Waste Incinerator Modelling in VALI 5

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This article describes the modelling of the household waste incinerator of Uvélia in Herstal that aims to validate and reconcile the data collected on the site. This model also allows to obtain different performance indicators, to carry out different analyses from the obtained information, and to highlight a possibility of improvement of the process.

Keywords: waste incineration, modelling, data validation & reconciliation, process management, performance monitoring, power generation

Cet article décrit la modélisation de l'incinérateur de déchets ménagers du site d'Uvélia à Herstal, modélisation ayant pour but la validation et la réconciliation des données récoltées sur le site. Ce modèle permet également d'obtenir différents indicateurs de performance, de procéder à différentes analyses de l'information obtenue, et de mettre en évidence une possibilité d'amélioration du procédé.

Mots-clefs : incinération des déchets, modélisation, validation et réconciliation de données, gestion de procédé, suivi des performances, production d'électricité

1. Introduction

Given the current context, environmental protection is becoming more and more important in the political point of view. This is particularly reflected in increasingly stringent energy efficiency and emission standards. It is therefore crucial for industries to increase their mastery of their processes.

The improvement of the performance of a process can be achieved by increasing the knowledge and the control of that process. For this purpose, gathering information and measurements in a model allows to check the state of the process, to calculate the values of relevant performance indicators and to increase the precision on value acquisition for key variables.

The method used in that purpose is the Data Validation and Reconciliation (DVR). This method can reduce the uncertainties on some parameters by confronting different sources of information for their values, as measurements and calculations. A software called VALI 5, applies this method, and also allows to highlight the influence of each parameter thanks to sensitivity analyses.

2. Context

Before describing the modelling and its principles, the understanding of the operation of the plant as well as the tools used to obtain the model is strongly needed. Section 2.1 describes the modelled power plant, Uvélia, and its process. The software used for the modelling, VALI 5, is presented in section 2.2.

2.1. Uvélia

Uvélia is an energy recovery unit located in Herstal. It ensures the energy recovery from waste for 72 communes affiliated with intermunicipal companies which are Intradel, but also part of AIVE and BEP. It represents the waste of around 1 million inhabitants. [1]

The collected waste comes from residual household waste, PMC (Plastic, Metal packaging and beverage Cartons) sorting residues, bulky items and ordinary industrial waste. Previously, the unit also incinerated sewage sludge, but this activity was abandoned due to the difficulty of operation. [2]

In 2014, the company recorded the incineration of 378,284 tonnes of material. These have been reduced into around 100,000 tonnes of bottom ash, which are recycled for the construction sector. Energy recovery made it possible to generate 225,468 MWh

of electricity transmitted to the network, which represents around 0.32% of the Belgian electricity. For the company, this represented a turnover of 42 M € and enabled them to employ 73 full-time equivalents. [3]

In Wallonia, there are 3 other incinerators. Together, they make it possible to incinerate nearly a million tonnes of waste per year. Their respective capacities are listed in Table 1.

Table 1: Authorized processing capacities of the Walloon incinerators [4]

	AUTHORIZED PROCESSING CAPACITY
THUMAIDE (Ipalle - Hainaut occidental)	400.000 tonnes
UVELIA (Intradel - Herstal)	370.000 tonnes
PONT-DE-LOUP (ICDI - CHarleroi)	110.000 tonnes
VIRGINAL (IBW - Brabant wallon)	116.000 tonnes

The Uvélia process of energy production is composed of 2 identical lines, whose each has a capacity of 21 t/h. These can generate 180 t/h of steam at 400°C and 40 bar. The steam circuit is based on an Hirn cycle [5] with 2 extractions of steam. In Figure 1, an illustration explaining the organization of the site is displayed.
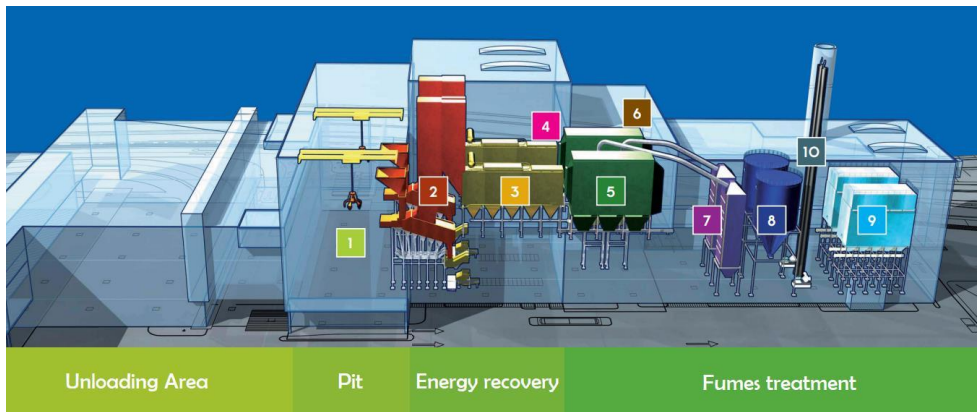

Figure 1 : Organization of the Uvélia site [6]

The waste is collected and brought by garbage trucks and barges and stored into a pit. Grapples are used to move the waste and mix it to homogenize the composition and therefore the properties of the material. It is then dumped into the hoppers of the ovens by the grapples.

A feed pusher distributes the waste on a grid. The waste residence time is approximately one hour, and the temperature inside the furnace is close to 1000°C. The furnace also has a fuel burner, which has two functions: preheat the furnace when the line is put into service, to limit the production of dioxins, and as a backup when the calorific value of the waste is too low.

The solid unburnable residues, called bottom ash, are collected, and used as raw material for the construction of roads and railways, while the fumes are sent to the heat exchangers. The boiler contains a multitude of tubes on which the thermal energy of the fumes is exchanged to turn liquid water under pressure into steam, in opposite current to maximize the final temperature of the steam going to the turbo generator group for electricity generation.

The fumes are then treated before being rejected in order to limit the emissions of pollutants. This part was not integrated into the model and is therefore not detailed here.

2.2. Vali 5

Belsim has developed different versions of its modelling, simulation, and DVR software. The latest version, released about one year ago, is the fifth one, and is therefore named VALI 5.

For a given configuration of a model and set of information, VALI 5 can provide the full consistent list of the values of the physical properties of the process, adjusting the redundant data to make them fit the equations with the lowest corrections. This aspect is explained in the third section. The software can also calculate custom indicators, make a sensitivity analysis to highlight the influence between the different parameters, or even generate reports to summarize all these results.

To obtain these results, it is of course needed to enter the necessary information. For the chemical aspect, the components, the different types of mixtures, called thermods, or the reactions occurring in the plant can be cited.

The process can be simply drawn through a graphical interface. The different units, the flows, and the arrangement between them are represented. The thermodynamic equations are then determined automatically by VALI.

Finally, the data must also be added, or more exactly provide the tags; in other words the numerical values of the physical properties of the model as well as their uncertainties. This can for example concern the temperature, pressure, mass or volume flow rate for a flow. It is also possible to provide pressure gradients, heat losses or

exchanges for equipment, etc. It is also possible to add information in another form, such as additional manually entered equations.

3. Data Validation and Reconciliation

In order to know how the model can be built, it is necessary to understand the basic theoretical principles which the DVR method is based on.

3.1. Principle

In industrial processes, the variables are physical parameters as the flow rates, the temperatures, the pressures, the compositions, the enthalpies, or the densities. The equations are mass balances, for each compound, energy balances, phase equilibria, chemical reactions, efficiencies, or empirical equations. Since the model generates a set of variables and a system of equations to solve, we first have to define some mathematical notions.

The degree of freedom is the difference between the number of variables and the number of equations. Some variables are unknown, and some others are measured.

The redundancy is the difference between the number of variables for which we have measurements and the degree of freedom. In other words, it is the number of additional data without which we would have as many unknowns as equations. There are therefore 3 possible cases concerning the resolution of the system.

If the redundancy is negative, there are an infinite number of solutions and therefore the operating conditions cannot be determined. If the redundancy is zero and the information is correctly distributed, there is one and only one solution; this case is called simulation. The last case is when the redundancy is positive, so there is an excess of information. Since there are always slight measurement errors, there is no mathematically correct solution. This is where the DVR is applied, this method not only allows to find a solution, but also to make it more accurate than in a simulation case. It also means that the measurement can be corrected to ensure the consistency of the balances.

The first step of the DVR is the validation. The raw data retrieved (measurements of connected instruments, manual inputs, etc.) are first verified to ensure their quality, for example considering a lower limit and an upper limit for the value.

The second step is the reconciliation, which means the determination of the most probable values for each parameter according to all the sources of information: measurements and calculations from other measurements. The solution is then the one for

which each equation is verified and where the correction made to the measurements is the smallest. These corrections, the reconciliation, then involve new concepts.

3.2. Indicators

The statistical error of the measurement values can be described as a normal distribution. Therefore, 2 parameters are enough to describe the probability density on the deviation from the real value. These parameters are the value (μ) and the standard deviation (σ). It is illustrated in Figure 2.
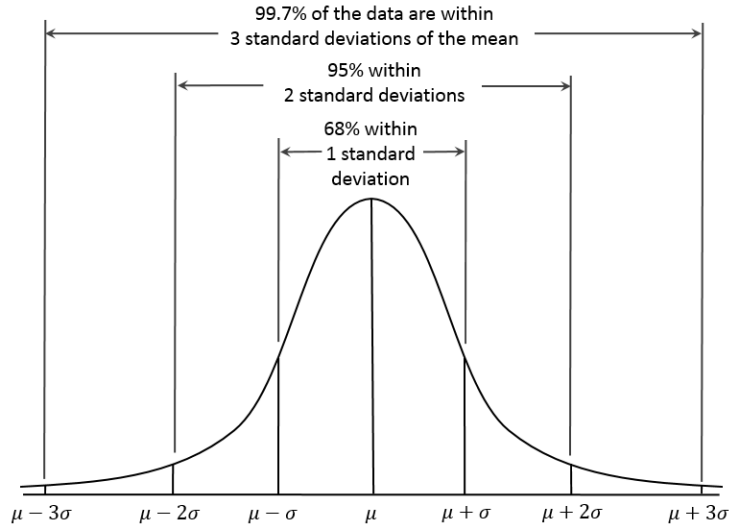

Figure 2 : Normal distribution [8]

This measurement error is often due to the imprecision of the sensor. But there can also be a lack of accuracy, that is called systematic error. It is, for example, due to a bad calibration.

The individual penalty represents the magnitude of the correction. For a measurement y_i, it is defined as the square of the correction divided by the uncertainty, written as following:

$$penalty(y_i) = \left(\frac{y_i - y_i^*}{\sigma(y_i)} \right)^2$$

where y_i is the measured value, y_i^* is the reconciled value and $\sigma(y_i)$ is the standard deviation on y_i. A small penalty means a low correction compared to the uncertainty, which indicates that the measurement was fairly accurate.

The objective function, in optimization, is what we want to minimize by acting on the parameters. In the case of the DVR, the optimization variables are the reconciled values of the measurements. The objective function is simply defined as the sum of the individual penalties, for reconciled values that satisfy the entire system of equations of the model:

$$Obj = \min\left(\sum_i penalty(y_i)\right)$$

Other indicators exist to illustrate the quality of the solution, as the gain that shows the reduction of the uncertainty after reconciliation, or the quality, an indicator which integrates the objective function and the notion of confidence. However, they are not used in this context.

3.3. Benefit

Of course, the accuracy of the results is essential to make good decisions regarding the maintenance. As said in the introduction, information redundancy makes it possible to increase this accuracy. It is therefore interesting to increase the level of redundancy. This can be done by adding measurement devices, which is quite expensive, or by adding assumptions in the form of values or new equations.

Sometimes in processes, security margins are required. For instance, there can be a maximum temperature in a unit to avoid overheating. To limit the risk of exceeding that limit despite the lack of precision, a margin has to be considered and it is nearly proportional to the uncertainty on the thermometer. Since adding sources of information to the calculation of the temperature value allows to reduce the uncertainty thanks to reconciliation, it allows to adapt the margin, so to slightly increase the temperature. Consequently, the performance of the process could be improved by the DVR.

4. Modelling of the Process

4.1. Documentation

Several documents are available to build the model. The main sources of information are:

- The process flow diagrams (PFDs): they illustrate the different streams and units and they show how they are linked together and with other parts of the process.

- The piping and instrumentation diagrams (P&IDs): they list different measuring instruments, flows and units, their names and locations on several diagrams corresponding to different parts of the PFDs.
- The energy and material balances: it gives the values of the parameters as estimated at the time when the construction of the plant began, they are called <u>design data</u>. The parameters relate to temperatures, pressures, and flow rates in the pipes. There is then one value for each parameter.
- Data tables from the data history system: the values of the parameters are changing continuously; a value is then registered at regular time intervals, every 10 minutes in this case. They are called <u>operational data</u>.

These documents are linked to different parts of the process that can be listed as the steam circuit, the combustion lines, and a cooling water circuit. The modelling is described for each part in the next sections.

4.2. Modelling in VALI

The process can be divided in several parts: the water circuits and the combustion lines. The water circuits include the steam circuit for the conversion of the heat energy to mechanical energy and the cooling water circuit, and the combustion lines concern the combustion of the waste and the fumes processing.

Water circuits

The main part covers the entire steam circuit, from its exit from the boiler to its reintroduction in the form of pressurized liquid water. The steam circuit also includes the turbine, condensers, and a whole series of other equipment such as heat exchangers and tanks. It contains only water that is considered pure, and there is no chemical reaction.

There is also a cooling water circuit. It is the part that cools down the alternator and bring a cold source to the vacuum system. No reaction is to be considered and the only thermods (mixture of compounds) are water and air.

The modelling can start from the high-pressure steam coming out of the boilers of both lines. The two streams are gathered, and in reality, there is a 30-meter pipe (pipe1) between that reconnection and the turbine, where temperature or pressure drops can occur. Before being entered in the turbine, the flow can be split into 3 directions: a by-pass to avoid overheating in the turbine, another flow used for example for the combustion air preheating, and the flow connected to the turbine. In typical operation, the whole flow rate enters into the turbine.

The process is therefore modelled as illustrated in fig. 3, where BB1 stands for black box 1 and SPL1 for splitter 1.
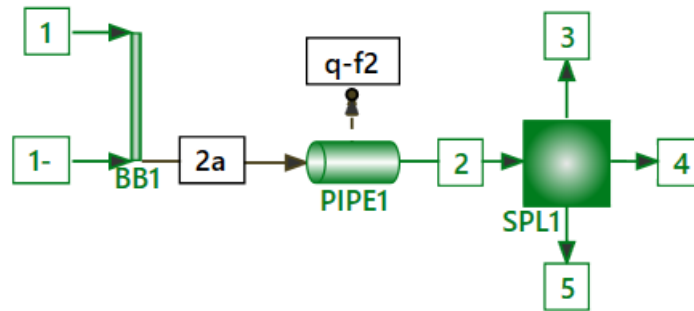

Figure 3 : Modelling of the steam outlet of the boiler

To allow the solver to find a solution for this process part, a given number of parameters must be given. To fully determine a flow, the chemical composition, temperature, pressure and total flow rate must be given. But as it was said, the streams are connected together with VALI units that automatically generates equations, it is then unnecessary to give values for all the parameters of all streams.

If its pressure drop is fixed as null, the black box 1 determines exactly what is the stream 2a, since mass flow rates are conserved for each compound (only water in this case) as well as the energy. The pipe1 can only modify the temperature and the pressure, 2 additional parameters at least must then be fixed. And finally, the composition cannot change in a splitter and the temperatures and pressures of the outlets cannot be different: the only things to fix to determine the properties of the outlet is then 1 only pressure drop and 2 flow rates, since the last one can be calculated with mass balance.

Any additional information becomes redundant and allows to check the consistency with the previously given data, but if wrong values are implemented, the solver could be unable to find a solution.

It would be too long to explain each step of the modelling here, and that is not the topic of the paper, but the rest of the process must of course be modelled. The main next units to model are the turbine, a separator at its outlet, the condenser, the storage tanks, and the feed water pumps. The results can be seen since the first units were modelled, but it is more interesting to analyse the results after completing the model. The boiler can then also be modelled, with the energy aspect of the combustion.

Combustion lines

The combustion lines integrate the primary air heaters, the furnaces, their air, waste and fuel inlets, and the outlet fumes. The model then contains much less units than in the steam circuit. However, the chemical aspect is much more complex. The fuel is known, but not used in typical operation, unlike the waste. Its composition is very variable and not so well known. Therefore, another type of fuel is to be used instead. This fuel must be compatible with the fumes composition that can be measured. Additionally, we suppose that there is no carbon, no nitrogen, no oxygen, and no hydrogen remaining in the bottom ash since it is composed of unburnable elements.

The model allows to calculate a calorific power anyway, since the mass flow rate of the waste entered in the furnace is known, with a very imprecise incineration time, and the communicated heat is also known, considering the properties of the high pressure steam flows and the ones of the feed water flows at the inlet of the boiler.

4.3. Data Entry

Two types of data can be entered into the model, depending on if the goal is to investigate the design conditions or the operational conditions. The consistency of the design data may be compromised if the process has change since the design of the plant. It is then crucial to be sure that the model matches the process for the date of the data provided.

As it was explained, in design conditions, there is one only value for each parameter. In the water circuits, each material flow is the same type. The used data is then given in one table, within the 39 columns represent 39 of the main flows, and the rows are giving each type of measurement: temperature, pressure, flow rates.

Table 2: Part of the Water Circuits Design Data

		1	1'	2	3	4	5
Pressure	bar(a)	40	40	40	40	40	40
Temperature	°C	400	400	399	399	399	399
Mass Flow Rate	t/h	80	80	160	0	160	0
Vol. Flow Rate	m³/h	5801	5797	11850	0	11850	0

The design data have similar tables for the combustion lines, but the amount of contained information is more limited.

The operational data cannot be classified in the same way because the values of the parameters vary over time. Each cell of the previous tables therefore becomes a column and the rows are time intervals. The columns are designated by a tag name, which includes a given flow and a given type of measurement.

The data history system collects the data of the whole process and store it in spreadsheets. A set of tables is given for all the parts of the circuits, most often a table for each unit of the process.

Table 3: Part of the Operational Data

Day	FEED WATER PUMPS				
15-04-18	**PDT 30016**	**PDT 30011**	**LT 30094**	**TT 30097**	**PT 30169**
From 0H00 to 23H59	Dif. Pressure filter pump P30002	Dif. Pressure filter pump P30001	Feed Water Tank Level	Feed Water Tank Temp.	Feed Water Tank Pressure
	mBars	mBars	cm	°C	Bars
00:00	10,98	12,41	194,80	125,92	1,37
00:10	10,88	12,32	194,26	125,67	1,37
00:20	11,30	12,83	194,48	125,95	1,40

There are therefore some searches to fix on the tags to select the useful ones and to associate their name with their correct location in the VALI model.

In practice, some difficulties have been faced: the collected data are sometimes inconsistent, which can mean that the model must be corrected or that the instrument is defective, and sometimes the data are insufficient. Most of the time, the missing information can be approximated, we thus have for example some null flow rates, null pressure drops, atmospheric pressure of one atmosphere, an air of 15°C with 78% nitrogen, 21% oxygen and 1% argon or carbon dioxide [9], approximated unimportant pressure values, etc. But others are important and hard to estimate. Despite those assumptions, the documentation allows us to get accurate and useful analyses of most of the process parts.

5. Analysis of the Results

The model was first run without any redundancy, to avoid dealing with data inconsistencies during the different modelling steps. It was then a simulation case, but an analysis with this set of data gives no additional information to the case in which all the available data are implemented, this analysis is then not interesting to achieve.

Some assumptions added while building the simulation model remain in the new versions of the model, using all the provided data. An assumption is requiered when there is no other way to calculate the value. Most of the time, a value with an unnecessary assumption is reconciled, which allows to spot it. But the only way to be sure that none can be removed is to check them one by one.

The calorific value of the waste can be calculated. Since the waste is modelled as a mix of 65% methane and 35% ethane, its calorific value is 49.23 GJ/t. [10] Multiplying that value by the flow rate of 5.13 t/h, the heat production is found, 252 GJ/h, or 70.16 MW, for each line. This means that the heating efficiency is around 59.17 MW / 70.16 MW = 84.3%. And finally, dividing that value by the waste flow rate of 21 t/h per line, its design calorific value is obtained: 12.03 MJ/kg. For the month of April 2018, it varies between 9 and 13, with an average value of 10.96 MJ/kg.

5.1. Design Data

Here, there is relatively important missing information concerning the temperatures at the inlet mixer of the dry cooler, the cooling of the grids, and primary air heating in general. The indication is broad because a lack of information always concerns a set of tags, not a precise tag, since they are linked by equations. It would therefore be incorrect to say that a particular measure in a particular place was necessary.

All the available data were implemented, and the solver can find a solution but had to make non neglectable corrections. The received data are then sufficiently consistent, but that consistency can be checked considering the penalty on each tag.

The largest penalty actually comes from a flow rate. Looking for the problem, we can find out that a mass balance in a part of the process is not exactly respected in the given data, some flow rates have therefore been slightly corrected. The difference was then reported.

The results given by the model for design data represent the operation and the performance as it was designed. They are mostly interesting when compared to the results in operational conditions.

5.2. Operational Data

Again, there are assumptions, centred around the same parts of the process, but a solution can be found. Here, the objective function is about 15, depending on the period of time that is used. Even knowing what the objective function is, the value is difficult to interpret, but is useful when compared in different cases. Here, this shows that, logically, the measured values are less precise than the planned values, with which the objective function was 8.55.

It would be complex to show all the results, but a few ones can be presented. The most important unit of the plant is the turbine; it is the equipment that allows the energy production; it is then important to monitor its performance. As key performance indicators, the efficiencies of the 3 turbine stages can be considered. The net power can also be analysed, it is the turbine power from which the power of the pumps is substracted. A good indicator using it is the mechanical efficiency: the ratio between the net power and the power provided by the turbine.
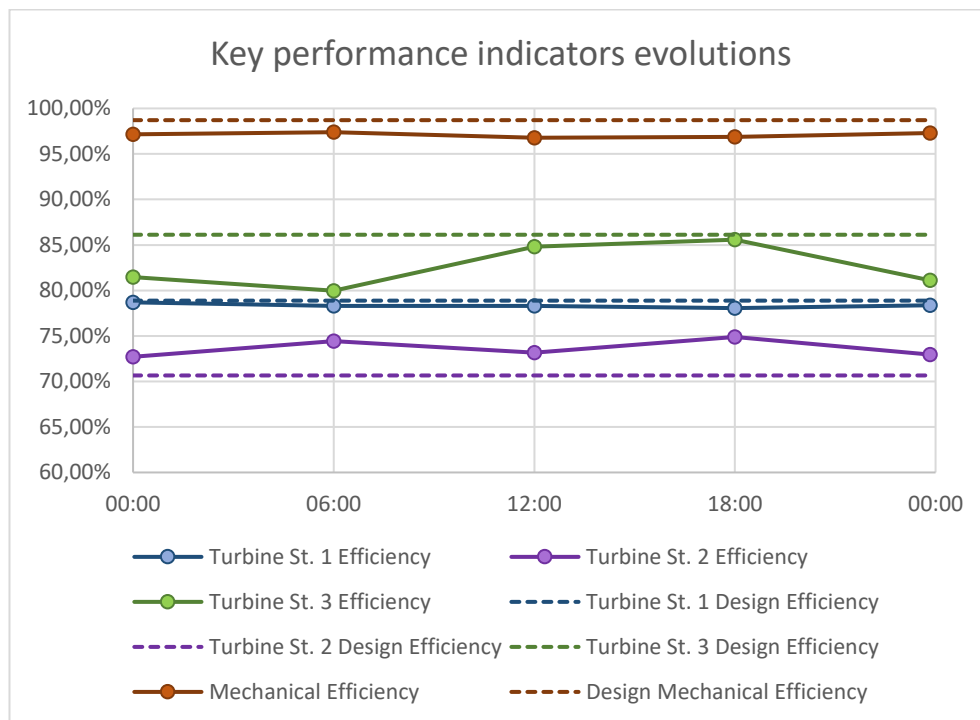

Figure 4: Key performance indicators evolutions

Concerning the examples presented in fig. 4, we see that the stage two of the turbine, represented in purple, is more efficient than expected, unlike the third stage, displayed in green. This can be due to a different use of the turbine, for example if there

is a higher or smaller extraction flow rates, or it can mean that the measurement devices are diverging and/or that, only for the case of third stage of the turbine, that it is becoming less performing. Checking that potential problem could be considered.

It is also observable that the mechanical efficiency is less than the planned value. Given the large number of parameters which can influence the final value of the mechanical efficiency, it is difficult to see directly which one is responsible for its decrease. It could be one of the temperatures, flow rates or pressures of the inlet, outlet, or extraction flows of the turbine, it can be one of the pressure increase in the other pumps of the process, or even another parameter not directly linked. To know what parameter influences the most the mechanical efficiency, a sensitivity analysis can now be run.

5.3. Sensitivity Analysis

The sensitivity analysis tells for any indicator which are the data that are influencing the most its value. Here, the mechanical efficiency is given as KPI (Key Performance Indicators), the analysis results show that the most important parameter are:
1. The outlet pressure of the feed water pumps (34.37%)
2. The efficiency of the feed water pumps (32.22%)
3. The temperature of the high pressure steam (10.06%)
4. Other parameters (23,35%)

The outlet pressure of the feed water pumps is determined as the most influent parameter. Indeed, the whole flow rate of the water to boil is going through those pumps and the pressure increase is extremely high: 82.27 bar in design data and the average in operational condition for the given date (15th April 2018) is even 92.4 bar.

The efficiency of those pumps is nearly as important for the same reasons but increasing it by replacing the pumps would be expensive and probably not the most profitable possible investment. Of course, the temperature of the steam is really important too, but to heat more, more waste would be needed, which is not possible since the amount of waste to incinerate is fixed by the rejects of the inhabitants.

The problem seems to be the pressure increase, it is tremendous and since the produced steam has anyway a pressure around 40 bar, one can wonder why the pressure increase cannot be smaller and where the pressure drops so largely. The cost of that can also be estimated and it is needed to check if the process cannot be modified to reduce that cost. That important aspect is discussed in the next section.

6. Improvement Opportunity

The analysis of the results revealed a presumably very high pressure drop, between the outlet of the feed water pumps and the outlet of the boiler. This pressure drop was initially forecast at 44.54 bar in the design data and the average is 54.95 with operational data of the 15th April 2018.

This pressure drop is mainly due to a control valve, and a little to pressure losses and height difference. So, we want to investigate the possibility to reduce the outlet pressure of the feed water pumps and the pressure drop in the valve without impacting the proper operation of the process.

6.1. Technical Feasibility

To work properly, that valve requires a pressure margin. Its data sheet suggests that the minimum pressure at the inlet of the valve is 82 bar. Since it is around 95 in operational conditions, it means that it could be reduced by around 13 bar.

To confirm that the outlet pressure of the pumps is adaptable too, it is needed to check the type of pump as well. To reach the high level of pressure, the selected type of machines is multi-stage pumps. It is possible to make a destaging, in other words, to remove one or more stages on the pumps, or an impeller trimming. However, without a complete mechanical study on the subject, the decrease of the outlet pressure of stage removing cannot be determined. It would also be possible to use pumps with speed variators but for a same price it reduces the reliability of the system.

6.2. Financial Profitability

Even if the feasible decrease of the outlet pressure is not known, the most optimistic case can be studied to have an idea of the maximum possible saving.

Considering that the outlet pressure is never under 90 bar in current operational conditions, its value can be reduced by 8 bar staying above 82 bar. The saving which could be achieved can then be approximately calculated.

The saveable power in the pumps is:
$$\Delta P_{pumps} = Q_m * g * \Delta H = 46.4 \frac{kg}{s} * 9.81 \frac{m}{s^2} * 8\ bar * 10 \frac{m}{bar} = 36.4\ kW$$

Assuming that the conversion efficiency is around 80%, that the installation operates 8500 h/year and that the price of electricity is around 27€/MWh, this leads to a saving of around $C = P * T * eff * price = 6686€/year$.

These assumptions can be checked to give more precision and credibility to the information, which is not so high compared to improvements made in practice by Uvélia engineers.

7. Conclusion

To conclude, a validation model of the energy aspect of the installation have been realized and concrete results have been obtained and analysed. It allowed to verify the general good operation with a satisfying consistency. It also pointed out a reducible energy loss in the steam circuit. However, using more operational data in the model can be a future improvement.

The main problem of that modelling for now is the lack of information. The design and operational data extracted from the documentation of Uvélia was validated with some assumptions through the model. Some tags are missing because there is no instrument to record it, because its measurement is not sent to the data history system or because the value was not stored or exported. Solving those issues is a direct way of improvement of the model since more operational data means less assumptions or more redundancy.

The lack of data was particularly impacting for the waste combustion aspect. However, it is not a lack of documentation provided by Uvélia since they do not have the composition of this matter either. Having the compositions of the waste and ash and their flow rates would allow to model combustion part more accurately. Some possibilities exist in VALI to model solid fuels and they can be considered. In this version of the model, the waste is replaced by a mix of methane and ethane, modelling this aspect properly is therefore an opportunity for improvement that can be considered.

There are therefore several ways to continue and improve this work. Additionally, the modelling of the electrical aspect can be considered as well as the modelling or analysis of the fumes processing. It is possible to study the impact of some changes in the Uvélia plant, as the decrease of the pressure jump of the feed water pumps or the possibility of adding a reheating of the steam. These can be subjects for another master thesis, which would be linked to this one.

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