DSO Market Formulation

D4.3.2 EcoGrid 2.0

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1 Introduction

Due to changing electricity demand and supply, we see substantial changes in the stress placed on distribution lines over time. To cope with these fluctuations, insufficient thermal capacity, and general ageing of distribution lines, investment is required to ensure that consumers have access to a reliable source of generation. Peak usage of distribution lines is only expected to grow as countries around the world see an increase in the penetration of renewable generation, which is often intermittent.

Throughout the world, household consumers generally pay an energy price for electricity generation, transmission, and distribution. Thus, for both technological and financial reasons, there has been an insufficient incentive for consumers to alter consumption patterns based on the true cost (e.g. marginal cost of generation and degradation of infrastructure).

We have the goal of decreasing greenhouse gas emissions, improving the life of the network, and the overall welfare of the system at large. Thus, it would be beneficial to create a market where aggregators that control some flexible consumer demand, use this flexibility to cut their consumption during peak hours.

The EcoGrid 2.0 project aims to develop a marketplace for distributed energy resources, e.g. private households to reduce consumption at times and during events where there is a limited supply, preventing the need to use expensive sources of generation, curtailing inflexible consumers, or accelerating the degradation of distribution infrastructure.

We develop a market platform that takes in offers from aggregators to satisfy the Distributed System Operator (DSO) bids for demand response. This report details the formulation and presents results from a case study that demonstrates the importance for aggregators to submit both a reserve price (that should be used to indicate their opportunity cost of not participating in the Transmission System Operator (TSO) market) and a dispatch price (that should be used to indicate lost welfare from being activated).

As demand and supply change over days and have inherent uncertainty, there will be tradeoffs between services that are activated every day (unconditional) and services for which the DSO has to trigger the activations (conditional). The market clearing tool will take in offers from the DSO and aggregators, to determine, based on the offer blocks and offer prices, the combination of DSO services and aggregator service blocks that maximise system surplus.

Without a cost or a limit on the number of activations for a signal based service, we see that the DSO has an incentive to state the activation probability is rarer than the real probability.

Agents then bid assuming their units are dispatched less often, submitting a lower bid than they would otherwise need to make a profit. There are trade-offs between limiting the number of activations and paying extra for these activations.

With dispatch limits, the aggregator has certainty in the profitability and the amount of discomfort they expose to their consumers. However, the DSO may end up having to solve a complicated stochastic optimisation problem to determine when to optimally dispatch aggregators, and determine the value of conditional services.

With a payment adjustment, aggregators incorporate the cost of activating each block into the contract. Thus the DSO would only need to compare the benefit of activating the service and the cost of activation each day. However, if estimates for the number of activations is incorrect, the solution may no longer be optimal. In subsubsection 2.4.3 we demonstrate how we adjust the payments to aggregators, and how that changes the profit of each agent.

We also compare results from models that relax an integer constraint (allowing the DSO to clear fractions of the aggregator's block offers) on the demand response aggregators and compare this to the model to different methods for market clearing when this constraint is not relaxed.

2 Model Formulation

We consider a Distributed System Operator (DSO) that buys flexibility-based services from aggregators within a competitive market. These are medium-term contracts that will either be activated every day or will be signalled by the DSO to order aggregators to provide this service.

Aggregators (AGG) have agreements to provide a minimum service to their customers while having some control over their consumption. The AGG can then use this flexibility to participate in either the TSO level market, providing real-time stability, or in this DSO market, which is primarily used to reduce power consumption peaks.

Now we define the relevant sets, parameters, and variables that we use in the formulation of this market clearing tool. We use the convention that calligraphic letters are sets, Roman type text denotes parameters, and math-type text denotes variables and indices, and bold is used to denote parameters and variables that are not fully indexed.

2.1 Set definition

$p \in \mathcal{P}$:= All services that may benefit the DSO. Each p may have a different benefit to the DSO, along with different blocks of upward regulation requirements, number of expected activations, and criteria for activation. For our case study p is (Time, SignalS, SignalF).

$i \in \mathcal{I}$:= Set of conventional units that do not require a rebound period with their offers

$c \in \mathcal{C}$:= Set of aggregated demand units that do have a rebound period with their offers

$d \in \mathcal{D}$:= Set indexing possible block offers for each aggregator

$t \in \mathcal{T}$:= Set of hours with either a required response or a maximum allowed rebound

$t \in \mathcal{M} \subseteq \mathcal{T}$:= Hours that have a required response

2.2 Parameter definition

L := Length of contract each service p ($days$)

$\mathbb{P}_p$:= Proportion of days that DSO service p is expected to be needed

$\mathbb{T}_t$:= Length of block of time t (hrs).

$\mathrm{C}_{pt}^{R,DSO}$:= Capacity component of DSO service benefit. During response it reflects the benefit ($\$/KWh$) from reserving the block k for service p at time t. During rebound, this reflects the per unit cost of the allowed rebound.

$\mathrm{C}_{pt}^{D,DSO}$:= Activation component of DSO service benefit. During response it is the benefit ($\$/KWh$) from dispatching the block k for service p at time t. During rebound, this represents the per unit cost of the allowed rebound.

D_{pt}^{Reg} := Required overall upward regulation (KW) for service p, DSO service block k, at time t

D_{pt}^{Reb} := Allowed downward regulation (KW) for service p, DSO service block k, at time t

$\mathrm{C}_{pit}^{R,Con}$:= Reserve component of the cost ($\$/KWh$) for unit i to meet p at time t

$\mathrm{C}_{pit}^{D,Con}$:= Dispatch component of the cost ($\$/KWh$) for unit i to meet p at time t

$\bar{\mathrm{P}}_{pi}^{Con}$:= Limit of response (KW) for the conventional unit i to meet p

$\mathrm{C}_{pcd}^{R,DR}$:= Reserve component of the cost ($\$/Block$) for block d for the demand response unit c to meet p

$\mathrm{C}_{pcd}^{D,DR}$:= Dispatch component of the cost ($\$/Block$) for block d for the demand response unit c to meet p

Q_{pcdt}^{DR} := Parameter that defines the actual response and rebound (KW) for each block of activated demand response block d (belonging to aggregator c to meet service p)

B_{pcd}^{DR} := Number of discrete blocks that make up maximum utilisation of block d

2.3 Variable definition

p_{pit} := Upward regulation (KW) provided by unit i at time t used to meet service p

m_{pcd} := Binary variable indicating which service block d the aggregator will be called upon to use (ensures different blocks from the same aggregator aren't cleared)

r_{pcd} := The number of blocks d that the aggregator c will be called upon to meet service p

s_{pt} := During rebound periods, s_{pt} represents the amount of rebound utilised for service p, at time t.

z_p := Binary variable indicating which service p the aggregators will be used to meet.

2.4 Problem formulation

$$\min_{\Xi} \sum_{p\in\mathcal{P}} RC_p + \sum_{p\in\mathcal{P}} \mathbb{P}_p DC_p \tag{1}$$

$$RC_p = \sum_{i\in\mathcal{I}}\sum_{t\in\mathcal{T}} \mathbb{T}_t \mathrm{C}^{R,Con}_{pit} p_{pit} + \sum_{c\in\mathcal{C}}\sum_{d\in\mathcal{D}} \mathrm{C}^{R,DR}_{pcd} r_{pcd} + \sum_{t\in\mathcal{T}} \mathbb{T}_t \mathrm{C}^{R,DSO}_{pt}(s_{pt} - \mathrm{D}^{Reg}_{pt} z_p) \quad \forall p\in\mathcal{P}, \tag{2}$$

$$DC_p = \sum_{i\in\mathcal{I}}\sum_{t\in\mathcal{T}} \mathbb{T}_t \mathrm{C}^{D,Con}_{pit} p_{pit} + \sum_{c\in\mathcal{C}}\sum_{d\in\mathcal{D}} \mathrm{C}^{D,DR}_{pcd} r_{pcd} + \sum_{t\in\mathcal{T}} \mathbb{T}_t \mathrm{C}^{D,DSO}_{pt}(s_{pt} - \mathrm{D}^{Reg}_{pt} z_p) \quad \forall p\in\mathcal{P}, \tag{3}$$

subject to

$$p_{pit} \le \bar{\mathrm{P}}^{Con}_{pi} z_p \qquad \forall p\in\mathcal{P}, i\in\mathcal{I}, t\in\mathcal{T}, \tag{4}$$

$$r_{pcd} \le \mathrm{B}^{DR}_{pcd} m_{pcd} \qquad \forall p\in\mathcal{P}, c\in\mathcal{C}, d\in\mathcal{D}, \tag{5}$$

$$\sum_{d\in\mathcal{D}} m_{pcd} \le z_p \qquad \forall p\in\mathcal{P}, c\in\mathcal{C}, \tag{6}$$

$$s_{pt} \le \mathrm{D}^{Reb}_{pt} z_p \qquad \forall p\in\mathcal{P}, t\in\mathcal{T}, \tag{7}$$

$$\sum_{p\in\mathcal{P}} z_p \le 1, \tag{8}$$

$$\sum_{i\in\mathcal{I}} p_{pit} + \sum_{c\in\mathcal{C}}\sum_{d\in\mathcal{D}} \mathrm{Q}^{DR}_{pcdt} r_{pcd} \ge \mathrm{D}^{Reg}_{pt} z_p - s_{pt} \qquad [\pi_{p,t}] \qquad \forall p\in\mathcal{P}, t\in\mathcal{T}, \tag{9}$$

$$p_{pit} \ge 0 \quad \forall p\in\mathcal{P}, i\in\mathcal{I}, t\in\mathcal{T}; \tag{10}$$

$$r_{pcd} \in \mathbb{Z}_+ \quad \forall p\in\mathcal{P}, c\in\mathcal{C}, d\in\mathcal{D}; \tag{11}$$

$$s_{pt} \ge 0 \quad \forall p\in\mathcal{P}, t\in\mathcal{T}; \tag{12}$$

$$z_p \in \{0,1\} \quad p\in\mathcal{P}. \tag{13}$$

The objective (1) minimises the sum of reserve cost (also known as capacity cost) RC_p, and expected dispatch cost $\mathbb{P}_p DC_p$ for the duration of the DSO services. This objective is normalised to a single day, thus to calculate the actual cost, multiply this by the length of the contract, L in days.

Constraint (2) defines the cost of the reserve component of meeting the DSO service. This cost comprises:

- Cost from conventional units (first term)
- Cost from demand response units (second term)
- Negative of the benefit of the DSO service (third term)

Constraint (3) defines the cost of the dispatch for service. If the estimate for $\mathbb{P}_p$ is wrong, then the DSO would need to adjust their payments accordingly. Again this cost comprises

- Cost from conventional units (first term)

- Cost from demand response units (second term)
- Negative of the benefit of the DSO service (third term)

Constraint (4) defines an upper limit $\bar{\mathrm{P}}_{pi}^{Con} z_p$ on quantity of the upward regulation p_{pit}^{Con} of the conventional unit for each DSO service. It assumes that this may be different for each service.

Constraint (5) ensures that the number of cleared blocks is within the range that each aggregator specifies.

Constraint (6) ensures that only one type of block is cleared for each aggregator and is used to meet the DSO product p that clears the market.

During rebound periods, constraint (7) limits the amount of rebound to the size of the rebound block k.

Constraint (8) ensures that the market clears only one of the many possible DSO services.

Constraint (9) ensures that for each DSO service that we both meet the response requirement and we do not violate the rebound requirement at each time step. D_{pt}^{Reg} Defines the minimum response at each time step. Thus, at each time step t this constraint enforces that some combination of bids from conventional units p_{pit}^{up} and demand response units $Q_{pcdt}^{DR}\, r_{pcd}$ (an illustration of Q_{pcdt}^{DR} is given in Figure 1) meet or exceed the DSO service requirement D_{pt}^{Reg}. During periods that allow for a rebound, s_{pt}^{up} represents the amount of rebound that clears the market at each time step. The dual of this constraint defines the marginal cost of upward regulation $\pi(p, t)$ at each time step.

In the LP version of this problem, where the integer constraint on $\boldsymbol{r}$ and $\boldsymbol{z}$ are relaxed, $\boldsymbol{\pi}$ are the prices that correspond to the aggregators bidding into each service optimally. Now, as there are integer constraints, these prices will not necessarily lead to optimal demand response decisions. Thus, when determining the method of market clearing, we need to consider the trade-offs.

In some cases, the market clearing method may lead to the DSO overpaying units for their demand response, while others may underpay aggregators (meaning the aggregator won't recover the cost of participating in this market), or lead to far from optimal demand response decisions.

We list potential means of market clearing below, and in the results, we compare each of these methods using a case study and compare this with the model where we relax integer constraints.

Once the model is solved, we both dispatch and pay aggregators based on the cleared bids and the clearing price for each service at each time step. Below we present how we calculate the payments and profit of each agent, assuming each agent is offering at marginal cost.

2.4.1 Payment to each aggregator for meeting each DSO service

Here is how we calaculate the payments to each agent from the DSO for meeting each service. We assume agents are paid once by the DSO immediately after the market has cleared and they agree to meet the service.

$$PAY^{Con}_{pi} = \sum_{t\in\mathcal{T}} \pi_{p,t} p_{pit}, \tag{14}$$

$$PAY^{DR}_{pc} = \sum_{t\in\mathcal{T}} \sum_{d\in\mathcal{D}} \pi_{p,t} \mathrm{Q}^{DR}_{pcdt} r_{pcd}. \tag{15}$$

2.4.2 Profit of each aggregator for meeting each DSO service

Using the clearing price and corresponding decision variables we calculate the profit of each agent.

$$PROF^{Con}_{pi} = PAY^{Con}_{pi} - \sum_{t\in\mathcal{T}} \mathbb{T}_t \mathrm{C}^{R,Con}_{pit} p_{pit} - \mathbb{P}_p \sum_{t\in\mathcal{T}} \mathbb{T}_t \mathrm{C}^{D,Con}_{pit} p_{pit}, \tag{16}$$

$$PROF^{DR}_{pc} = PAY^{DR}_{pc} - \sum_{d\in\mathcal{D}} \mathrm{C}^{R,DR}_{pcd} r_{pcd} - \mathbb{P}_p \sum_{d\in\mathcal{D}} \mathrm{C}^{D,DR}_{pcd} r_{pcd}, \tag{17}$$

$$PROF^{DSO}_{p} = \sum_{t\in\mathcal{T}} \mathbb{T}_t \mathrm{C}^{R,DSO}_{pt} (\mathrm{D}^{Reg}_{pt} z_p - s_{pt}) + \mathbb{P}_p \sum_{t\in\mathcal{T}} \mathbb{T}_t \mathrm{C}^{D,DSO}_{pt} (\mathrm{D}^{Reg}_{pt} z_p - s_{pt}) \tag{18}$$

$$- \sum_{i\in\mathcal{I}} PAY^{Con}_{pi} - \sum_{c\in\mathcal{C}} PAY^{DR}_{pc}. \tag{19}$$

2.4.3 Changes in number of dispatch days

To adjust the payments to each aggregator based on the actual number of times $\mathbb{Q}_p$ they are dispatched at the end of the contract, and the dispatch cost that they bid, we calculate the adjustments in the payments to each company using the following.

$$NEWPAY^{Con}_{pi} = PAY^{Con}_{pi} + (\mathbb{Q}_p - \mathbb{P}_p) \sum_{t\in\mathcal{T}} \mathbb{T}_t \mathrm{C}^{D,Con}_{pit} p_{pit}, \tag{20}$$

$$NEWPAY^{DR}_{pc} = PAY^{DR}_{pc} + (\mathbb{Q}_p - \mathbb{P}_p) \sum_{d\in\mathcal{D}} \mathrm{C}^{D,DR}_{pcd} r_{pcd}. \tag{21}$$

Thus to calculate final profit of each company for meeting each service, we have the following.

$$NEWPROF^{Con}_{pi} = NEWPAY^{Con}_{pi} - \sum_{t\in\mathcal{T}} \mathbb{T}_t \mathrm{C}^{R,Con}_{pit} p_{pit} - \mathbb{Q}_p \sum_{t\in\mathcal{T}} \mathbb{T}_t \mathrm{C}^{D,Con}_{pit} p_{pit}, \tag{22}$$

$$NEWPROF^{DR}_{pc} = NEWPAY^{DR}_{pc} - \sum_{d\in\mathcal{D}} \mathrm{C}^{R,DR}_{pcd} r_{pcd} - \mathbb{Q}_p \sum_{d\in\mathcal{D}} \mathrm{C}^{D,DR}_{pcd} r_{pcd}, \tag{23}$$

$$NEWPROF^{DSO}_{p} = \sum_{t\in\mathcal{T}} \mathbb{T}_t \mathrm{C}^{R,DSO}_{pt} (\mathrm{D}^{Reg}_{pt} z_p - s_{pt}) + \mathbb{Q}_p \sum_{t\in\mathcal{T}} \mathbb{T}_t \mathrm{C}^{D,DSO}_{pt} (\mathrm{D}^{Reg}_{pt} z_p - s_{pt}) \tag{24}$$

$$- \sum_{i\in\mathcal{I}} NEWPAY^{Con}_{pi} \tag{25}$$

$$- \sum_{c\in\mathcal{C}} NEWPAY^{DR}_{pc}. \tag{26}$$

2.5 Possible market clearing methods

LP

We solve the LP version of the problem, completely relaxing the integer constraint on $\boldsymbol{r}$. We then use the dual of equation (9) to determine the price of upward regulation for each DSO service at each time step.

MIP allowing blocks dispatched below cost to be removed

We solve the MIP to find the optimal demand response decisions that satisfy each of the DSO products (giving $\boldsymbol{p}^*$, $\boldsymbol{r}^*$, and $\boldsymbol{s}^*$), fixing $\boldsymbol{r} = \boldsymbol{r}^*$ and $\boldsymbol{z} = \boldsymbol{z}^*$. We then use the dual of equation (9) to determine the price of upward regulation for each DSO service at each time step. If a unit finds one of their block bids lead to them not making a profit, they can remove it ($\boldsymbol{r}^* := \boldsymbol{r}^* - \boldsymbol{r}^*_{RemovedBid}$). We then fix $\boldsymbol{r} = \boldsymbol{r}^*$, and the process is then repeated without the removed bid until all of the block bid owners are happy.

MIP with side payments

If aggregators remove all of their unprofitable bids, the extra cost to the DSO from not having these services available may significantly outweigh the reduced payments to the aggregators. Thus, instead of removing these bids, the DSO can instead compensate these aggregators to ensure they break even.

The first part of this is identical to the market clearing method. We solve the MIP to find the optimal demand response decisions that satisfy each of the DSO products (giving $\boldsymbol{p}^*$, $\boldsymbol{r}^*$, $\boldsymbol{s}^*$, and $\boldsymbol{z}^*$). We then fix $\boldsymbol{r} = \boldsymbol{r}^*$ and $\boldsymbol{z} = \boldsymbol{z}^*$, re-solving the LP version of the problem. We then use the dual of equation (9) to determine the price of upward regulation for each DSO service at each time step. However, now the DSO pays each aggregator that has a negative profit enough to have precisely 0 profit from that service. Thus, PAY^{DR}_{pc} is now

$$PAY^{DR}_{pc} = \sum_{d \in \mathcal{D}} \left(\max \left(\sum_{t \in \mathcal{T}} \pi_{p,t} \mathrm{Q}^{DR}_{pcdt} r_{pcd} \quad , \quad (\mathrm{C}^{R,DR}_{pcd} + \mathbb{P}_p \mathrm{C}^{D,DR}_{pcd}) r_{pcd} \right) \right). \tag{27}$$

LP prices set with MIP upper bounds

An alternative to the use side payments, is instead solving the MIP model then solving the integer-relaxed version of the model using this solution as an upper bound. This ensures that each of the dispatched aggregator bids are profitable through the recalculated market clearing prices instead of side payments.

We solve the MIP to find the optimal demand response decisions that satisfy each of the DSO products (giving $\boldsymbol{p}^*$, $\boldsymbol{r}^*$, $\boldsymbol{s}^*$, $\boldsymbol{z}^*$). We then resolve the LP version of the problem enforcing the bounds ($\boldsymbol{p} \leq \boldsymbol{p}^* + \varepsilon$, $\boldsymbol{r} \leq \boldsymbol{r}^* + \varepsilon$, $\boldsymbol{s} \leq \boldsymbol{s}^* + \varepsilon$, and $\boldsymbol{z} \leq \boldsymbol{z}^* + \varepsilon$, where ε is a small positive number). We then use the dual of equation (9) to determine the price of upward regulation for each DSO service at each time step.

3 Results

Now we present a case study that compares the clearing method used in each of these models.

We also compare the effect of, for services that are activated based on signals, that the number of days that the signal is activated is different to what DSO announced.

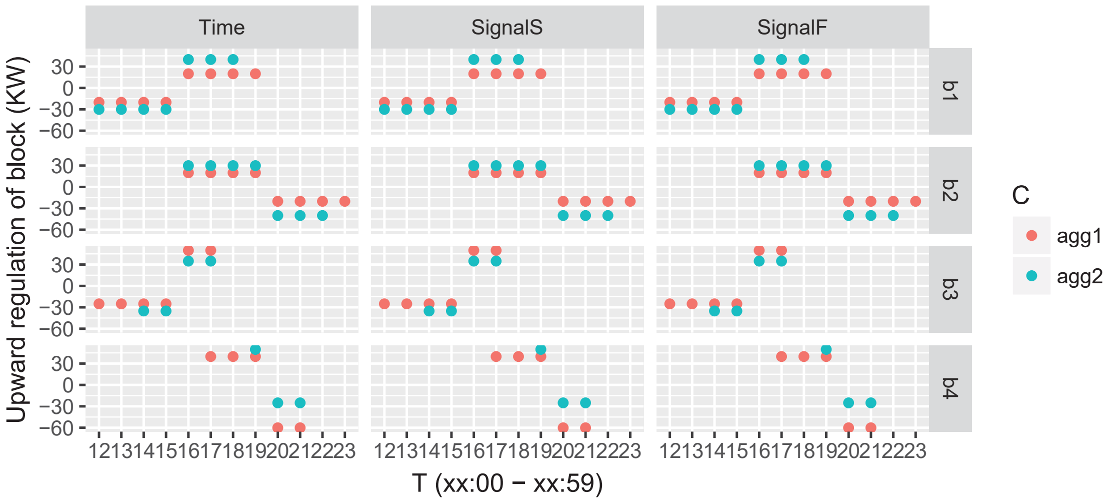

Figure 1: Visualisation of the blocks that each demand response units have offered. For this case study, we assume the blocks offered across services are identical, however this does not necessarily have to be the case.

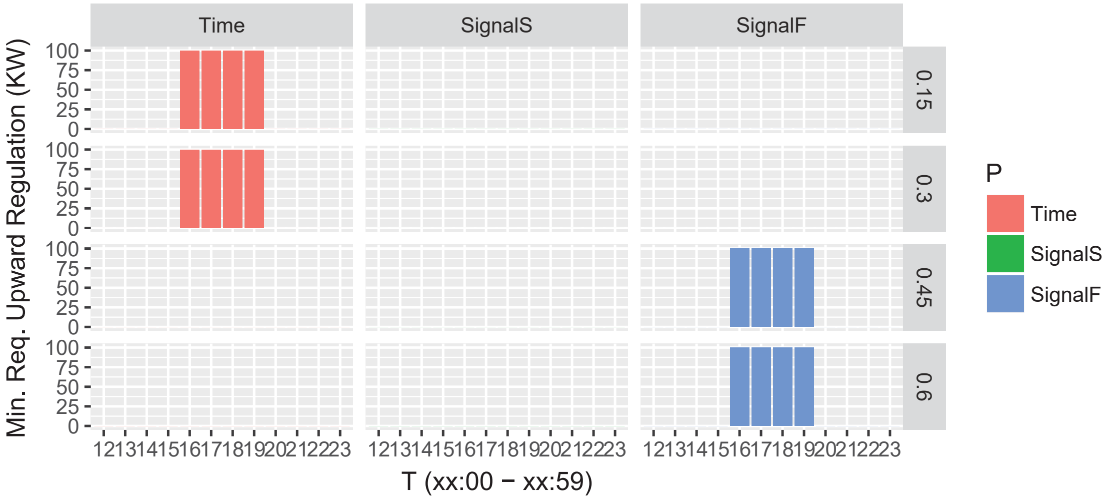

Figure 2: Cleared response for each type of service. For this case study, this is the same across all stated market clearing methods. The daily probability of activation for the *SignalF* is changed and shown on the right hand side of each facet of the plot (0.15, 0.3, 0.45, 0.6).

Table 1: Days expected to activate service p.

Service	$\mathbb{P}_p$	Length of service (Days)	Number of activation days
Time	1.0	L	L
SignalS	0.3	L	$0.3 \cdot$ L
SignalF	0.45	L	$0.45 \cdot$ L

Table 4: Reserve and dispatch benefit from service p.

Service	Time	$C_{pt}^{R,DSO}(\$/KWh)$	$C_{pt}^{D,DSO}(\$/KWh)$
Time	Response	1	6
SignalS	Response	1	10
SignalF	Response	1	10
Time	Rebound	0	1
SignalS	Rebound	0	1
SignalF	Rebound	0	1

Table 2: Reserve and dispatch cost, as well as bounds on the number of blocks d that can clear the market. In this example these costs are the same across services p. In this case study, the blocks across services have the same shape

Unit	Block	$C^{R,DR}_{pcd}$ ($\$/Blk$)	$C^{D,DR}_{pcd}$ ($\$/Blk$)	B^{DR}_{pct} (Blk)
$agg1$	$b1$	150	55	2
$agg1$	$b2$	150	55	2
$agg1$	$b3$	150	55	1
$agg1$	$b4$	150	55	1
$agg2$	$b1$	150	60	1
$agg2$	$b2$	150	60	1
$agg2$	$b3$	150	60	1
$agg2$	$b4$	150	60	1

Table 3: Reserve and dispatch cost of each conventional unit i for service p.

Service	Unit	$C^{R,Con}_{pit}$($\$/KWh$)	$C^{D,Con}_{pit}$($\$/KWh$)	$\bar{P}^{Con}_{pi}$ (KW)
$Time$	$conv1$	2	4.0	30
$Time$	$conv2$	2	4.1	30
$SignalS$	$conv1$	1	4.0	30
$SignalS$	$conv2$	1	4.1	30
$SignalF$	$conv1$	1	4.0	30
$SignalF$	$conv2$	1	4.1	30

3.1 Solve model as LP

In this subsection, we assume that all demand response units can be activated partially, removing the integer constraint on $\boldsymbol{r}$ and $\boldsymbol{z}$. Although this is unrealistic, it allows us to set a benchmark model.

In Figure 3 we see that the market clearing algorithm has chosen the $SignalF$ as the service that will lead to the highest total surplus. In Figure 4 we see how these offer blocks come together to meet the response requirements without violating the rebound requirement. In Figure 5 we increase $\mathbb{P}_{SignalF}$, which increases the benefit of clearing this service and increases the expected required number of activations. Specifically, when we set $\mathbb{P}_{SignalF} = 0.15$ or $\mathbb{P}_{SignalF} = 0.30$, we see that the $Time$ service is cleared rather than the $SignalF$ service.

In Figure 6, we plot the upward regulation price at each time t. With a non-zero rebound clearing price, a demand response unit will have to pay this price per unit of downward regulation for each of their activated blocks.

We see in Figure 8, focusing on the plot where $\mathbb{P}_{SignalF} = 0.45$ (FixPropEst) we see the difference in prices between the response period and the rebound period is sufficient for each demand response unit to recover their costs. However, as the amount of dispatch days for $SignalF$ deviates from 0.45 we see that if we do not adjust payments based on their dispatch costs, some agents will not recover their costs (seen where $\mathbb{P}_{SignalF} = 0.6$ in the *FixPropEst* model. In Figure 9 we plot the payment to each from the DSO.

In the LP version of the model, as long as each service is activated on average $\mathbb{P}_p$ times per day, then we will obtain the optimal offering strategies for each service assuming they are price takers. However, if a signal based service is activated more often than previously specified, the solution may no longer be optimal for that number of activation days. We also note that with this model, in both the *FixPropEst* and *PaymentAdjust* models, the DSO will have an incentive to say the number of dispatch days is much lower than reality as the bids would clear at a lower price. However, we would then have suboptimal decisions, and the aggregators may then offer dispatch costs that would factor this in (e.g. saying the dispatch cost is $\frac{\mathbb{Q}_p}{\mathbb{P}_p}\mathrm{C}^D$), negating any benefit to the DSO's mischaracterization of the probability, and increasing the uncertainty in the profit of each agent (assuming there is uncertainty in the number of activations of each service).

Instead of adjusting payments based on each agents dispatch cost is setting a maximum number of activations for each product. This has the advantage of eliminating the incentive to understate the required number of activations. However, now to optimise the use of this product, the DSO will have to solve a multi-stage MIP. Also, it is plausible to see a situation where the DSO will signal the service activation while it costs the aggregators more than the benefit it provides to the network. For example, say the DSO has purchased a signal based service with up to 10 activations. If near the end of the contract duration, there are still 9 activations for the service, the DSO may activate them for all of the remaining days, even if this costs the aggregators much more than the benefit it provides to the DSO.

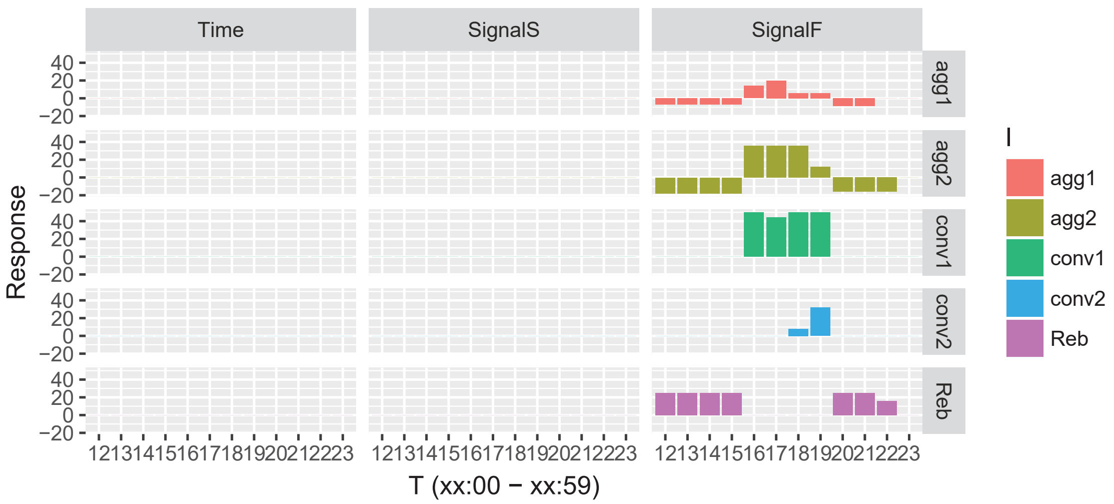

Figure 3: LP relaxation model: Upward regulation of each demand response unit in KW across all service types.

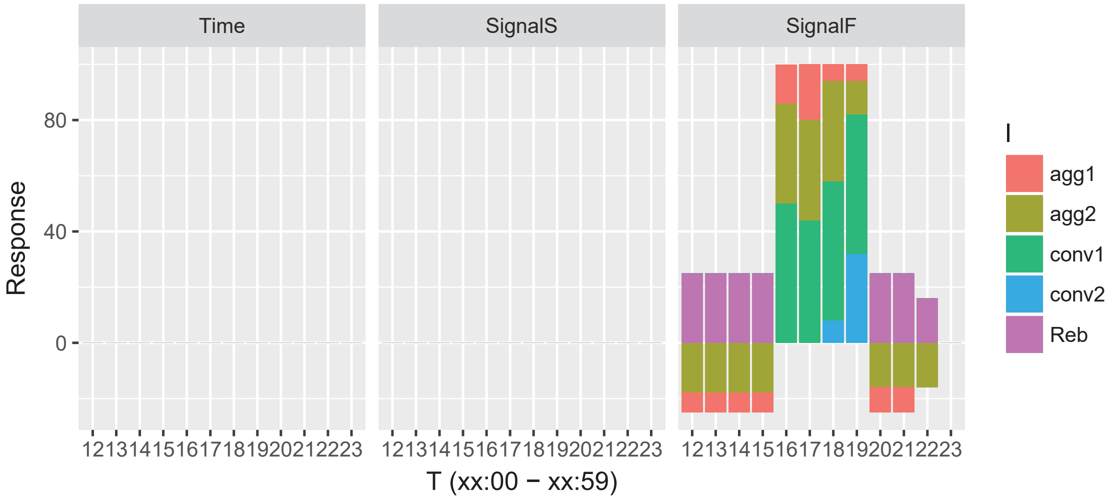

Figure 4: LP relaxation model: Stacked upward regulation of each demand response unit in KW across all service types. Shows that these units combine to satisfy the response and rebound requirements.

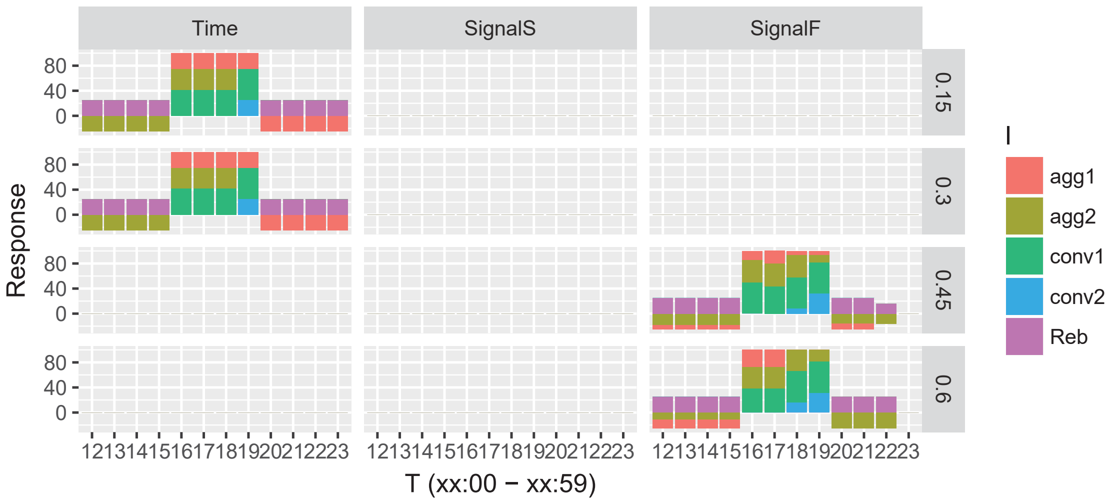

Figure 5: LP relaxation model: Stacked upward regulation of each demand response unit in KW across all service types. In each facet row we change the value of $\mathbb{P}_{SignalF}$ to the value shown in the right side of the plot (0.15, 0.3, 0.45, and 0.5 respectively). This plot shows how the market clears different DSO services as $\mathbb{P}_p$ changes.

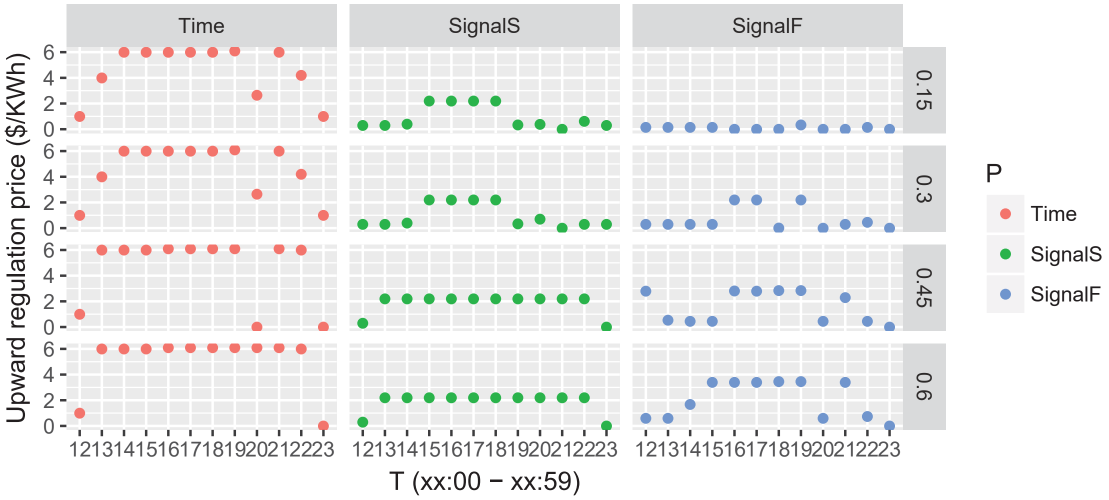

Figure 6: LP relaxation model: Upward regulation price for each service p at each time t.

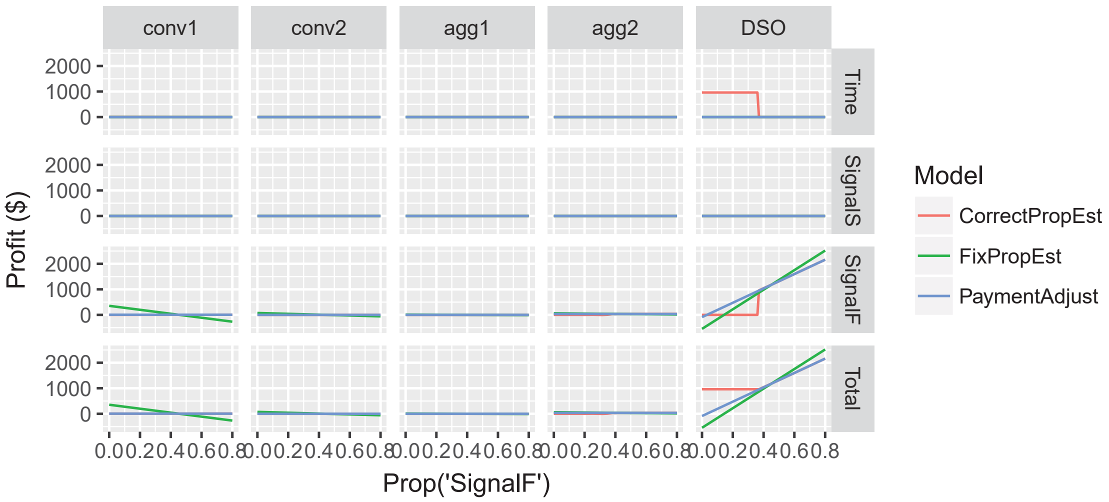

Figure 7: LP relaxation model: Agent Profit as the utilisation of a signal based service changes. *CorrectPropEst* assumes the DSO states the correct value for $\mathbb{P}_{SignalF}$ (thus no end of horizon adjustment is required). *FixPropEst* assumes that agents bid and are paid assuming $\mathbb{P}_{SignalF}$=0.45 and do not receive (or pay) an adjustment for being dispatched more or less often then $0.45 \cdot \text{L}$. *PaymentAdjust* adjusts the payment to each agent using the equations in sub-sub section 2.4.3.

Figure 8: LP relaxation model: Profit of each aggregator and the DSO service provider. *FixPropEst* assumes that agents bid and are paid assuming $\mathbb{P}_{SignalF}$=0.45 and do not receive (or pay) an adjustment for being dispatched more or less than $0.45 \cdot \text{L}$ days. *PaymentAdjust* adjusts the payment to each agent using the equations in sub-sub section 2.4.3.

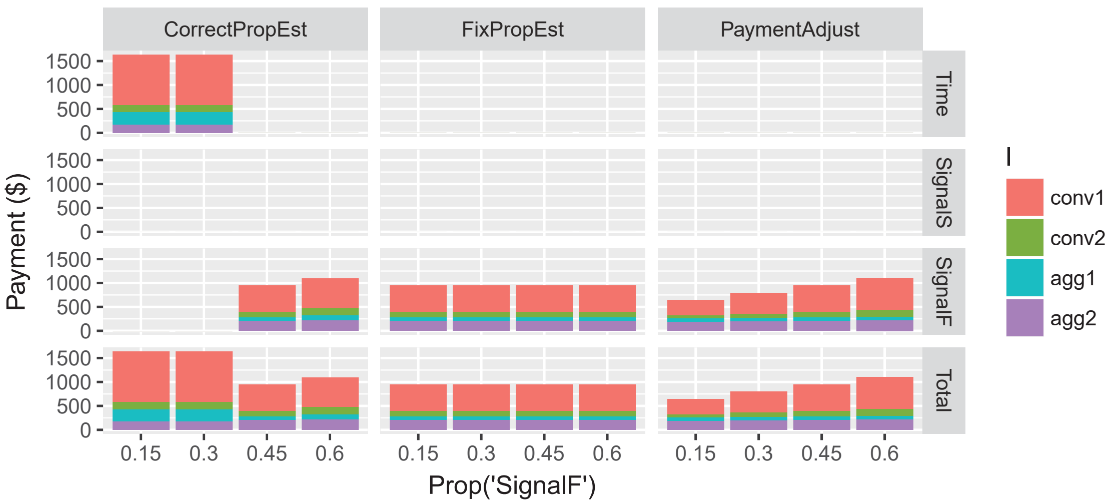

Figure 9: LP relaxation model: Payment to each aggregator. *FixPropEst* assumes that agents bid and are paid assuming $\mathbb{P}_{SignalF}$=0.45 and do not receive (or pay) an adjustment for being dispatched more or less than $0.45 \cdot \text{L}$ days. *PaymentAdjust* adjusts the payment to each agent using the equations in sub-sub section 2.4.3.

3.2 Opt out market clearing

Now including the integer constraint on $\boldsymbol{r}$, we compare different methods of clearing the market and highlighting the potential advantages and disadvantages of each method. We start with a method that simply solves the original problem (including the integer constraint on $\boldsymbol{r}$), fixes $\boldsymbol{r}$, then resolves the model to determine the payment to each agent.

In Figure 10, we see that part of the optimal solution may include upward regulation by a conventional unit during the rebound period. In this case, as the downward regulation of the $agg2$ service (both in $Time$ and $SignalF$) exceeds the allowed $25KW$ rebound, we require some upward regulation by the conventional unit to ensure feasibility. In 11 we see that these services combine to satisfy the minimum response and maximum rebound constraints. In Figure 12, we again note the potential importance that the number of dispatch days for each has on determining the service for which they will be used.

In Figure 13, we plot the upward regulation price at each time t. Again, with a non-zero rebound clearing price, a demand response unit will have to pay this price per unit of downward regulation for each of their activated blocks. However, in 14 we see that $agg2$ has a negative profit, due to the integer constraint, the difference in the market clearing prices during the response and rebound period now insufficient for $agg2$ to make a profit. Thus, in this model, they can choose to remove their bid, which would lead to suboptimal demand response decisions. We see in Table 4 how the removal of this bid affects both the system cost and the agent cost.

In Figure 14, similar to the LP model there still appears to be an incentive for the DSO to understate the number of activations even with the payment adjustment.

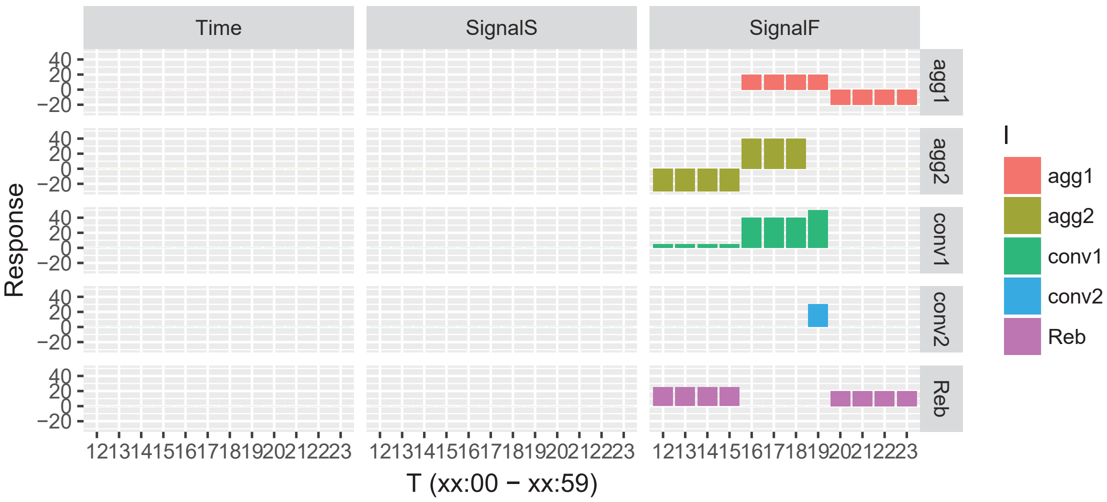

Figure 10: Opt out market clearing (before opt out): Upward regulation of each demand response unit in KW across all service types.

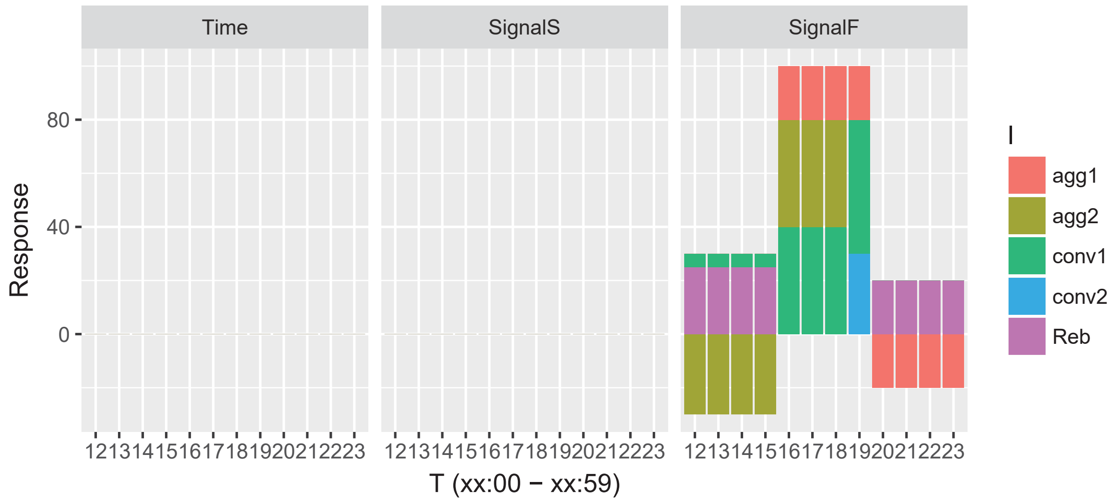

Figure 11: Opt out market clearing (before opt out): Stacked upward regulation of each demand response unit in KW across all service types. Shows that these units combine to satisfy the response and rebound requirements.

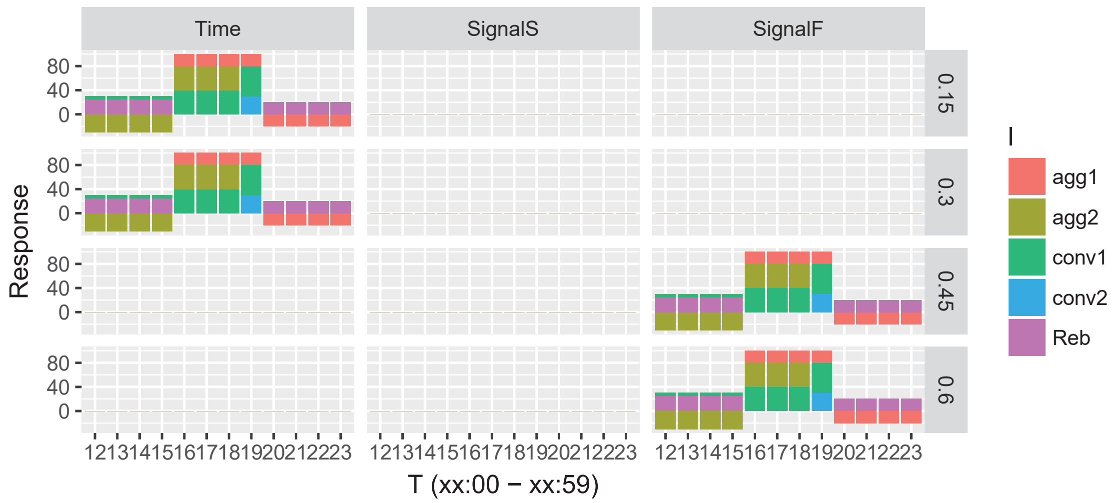

Figure 12: Opt out market clearing (before opt out): Stacked upward regulation of each demand response unit in KW across all service types. In each facet row we change the value of $\mathbb{P}_{SignalF}$ to the value shown in the right side of the plot (0.15, 0.3, 0.45, and 0.6 respectively). This plot shows how the market clears different DSO services as $\mathbb{P}_p$ changes.

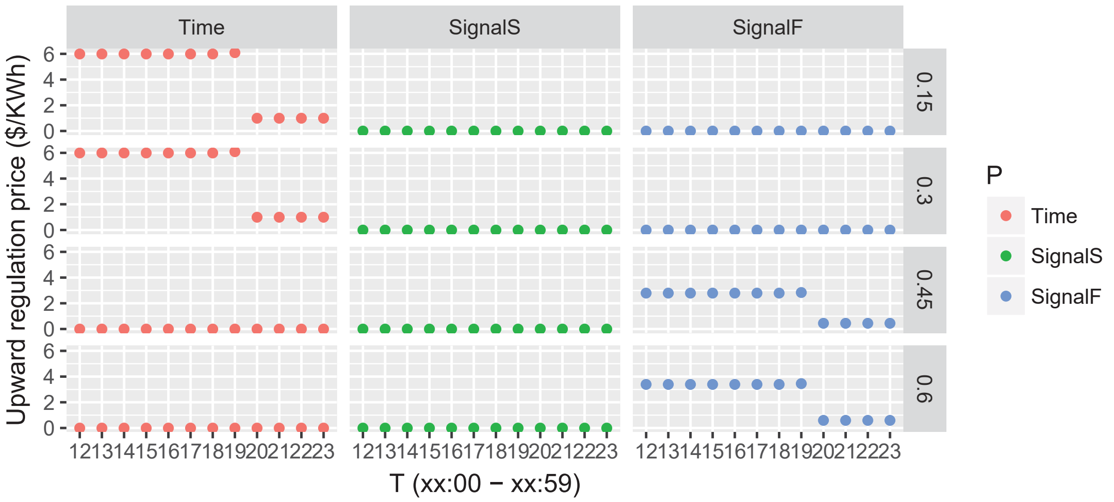

Figure 13: Opt out market clearing (before opt out): Upward regulation price for each service p at each time t.

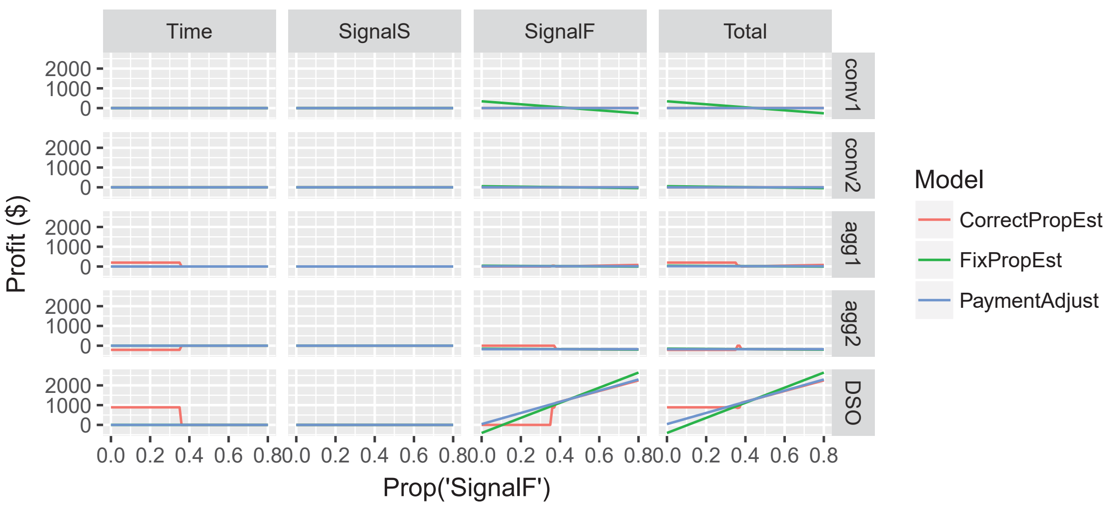

Figure 14: Opt out market clearing (before opt out): Agent Profit as the utilisation of a signal based service changes. *CorrectPropEst* assumes the DSO states the correct value for $\mathbb{P}_{SignalF}$ (thus no end of horizon adjustment is required). *FixPropEst* assumes that agents bid and are paid assuming $\mathbb{P}_{SignalF}$=0.45 and do not receive (or pay) an adjustment for being dispatched more or less than $0.45 \cdot \text{L}$ days. *PaymentAdjust* adjusts the payment to each agent using the equations in sub-sub section 2.4.3.

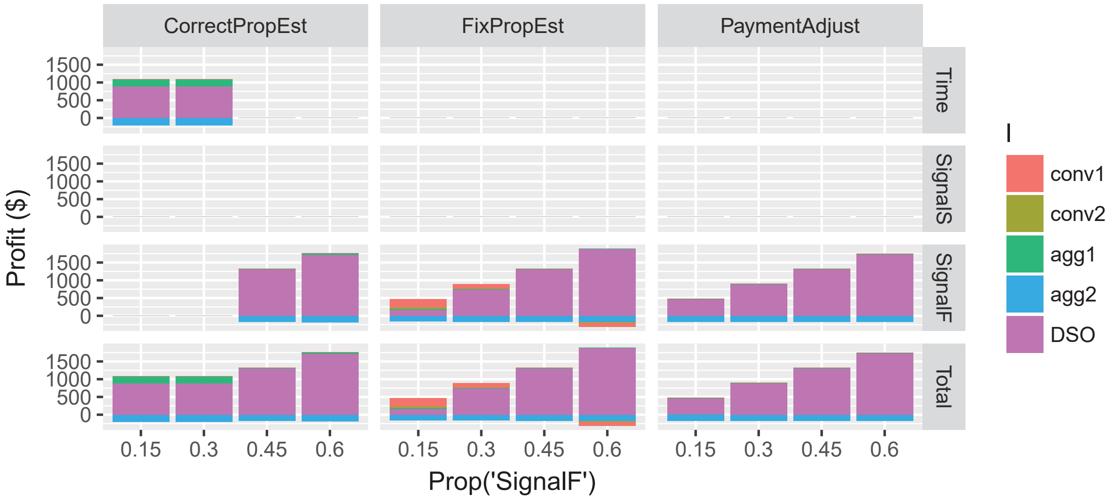

Figure 15: Opt out market clearing (before opt out): Profit of each aggregator and the DSO service provider. *FixPropEst* assumes that agents bid and are paid assuming $\mathbb{P}_{SignalF}$=0.45 and do not receive (or pay) an adjustment for being dispatched more or less than $0.45 \cdot \mathrm{L}$ days. *PaymentAdjust* adjusts the payment to each agent using the equations in sub-sub section 2.4.3.

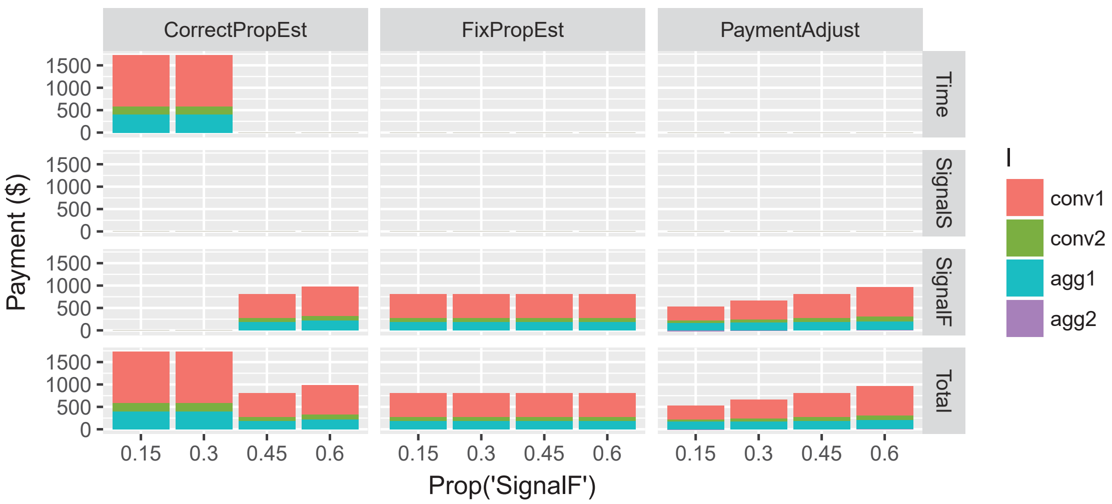

Figure 16: Opt out market clearing (before opt out): Payment to each aggregator. CorrectPropEst assumes that agents bid and are paid assuming $\mathbb{P}_{SignalF}$=0.45.

3.3 Removing unprofitable bid and resolving

The aggregator $agg2$ is dispatched below cost in meeting both the $Time$ product and the $SignalS$ product. Thus, it may decide to remove its bid from the market. Now we show the results after resolving this model fixing $r_{Time,agg2,b1}$ and all other block bids not currently used to 0. We talk more about this section in the discussion in section 4.

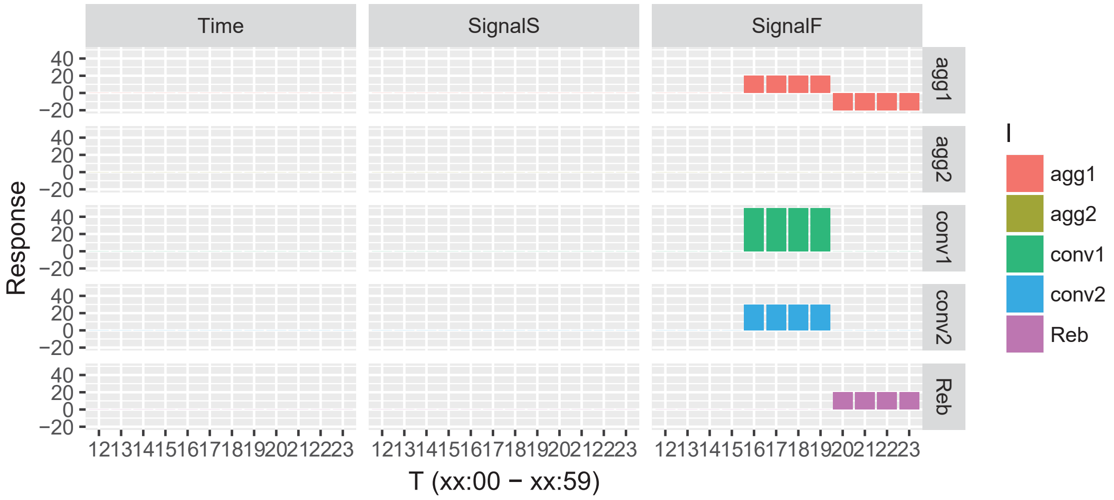

Figure 17: Opt out market clearing (after opt out): Upward regulation of each demand response unit in KW across all service types.

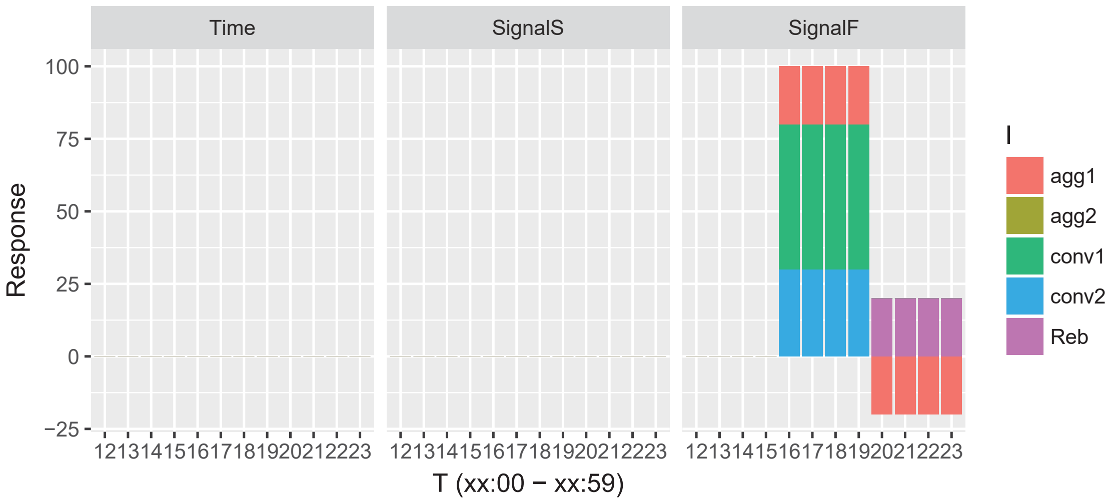

Figure 18: Opt out market clearing (after opt out): Stacked upward regulation of each demand response unit in KW across all service types. Shows that these units combine to satisfy the response and rebound requirements.

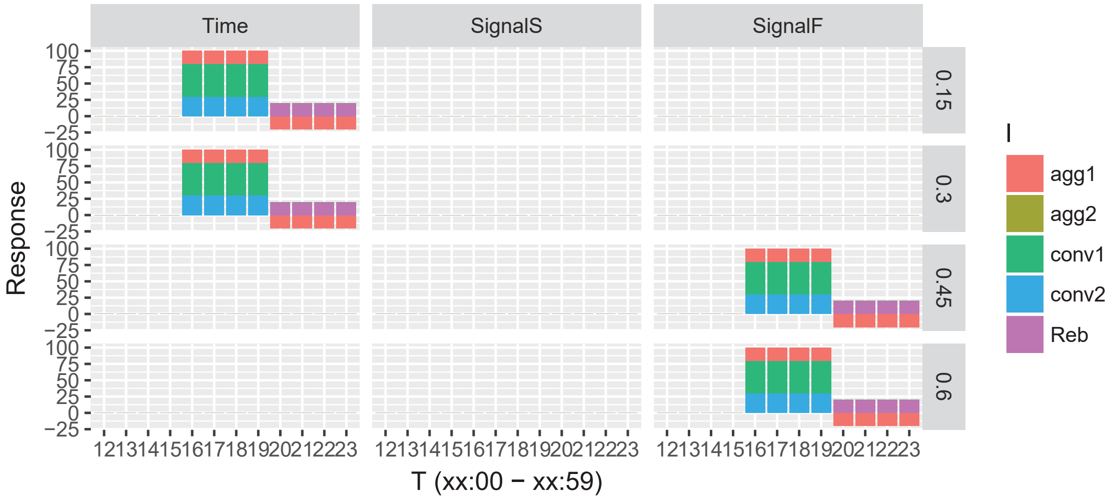

Figure 19: Opt out market clearing (after opt out): Stacked upward regulation of each demand response unit in KW across all service types. In each facet row we change the value of $\mathbb{P}_{SignalF}$ to the value shown in the right side of the plot (0.15, 0.3, 0.45, and 0.5 respectively). This plot shows how the market clears different DSO services as $\mathbb{P}_p$ changes.

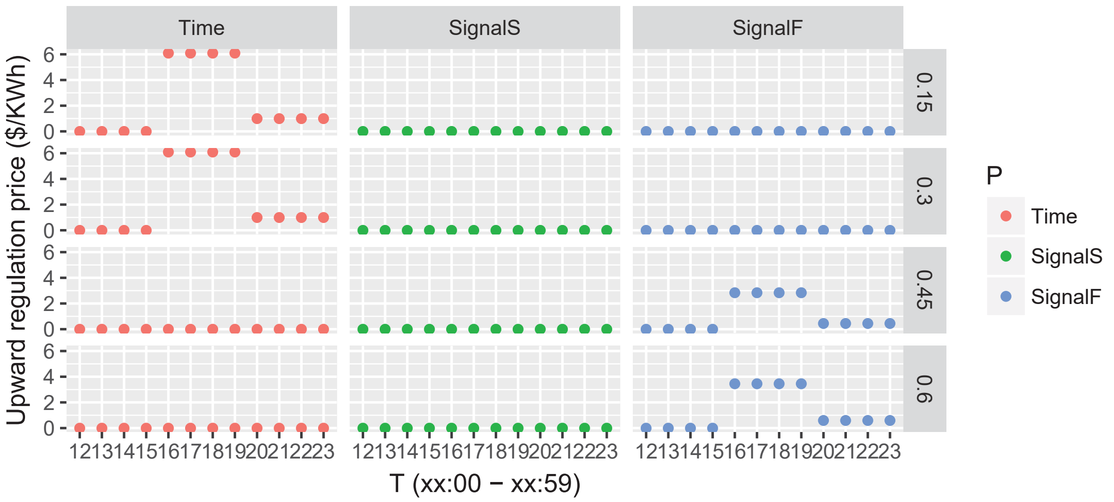

Figure 20: Opt out market clearing (after opt out): Upward regulation price for each service p at each time t.

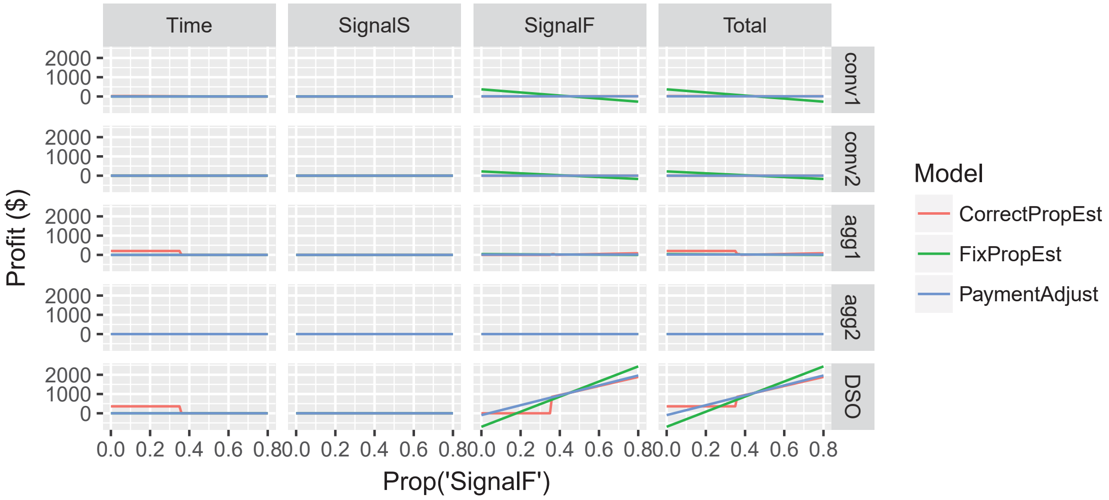

Figure 21: Opt out market clearing (after opt out): Agent Profit as the utilisation of a signal based service changes. *CorrectPropEst* assumes the DSO states the correct value for $\mathbb{P}_{SignalF}$ (thus no end of horizon adjustment is required). *FixPropEst* assumes that agents bid and are paid assuming $\mathbb{P}_{SignalF}$=0.45 and do not receive (or pay) an adjustment for being dispatched more or less than $0.45 \cdot \text{L}$ days. *PaymentAdjust* adjusts the payment to each agent using the equations in sub-sub section 2.4.3.

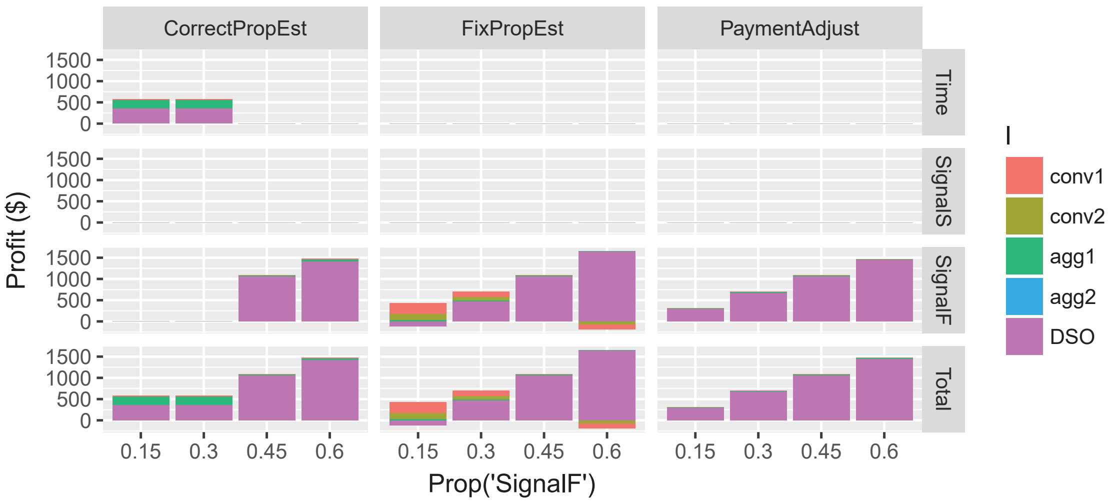

Figure 22: Opt out market clearing (after opt out): Profit of each aggregator and the DSO service provider. *FixPropEst* assumes that agents bid and are paid assuming $\mathbb{P}_{SignalF}$=0.45 and do not receive (or pay) an adjustment for being dispatched more or less than $0.45 \cdot \text{L}$ days. *PaymentAdjust* adjusts the payment to each agent using the equations in sub-sub section 2.4.3.

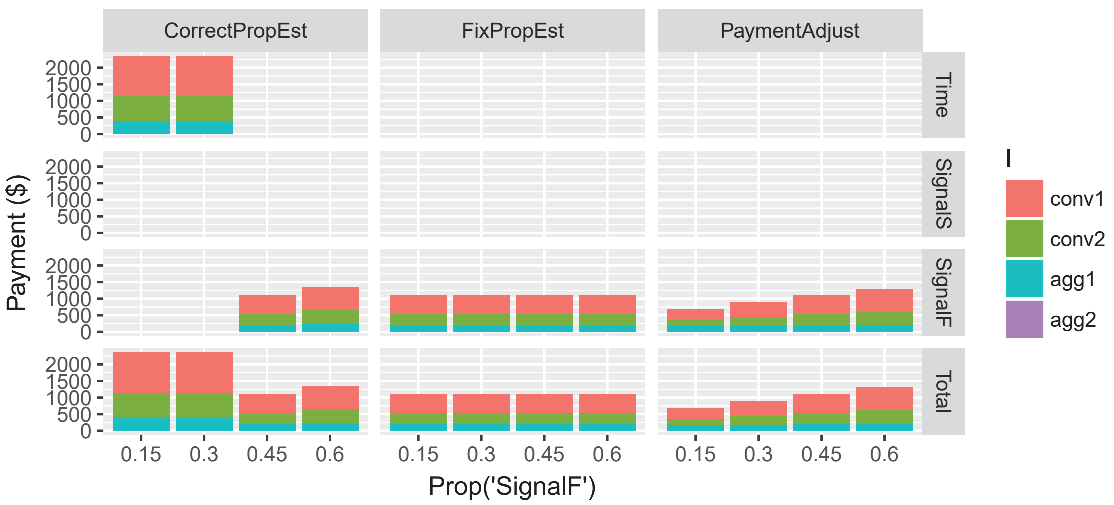

Figure 23: Opt out market clearing (after opt out): Payment to each aggregator. CorrectPropEst assumes that agents bid and are paid assuming $\mathbb{P}_{SignalF}$=0.45.

3.4 MIP with side payments

Comparing Figure 10 with Figure 24, and Figure 13 with 27, we see that these models have the same demand response decisions and upward regulation prices (before the bid is removed from the 'Opt out' model). Due to the side payments, in 29 we see that now no agent has a negative profit.

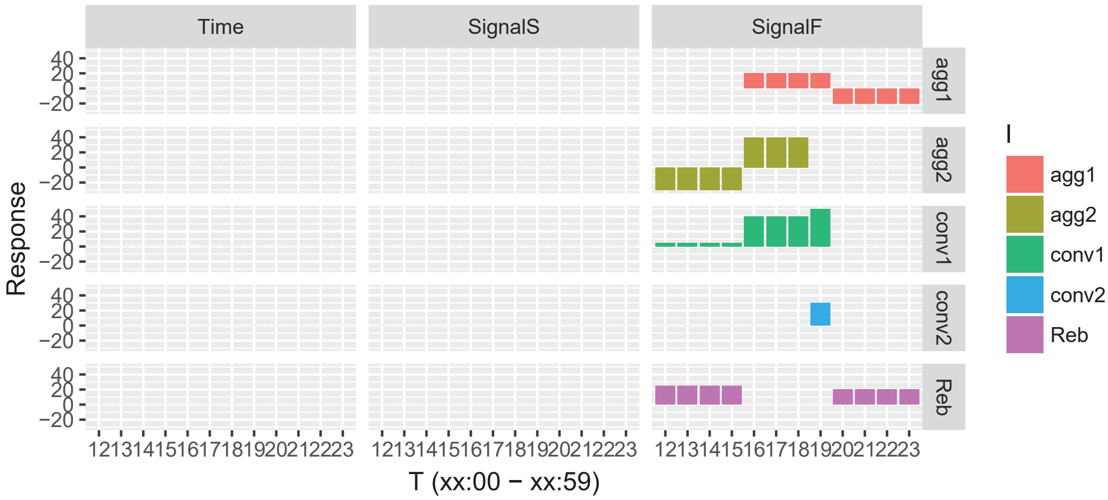

Figure 24: MIP with side payments: Upward regulation of each demand response unit in KW across all service types.

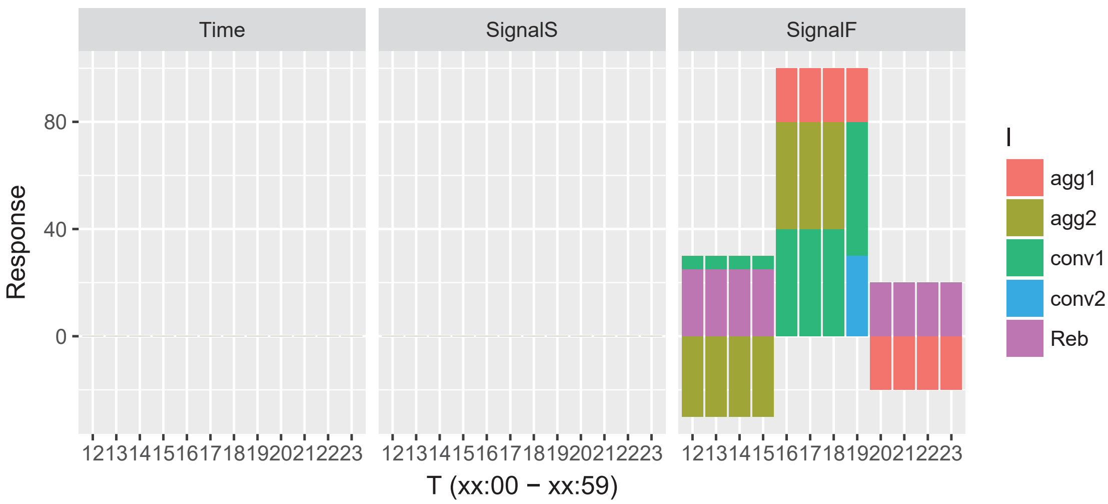

Figure 25: MIP with side payments: Stacked upward regulation of each demand response unit in KW across all service types. Shows that these units combine to satisfy the response and rebound requirements.

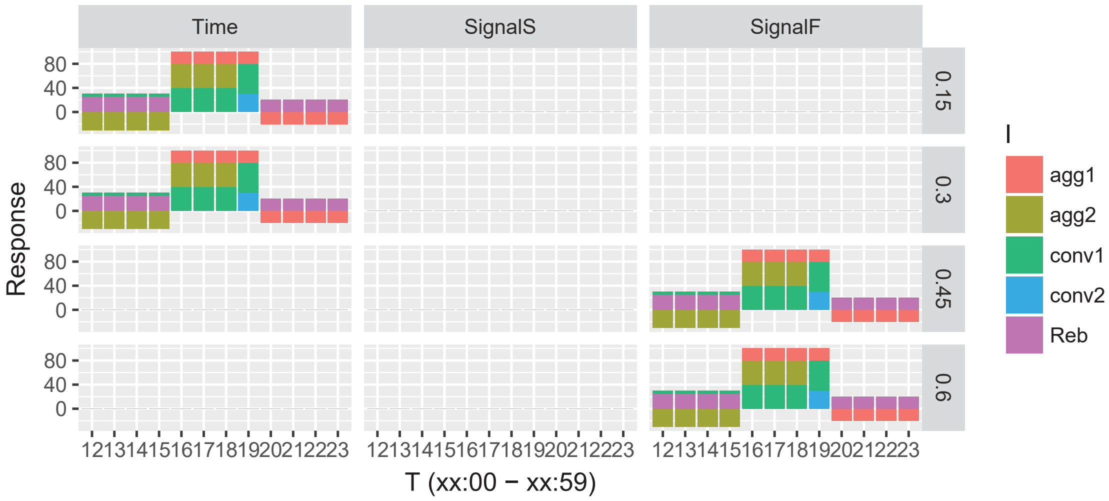

Figure 26: MIP with side payments: Stacked upward regulation of each demand response unit in KW across all service types. In each facet row we change the value of $\mathbb{P}_{SignalF}$ to the value shown in the right side of the plot (0.15, 0.3, 0.45, and 0.5 respectively). This plot shows how the market clears different DSO services as $\mathbb{P}_p$ changes.

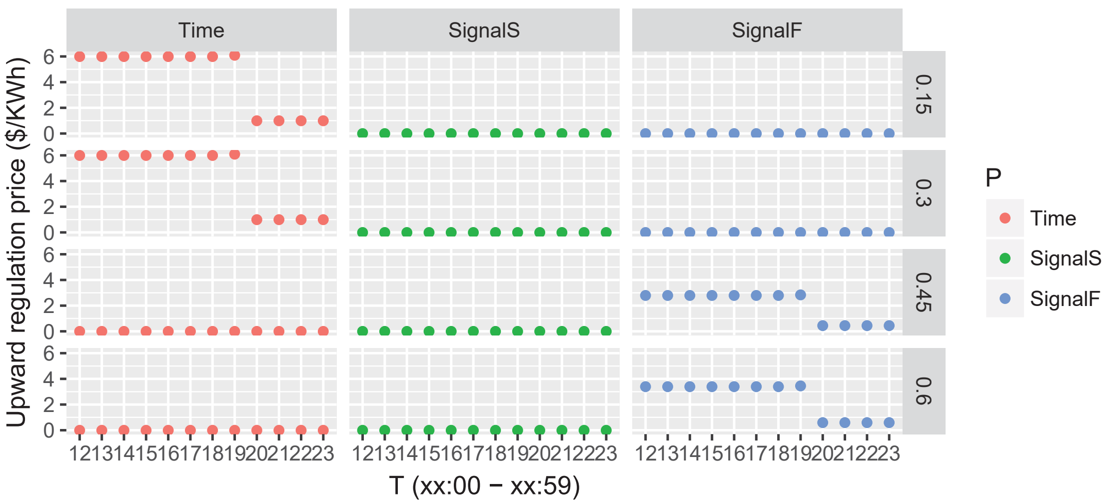

Figure 27: MIP with side payments: Upward regulation price for each service p at each time t.

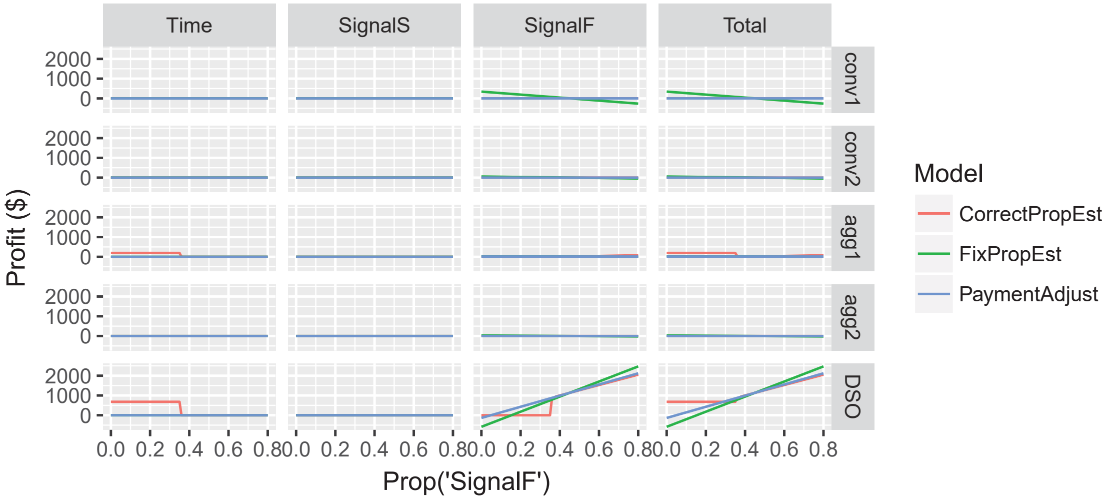

Figure 28: MIP with side payments: Agent Profit as the utilisation of a signal based service changes. *CorrectPropEst* assumes the DSO states the correct value for $\mathbb{P}_{SignalF}$ (thus no end of horizon adjustment is required). *FixPropEst* assumes that agents bid and are paid assuming $\mathbb{P}_{SignalF}$=0.45 and do not receive (or pay) an adjustment for being dispatched more or less than $0.45 \cdot \text{L}$ days. *PaymentAdjust* adjusts the payment to each agent using the equations in sub-sub section 2.4.3.

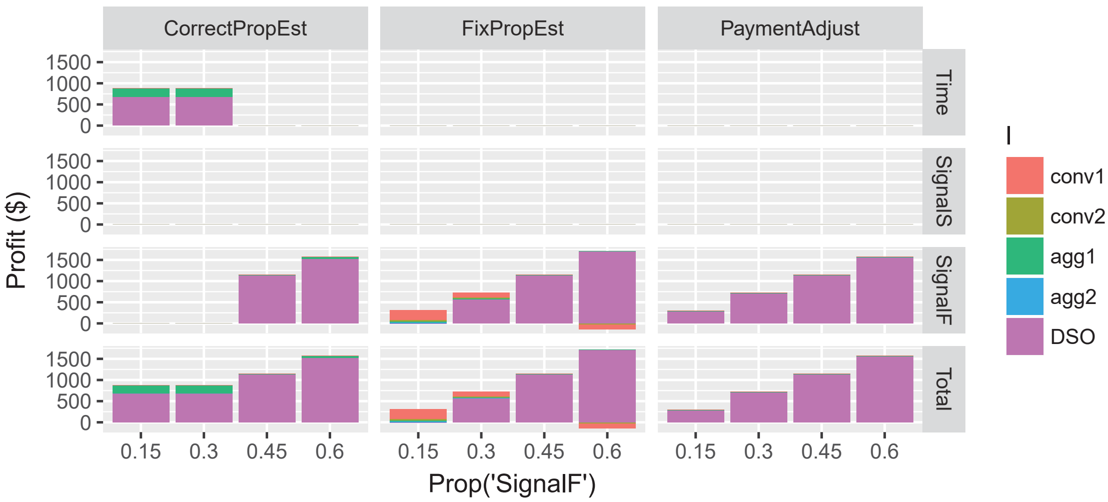

Figure 29: MIP with side payments: Profit of each aggregator and the DSO service provider. *FixPropEst* assumes that agents bid and are paid assuming $\mathbb{P}_{SignalF}$=0.45 and do not receive (or pay) an adjustment for being dispatched more or less than $0.45 \cdot \text{L}$ days. *PaymentAdjust* adjusts the payment to each agent using the equations in sub-sub section 2.4.3.

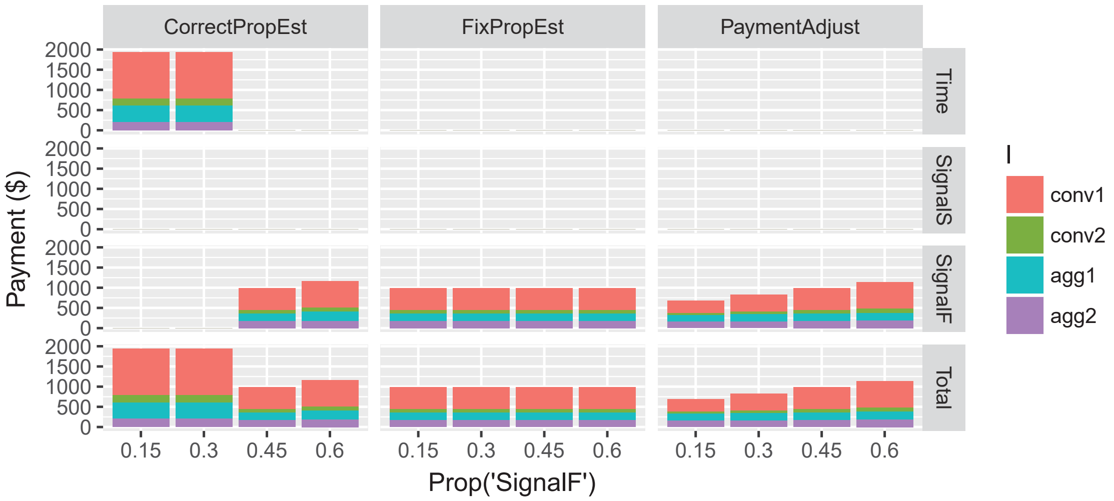

Figure 30: MIP with side payments: Payment to each aggregator. CorrectPropEst assumes that agents bid and are paid assuming $\mathbb{P}_{SignalF}$=0.45.

3.5 LP prices set with MIP upper bounds

Here we show the results for our case study when we solve the problem as a MIP, thus providing the minimum cost solution based on the aggregators bids. We then resolve as an LP setting the MIP solution as an upper limit for each decision, obtaining the clearing price. Thus, the price at each time step should be determined While prices are cleared high enough for all of the bids to be profitable, we see that in figure 36 the profit from the *SignalF* service for the DSO is negative, where they could improve their profit to zero for this service by exclusively not purchasing any regulation.

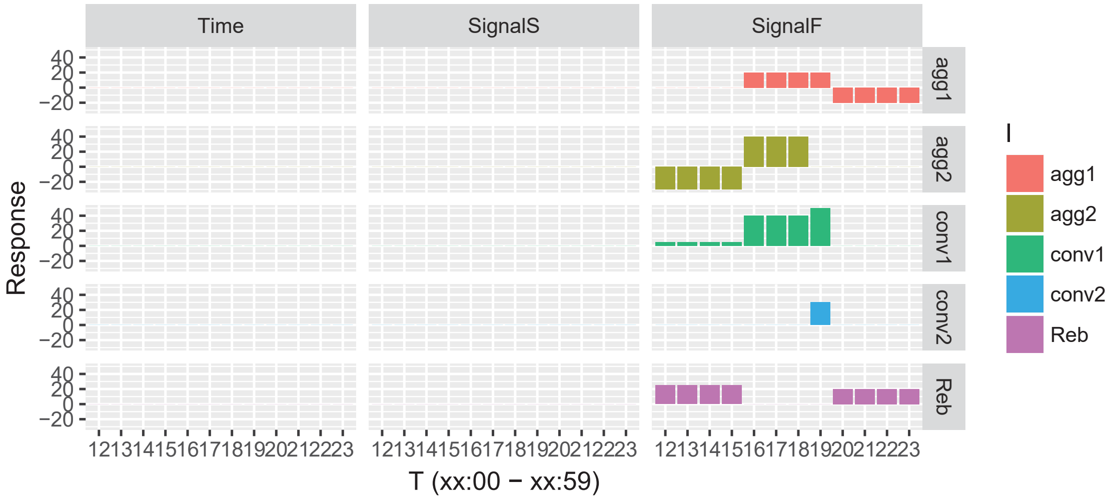

Figure 31: MIP upper bound LP price: Upward regulation of each demand response unit in KW across all service types.

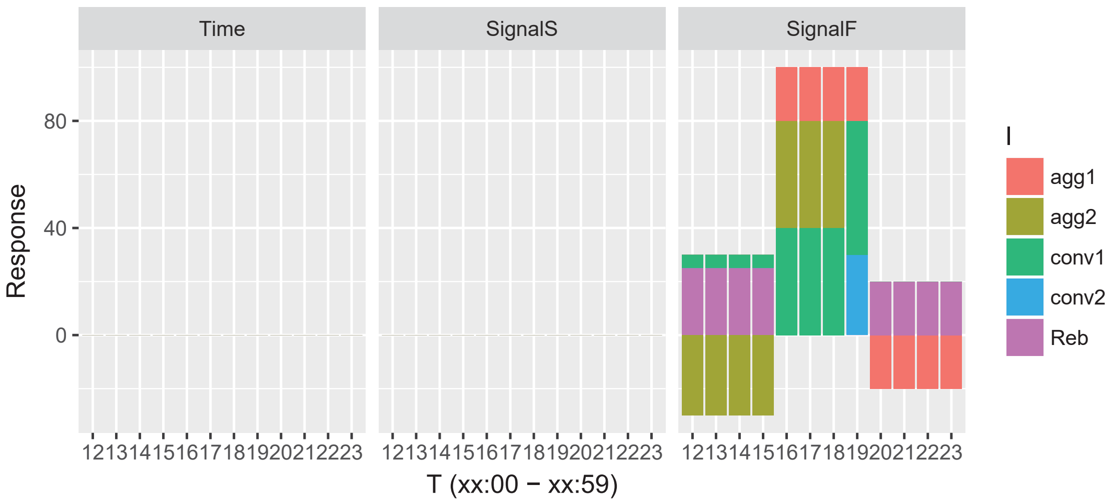

Figure 32: MIP upper bound LP price: Stacked upward regulation of each demand response unit in KW across all service types. Shows that these units combine to satisfy the response and rebound requirements.

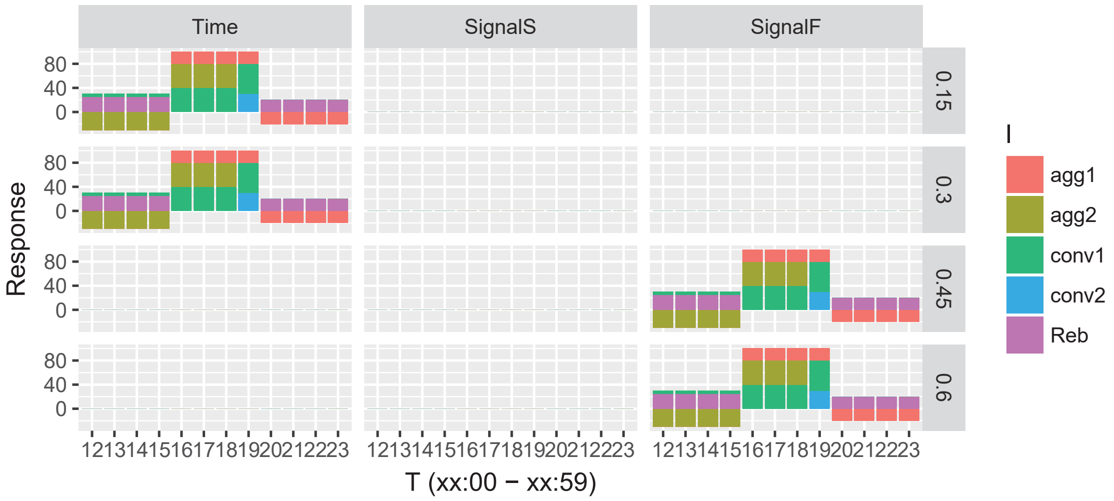

Figure 33: MIP upper bound LP price: Stacked upward regulation of each demand response unit in KW across all service types. In each facet row we change the value of $\mathbb{P}_{SignalF}$ to the value shown in the right side of the plot (0.15, 0.3, 0.45, and 0.5 respectively). This plot shows how the market clears different DSO services as $\mathbb{P}_p$ changes.

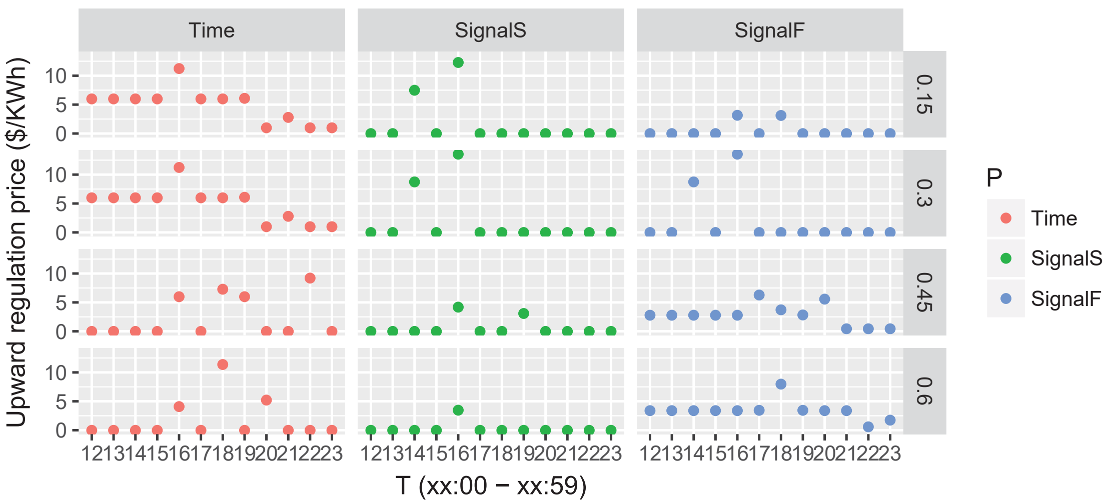

Figure 34: MIP upper bound LP price: Upward regulation price for each service p at each time t.

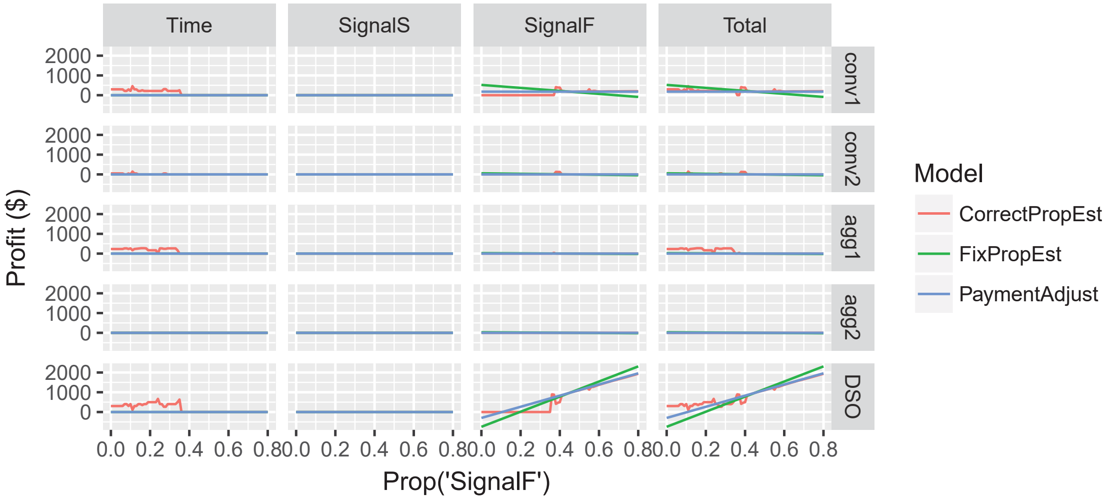

Figure 35: MIP upper bound LP price: Agent Profit as the utilisation of a signal based service changes. *CorrectPropEst* assumes the DSO states the correct value for $\mathbb{P}_{SignalF}$ (thus no end of horizon adjustment is required). *FixPropEst* assumes that agents bid and are paid assuming $\mathbb{P}_{SignalF}$=0.45 and do not receive (or pay) an adjustment for being dispatched more or less than $0.45 \cdot \mathrm{L}$ days. *PaymentAdjust* adjusts the payment to each agent using the equations in sub-sub section 2.4.3.

Figure 36: MIP upper bound LP price: Profit of each aggregator and the DSO service provider. *FixPropEst* assumes that agents bid and are paid assuming $\mathbb{P}_{SignalF}$=0.45 and do not receive (or pay) an adjustment for being dispatched more or less than $0.45 \cdot \mathrm{L}$ days. *PaymentAdjust* adjusts the payment to each agent using the equations in sub-sub section 2.4.3.

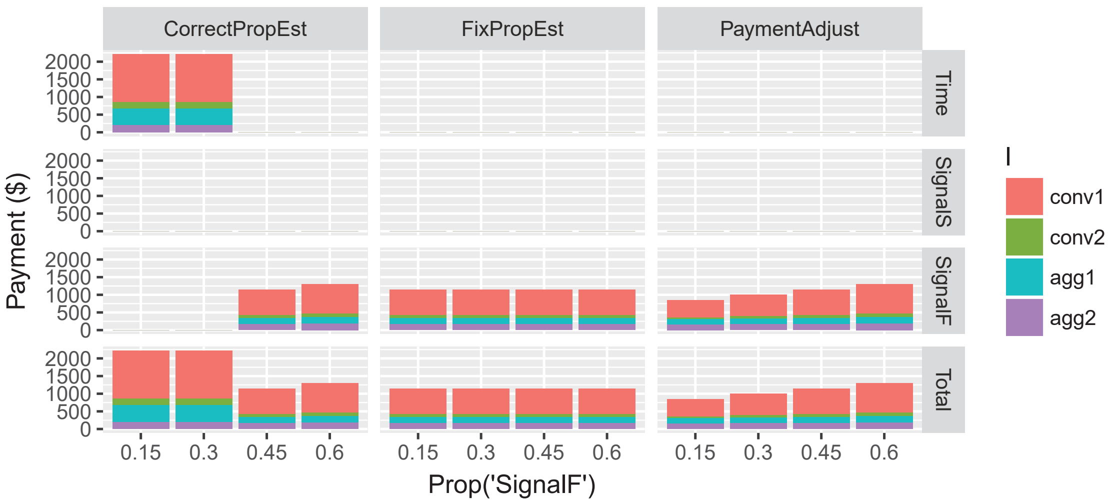

Figure 37: MIP upper bound LP price: Payment to each aggregator. CorrectPropEst assumes that agents bid and are paid assuming $\mathbb{P}_{SignalF}$=0.45.

4 Discussion

In Table 5, we see that modelling the integer constraints on the demand response units *agg*1 and *agg*2, can substantially reduce the cost of the demand response. Without any uplifting, *agg*2 has a negative profit despite being providing load-shifting that is very beneficial to the system (as shown when we remove one of its blocks). With given bids, the use of side payments is the cheapest method for the DSO to prevent any negative profits (without turning this into a pay-as-bid model) and supports the optimal demand response decisions. The MIP upper bound method does not require any side payments. However, it increases the payments the DSO pay each aggregator and does not encourage smaller block bids.

Thus, overall the side payments method seems to be the least complicated and will lead to the optimal dispatch decisions. However, there may be second order effects where the 'opt-out' method of market clearing may encourage smaller block bids into the market, preventing the need of side-payments all together.

Table 5: Profit of each agent and the system as a whole in each model.

	LP	MIP fix $\boldsymbol{r}$	MIP after bid removed	MIP after side payments	MIP upper bound price
conv1	5.20	2.25	9.00	2.25	179.25
conv2	0.00	0.00	0.00	0.00	0.00
agg1	0.00	14.15	16.85	14.15	0.00
agg2	34.22	-177.00	0.00	0.00	0.00
DSO	1176.74	1310.50	1062.00	1133.50	970.65
Total	1230.02	1149.90	1087.85	1149.90	1149.90

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