OPTIMISING THE MANUFACTURE OF ORGANO-MINERAL FERTILISER

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Abstract

With an ever increasing population, sewage sludge management has become a critical issue. The European FP7 project END-O-SLUDG aims to address these challenges by focusing on efficient and innovative processes. One of the processes under consideration is the manufacture of Organo-Mineral Fertiliser (OMF), which is a nutrient balance fertilizer specifically formulated to suit UK farming practices. It is a pasteurized, granular and virtually dust-free product obtained from a series of mixing and dehydration processes. Under END-O-SLUDG, a pilot OMF manufacturing facility is to be installed at Ellesmere Port Wastewater Treatment Works to test the technology. The plant will provide sufficient product for scientific investigations and trials.

In order to optimise the process from an energy perspective, dehydration technologies and available energy sources were investigated. Each potential energy source was matched to a suitable technology, which ultimately provides warm air for dehydration. It was found that a heat pump would be able to utilise energy in the environment and provide air at the required temperature for dehydration.

By analysing the available quantities and properties of the sludge at each stage of the process, a heat and mass balance of the system was created to determine optimal mass and energy flows. While vital in the design stage, it also illustrated potential energy savings utilising waste heat.

Finally, it is shown that effective experimental design, if analysed correctly, can provide invaluable information for optimising a new process. Each variables effect on a measured output can be accurately estimated, thus allowing for optimal adjustment of the process variables. This work brings the OMF process a step closer to becoming a viable option for sustainable sludge management.

Key words

Biosolids; OMF manufacture; dehydration; granulation; heat efficiency; optimisation

Introduction

The objectives of this paper are as follows:

- To provide an overview of the Organo-Mineral Fertiliser (OMF) production process.
- To analyse the suitability of several dehydration processes for use in the production of OMF.
- To match dehydration technology to the available energy sources.

- Through the use of a heat and mass balance of the process, establish an appropriate setup.
- To put forward a method for determining optimal settings for the variables associated with the dehydration process.

A Background to OMF Production

There are several sludge dehydration processes available on the market today. The OMF production process aims to not only granulate dewatered sludge, but to add urea to produce a more effective fertiliser and a marketable product. Figure 1 shows the granulation process.

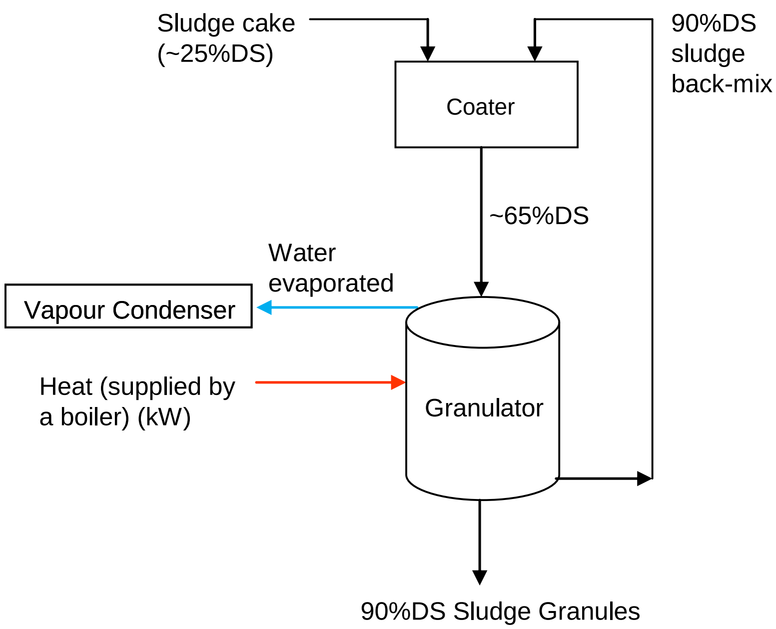

Figure 1: A sludge granulation process

Dewatered sludge cake at approximately 25%DS is mixed with dry sludge and then passed through a granulator. As well as producing granules in an acceptable size range (3-5mm), the granules are dehydrated to 90%DS. This dehydration allows the granules to be safely stored, without risk of mould growth. Figure 2 shows the proposed modifications to the process, to enable the production of OMF.

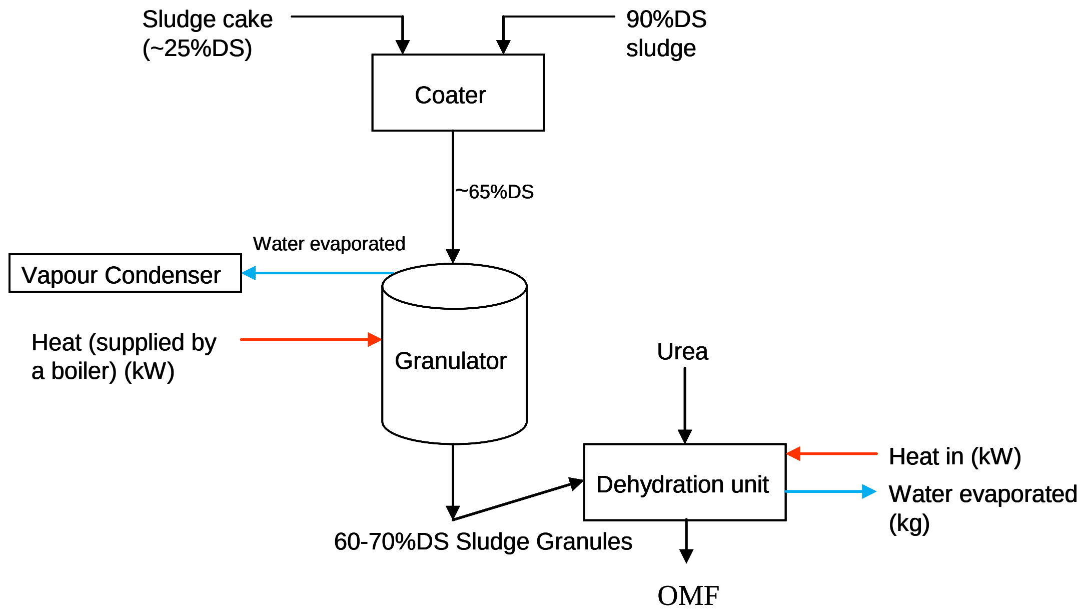

Figure 2: The OMF production process

One modification to the process shown in Figure 1, is to add urea to the sludge. Urea granules will be ground into a powder and then spread over the sludge granules. Through testing it has been established that urea powder quickly dissolves in 60%DS sludge granules. The urea will increase the nitrogen content, bringing the N:P:K ratio up from 4:4:0 to 10:4:0.

The dehydration of the sludge is an energy intensive process and depending on the throughput and amount of water evaporation, could easily require a 500kW heat source. The End-O-Sludg project aims to make use of waste heat to save energy where possible. For the pilot plant installation, the dehydration unit will use a heat exchanger to convert waste heat to warm air (50-60°C). The warm air will percolate through the sludge granules over a period of time, which will be decided with testing.

Dehydration Technologies

An investigation was conducted into several different dehydration technologies. An experiment was run on a packed bed heat exchanger, where an electric space heater was used to heat up media contained in a cavity. Once the media was heated up, the fan was reversed, sucking air over the heated media and thus blowing out warm air. The amount of useful energy output was measured. Effectively the high grade heat that was input, around 500°C, was converted to low grade heat, 50-60°C. The problem with this was, despite insulation being provided to minimise heat loss, the efficiency of the exchanger was very low regardless of the type and quantity of media tested.

While the packed bed heat exchanger was ruled out, there was still the potential to use a water/air heat exchanger – given energy available in the form of hot water (70-80 ˚C) from the

CHP cooling circuit. Calculations were done to establish the efficiency of a water/air heat exchanger, which would be able to convert energies of similar heat grades. It was determined that this would be an effective means of utilising the available energy, given the dehydration bed only needs low grade heat.

Research was conducted into the suitability of using a heat pump to extract energy from the environment. A heat pump manufacturer was contacted and Tables 1 and 2 show some of the capabilities of heat pumps.

Table 1: Heat pump power inputs and outputs for a 25kW plant room

25kW Plant Room				
Air Temperature Input (°C)	Air Temperature Output (°C)	Power Output (kW)	COP	Power Input (kW)
0	65	21.6	2.03	10.64
5	65	25.2	2.22	11.35
15	65	39	2.89	13.49

Table 2: Heat pump power inputs and outputs for a 50kW plant room

50kW Plant Room				
Air Temperature Input (°C)	Air Temperature Output (°C)	Power Output (kW)	COP	Power Input (kW)
5	50	52	2.54	20.47
15	50	80	3.67	21.80

Note: COP stands for coefficient of performance

Significant amounts of energy can be extracted from relatively low temperature sources (0-15^{o}C), meaning sources would not be season specific. The pumps are modular in the design, so they can be stacked to provide a bigger overall power output. While power is required to run the compressor, the output is at least double the input for all of the above scenarios.

One final technology was investigated, that being the power chip. This technology allows high grade heat to be converted to electricity. The claims are a conversion of between 30-50% of the energy to electricity. One possible source of high grade heat is the CHP exhaust. The online calculator shows the ability to convert 60kW of the 174kW available using this technology. The chip is also incredibly compact, with the ability to convert to electricity at approximately 100W/cm^2 of chip. Therefore, 60kW would require about 0.06m^2 or 600cm^2.

Available Energy Sources at Ellesmere Port WwTW

An investigation was conducted, looking specifically at Ellesmere Port WwTW, to determine energy sources that could be utilised using the above technologies. A list of these, along with the potential technologies is shown in table 3.

Table 3: Energy sources and suitable technology to extract the energy

Energy Source	Temperature	Method of Utilising Energy	Expected Energy Recovered (kW)	Process Application
CHP cooling water circuit	70-80°C	Heat exchanger	19-50	Dehydration
CHP Exhaust	500°C	Power Chip	60	Various
Vapour condenser – HE exit stream	75°C	Heat exchanger	20	Dehydration
Condenser – Cooling water stream	~15°C	Heat pump	Multiples (up to 6) of 25-60	Dehydration
Final effluent	~5-15°C	Heat pump	Multiples (up to 6) of 15-60	Dehydration
Air/ground	~0-15°C	Heat pump	Multiples (up to 6) of 10-60	Dehydration

If the energy is very low grade (ambient air temperature or lower) then a heat pump would be required. Where the available energy is of a low grade, but around the temperature required for dehydration, then a heat exchanger would be most suitable. Where the available energy is of a high grade heat, conversion to electricity would be more advantageous.

Heat and Mass Balance

Given the large number of possibilities for utilising energy in the OMF production process, and the potential for adjusting the throughputs, a heat and mass balance was required. This is shown in Figure 3.

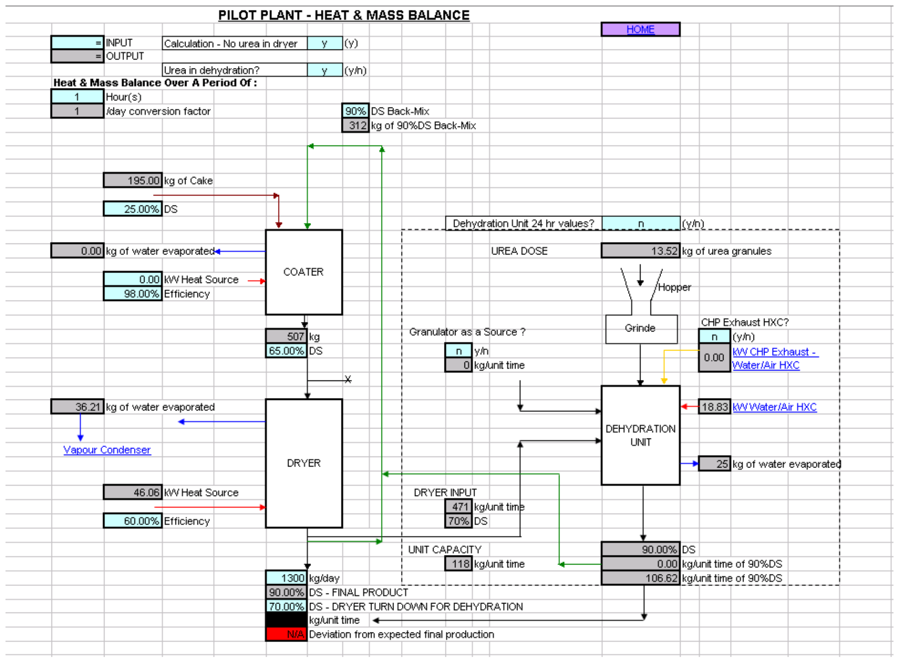

Figure 3: Heat and Mass Balance of the Pilot Plant

The mass and energy flows across the granulator (coater and dryer) and the dehydration unit are shown. Cake and 90%DS are input into the dryer to create an aggregate 65%DS mix. This is then passed through the granulator, which dries and granulates the sludge up to 70%DS (adjustable up to 90%DS). The sludge granules are transferred to the dehydration unit and the urea powder will quickly dissolve in the 60-70%DS granules. Warm air is then percolated through the granules, evaporating the moisture and thus drying the granules up to 90%DS.

The heat and mass balance was designed to be as flexible as possible. This allows %DS to be adjusted, along with heat sources at various stages of the process. Additionally, the time period over which the flows are shown can be adjusted. Figure 3 shows the values per hour. The granulator does not need to be adjusted much as far as the balance is concerned; as long as it provides enough granules for the dehydration unit. There are many potential energy sources to consider for the dehydration unit however. Table 4 shows how these are selected.

Table 4: Selection of energy sources

Potential Energy Sources - Full Scale Scenario 1

Full-scale production (Ellesmere Port)

	Energy Sources	Energy Grade	Utilise? (y/n)	Temperature of Source (°C)	No. of Heat Pumps (1-6)	CHP Load	Power from Heat Source (kW)
1)	CHP Cooling Water Circuit	low	n	80	N/A	100%	0.00
2)	CHP Exhaust	high	y	505	N/A	100%	66.40
3)	Waterleau Dryer Vapour Condenser	low	n	85	N/A	N/A	0.00
4)	Final Effluent	low	y	5	2	N/A	27.70
			n	15	2	N/A	0.00
5)	Air/Ground Heat Source (Heat Pump)	low	y	0	2	N/A	21.92
			n	5	1	N/A	0.00
			n	15	2	N/A	0.00

Heating Stage	Source	Power	Units
Dehydration	Heat Pumps	49.62	kW
	Heat Exchangers	0.00	kW
Dryer	Electricity	66.40	kW
Total (low grade)		49.62	kW
Total (high grade)		66.40	kW
Total (all)		116.01	kW

Table 4 allows the selection of energy sources as well as the number of units to utilise the energy source. For example, several heat pumps could be used to maximise the power output.

Figure 4 shows the heat and mass balance, this time using the dehydration unit to subsidise the energy requirements of the granulator.

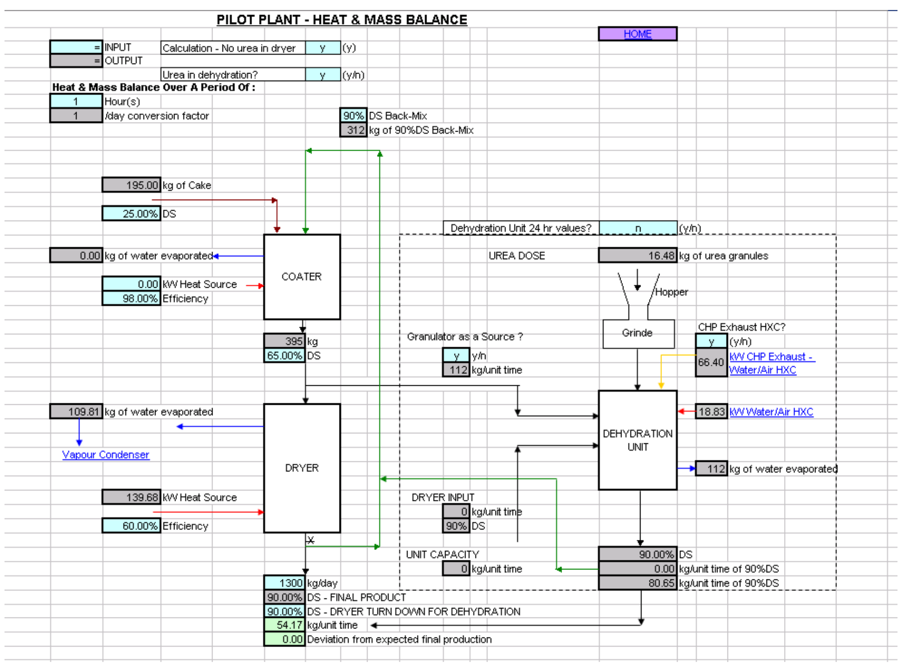

Figure 4: Heat and Mass Balance – scenario 2

Figure 4 illustrates an important example of using waste energy to save money and reduce the carbon footprint of the plant. The 65%DS granules now have a side stream to the dehydration unit, allowing the dehydration unit to run in parallel. The waste energy can now be subtracted from the granulator energy requirements. Looking back to table 4, several hundred kW of energy can be obtained from waste heat. Therefore, the energy requirements of the granulator are vastly reduced.

Optimisation of Process Variables

Once the pilot plant is installed and commissioned, there are several variables which will have a big impact on efficiency and speed of production. In order to ensure a balance between these outputs, testing will have to be conducted. While it is not difficult to establish what factors will have an effect on the output, what is not clear is the comparative significance of these variables. The granulator is an industry established piece of kit and therefore has been designed to perform well at certain settings. However, the dehydration unit is new technology and so optimal settings will have to be established. The main variables in the operation of the dehydration unit are as follows:

1. Granule Quantity – This affects the air flow through the granules as well as increasing the amount of water to be evaporated. Too many and the air will not effectively percolate and heat will be lost, too little and the heat will not be used up by the time it exits the dehydration unit.
2. Air Temperature – A high air temperature should more effectively evaporate the moisture in the granules, but at the cost of more heat loss due to the greater temperature differential.
3. Air Flow Rate – This is closely linked with the other variables. A decent air flow rate will be required to expose all the granules to the dehydrating air. However, if this is not matched with the quantity of granules, then big heat losses will occur. It is expected that the interaction between this and the granule quantity will be significant.
4. Duration of Dehydration – Again the interaction of this variable with the others is expected to be significant. Obviously dehydration should not continue beyond what is required, but it may be that a low temperature (~50^{o}C) for a long time is better than a high temperature (~60 ^{o}C) for a short time.

Factorial Experimental Design

Factorial experimental design involves a method of experimental design and analysis, to reveal the significance of the measured variables. This then allows the user to optimise the variables as they see fit. To start with, the variables must be identified and then two distinct levels must be determined; high (+) and low (-). The experiment then consists of running all the combinations of variables and levels and measuring the output in each instance. Table 5 shows a suitable design for the associated variables of the dehydration unit:

Table 5: Experimental Design

Treatment Combinations	GQ	AT	AFR	D
-1	-	-	-	-
a	+	-	-	-
b	-	+	-	-
ab	+	+	-	-
c	-	-	+	-
ac	+	-	+	-
bc	-	+	+	-
abc	+	+	+	-
d	-	-	-	+
ad	+	-	-	+
bd	-	+	-	+
cd	-	-	+	+
bcd	-	+	+	+
acd	+	-	+	+
abd	+	+	-	+
abcd	+	+	+	+

Where: GQ = Granule Quantity
AT = Air Temperature
AFR = Air Flow Rate
D = Duration

There are two outputs to measure: % Dry Solids (%DS) and the energy efficiency (%Ef). Both need to be measured and analysed to determine the variables effects on each. Energy efficiency is simply heat energy out/heat energy in and %DS will give an indication of how effective the drying has been. Finally, to minimise experimental error, two repeats should be performed.

Once analysis is complete, the significance of each variable and interaction on each output will be known; this can be illustrated with graphs. This will provide invaluable information for adjusting the variables in order to achieve good efficiency and effective drying, maybe focusing on one more than the other in certain situations. To provide an example of the output of analysis, figures 5-7 give examples of graphs that are obtained and briefly what information can be obtained from them.

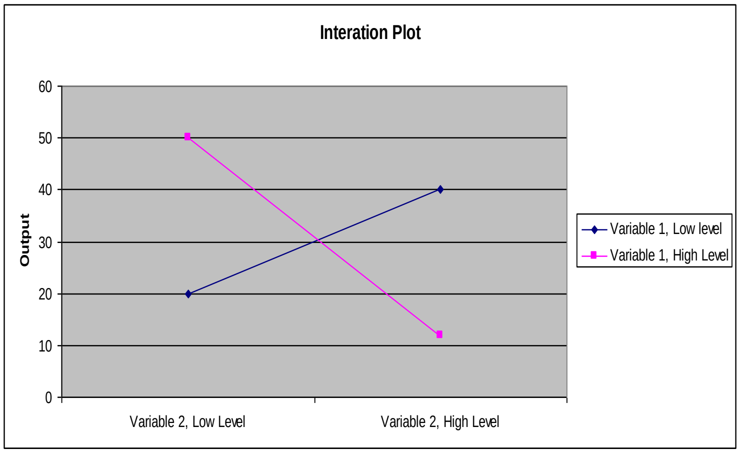

Figure 5: Main Effects Plot 1

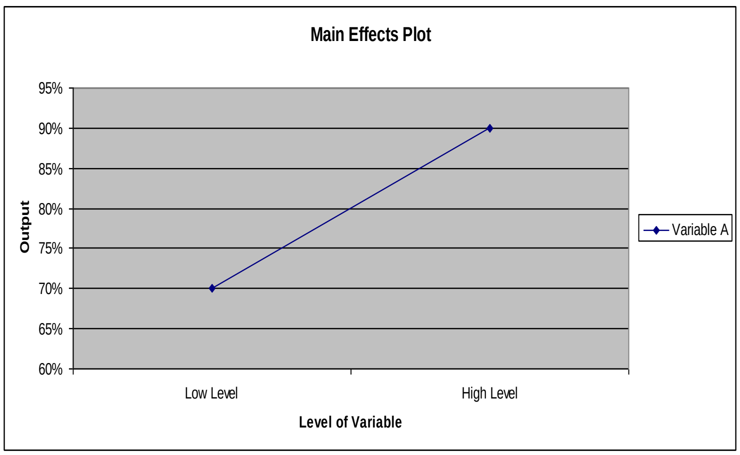

Figure 6: Interaction Plot

One of the key outputs of the analysis will be a simple plot showing the output variability at the two levels of each factor. In this example there is a clear effect on the output as the factor varies between the high and low level. As well as single variable plots, it's important to understand how the interaction of factors affects the output.

In figure 6, the graph shows the interaction between variables 1 and 2 as they are varied between the two levels. When both variables are at the high level, the output is reduced. Whereas, when at least one variable is at a high level, the output is high. A Pareto chart provides an effective illustration of the relative significance of the factors (see Figure 7). Figure 7 shows the percentage variability on the y-axis and the variables and interactions along the x-axis. Therefore, the first variable or interaction of variables is very dominant in this example, taking account of well over 50% of the variability. If the effect on the output is known, then each variable can be adjusted accordingly. Extra attention and resources can be used to control any dominant variable in order t o achieve the desired output and to maintain consistency in performance.

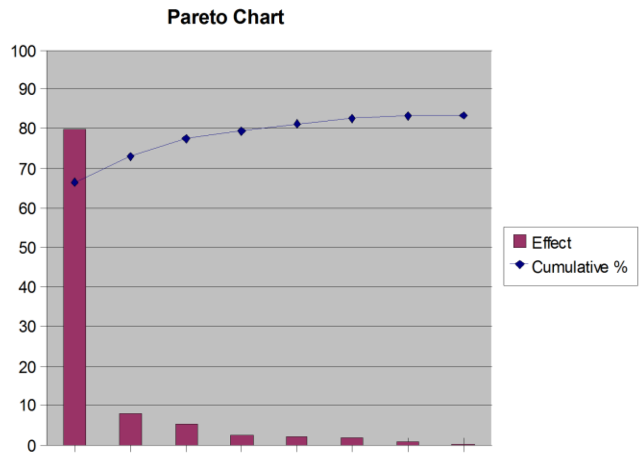

Figure 7: Pareto Chart Showing Significance of Variables and Interaction Terms

Conclusions

- The OMF process consists of converting sludge cake to a storable and usable product. This is achieved through the use of granulation and dehydration. Additionally, urea is impregnated into the granules before final dehydration, to increase the nitrogen content of the product and make it a more effective fertiliser.
- It has been established that low grade heat sources should be utilised with heat pumps or heat exchangers. If a heat exchanger is used, the source would need to be around the same temperature as desired from the heat exchanger output.
- Transferral of high grade to low grade heat is potentially very inefficient. However, there is technology available which provides the possibility of converting high grade heat to electricity, which has obvious benefits.
- There are many sources of energy available, even if it's just making use of energy in the surroundings with a heat pump. While the heat pump will require an energy input, the output can be two to three times this amount.
- Any waste heat or energy that can be effectively utilised will not only save money, but reduce the carbon footprint of the plant. Not only this, but waste energy could be used as a back-up to the energy supply, in the event of problems with the primary source.
- A heat and mass balance of the process is essential to understand the flows required at each process stage. It also helps to illustrate the energy savings and if designed so that the values can be varied, many different scenarios can be examined.
- New technology needs to be optimised through experimentation, but a structured approach to finding the optimal parameters is necessary to save time and resources. One way of achieving this is through factorial experimental design, which provides information on how each variable and interaction of variables affect a measured output. Using this, the user can quickly determine how to adjust the variables to achieve the desired output.

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