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Identification and Quantification of the Flexibility Potential of a Complex Industrial Process for Ancillary Services Provision

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Abstract—As the share of variable renewable energy sources in the electricity generation mix increases, so does the need for power system flexibility. Demand side flexibility has been identified as a great opportunity to facilitate the integration of this volatile production. An important part of demand side flexibility is the modulation of the consumption of industrial processes. With the emergence of ancillary services markets, operating industrial processes in a flexible manner might generate additional value. This paper proposes a flexibility assessment tool to quantify the potential of a given industrial plant for grid services provision. We start by formulating the feasible operating region of a given industrial asset, generating a set of operating points and their corresponding power ramping potential. A weekly simulation is then performed which leads to a set of most-observed operating points, themselves leading to a set of potential ancillary services bids from the industrial process.

Index Terms—Ancillary Service Provision, Flexibility Quantification, Flexibility Valorisation, Multi-product Industrial process

I. INTRODUCTION

The increase in global warming and depletion of natural resources inevitably lead society to make an energy transition. Increased renewable energy penetration in the energy mix is a major part of this energy transition. However, Variable Renewable Energy (VRE) sources make energy production more volatile. Power system flexibility has already been identified as one of the main levers to manage this supply volatility [1]. While conventional generation flexibility has been the go-to for many years, it is slowly being pushed out of the scheduling by the growing share of VRE in the power mix, therefore reducing the amount of dispatchable power used in system balancing. VRE not only reduces the amount of flexibility that generators can provide in the power system, it also increases generation uncertainty and seasonal dependency [2].

As a result, new ways must be found to provide power system flexibility. Demand-side flexibility has been identified as a great opportunity to facilitate the integration of VRE. Flexibility provided by the modulation of industrial processes, also called industrial flexibility, is an important pool of demand side flexibility owing to their large power and energy demand [3]. The valorisation of the available flexibility levers is vital

for industrial actors trying to provide grid services. Valorisation analyses can only be performed with relevant information regarding the capacity of a plant to provide said services [4]. Identifying and quantifying the existing flexibility levers in a complex industrial process is a much researched subject. However, the existing work does not focus on the provision of grid services when quantifying the flexibility of industrial processes. There is therefore a need for decision making tools to help industrial actors with grid services provision. This paper proposes a systematic approach to identify and quantify existing flexibility levers within a multi-product industrial plant in the context of flexibility services provision.

II. BIBLIOGRAPHY AND STATE OF THE ART

The problem of assessing the flexibility potential of a plant has been researched for many years. In the seminal work by Swaney and Grossmann [5], they define flexibility as “the ability of a design to tolerate and adjust to variations in conditions which may be encountered during operation”. They introduce a flexibility index that gives a measure of the feasible space under steady-state operation by formulating an optimization problem to find the largest possible hyper-rectangle within the flexibility region of a process. With the flexibility index comes the flexibility test to assess whether a process is flexible enough under given uncertain conditions. Since then, flexibility analysis has become a prolific topic. Other optimization methods have later been applied to analyse process flexibility [6, 7], and parallel have been made between flexibility analysis and robust optimization methods [8]. Surrogate model approaches have also been used to assess the flexibility of a process [9, 10]. Grossmann et al. published a historical overview [11] of the various publications on the subject of flexibility analysis. The aforementioned works focused on representing the outer envelope of the flexibility region, but more recent work focused on producing a more complete description by applying quantifier elimination [12], space projection [13], or Cylindrical Algebraic Decomposition [14, 15]. When analyzing the flexibility of a process, the accent is put on remaining within the feasible space while under uncertain conditions. While the later work aims at representing the whole feasible space of a given process,

it does not consider the possible valorisation of flexible movement within this space. However, with the evolution of power systems, and the emergence of Ancillary Services (AS) markets, operating industrial processes in a flexible manner might generate additional value [16]. Therefore, there is a need for flexibility assessment tools that will quantify the potential of a given industrial plant for grid services provision. The main contribution of this paper is twofold. First, we propose to quantify the flexibility available for ancillary provision in an industrial plant by identifying feasible operating points and their associated power flexibility potential. Second, we analyze the behavior of the plant under a given set of conditions, and extract a list of potential bids for ancillary provision based on the expected consumption profile. In Section III we present the process and the assumptions made regarding its modeling and operation. Section IV describes the feasible space of operation. The flexibility of the plant is then analyzed, first in Section V, which considers the potential value of decreasing the efficiency of the plant to increase plant consumption, and second in Section VI where the available power ramping of the plant is shown under standard operation.

III. USE-CASE PRESENTATION

The use-case considered in this study is an industrial manufacturing process taking raw material as an input, and transforming it into two product outputs. A representation of the system is shown in Figure 1. The process behavior is simulated by solving the following optimization problem (Whose symbols and equations are explained next):

$$\begin{aligned} & \underset{\substack{E_{t, \{PC_1, PC_2\}}, \\ Q_t^{In}, Q_{t, \{p_1, p_2\}}^{Out}, \\ L_{t, p}, W_{t, \{p_1, p_2\}}}}{\text{minimize}} \sum_t^T E_t^{DA} \cdot \delta_t^{DA} - \sum_p (L_{T, p} - L_{0, p}) V_p \quad (1) \\ & \text{s.t. :} \end{aligned}$$

Mass Conservation Constraints:

$$Q_t^{In} = f(Q_{t, \{p_1, p_2\}}^{Out}, W_{t, \{p_1, p_2\}}, \text{Parameters}), \quad \forall t \quad (2)$$

Product Storage and Demand:

$$L_{t, p} = L_{t-1, p} + Q_{t, p}^{Out} - Q_{t, p}^{Demand}, \quad \forall t > 1, p \quad (3)$$

$$L_{T, p} \geq L_{0, p}, \quad \forall p \quad (4)$$

Power Components:

$$E_{t, c} = g(Q_{t, c}, \text{Parameters}), \quad \forall t, c \quad (5)$$

Energy Balance:

$$E_t^{DA} = \sum_c E_{t, c}, \quad \forall t \quad (6)$$

With:

$p \in \{p_1, p_2\}$ the two products,

$t \in \{0, \dots, T\}$ the time steps,

and $c \in \{PC_1, PC_2\}$ the two power components

For simplicity, at this stage of the work and for this whole paper, linear behavior is assumed for the optimization. We therefore make the assumption that the processing behavior,

and the corresponding mass conservation constraints, can be described in a linear fashion. The same assumption is made for the constraints linking the power consumption of the components to the components throughput. The exact product quantities and units are of little interest for this study, and will therefore be expressed with a general unit U, and the flow in U/h.

The optimization problem mainly aims at minimizing the overall electricity consumption cost. This is the purpose of the first term of the objective function. The electricity is purchased on the day-ahead market (DA) and the plant power consumption is represented by 2 power components (PC_1 and PC_2). The purpose of the second term of the objective function is to assign a monetary value V_p to any excess product p in storage at the end of the simulation. This excess product in storage is represented by the difference between the first and final state of storage for each product. The demand has to be met regardless of the electricity price, therefore there is no need to put it in the objective function. A certain monetary value (V_{p1} and V_{p2}) is assigned to each product, expressed in €/U. The input flow Q^{In} is linked to the two output flows (Q_{p1}^{Out} and Q_{p2}^{Out}) by a set of mass conservation constraints represented by (2). Product outputs present a codependency, as both the minimum and maximum amounts of available product output are dependent on each other. The process has the possibility to waste a certain amount of each product (W_{p1} and W_{p2}). The maximum amount of waste is constrained by the input flow. Each product ($p1$ and $p2$) is stored in the corresponding stock (L_{p1} and L_{p2}), and the demand flows (Q_{p1}^{Demand} and Q_{p2}^{Demand}) are drawn directly from the respective product stocks. The storage level evolution is modeled by (3). A two-way efficiency of 1 is assumed for the product storage model, the storage evolution at time t is therefore only dependent on the previous state of the storage $L_{t-1, p}$, what is put in storage $Q_{t, p}^{Out}$, and what is drawn from it to satisfy the corresponding demand $Q_{t, p}^{Demand}$. Equation (4) ensures that the level at the end of the simulation is higher or equal to its initial level. This is necessary as the span of the simulation is limited, and stored product needs to be kept for any following time steps not included in the simulation. As previously mentioned, the electricity consumed by the power components (E_{PC1} and E_{PC2}) is expressed as a linear function of the throughput (Q^{In} for PC_1 and Q_{p2}^{Out} for PC_2). The electricity consumption is expressed in kWh, and the power in kW. The corresponding constraint is (5). Finally, the total plant electricity consumption E^{DA} is the sum of the electricity consumption of the power consuming components as shown in (6). Regarding the variable bounds, each flow has both minimum and maximum values to be respected, as well as a maximum ramping constraint. The maximum ramping of the flows is expressed in U/min. In this work, the time resolution will be set to an hour. We assume that this resolution could be decreased to a minute with the same linear assumptions.

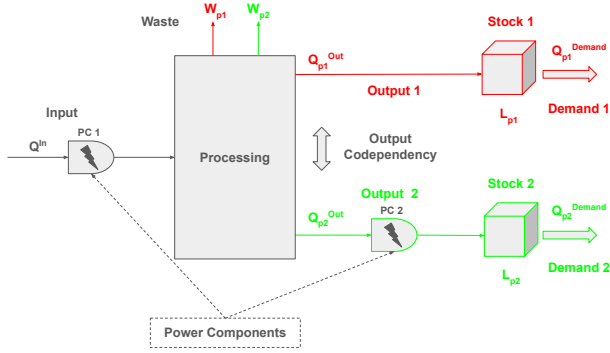


Fig. 1. Use-case overview

IV. FEASIBLE SPACE OF OPERATION

Before quantifying the flexibility, the overall operating space of the plant has to be assessed. Since the output only consists of 2 products in our use-case, the feasible space can be represented in 2 dimensions, one per product. The aim is to create a grid of potential operating points, based on a combination of each product output. Each axis of the grid will consist of a range of possible product outputs. The range of values on these axes are created based on the known maximum and minimum possible outputs for each product. The two axes create a grid of possible couples of product outputs. Each potential operating point will be tested for feasibility, and the feasible space will consist of all the feasible operating points. In order to check a point for feasibility, the product outputs will be forced to the corresponding operating point values. The optimization problem will run over a single time step. To ensure the satisfaction of (4) regardless of the chosen operating point, the demands are set to zeros when solving the problem. If the problem is feasible and returns a solution, the optimal power consumed by the plant is recorded for the corresponding operating point, otherwise the operating point is set as unfeasible. Figure 2 shows a heatmap of the feasible operating points, with the magnitude being the corresponding optimal power consumption. We can observe that the variation of product output 2 has more impact on the plant power consumption, which can be explained by the fact that an additional power component is necessary to manufacture it, as shown in Figure 1. We can also point out the fact that while each product has a set minimal value, the operating point at which both product outputs are at their minimum is not feasible. The same observation can be made regarding the maximal output values. Finally, some of the operating points present similar power consumption levels, for different power productions. It is for instance the case of operating points $\{1,700; 3,400\}$ U/h and $\{1,800; 3,400\}$ U/h, which both consume 12,086 kW. This indicates that some of the feasible operating points are more efficient than others, as they deliver a higher product output for the same power consumption. We can therefore expect some operating points to be favored when operating the plant optimally.

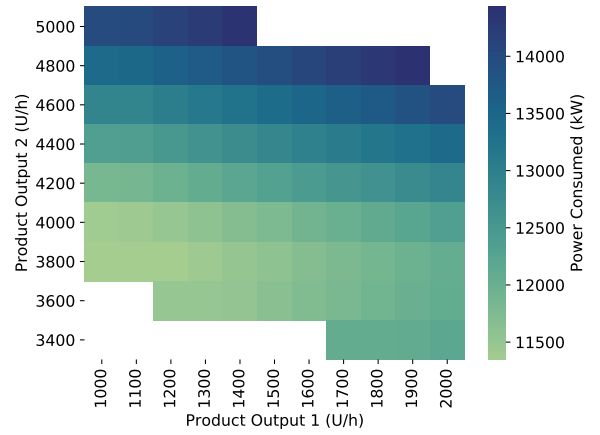


Fig. 2. Optimal power bought for each operating point

V. EFFICIENCY MANAGEMENT FOR POWER CONSUMPTION FLEXIBILITY

In this section, we consider the impact of varying the plant efficiency on power consumption by modulating product waste. By modulating waste, the power consumption of a plant can be increased up to a certain maximum value for a given operating point. By consuming more than necessary for a given operating point, we loose on a potential increase in product output, therefore decreasing efficiency. The aim of this study is to link the cost of lost product to the gain in power flexibility, in order to quantify the minimum power valorisation necessary to make the lower efficiency profitable. While the conventional practices are that a plant has to run optimally in any situation, some particular situations might cause a loss of efficiency to become financially viable. An example would be a provision of downward regulation from the plant (and therefore an increase in consumption), with a plant that cannot afford to increase its product output due to stock constraints. Decreasing the efficiency would allow the plant to over-consume while keeping the same product output, therefore respecting its obligation toward the TSO and helping to balance of the grid. For this study, we employ the operating points describing the feasible operating space from Section IV. For each of these points, the optimization problem is run on a single time step, here with an incentive to consume as much as possible (in the form of a negative electricity price that will contribute to minimizing the objective function of the optimization problem). This run will return the maximum power that could be consumed by the plant for a given operating point. By combining this power consumption with the optimal consumption, which is also the minimum amount of power for a given plant output, a range of consumption can be established for every operating point. The next step is to quantify the minimum revenue that would make this inefficient operation worthwhile. To do so, we use the unitary values of the products, V_{p1} and V_{p2} . These values represent the selling value of a unit of product. They are multiplied by the amount of additional product that would have been

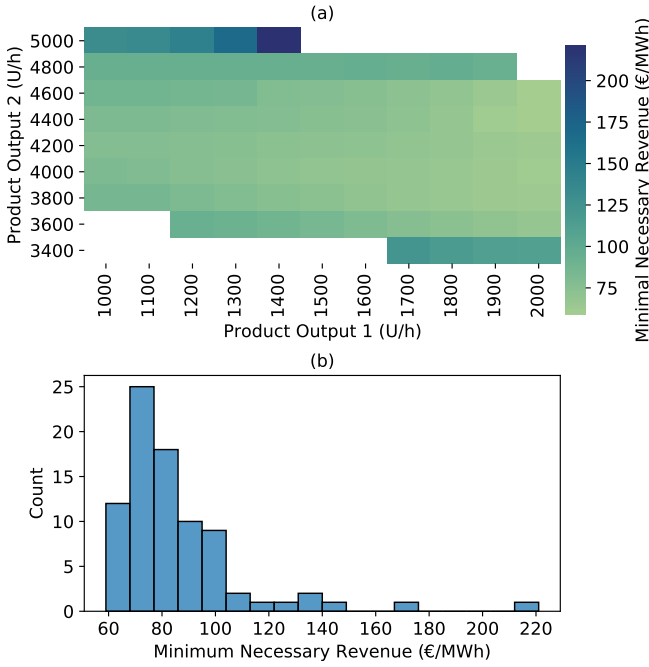


Fig. 3. (a) Minimum revenue for reduced production efficiency. (b) Histogram of the minimum revenue for reduced production efficiency

produced had we operated the plant optimally, thus yielding the minimal necessary revenue. Dividing this value by the amount of additional MWh that can be consumed, the minimal revenue is expressed in €/MWh.

An example of this could be the production of 100 U/h of product 1 and 200 U/h of product 2, using 1 MW of power. The plant could go up to 2 MW, with a similar output. However, the optimal production for 2 MW would be 200 U/h of product 1 and 400 U/h of product 2. This means that by reducing the efficiency to increase the consumption of 1 MW, we are missing out on the revenue corresponding to 100 U/h of product 1 and 200 U/h of product 2. Now let us imagine that each U of product 1 has a value of 2 €/U while the same value of product 2 is 1 €/U.

This would yield a lost revenue of $100 * 2 + 200 * 1 = 400$ €, for an increase in power consumption of 1 MW, ultimately leading to a necessary revenue of at least 400 €/MWh when valuating this extra electricity consumed. A heatmap of the various minimum revenue values and a histogram presenting the distribution of these values are shown in Figure 3.

In our case, the lost revenue ranges from 60 to 220 €/MWh. Obtaining this kind of revenue from downward regulation appears extremely unlikely. Therefore, reducing the efficiency would most likely be performed in emergency cases to avoid balancing penalties and minimize losses when they are unavoidable.

VI. OPERATIONAL FLEXIBILITY ANALYSIS

In this section, our analysis aims at quantifying the amount of power a plant could provide to AS. First, we assess the maximum ramping in both direction, for each operating point

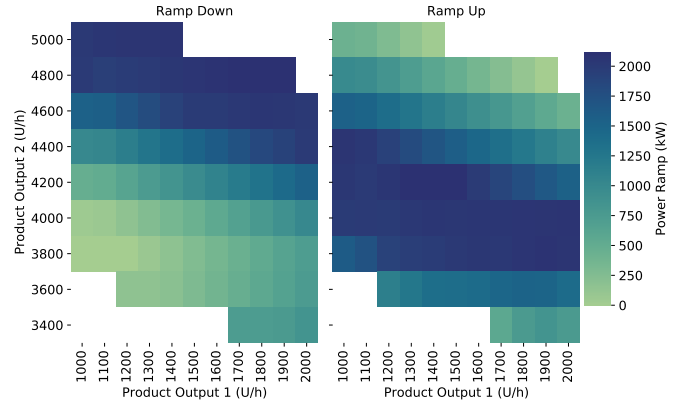


Fig. 4. Available power ramp for each operating point in both direction

presented in Section IV. Second, we perform a week long simulation, in order to locate the usual operating points that the plant goes through under standard conditions. Finally, we extract the usual amount of flexibility a plant could provide from these operating points.

A. Power Ramping Analysis

This analysis employs the optimal power consumption levels shown in Figure 2. Here, the optimization runs on multiple consecutive time steps. The goal is to calculate the number of time steps necessary to go from one operating point to another, for each possible combination of operating points. For each combination, the number of time steps needed is recorded, and only those that need a maximum of one time step are retained for this analysis. A transition in only 1 time step means that the power shift within the plant could be used to provide AS if the correct length is affected to a time step. For instance, for an ancillary service requiring the offered power in a maximum of 5 minutes, choosing a 5 min time step would ensure that any power shift could be applied to this particular service.

Each operating point can have multiple transitions respecting the one time-step condition. Only the two extreme transitions will be kept for each operating point. The first will be the largest negative power ramping, and the second will be the largest positive ramping. Extracting these two transitions for every operating points will illustrate the maximum available power flexibility of each operating point in both directions. These ramping capacities are illustrated in Figure 4.

For both directions, the available ramp ranges from 0 to 2 MW. As it could be expected, the more the plant consumes, the more upward regulation it can provide by ramping-down its power. The opposite observation can be made for the ramping-up capacity of the plant. However, the ramping-up capacity is lower when product 2 is at its minimal output capacity.

When considering ancillary service provision, it is important to consider both symmetric and asymmetric provision, as some ancillary services will only allow symmetrical bidding. The face ramping value shown in Figure 4 can be kept for asymmetrical bidding. However, when considering symmetrical bidding, a new heatmap has to be drawn, presented in Figure 5.

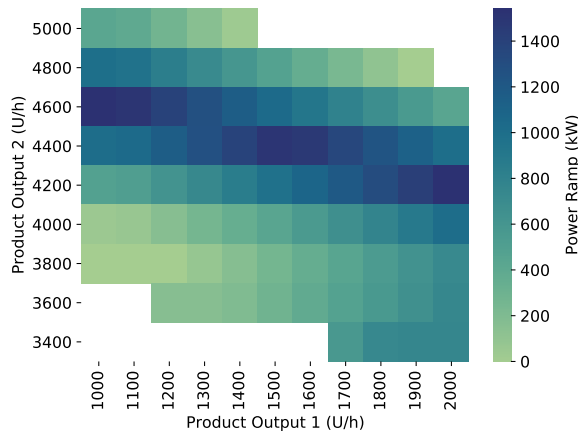


Fig. 5. Available symmetrical power ramp for each operating point

This heatmap presents the lowest ramping value of the two directions, for each operating point. The observed available ramp for symmetric provision ranges from 0 to 1.5 MW. While the asymmetrical ramping favors extremes in product output, symmetrical ramping favors the center of the feasibility region. In both cases, product 2 appears to have more impact on the available ramping. This is once again most likely due to the fact that it needs an additional power component.

B. Weekly Simulation

Following the identification of the ramping potential of the various operating points, we run a weekly simulation to establish which of these operating points are the most commonly used in specific circumstances. The demand profile and electricity prices have been set to resemble the plant's usual operation. The demand profile for this week-long simulation is presented in Figure 6. The profile is a succession of similar daily demand evolutions, with different magnitudes from one day to the next. The electricity provision is done through the day-ahead market. The used prices are presented in Figure 7. Finally, the characteristics of the product storage are presented in Table I. Each storage has a total capacity, expressed in kU, and both minimum and maximum filling values, expressed as a percentage of the total capacity of the storage.

The optimization problem run for this simulation is similar to the one used in the previous sections. By minimizing the cost, the problem will play around both the varying prices and the demand. This will allow the problem to navigate between operating points. The storage level evolution and the power consumption of the power plant and its components are presented in Figure 8. We can observe that the plant effectively changes its consumption to reduce the overall cost of the simulation, therefore going through multiple operating points. In addition, it is worth noting that most of the power consumption comes from power component 2, which is only used when producing product 2.

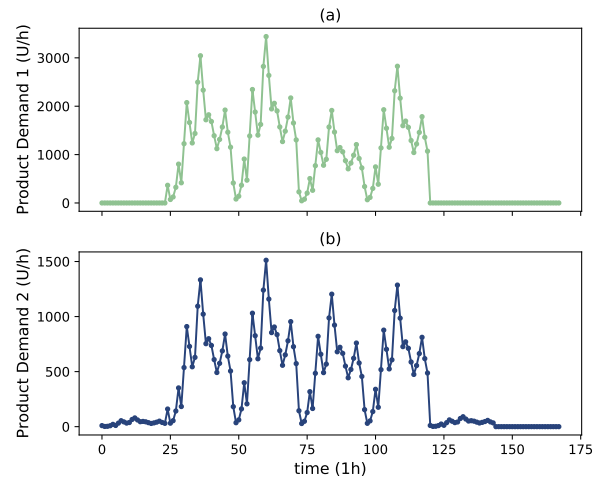


Fig. 6. Demand profile for (a) product 1 and (b) product 2

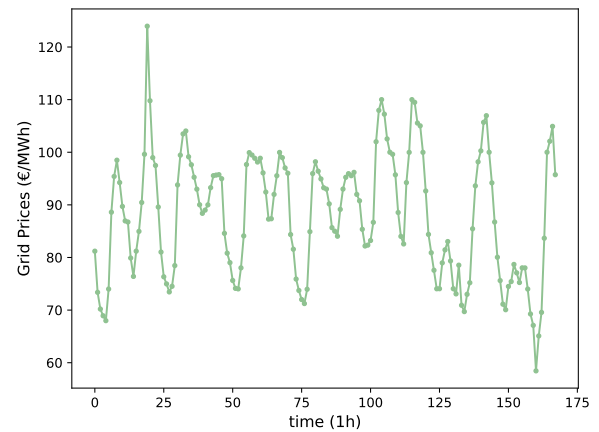


Fig. 7. Electricity prices

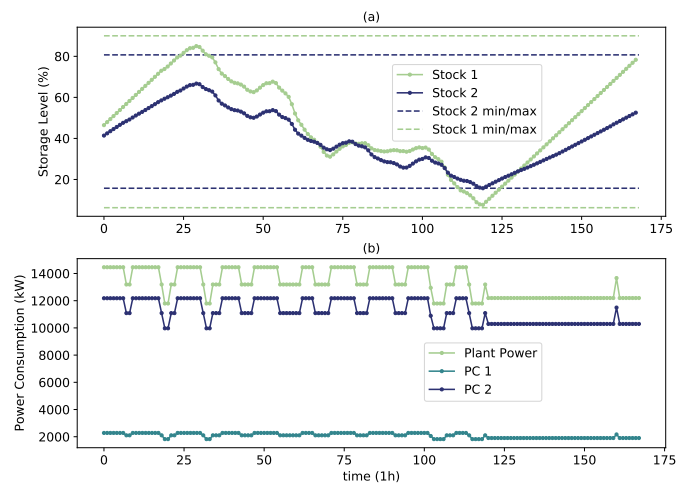


Fig. 8. (a) Storage level evolution and (b) power consumption for the weekly run

TABLE I
PRODUCT STORAGE CHARACTERISTICS

	Capacity (kU)	Min (%)	Max (%)
Product 1	61	90	6
Product 2	133	80	15

TABLE II
USUAL OPERATING POINTS WITH FREQUENCY OF OCCURRENCE AND AVAILABLE RAMPING

Product 1 (U/h)	Product 2 (U/h)	Frequency (%)	Ramp Down (kW)	Ramp Up (kW)
2000	3800	28.0	730	2071
2000	4600	26.8	2014	440
2000	4200	17.3	1539	1543
1000	5000	13.7	2017	436
1600	3800	6.5	356	2046
1000	4600	6.0	1543	1540
1100	5000	0.6	2052	402
1000	4000	0.6	51	1991
2000	4000	0.6	1009	2073

C. Usual Operating Points Distribution

The operating points used during the weekly simulations are extracted, and their frequency of occurrence is presented in Figure 9. We can observe that only a fraction of all of the possible points is used, and that around 60% of the total time steps are observed at two specific operating points $\{2,000; 4,600\}$ U/h and $\{2,000; 3,800\}$ U/h with around 30% frequency each. Other than these two points, the plant will tend to go toward one extreme or the other when considering the output of product 1, while covering a broader part of the spectrum when considering the output of product 2.

For each of the extracted operating points, we gather the available power ramping in both directions. This is presented in Table II, along with the frequency of occurrence for each operating point. In addition, a histogram of the distribution of the available ramping is presented in Figure 10. The same histogram also shows the distribution of the available symmetric ramping. Table III shows the frequency of occurrence for a given ramp or higher. We can observe that the plant can deliver at least 2 MW of upward regulation 41% of the time, and a similar amount of downward regulation around 35% of the time. The same ramp cannot be obtained for symmetric provision. The largest symmetric power ramping is 1.5 MW, and only 23% of the time.

Finally, when considering ancillary services provision, a graphical representation of the overall available bids could prove useful. The available bids, sorted by frequency of occurrence, can be found in Figure 11 for asymmetrical bidding, and Figure 12 for symmetrical bidding. As previously stated, we can observe that a bid for 2 MW in either direction can be sent 35% and 41% of the time for downward and upward regulation respectively, while a maximum of 1.5 MW can be delivered symmetrically, and only 23% of the time.

VII. CONCLUSION

This work serves as a preliminary study of industrial flexibility quantification for ancillary services provision. It

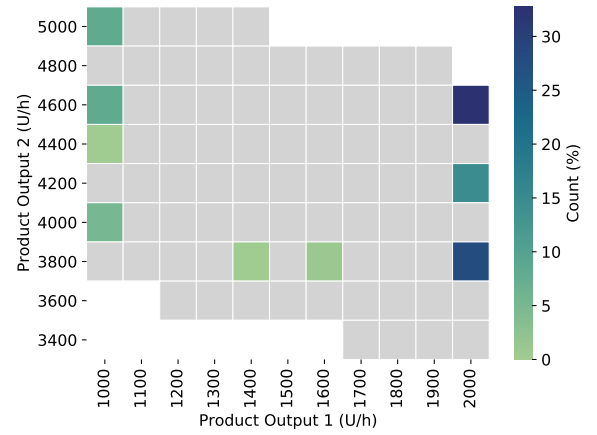


Fig. 9. Operating Point Distribution under standard demand and power price conditions

TABLE III
PERCENTAGE OF AVAILABLE RAMP

Ramp	Up	Down	Symmetric
>500 kW	59%	93%	52%
>1000 kW	59%	65%	24%
>1500 kW	59%	64%	23%
>2000 kW	35%	41%	0%

describes the feasible operating space of an industrial process, represented using a linear model. The resulting operating points and power consumption levels were first used to assess the viability of efficiency management for downward regulation provision. We thus showed that varying the operational efficiency of this process would require extensive revenue for each MWh made available for service provision. Next, using the same operating points, we assessed the available flexibility within the feasible region, in terms of power ramping, leading to the available power ramping, both up and down, for each operating point. Finally, a weekly simulation was performed

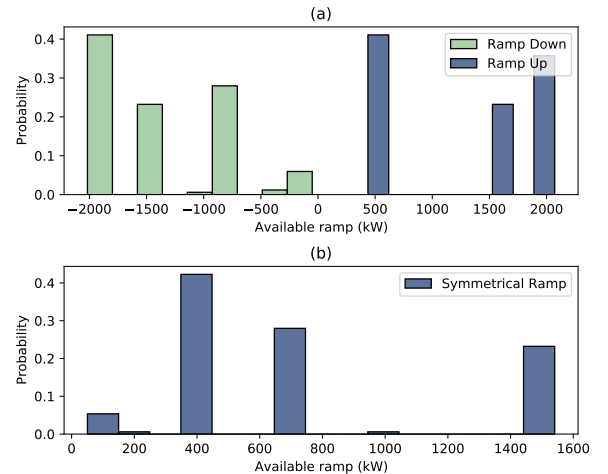


Fig. 10. (a) Available asymmetrical ramping distribution. (b) Available symmetrical ramping distribution.

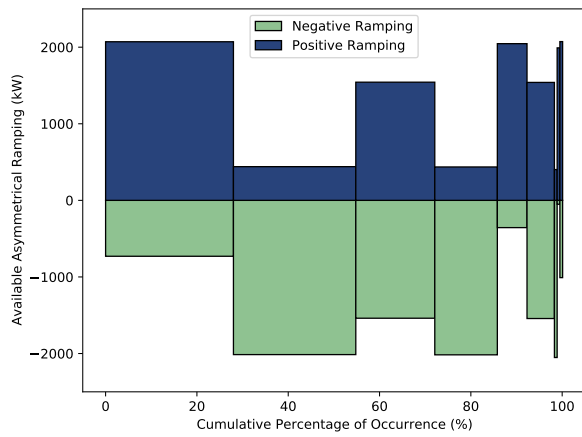


Fig. 11. Asymmetrical bidding opportunity with cumulative frequency

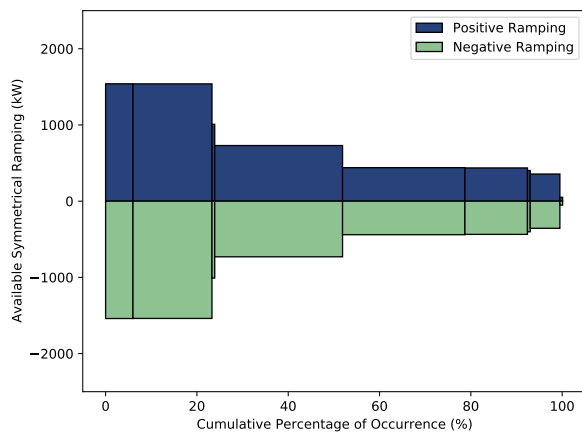


Fig. 12. Symmetrical bidding opportunity with cumulative frequency

to assess the frequency of occurrence of each operating point, and express the possible ramping of the plant with the corresponding frequency of availability. Finally, potential market participation bids were presented, both for symmetrical and asymmetrical bidding, once again with the corresponding frequency of availability. Following the results of this work, two paths can be considered for potential future research. First, this study was performed on a linear model, with a simple use-case comprising only two interdependent product outputs. Complexifying the model by increasing the amount of output and by considering nonlinearities could lead to a valid approach regardless of the particular use-case. Comparing the effect of adding non-linearity to the model would also help to choose between both models when building up service provision strategies for industrial assets. Second, the use-case considered here has fixed dimensioning for all of its components. Changing the size of one or more components would impact the overall flexibility of the plant. By linking a cost to each change, the necessary service valorisation for the additional flexibility could be extracted. Coupled with provision strategies and expected revenue, this could allow for viable financial analysis when considering either the modifica-

tion of an existing plant, or when adding a possible ancillary service provision for the design of a new plant.

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