexibility for all market sessions of the day

2) *Case study 2: Spanish system level simulation*

In this section, simulation results for 396 representative MV distribution networks are presented. The objective is to estimate the overall potential contribution of the 124,539 heat pumps connected to the considered power system to solve partially the system regulation needs depicted in Fig.4.

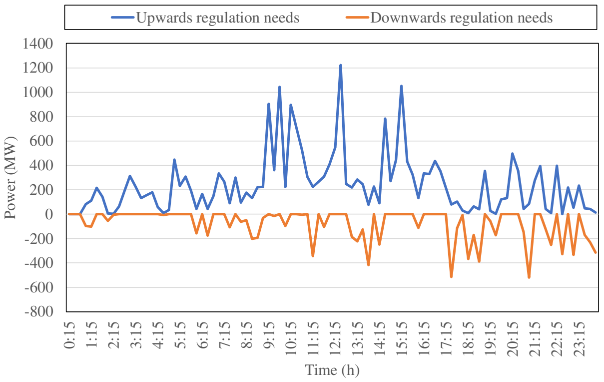

Figure 4. Upward and downward power regulation needs of the entire system

The same procedure as for the sample distribution network in section III.B.1 is applied to all distribution networks. Fig. 5 shows the percentage of contribution of the TCLs flexibility to solve power system regulation needs for each time-step of the day in each direction (for explanatory purposes, downward information is displayed in negative values). It can be observed that, in general, the contribution percentages are comprised between the 0 and the 20% of the total power system regulation needs for most of the time-steps of the day. However, there are certain times of the day in which the amount of TCLs flexibility accepted by the market is much higher, reaching even percentages close to the 80%.

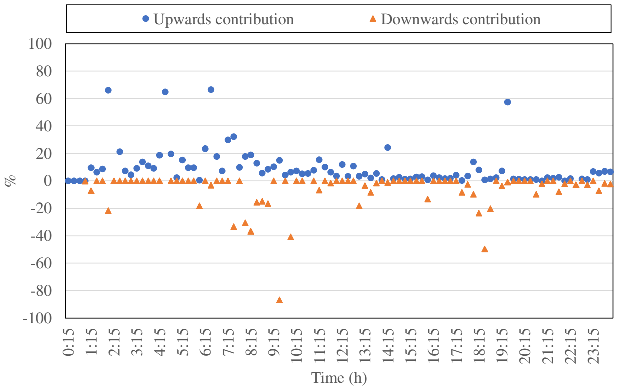

Figure 5. Upward and downward contribution percentages by TCLs to solve the overall power system regulation needs for each time-step of the day

Simulation results demonstrate that the participation of the TCLs in the "Integrated Reserve Market" can contribute to solve the 6.28% of the overall upward system regulation needs and the 12.93 % of the overall downward system regulation needs forecasted for the considered day.

A detailed analysis of the contribution percentages (accepted bid quantities respect to the regulation needs) per distribution network for the overall day is shown in Fig. 6. It can be seen that there is a high variability from one network to another. Many factors are influencing this variability including, among others, the amount of flexibility required by the "Integrated Reserve Market" for each network, the TCLs flexibility available in each network, the presence of other flexibility providers, such as storage systems or CHPs, which are able to supply the required flexibility at more competitive prices, etc.

The considered values for the δ^k parameter have also a strong influence on the results. Further work should consider this parameter as another variable for the sensitivity analyses.

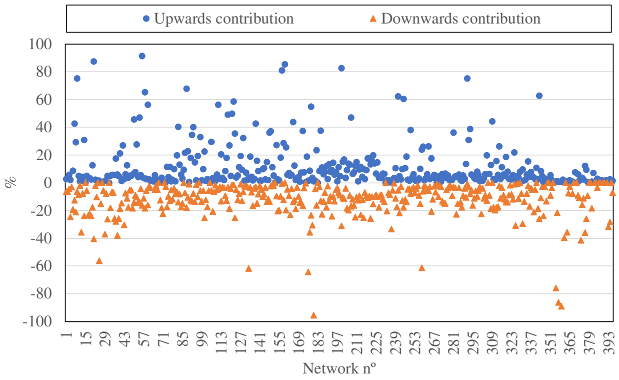

Figure 6. Upward and downward contribution percentages by TCLs to solve power system regulation needs per distribution network

3) *Computational scalability analysis*

Participation in the considered real-time market requires that market participants be able to generate their bids within the required time scale. This part of the study performs a computational scalability analysis based on two different sensitivity analyses to check the feasibility of the developed algorithm for the considered real-time application. First, the population size of TCLs in the networks is increasing, and then, the number of temperature control intervals.

The first sensitivity analysis considers three scenarios with increasing number of TCL devices connected to the distribution networks to check the influence of the population size on the computational time, assuming one temperature control interval. The second sensitivity analysis defines other three scenarios with increasing number of temperature control intervals (N_{sp}^{prof}), as this parameter is directly linked to the number of flexibility bids finally delivered to the market. For the definition of this second sensitivity analysis, the "large" scenario in terms of number of TCLs from the first sensitivity analysis has been taken as a basis (that is, 124,539 TCLs). Information about the six scenarios considered is presented in Table III.

TABLE III. SENSITIVITY ANALYSES

Scenario	**I-Population size** [a]		**II-Number of control intervals** [b]
	Number of TCLs	***Percentage of TCLs from Case Study 2 [%]***	N_{sp}^{prof}
Small	37,362	30	1
Medium	74,724	60	3
Large	124,539	100	5

a. Considering one temperature control interval

b. Considering a fixed number of TCLs from large scenario (124,539)

Table IV shows the total computational time in seconds that the TCL aggregation algorithm required in simulation to generate the flexibility bids for each market session in each of the six considered scenarios.

TABLE IV. RESULTS OF THE SENSITIVITY ANALYSES

Scenario	**Total Computational time [s.]**	
	I-Population size [a]	***II-Number of control intervals*** [b]
Small	740	1550
Medium	1090	3050
Large	1550	4290

a. Considering one temperature control interval

b. Considering a fixed number of TCLs from large scenario (124,539)

As expected, the computational time increases with both, the increase on the TCL population size and the increase on the number of possible control actions as it is a combinatorial problem.

The available time for the TCL aggregator to generate the bids will depend on the market characteristics. In the considered case study, there would be 1 hour (3600 sec.) to perform the whole market process including aggregation, market clearing and disaggregation processes. Fig. 7 shows the computational time per process for both sensitivity analyses.

It can be checked that, in several cases, the total simulation time exceeds the time requirements of the market (3600 sec.). However, this is mainly related to the high amount of time required by the market operator to clear the market and the fact that, as the number of control options increases, the number of possible flexibility profiles to simulate increases greatly also. In a real implementation, the computational time required for the aggregation could be extremely reduced because the generation of the bids for each distribution network are independent processes that can be carried out in parallel, i.e., locally per each distribution network or by a distributed control of TCLs. The computational time for the distribution network with the highest number of TCLs is less than one minute. Therefore, it can be concluded that the aggregation algorithm fulfills the requirements for participation in the considered market. These results show that the algorithm could even be used in more demanding market configurations of up to 5 minutes including aggregation, market clearing and disaggregation processes.

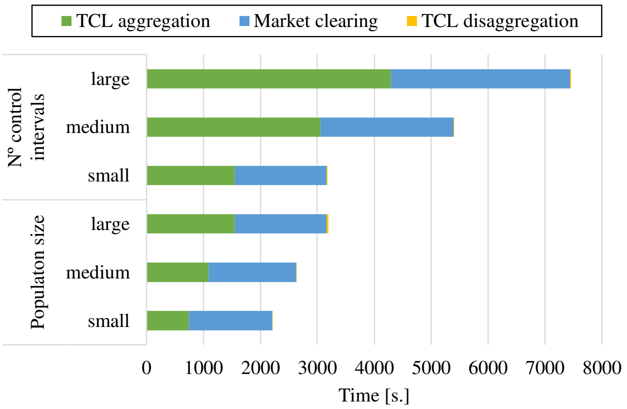

Figure 7. Total time required by the aggregation, market clearing and disaggregation processes for the different scenarios

IV. CONCLUSIONS

This paper demonstrates the capability of aggregated TCLs to provide significant amounts of flexibility in real time flexibility markets. To this aim, the aggregation model developed in [2] has been employed to define the bidding strategy of an aggregator of TCLs in a novel real-time ancillary market called "Integrated Reserve Market".

The study has been carried out in a simulation environment using data about the transmission system in Spain to which 396 representative MV distribution networks are connected. In the case study the control of domestic heat pumps in a future spring scenario is considered.

Simulation results demonstrate the proposed aggregation model is feasible for the application to real-time market. In addition, it is demonstrated that the participation of the TCLs in the "Integrated Reserve Market" can contribute to solving a significant percentage of the overall upward and downward system imbalances forecasted for the considered day. For the large-scale case study considered in this paper it is obtained that they can contribute to solving the 6.28% and the 12.93% of the upward and downward power system regulation needs respectively.

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APPENDIX A

Algorithm 1 Generation of the Aggregated Flexibility Bids

```
for $n = 1, \dots, N_{ts}^{prof}$ do
  for $s = 1, \dots, N_{sp}^{prof}$ do
    for $k = 1, \dots, N_{TCL}$ do
      for $t = 1, \dots, N_{ts}^{tot}$ do
        if $t < D_{prof}^{n}$ then
          Set $T_{sp}^{t,s,k} = T_{sp}^{s,k}$
        else
          Set $T_{sp}^{t,s,k} = T_{bc}^{k}$
        end if
        Estimate individual flexibility per k: $P_{flex}^{t,s,k}$
        Estimate individual cost per k: $c_{flex}^{t,s,k}$
      end for
      Estimate individual flexibility profile per k:
        $P_{flex\_prof}^{n,s,k} = \{P_{flex}^{t,s,k} \mid \forall t \in \{1, \dots, N_{ts}^{tot}\}\}$
      Estimate individual cost profile per k:
        $c_{flex\_prof}^{n,s,k} = \{c_{flex}^{t,s,k} \mid \forall t \in \{1, \dots, N_{ts}^{tot}\}\}$
    end for
    Create aggregated bids:
      $Bid^{n,s} = \left\{ ( P_{flex_{bid}}^{n,s}, c_{flex_{bid}}^{n,s} ) \ \forall n, s \right\}$
      where:
      $P_{flex\_bid}^{n,s} = \sum_{k=1}^{N_{TCL}} P_{flex\_prof}^{n,s,k}$
      $c_{flex\_bid}^{n,s} = \sum_{k=1}^{N_{TCL}} c_{flex\_prof}^{n,s,k}$
  end for
end for
Output: Final set of bids $Bid_{set} = \{Bid^{n,s} \ \forall n, s\}$
```