BoaNiCO_2 Factory trial, 2022

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Comparing energy consumption of three production methods on an adjusted BOA-500 based on factory data

Principal
This research project is conducted by Zetadec for consortium Nicoflo and ZO-Salland

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1 Introduction

Energy consumption of manufactured goods, including animal feed, is a relevant factor in any area of industry to keep it's 'licence to produce' from a societal perspective. Increases in human population, growth, climate change and urbanization makes the question on prudent and efficient use of energy and reduction of associated Green House Gases (GHG) or Carbon emissions ever more relevant. Within the feed industry a number of projects have been targeting possible measures to reduce carbon footprint and GHG emissions. These projects were aiming at a more system specific approach on measures to reduce energy consumption, GHG and carbon footprint in the feed industry. Further improvements in equipment and intrinsically energy-low equipment was not the focus of these projects. Recent developments have shown that further refinement of equipment may lead to reductions of up till 20% in specific mechanical energy use (van Culemborg and Duitshof, 2019). Nico Treurniet has made an upgrade to an existing feed production unit, duly named the BOA-NiCO_2 which, together with changes in processing conditions, results in a reduction of electrical energy and gas consumption (Holterman, 2019).
This report contains the results of a factory trial comparing the effect of two production methods of a BOA-500, the normal production method and the BOA-NiCO_2 method, on energy consumption, pellet quality and production capacity. The comparison of the different production methods is made with the use of automatically collected data from the MES layer of the factory during several weeks of production.

1.1 History of the BOA-NiCO_2

Treurniet voeders, a feed producer in Berkel en Rodenrijs (NL) was led by Nico Treurniet. In the factory Treurniet had a conventional BOA-500 installed in 1995. Since the installation of the BOA-500 Mr. Treurniet started experimenting with the setup of the BOA to further improve the workings of the machine. With the adaptations Mr. Treurniet managed to decrease the electrical energy consumption and removed the need for high quality steam while keeping good quality pellets. The main focus of the adaptations of Mr. Treurniet are on the RPM, Delta T (the temperature increase achieved by the friction rings), friction-rings and roller design but also adaptations to other parts of the machine have been made. Because of all the adaptations the concept of production was called the BOA-NiCO_2 and Mr. Treurniet patented the adaptations he made.
All the experimenting with the BOA-NiCO_2 was performed by Mr. Treurniet in his own factory. After production of Treurniet-voeders stopped in their factory in Berkel en Rodenrijs and Mr. Treurniet retired, the wish emerged to perform independent trials to show the performance of the BOA-NiCO_2.

1.2 Consortium

For the performance of the independent trials a new production location needed to be found in which the BOA-NiCO_2 could be installed. The factory of ZO-Salland and its director Hans Verheul showed interest in the BOA-NiCO_2 and involvement in the trial. Furthermore, the factory of ZO-Salland already had a BOA-500 fitted in an identical production line, which accommodates the comparison between both machines. A consortium was formed between Mr. Treurniet & ZO-Salland and a fund was granted by the Dutch Ministry of Economic affairs to perform the experiment.
To assure an independent test on the performance of the BOA-NiCO_2 Zetadec is chosen by the consortium as external party to set up and supervise the trials and analyse the results.

Zetadec is a Dutch research & development and consultancy company in the field of compound feed technology and processing of raw materials. Zetadec offers services to develop new products and processes. These services can either be product formulation, process development, conceptualization & optimization of manufacturing lines, with focus on the interaction between raw materials and (feed) processing equipment. Additional services include design of experiments, mathematical modelling, statistics and data mining. Zetadec is experienced in feed manufacturing unit operations such as, grinding, mixing, pelleting, extrusion, high shear granulation, cooling and coating. Zetadec has access to state-of-the-art laboratory facilities. In its own laboratory Zetadec performs analyses on functionality, texture, flowability, hardness & durability and can set-up "proof-of-principle" experiments. In addition, Zetadec operates a pilot plant in which processing trials are performed.

1.3 Aim of the project

The aim of the project is to compare the energy consumption of a normal BOA 500 to the energy consumption of an adjusted BOA 500 the BOA-NiCO_2 and compare alternative production methods on the Boa-NiCO_2 compared to a standard BOA 500.

The project is divided into two parts:

- The first part is focused on the effect of the production method, RPM & Steam supply, on energy consumption, pellet quality and production capacity.
- The second part is to compare the effect of different friction rings and rollers on energy consumption, pellet quality and production capacity.

This report focuses on the first part of the project and describes the relation between RPM and steam consumption on energy consumption, pellet quality and production capacity. This trial is focusing on the differences between production methods

The hypothesis is that production at a lower RPM without steam addition results in a reduction in energy consumption while keeping proper pellet quality and production capacity.

2 Material and methods

2.1 Trial setup

This trial focuses on the effect of RPM and steam addition which can be varied with the BOA-NiCO_2, thus the machine can run on the normal BOA-500 production method and on the BOA-NiCO_2 production method. Because of this flexibility and to reduce the effect of variation between production lines it was decided for this trial to perform all measurements on the same production line while varying the production method.

The production methods of the trial can be divided into three individual classes based on the RPM and steam usage of the BOA-NiCO_2.

1. Normal, high RPM with steam
2. Normal, high RPM without steam
3. NiCO_2, low RPM without steam

In this report the term BOA-NiCO_2 is used to name the machine as adjusted by Mr. Treurniet and NiCO_2 will be used to depict the production method developed by Mr. Treurniet on the BOA-NiCO_2

For the comparison between the different production methods with the BOA-NiCO_2 data was collected between 30-01-2022 and 27-03-2022. During this time period the production method was changed every week by the operators of ZO-Salland. One week production took place on the NiCO_2 method with the use of reduced RPM and without steam the other week production took place on the traditional way at maximal RPM (with or without steam).

2.2 Factory

The factory of ZO-Salland is located in Haarle, NL and consists of three production lines. This trial is performed on the second production line, which consists of:

- The BOA-NiCO_2
  - 132 kW electro motor
  - Frequency driven with a ABB type ACS800-07-0210-3 frequency drive
  - Normal friction rings and rollers fitted
- Steam reduction system placed by Heemhorst
- A Paladin 1200 Pellet mill
  - Two 75kW elector motors
  - 5mm die hole diameter and 75 mm die thickness
- A 1900mm*1900mm Heemhorst counterflow cooler

The hammer mill of ZO-Salland is a Heemhorst Hemos 2000 fitted with a 3.0 and a 3.5 mm sieve.

2.2.1 Steam boiler

The steam boiler is a Ten Horn (type: 12.02AT) installed in 1960 with a Weishaupt (type: G 7/1D) burner installed in 2000. During the second day of manual measurements in the factory steam pressure before pressure reduction is determined to be 7.76 bar (SD:0.15, n:10) on average.

The test report of HKB Boiler solutions (25-05-2020) provides the data used to calculate the boiler performance in Table 1.

Table 1. Boiler performance

Load	Minimal	Maximal
Steam production (kg/hr)	708	1121
Gas usage (M^3/hr)	60.2	95
Gas M^3/kg steam	0.08502	0.08474

An average gas consumption of 0.085 M^3 gas per kg steam is used to provide estimations on the actual reduction of gas usage during the trial. Any loss of steam due to condensation of steam when flowing from the boiler to the pelting lines is not accounted for in the gas consumption calculations.

2.3 Manual measurements

Besides the automatically collected data, additional data is manually collected. The manual measurements can be divided into two categories, regular measurements on pellet quality during regular production and dedicated testing days on which multiple measurements on the production process are preformed throughout the factory.

2.3.1 Pellet durability

Holmen Pellet Durability Index (PDI) of the pellets was analysed by the operators of ZO-Salland using the Holmen NHP 100 (Figure 1). Samples (100 grams) were weighed, tested in the NHP 100 for 60 seconds and weighed again. Holmen PDI was calculated as shown in the following equation:

$$Holmen\ PDI\ (\%) = \frac{Sample\ weight\ after\ tumbling\ (g)}{Sample\ weight\ before\ tumbling\ (g)} \times 100\%$$

Figure 1. Holmen NHP 100 pellet durability tester

2.3.2 Manual testing days

During two days the factory of ZO-Salland was used for manual measurements of the production lines. During these days manual measurements on:

- Temperatures
- Environmental conditions
- Moisture contents
- Pellet quality
- Steam pressures & temperatures

Were used to assess the state of the production lines and as a check for the automatically registered datapoints by the BatchReporter.

The first day was used to produce long runs of a formulation in which the production parameters were constantly adjusted. The goal of this day was to provide the team of Zetadec and the operators of ZO-Salland an opportunity to find the limits of the newly installed BOA-NiCO_2 and provide insight in the production process. Furthermore, measurements on moisture content and processing temperatures of this day are used to determine estimates on steam quality.
Based on the experiences of this day the operators of ZO-Salland started to optimize their production process.

The second day was performed 2 months after the first day. During this day shorter runs with only one set of parameters (parameters were chosen based on operator experiences of the past two months) were produced and measured to provide both reliable entries in the database and manual measurements. These manual measurements are used to check the automatically collected data.

The individual measurements of the manual testing days will only be used to provide insight and check the automatically collected data.

2.4 Data collection

A batch reporter tool, custom made by Oostec (Hengelo, NL), is used to collect PLC data for the different production runs into a database. The BatchReporter is programmed to automatically determine the stable part of each pelleting batch and reports the averages of the most parameters during the stable part of the batch. Thus, the data is excluding fluctuations caused by the start-up, stopping or calamities such as blockages of the pelleting line. The exact method used to determine stable processing conditions and the average datapoints is determined by Oostec under their responsibility.

For the parameters on total energy consumption (PLx_BOAx_E_Gemeten, PLx_Px_E_Gemeten, PLx_BOAx_E_Berekend, PLx_Px_E_Berekend) the batchreporter registers the totals of the batch to the database.

For each batch the batch reporter collects the parameters described in Table 2.

Table 2. Parameters collected by the batchreporter

NAAM	OMSCHRIJVING	EENHEID
BatchID	Unique database ID	
BatchNummmer	Batch number used by ZO-Salland	
ProductNummer	Product number used by ZO_Salland	
ProductNaam	Name of the product, linked to product number	
Lijn	Number of the production line	
LijnNaam	Name of the production line	
StartTijd	Time production started	
StopTijd	Time production was finalised	
GevraagdGewicht	Requested amount of feed	kg
GeproduceerdGewicht	Actual produced amount of feed	kg
PLx_Px_TijdStabiel	Algemeen Pers stabiel periode	sec
PLx_Px_TijdDuur	Algemeen Pers duur periode	sec
PLx_CapGem	Algemeen Gemidelde capaciteit (na opstart)	ton/uur
PLx_BOAx_FStmGem	BOA Stoom flow	kg/uur
PLx_BOAx_FWatGem	BOA Water flow	kg/uur
PLx_BOAx_FR_Tsp	BOA Gevraagde temperatuur voor frictie ringen	°C
PLx_BOAx_FRpre_T	BOA Temperatuur voor frictie ringen	°C
PLx_BOAx_Frpost_T	BOA Temperatuur na frictie ringen	°C
PLx_BOAx_PpostStart	BOA Gemiddeld vermogen (na opstart)	KW
PLx_BOAx_Psp	BOA Gewenst vermogen	KW
PLx_Px_E_Gemeten	Pers Totaal energieverbruik gemeten	KWh
PLx_BOAx_FrOGem	BOA Gemiddelde frictiering opening (na opstart)	mm
PLx_BOAx_Ngem	BOA Toerental	rpm
PLx_BOAx_Verdichten	BOA Mixer of verdichter	0/1
PLx_Px_PpostStart	Pers Gemiddelde vermogen (na opstart)	kw
PLx_BOAx_E_Gemeten	BOA Totaal energieverbruik gemeten	kwH
PLx_KOx_Tuit	Koeler Temperatuur uitgaande lucht	°C
WinDos_Zeven	Zeven_ (0=niet, 1=fijn, 2=grof)	0/1/2
WinDos_Kruimelen	Kruimelen (0=niet, 1=wel)	0/1
WinDos_Opbrengst	Opbrengst (T/U)	ton/uur
WinDos_Capaciteit_toevoer	Capaciteit toevoer (kg/omw)	kg/omw

WinDos_Stoomtemperatuur	Stoomtemperatuur (C)	°C
WinDos_RegelVermogenBoven	Regel vermogen Boven (kw)	kw
WinDos_RegelVermogenBoven_kwht	Regel vermogen Boven (kwh/t)	kwh/t
WinDos_Conusdruk_Exp	Conusdruk Exp (bar)	bar
WinDos_MaxVermogenPers	Max. vermogen Pers (kw)	kw
WinDos_RegelKarakteristiek	RegelKarakteristiek (1 t/m 3)	01/02/03
WinDos_Talken	Talken (0=niet, 1 = wel)	0/1
WinDos_Water_sp	Water setpoint	*NA*
PLx_BOAx_E_Berekend	*NA*	KWh
PLx_Px_E_Berekend	*NA*	KWh

The parameters starting with WinDos are setpoints supplied by the automation system and are set uniquely for the different products.

2.5 Calculations

2.5.1 Production method determination

The raw data does not supply a label about which production method is used. Therefore, a label is manually added based on the information on RPM(PLx_BOAx_Ngem) and steam flow (PLx_BOAx_FStmGem),

- If RPM is >1198 and steam flow >0.5 kg/hr the production method is Normal_WithSteam
- if RPM is >1198 and steam flow <0.5 kg/hr the production method is Normal_WithoutSteam.
- If the RPM measurement value is <1198 (263.5rpm) and the steam flow is >0.5 kg/hr the production method is classified as $NiCO_2$

In the case a production method was classified with an RPM <1198 and a steam supply it was classified as an unknown production method and excluded from the trial.

2.5.2 RPM

The RPM of the boa is supplied as the RPM of the electrical motor and not the actual RPM of the BOA after transmission. Therefore, a correction factor of 0.22 is used for the BOA-$NiCO_2$ to require the actual RPM of the BOA mixer-shaft.

2.5.3 Electrical energy

The electrical energy of the pellet mill in line 2 is not directly measured with a kWh meter but a calculation in the PLC is used to determine the energy consumption of the pellet mill. The pellet mill in line 1 has a kWh meter and the calculated energy consumption. Therefore, pellet mill 1 is used to check the quality of the calculation, Figure 2 shows that there is a difference between the measured and the calculated values by the PLC of pellet mill 1, because the red line and black line are not on top of each other, Therefore, a correction factor of 1.377 was required to align the measured and calculated energy consumption. Since both pellet mills are of the same type with the same electro motor it is assumed that pellet mill 2 requires the same correction factor to approximate the real energy consumption with the calculated values from the PLC.

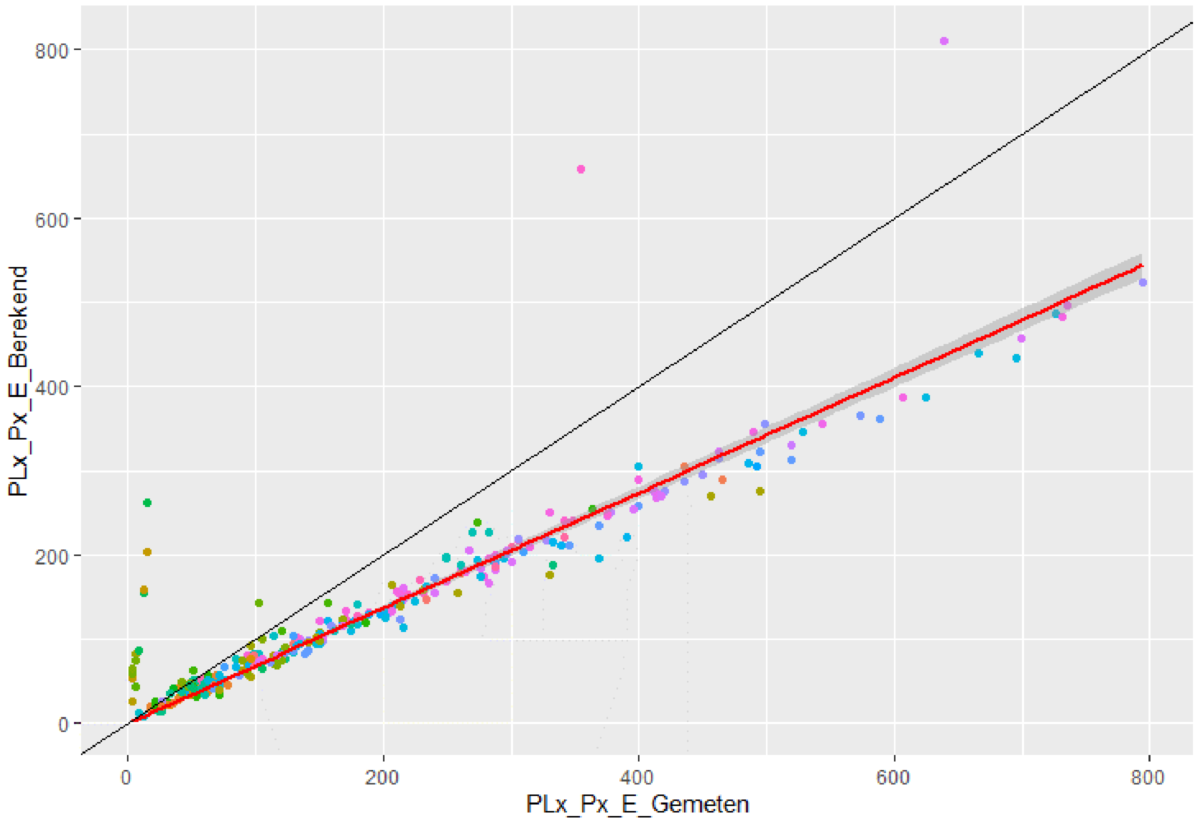


Figure 2, Measured versus PLC calculated electrical consumption pellet mill 1

For the BOA-NiCO2 in pelleting line 2 the measured energy consumption is recorded and used.

2.5.4 Specific mechanical energy

Specific mechanical energy (SME) is the electrical energy consumption expressed in kWh/ton. SME is calculated for the BOA and the pellet mill with the following formula's:

$$SME\ (BOA) = \frac{PLx\_BOAx\_E\_Gemeten}{GeproduceerdGewicht/1000}$$

$$SME\ (Pellet\ mill)\ = \frac{PLx\_Px\_E\_Berekend * 1.377}{GeproduceerdGewicht/1000}$$

2.5.5 STE

Specific thermal energy is the energy added to the feed mash with the use of steam expressed as kWh/ton. To determine the STE of steam the steam pressure, steam temperature, degree of saturation and steam flow are required. The pressure and temperature determine the energy content of the steam, unfortunately steam pressure and temperature are not automatically registered in the factory of ZO-Salland.
Based on the manual measurements of the steam pressure during the manual factory tests,it is assumed that pressure is stable at 2.2 bar and that the steam is saturated. Saturated steam has a temperature of 123.27°C at 2.2 bars and has alatent heat of 2193 kj/kg and the specific heat of water is 4.182 kj/kg/°C.

The STE is estimated with the following formula:

$$STE = \frac{\text{PLx\_BOAx\_FStmGem} \times 2193 + (4.182 \times (123.27 - \text{PLx\_BOAx\_FRpre\_T}))}{3600} / \text{PLx\_CapGem}$$

2.6 Data selection

For the trial the following selection criteria are used to select production runs for the statistical analysis:

- Only runs produced on pelleting line 2.
- Runs produced between 30-Januari-2022 00:00:00 and 27-March-2022 23:59:59.

- Within the period of the trial selected formulations must be produced at least once on the $NiCO_2$ method and once on a normal method.

2.7 Statistics

Actual measurements on RPM and steam usage are confounding, due to the setup of the trial based on production methods. Therefore, it was decided to use the three production methods (Normal_with_stema, Normal_without_steam and $NiCO_2$) as factors in the statistical design and not assess the numerical effect of steam and RPM individually.

During the trial period many different formulations have been produced. These formulations may yield different results with respect to the performance of the pelleting line. Since we are not interested in the effect of the formulation per-sé, a mixed model which corrects for the random effect of product formulation is used to assess the effect of production method on SME, STE, Total energy consumption and pellet durability. The following model was used, in which Y is the response parameter, *ProductionMethod* is the fixed effect and *Formulation* is the random effect (the random effect is included with a variable intercept and fixed slope):

$$Y = ProductionMethod * \beta + Formulation * U + error$$

3 Results

3.1 Overview of data

During the data collection period of the trial 450 runs are produced. From these 450 runs, based on the selection criteria (Paragraph 2.6), for the trial 279 runs are selected. Of the selected runs the distribution over the production methods is:

- 132 runs produced with the $NiCO_2$ production method
- 98 runs produced with the normal method without steam
- 49 runs produced on the normal method with steam

The 279 selected production runs are divided across 45 different feed formulations and 5 animal species. The codes of the different formulations and the amount of runs for each of the formulations is provided in Table 3.

Table 3. Formulation codes

Formulation code	Number of runs	Formulation code	Number of runs
2001	20	2155	2
2004	9	2156	2
2008	3	2157	3
2010	15	2173	3
2012	28	2177	2
2014	13	2178	4
2017	40	2181	2
2020	14	2193	2
2043	3	2199	8
2055	18	2220	3
2082	2	2239	2
2089	4	2350	2
2104	2	2601	3
2106	3	2701	14
2115	3	2703	2
2120	2	2705	6
2121	4	2810	2
2122	2	2881	7
2124	4	4817	2
2126	2	4820	4
2127	2	21051	2
2137	3	28887	3
2143	3		

The division of the runs over animal species is as follows:

- 2 runs of a goat formulation
- 10 runs of a horse formulation
- 40 runs of a ruminant formulation high in protein
- 202 runs of a ruminant formulation high in energy
- 22 runs of a sheep formulation
- 3 runs of a swine formulation

Figure 3 provides the production method and amount of runs for each method during the different production weeks. The figure clearly shows an alternating pattern of producing on the $NiCO_2$ method and the normal method, every other week.

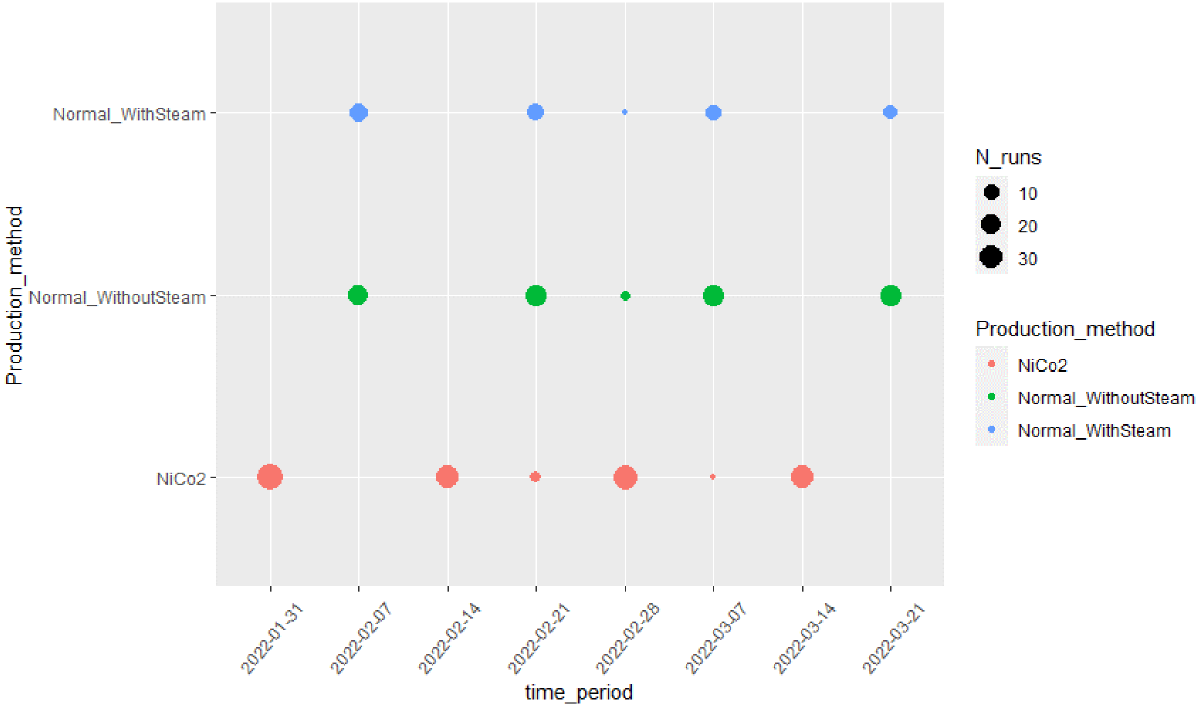


Figure 3. Distribution of the production methods over the weeks of the trial

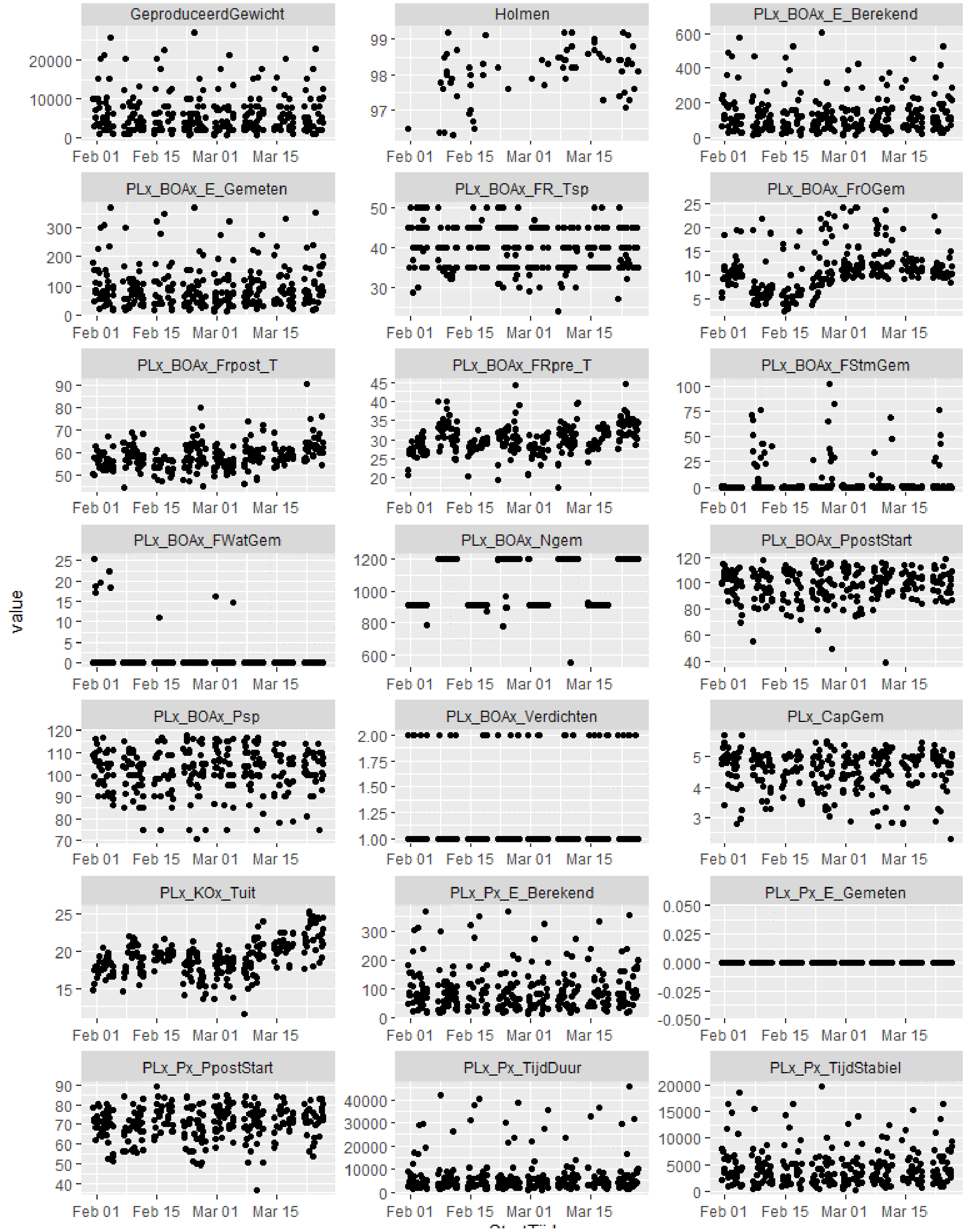


Figure 4. Overview of the raw data collected for different parameters during the period of the trial

An initial overview of the data points for the different parameters that are collected for pelleting line 2 and the selected runs is provided in Figure 4.

3.2 Quality of data

This section contains some checks on the quality of the collected data. For the checks some parameters are checked against related parameters, setpoint values, manual measurements, or alternative methods of calculation.

3.2.1 Capacity

The average capacity (PLx_CapGem) is used to calculate STE and total produced weight (GeproduceerdGewicht) is used to calculate SME. To check the relation between both methods Figure 5 compares the recorded produced weight with the calculated produced weight, the different colours are for the different formulations. To calculate produced weight the following formula is used:

$$Calculated\ produced\ weight = \frac{PLx\_CapGem \times TijdStabiel}{3.6}$$

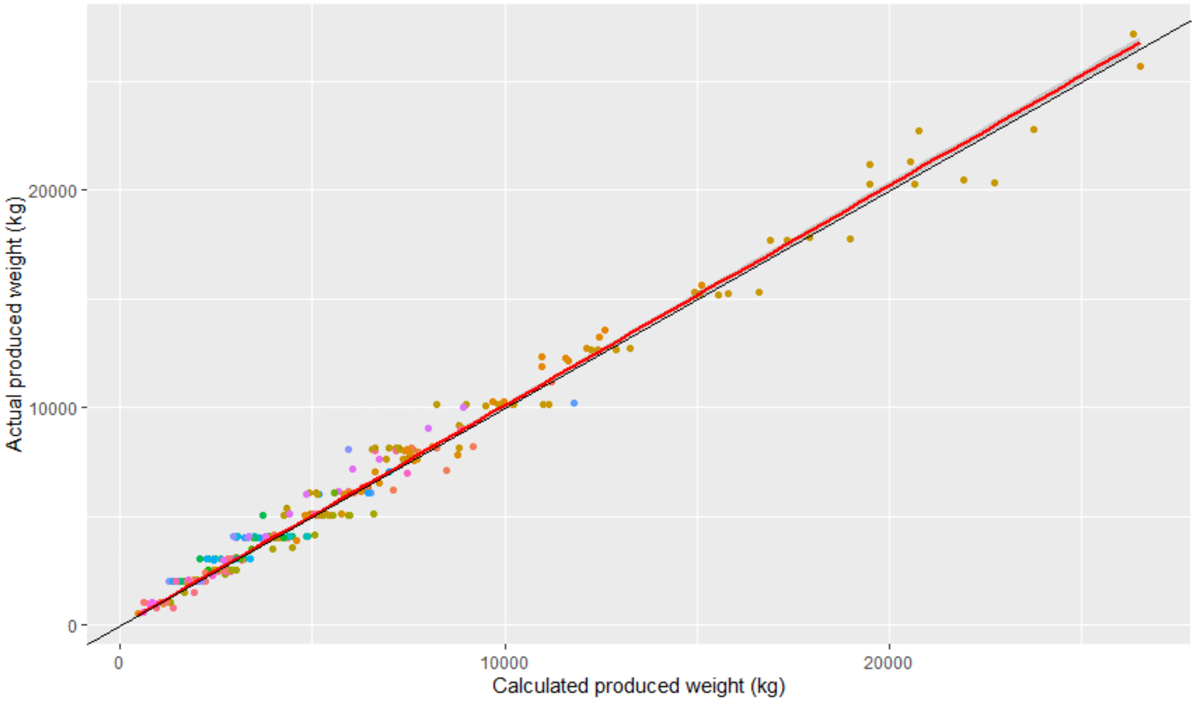


Figure 5. Check between calculated produced weight and actual produced weight

Because the red and black line are on top of each other in Figure 5 it can be stated that both measurements can be used in the SME and STE calculations.

3.2.2 Steam flow related to temperature before the friction rings

Steam flow should be affected by production capacity and temperature before the friction rings. A check on this relation is performed for the runs that have been produced with steam. For the check steam flow corrected for production capacity is plotted in Figure 6 against the temperature before the friction rings. The figure shows that a linear trend between the two parameters is visible however, there is also a high degree of variation in the data points.

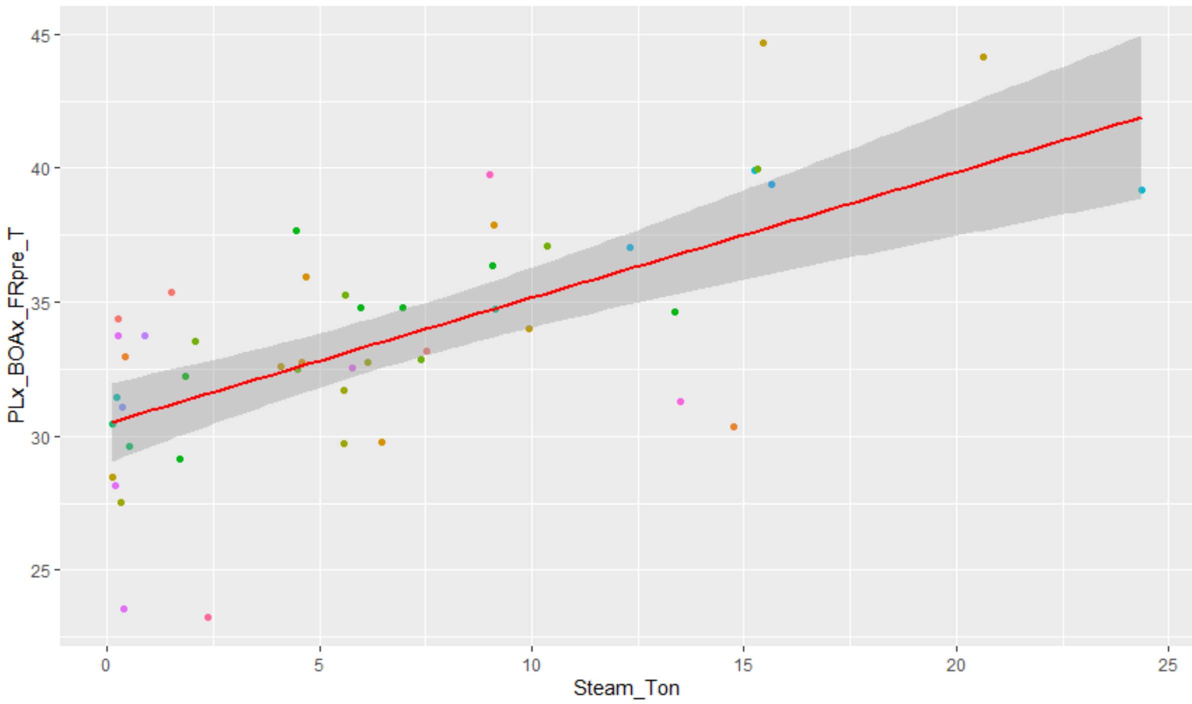


Figure 6. Steam addition (kg/ton) in relation to meal temperature before the friction rings

3.2.3 Setpoint values versus actual conditioning temperature

Figure 7 provides the requested conditioning temperature before the friction rings compared to the measured temperature before the friction rings. For the figure only runs that have been produced on the Normal production methods have been selected. The figure shows that there is a discrepancy between the requested temperature and the actual recorded measured temperature.

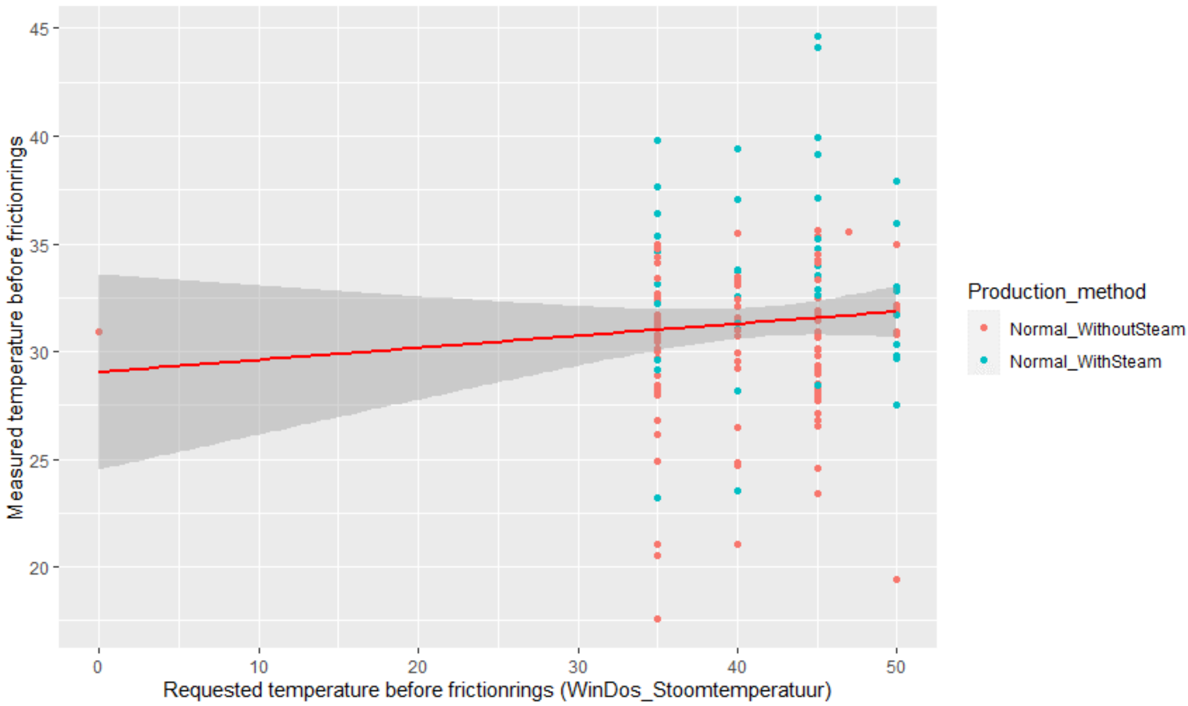


Figure 7, Set-point conditioning temperature versus the measured conditioning temperature

3.2.4 Requested versus measured BOA power consumption

Figure 8 shows the relation between the requested BOA power consumption and the measured BOA power consumption. In an ideal situation requested and measured power consumption are equal, which would result in a diagonal line in Figure 8. However, in this case there are some differences between the requested power consumption and the measured power consumption as can be seen by the spread of the datapoints in Figure 8. Despite the variation the collected and requested datapoints are within a similar range.

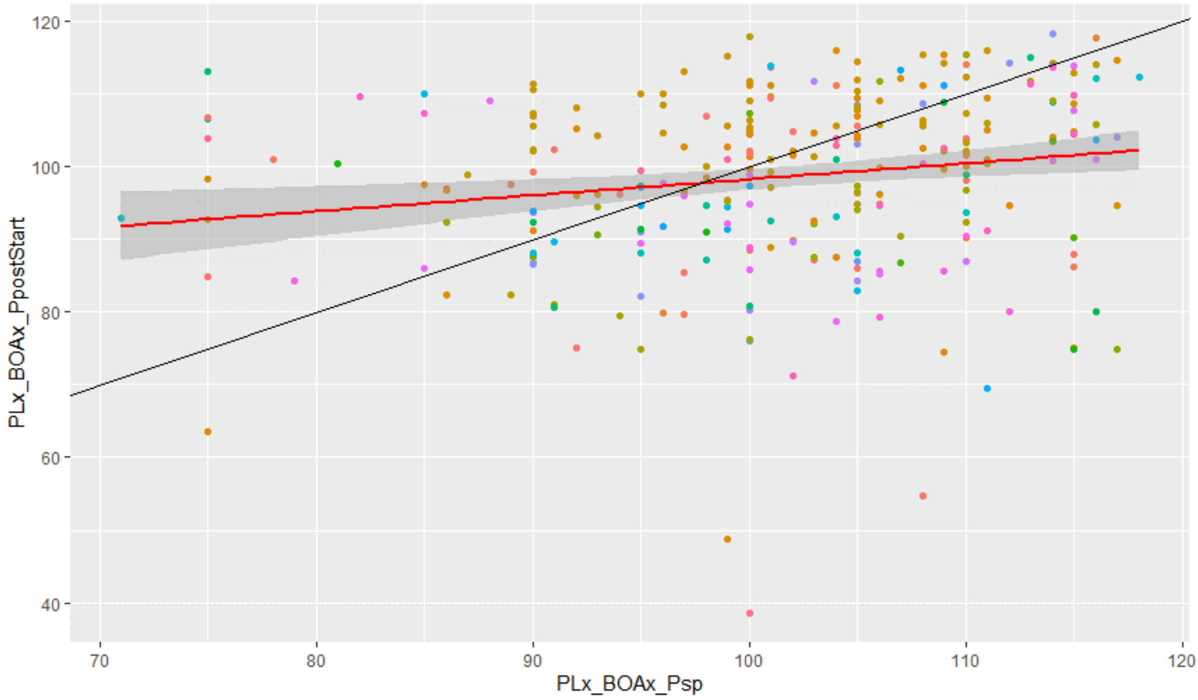


Figure 8. Relation between requested BOA power consumption (PLx_BOAx_Psp) and measured BOA powerconsumption (PLx_BOAx_PpostStart)

3.2.5 Temperature after BOA

The data collected during the trial day of 22-01-22 in the factory of ZO-Salland is used to check the automatic temperature measurements after the BOA with manual measurements of the temperature after the BOA. Figure 9 shows that the manual measurements result in a +- 10°C higher temperature measurement.

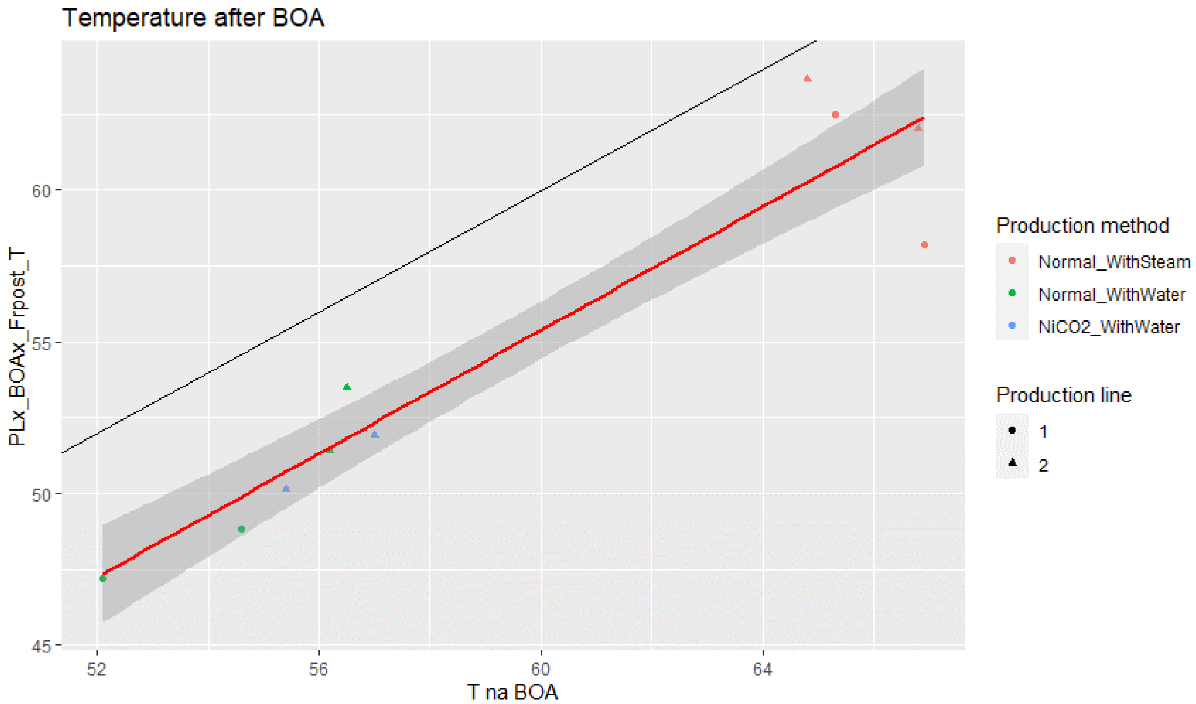


Figure 9, Automatically recorded and manual measured temperatures after BOA

3.3 SME

Figure 10 provides the calculated SME of the BOA, Pellet Mill and the combination of BOA + Pellet Mill, color coded for the different production methods. From the figure the SME for both the BOA-$NiCO_2$ and pellet

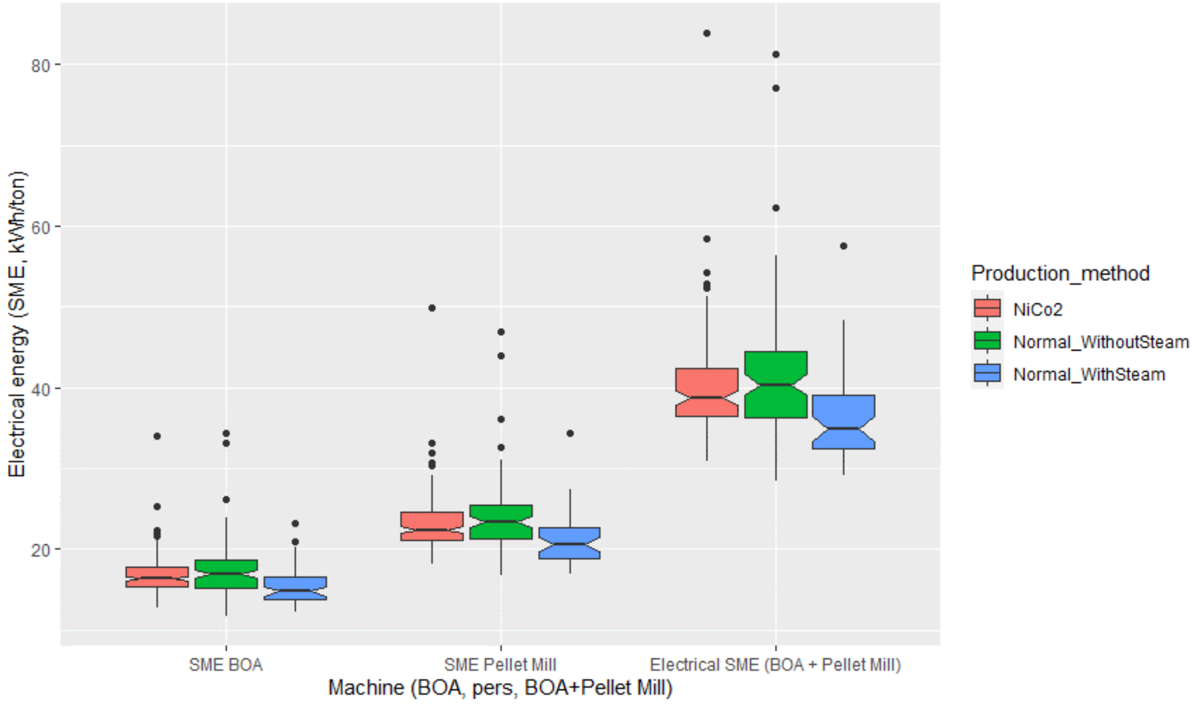


Figure 10. Electrical energy consumption of BOA, pellet mill and BOA+pellet mill

mill follow the same trend for the different production methods, $NiCO_2$ and Normal without steam consume more electrical energy compared to Normal with steam. For the mixed model only the total SME of the BOA+Pellet mill is used because the main interest is to gain insight in the total energy consumption of the pelleting line.

Error! Reference source not found. provides the fixed effect of production method on the SME of the BOA a nd pellet mill combined. The constant is the estimated SME for the $NiCO_2$ production method, corrected for the random effect of formulation. The results for the production methods Normal with steam and Normal without steam are supplied in relation to the Constant effect.

- The $NiCO_2$ production method resulted in a SME of 42.509 kWh/ton.
- The SME of normal production without steam is 42.509+0.586=43.095 KWh/ton, this is not significantly different from the total energy consumption of the $NiCO_2$ method($p>0.05$).
- The SME of Normal with steam is 42.509 -3.013=39.496 kWh/ton and the p-value (<0.001) indicates that the difference in kWh is significant from the $NiCO_2$ production method.

Error! Reference source not found. provides the visualisation of the SME estimates for the different p roduction methods, with error bars providing insight in the variation of the estimates.
The summary of the mixed model including the random effects is provided in appendix A.

Table 4. Electrical energy (SME) fixed effects

	Dependent variable:
	`Electrical SME`
Normal_WithoutSteam	0.586
	(0.641)
Normal_WithSteam	-3.013***
	(0.820)
Constant ($NiCO_2$)	42.509***
	(1.068)
Observations	279
Log Likelihood	-870.973
Akaike Inf. Crit.	1751.947
Bayesian Inf. Crit.	1770.103
Note: *p<0.05; **p<0.01; ***p<0.00	

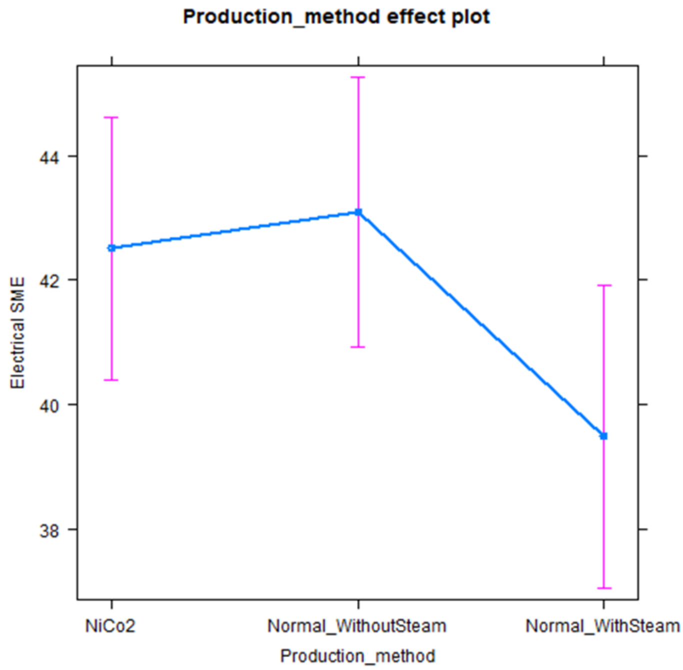


Figure 11. Visualization of the fixed effects for SME

3.4 Thermal energy consumption

Thermal energy consumption is based on the consumption of steam during the production process and can be expressed in different ways as actual steam consumption and as STE.

3.4.1 Steam consumption

For this report the steam consumption per ton of feed and the gas consumption per ton of feed (uncorrected for any steam loss in the factory) are supplied for the normal production method with steam in Table 5.

Table 5. Estimated steam and gas consumption of the normal with steam production method

	Steam consumption (kg/ton)	*Gas consumption (M^3/ton)*
Minimal	0.117	0.001
Maximal	24.4	2.0
Mean	6.75	0.574
SD	6.03	0.512

On average, runs that are produced with steam have a steam addition in the conditioner of 6.75 kg/ton which is equivalent to 0.574 M^3 of gas consumption per ton.

3.4.2 STE

To compare the BOA- $NiCO_2$ production method with the normal methods it is important to express the thermal energy consumption as STE in kWh/ton.
Table 6 provides the fixed effect of production method on the Thermal energy consumption (STE). The constant is the estimated STE for the $NiCO_2$ production method, corrected for the random effect of formulation. The results for the production methods Normal with steam and Normal without steam are supplied in relation to the Constant effect.

- The $NiCO_2$ production method resulted in a STE of 0.025 kWh/ton, which is not different from zero ($p>0.05$).
- The STE of normal production without steam is 0.025+0.013=0.038 KWh/ton, this is not significantly different from the total energy consumption of the $NiCO_2$ method($p>0.05$).
- The STE of Normal with steam is 0.025 +4.788=4.813 kWh/ton and the p-value (<0.001) indicates that the difference in kWh is significant from the $NiCO_2$ production method.

Figure 12 provides the visualisation of the STE estimates for the different production methods, with error bars providing insight in the variation of the estimates.
The summary of the mixed model including the random effects is provided in appendix A.

Table 6. STE fixed results

	Dependent variable:
	\`Thermal (STE)\`
Normal_WithoutSteam	0.013
	(0.233)
Normal_WithSteam	4.788***
	(0.294)
Constant ($NiCO_2$)	0.025
	(0.175)
Observations	279
Log Likelihood	-556.113
Akaike Inf. Crit.	1122.226
Bayesian Inf. Crit.	1140.382
Note: *p<0.05; **p<0.01; ***p<0.001	

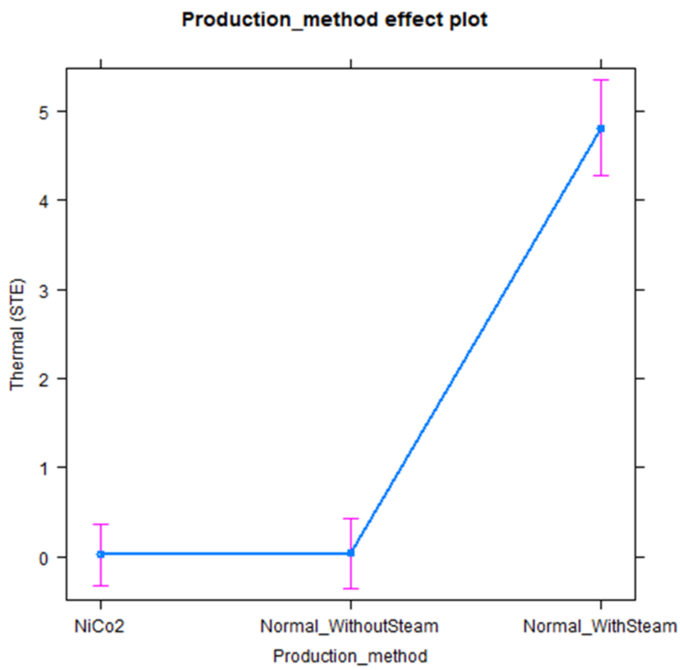


Figure 12. STE fixed results visualisation

3.5 Total specific energy consumption

The total specific energy consumption is the total energy consumption of the pelleting line and calculated by adding the SME and STE.

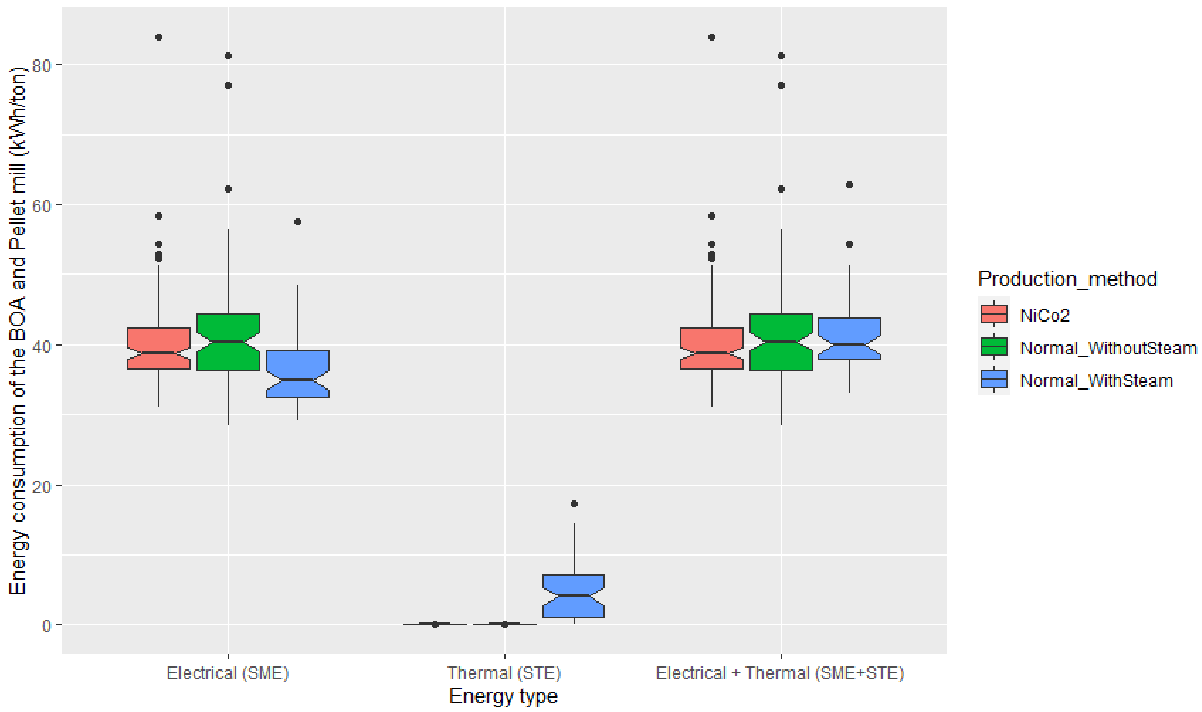


Figure 13. Overview of SME, STE and total specific energy (SME+STE)

Table 7 provides the fixed effect of production method on the total specific energy consumption (SME+STE). The constant is the estimated total specific energy consumption for the $NiCO_2$ production method, corrected for the random effect of formulation. The results for the production methods Normal with steam and Normal without steam are supplied in relation to the Constant effect.

- The $NiCO_2$ production method resulted in a total energy consumption of 42.575 kWh/ton.
- The total energy consumption of normal production without steam is 42.575+0.618=43.193 KWh/ton, this is not significantly different from the total energy consumption of the $NiCO_2$ method($p>0.05$).
- The total energy consumption of normal production with steam is 47.575 + 1.683=49.258 kWh/ton and the p-value (<0.05) indicates that the difference in energy consumption is significant from the $NiCO_2$ production method. Thus, production with the $NiCO_2$ method uses on average and corrected for an effect of formulation 1.683 kWh/ton less energy.

Figure 14 provides the visualisation of the STE estimates for the different production methods, with error bars providing insight in the variation of the estimates.
The summary of the mixed model including the random effects is provided in appendix A.

Table 7. Total energy consumption (SME+STE) fixed effects

	Dependent variable:
	\`Electrical+ Thermal (SME+STE)\`
Normal_WithoutSteam	0.618
	(0.648)
Normal_WithSteam	1.683*
	(0.829)
Constant ($NiCO_2$)	42.575***
	(1.100)
Observations	279
Log Likelihood	-874.760
Akaike Inf. Crit.	1759.519
Bayesian Inf. Crit.	1777.675
Note: *p<0.05; **p<0.01; ***p<0.001	

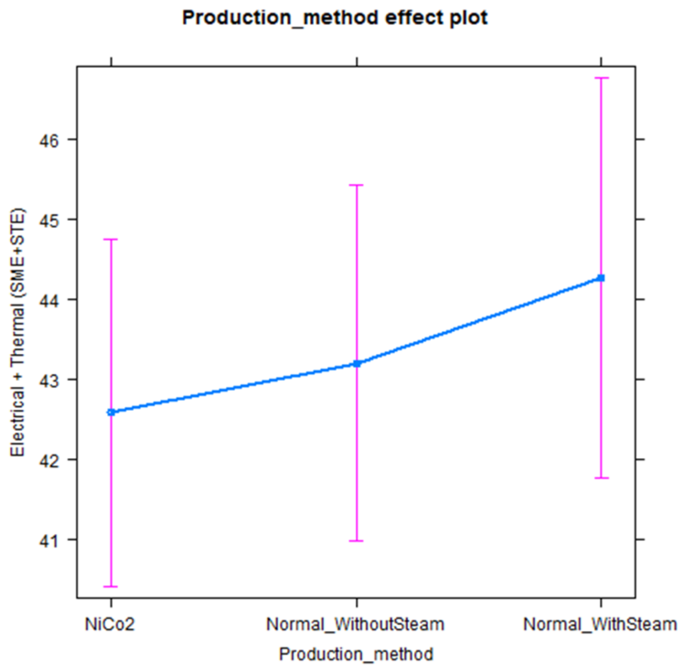


Figure 14. Total energy consumption (SME+STE) *fixed effects visualisation*

3.6 Durability

Table 7 provides the fixed effect of production method on the pellet durability. The constant is the estimated pellet durability for the $NiCO_2$ production method, corrected for the random effect of formulation. The results for the production methods Normal with steam and Normal without steam are supplied in relation to the Constant effect.

- The $NiCO_2$ production method resulted in a pellet durability of 98.128%
- The pellet durability of normal production without steam is 98.128%+0.336%=98.464%, this is statistically not different from the total energy consumption of the $NiCO_2$ method($p>0.05$).
- The pellet durability of normal production with steam is 98.128%-0.020%=98.108%, this is not significantly different from the measured pellet durability of the $NiCO_2$ method($p>0.05$).

Figure 15 provides the visualisation of the pellet durability estimates for the different production methods, with error bars providing insight in the variation of the estimates.
The summary of the mixed model including the random effects is provided in appendix A.

Table 8. Durability fixed effects

	Dependent variable:
	Pellet_durability
Normal_WithoutSteam	0.336
	(0.180)
Normal_WithSteam	-0.020
	(0.196)
Constant ($NiCO_2$)	98.128***
	(0.178)
Observations	66
Log Likelihood	-67.852
Akaike Inf. Crit.	145.704
Bayesian Inf. Crit.	156.652
Note: *p<0.05; **p<0.01; ***p<0.001	

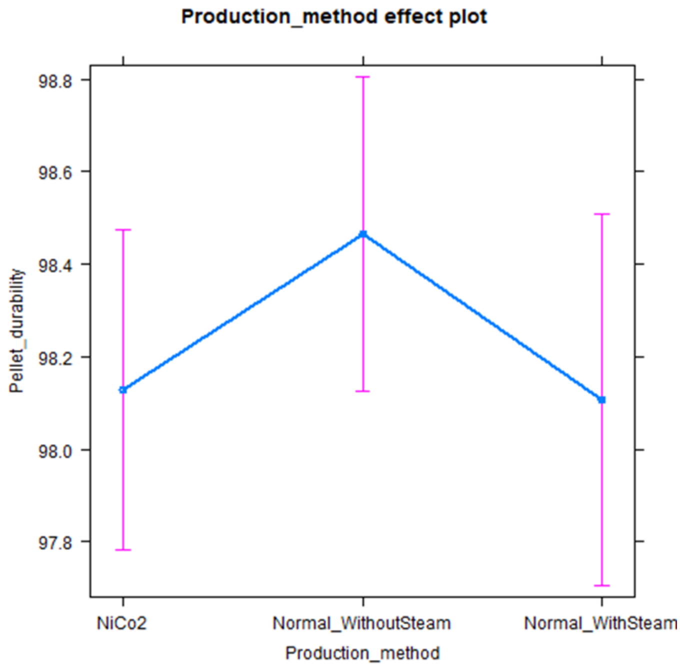


Figure 15. Durability fixed effects visualisation

3.7 Average capacity

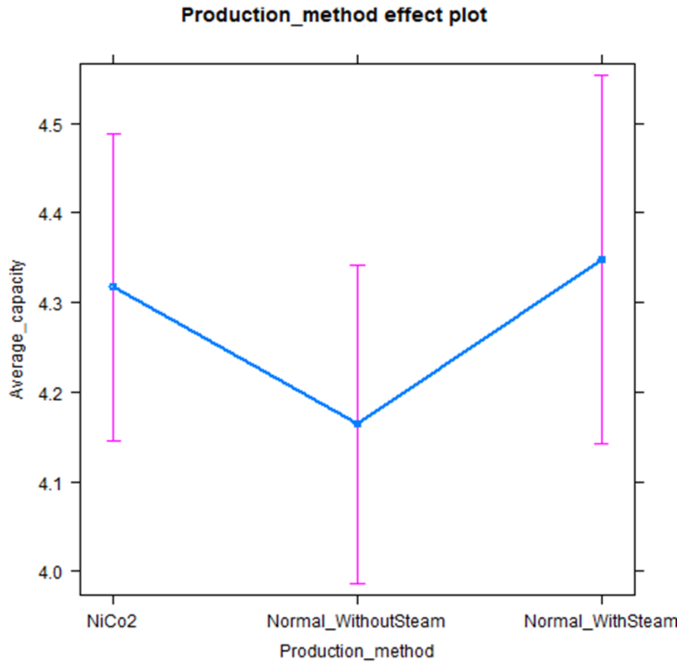
Error! Reference source not found. provides the fixed effect of production method on the average c apacity. The constant is the estimated average capacity for the $NiCO_2$ production method, corrected for the random effect of formulation. The results for the production methods Normal with steam and Normal without steam are supplied in relation to the Constant effect.

- The $NiCO_2$ production method resulted in an average capacity of 4.317 ton/hr
- The average capacity of normal production without steam is 4.317 – 0.153=4.164 ton/hr and the p-value (<0.01) indicates that the difference in average capacity is significant from the $NiCO_2$ production method.
- The average capacity of normal production with steam is 4.317+0.031=4.348 ton/hr, this is not significantly different from the total energy consumption of the $NiCO_2$ method(p>0.05).

Error! Reference source not found. provides the visualisation of the average capacity estimates for the d ifferent production methods, with error bars providing insight in the variation of the estimates.
The summary of the mixed model including the random effects is provided in appendix A.

Average capacity fixed effects

	Dependent variable:
	Average_capacity
Normal_WithoutSteam	-0.153**
	(0.059)
Normal_WithSteam	0.031
	(0.076)
Constant ($NiCO_2$)	4.317***
	(0.087)
Observations	279
Log Likelihood	-207.457
Akaike Inf. Crit.	424.913
Bayesian Inf. Crit.	443.069
Note: *p<0.05; **p<0.01; ***p<0.001	



Average capacity fixed effects visualisation

3.8 Energy costs estimation

The $NiCO_2$ method showed that it is possible to reduce the total energy required for the production of animal feed and removes the need of using gas to produce steam. A reduction in energy consumption does not automatically mean a reduction in production costs since the prices per KWh of energy from electricity differ from those of a KWh of energy from gas.
This section will use some general available prices (marktupdate.scholt.com; accessed 25-05-2022) for gas and electricity to provide insight into the energy costs of the different production methods. These calculations will differ from the actual costa a feed producer will have because of the variety in energy contract they can have.

For electricity and gas the average price of April and May (until the 25th) 2022 was is used, in that period electricity costed on average 0.193 euro/KWh and gas on average 0.956 euro/M^3.

Production method	**Gas costs (€/ton)**	**Electricity costs (€/ton)**	**Total energy costs (€/ton)**
Normal With steam	0.54	7.62	8.17
Normal Without steam	0	8.32	8.32
NiCO2	0	8.20	8.20

With the current energy prices and the in general low steam consumption by ZO-Salland the energy costs per ton are slightly lower for the normal production method with steam.

4 Discussion

4.1 Quality of data

Within this trial the quality of data is checked on several parameters by comparing the registered values to manual measurements, to setpoint values or to other related values. The comparisons show a certain degree of un-explained variation. This variation can have multiple causes such as:

- The accuracy and/or location of a sensor
- High degree of variation in the sensor output affecting the workings of the BatchReporter

- The setpoint values are collected at a different moment during the production run than the measured values.
- Differences in calculating different parameters.
- The method used to determine if the line is producing in steady state

Within this trial it is not possible to determine the exact cause of the variations in the collected data and the responsibility of the quality of the data collected by the DataCollector tool lays at Oosttec. However, the effects are assumed to be random and thus the effect on the outcome of the trial is assumed to be limited.

4.2 STE calculation

In a feed mill steam quality is an important parameter to assess the thermal energy consumed during production. However, quantitively measuring steam quality is one of the harder measurements that can be performed in a feed factory requiring specialized equipment which is not commonly installed in feed mills. A common method to estimate steam quality is looking up the combination of steam pressure and temperature in a steam table, providing the theoretical energy content of steam.
In the factory of ZO-Salland it was not possible to digitally register steam pressure and temperature into the database. Therefore, steam quality was assumed to be stable and the manual measurements for steam temperature and pressure recorded during the days of manual testing were used. The values used for this assumption have a large effect on the estimations of the STE.

4.3 Steam consumption

The factory of ZO-Salland uses a low amount of steam compared to other feed producers (Guerin and Thomas, 2013). Therefore, they are already using more electrical energy compared to thermal energy. If more steam is used the reduction of gas consumption is increased. Therefore, the NiCO2 production method will perform better in factories that have a higher steam consumption

For some difficult to pellet formulations operators choose to run the formulation without steam at a lower capacity to reduce the risk of die blockage. Under the normal operation method, it is expected that a maximum of 10% of the runs are ran without steam. The classification of runs based on the collected data classifies 66% of the normal production runs as produced without steam, this is much more than the expected maximum of 10%.
Adjusting the cut-off point for classification can adjust the number of runs classified as production without steam. However, with a lower cut off point the effect of variance in the steam flow meter will cause artifacts in the classification. The current cut-off point is set at 0.5kg steam per hour which is already a low steam addition of which it can be disputed if it will affect the meal temperature when production is running at normal capacities.
At this moment it cannot be explained why the data shows 66% of the runs produced without steam while the experience on the factory floor is that a maximum of 10% of the runs is produced without steam by the operators.

4.4 Water addition

During the trial only in a small amount of runs the steam addition was substituted by water addition in the BOA-NiCO_2. Therefore, it was not possible to measure the effect of adding (tap) water into the feed mash on electrical energy consumption. Since water functions as a lubricant during pelleting it is expected that if water would be added the energy consumption of the pellet mill should decline.

4.5 Effect of RPM

The trial used the three production methods to provide insight in the effect of steam addition and RPM on the different response parameters. For steam addition the trial provides clear insights in the effect of reducing the amount of steam used during production. For RPM (NiCO_2 versus Normal without steam) the effect is only visible for production capacity. For the other parameters no statistical significant differences were observed between normal without steam and NiCO_2. The measured results are not in-line with the experiences of Mr. Treurniet and the observations of the operators of ZO-Salland, they both noticed an effect of the RPM during production.
An explanation for the lack of an effect of RPM could be the distribution of the measurements over different formulations and the confounding relation between steam and RPM in the three production methods.

5 Conclusion

- SME is 4.6 kWh/ton lower for production with steam compared to production without stem. No differences in SME for the $NiCO_2$ method versus normal without steam
- STE is zero for $NiCO_2$ and Normal without steam and 4.9 kWh/ton on average for the production with steam. The steam addition is low in the ZO-Salland factory, compared to other factories. This can affect the outcome in energy reduction of the $NiCO_2$ production method.
- Total energy consumption (SME + STE) is lower for the $NiCO_2$ method compared to the Normal method with steam, the $NiCO_2$ method consumes on average 1.7 kWh/ton less energy compared to production with steam ($P<0.05$). However, there was no difference between the $NiCO_2$ method and normal without steam.
  - It can be concluded that an effect of steam addition on the total energy consumption is present.
- This study does not show an effect of changing RPM (Normal Without Steam versus $NiCO_2$) on total energy consumption (STE+SME).
- The $NiCO_2$ method is able to reduce steam and thus gas consumption. In this experiment on average 6.75 (SD: 6.03) kg steam/ton was saved. This corresponds with 0.574 (SD: 0.512) M3 gas per ton.
- The pellet durability is high (≈98%) for all three of the production methods and no differences in pellet durability are measured.
- Capacity is equal for the $NiCO_2$ and Normal production with steam, on average 4.3 ton/hr. For normal production without steam capacity is reduced by 0.15 ton/hr.
  - This effect can be the result of the lowered RPM for the $NiCO_2$ method

During the trial there was no water addition in the BOA during most production runs on the $NiCO_2$ method If moisture is added to substitute the moisture that is normally added with steam it is expected that the SME of the $NiCO_2$ production method will drop.

6 Outlook

ZO-Salland is a feed miller that is using a low amount of steam during normal production. This reduces the differences in energy consumption between the different production methods. Therefore, the effect of energy consumption reduction with the BOA- $NiCO_2$ is underestimated compared to factories that have a higher steam consumption per ton of feed.

Steam production is still the only process in a feed mill that has no viable electrical alternative. To achieve the reduction of fossil fuel consumption by the feed producing industry it is important to reduce the amount of steam consumed during production. With the BOA- $NiCO_2$ it is possible to produce feed with a high pellet quality at normal capacities without the addition of steam. Therefore, the BOA- $NiCO_2$ could help the feed producing industry to reduce their fossil fuel consumption.

Another benefit of the BOA- $NiCO_2$ over a normal BOA-500 could be that, because there is no requirement of steam, the machine is better able to correct for the moisture content in the feed mash. Subsequently wet products could be included in the feed without increasing the risk of blockages in the pelletizer while keeping production capacity up.

The BOA- $NiCO_2$ could prove better able to produce difficult formulations at normal capacities, where with a normal BOA-500 these formulations can impose challenges related to the usage of steam and production capacity. The collected data showed for some formulations a large difference in production capacity between the normal without steam and $NiCO_2$ production methods. Due to the limited number of cases in the dataset for which capacity was reduced it is not possible to base conclusions on these observations.

7 References

M. van Culemborg and S. Duitshof (2019) *Testing of a Mono roll versus double roll pelletizer*.

O. Guerin and M. Thomas (2013) *Data analysis of energy use in 3 feed factories*

J. Holterman (2017) *Nico Treurniet pioniert met BOA 500*, De Molenaar nr. 3 2017

8 Appendix

A MixedModel summaries

8.1.1 SME

```
Linear mixed model fit by REML ['lmerMod']
Formula: `Electrical SME` ~ Production_method + (1 | ProductNummer)
   Data: .y

REML criterion at convergence: 1741.9

Scaled residuals:
    Min      1Q  Median      3Q     Max
-3.2118 -0.5212 -0.1337  0.3446  4.4947

Random effects:
 Groups        Name        Variance Std.Dev.
 ProductNummer (Intercept) 40.82    6.389
 Residual                  21.80    4.670
Number of obs: 279, groups:  ProductNummer, 45

Fixed effects:
                                     Estimate Std. Error t value
(Intercept)                           42.5092     1.0678  39.812
Production_methodNormal_WithoutSteam   0.5864     0.6411   0.915
Production_methodNormal_WithSteam     -3.0131     0.8200  -3.674

Correlation of Fixed Effects:
                      (Intr) Prdctn_mthdNrml_WthtS
Prdctn_mthdNrml_WthtS -0.256
Prdctn_mthdNrml_WthSt -0.163  0.290
```

8.1.2 STE

```
Linear mixed model fit by REML ['lmerMod']
Formula: `Thermal (STE)` ~ Production_method + (1 | ProductNummer)
   Data: .y

REML criterion at convergence: 1112.2

Scaled residuals:
    Min      1Q  Median      3Q     Max
-2.8813 -0.1222 -0.0159  0.1222  6.5760

Random effects:
 Groups        Name        Variance Std.Dev.
 ProductNummer (Intercept) 0.2061   0.454
 Residual                  2.9904   1.729
Number of obs: 279, groups:  ProductNummer, 45

Fixed effects:
                                     Estimate Std. Error t value
(Intercept)                           0.02549    0.17516   0.146
Production_methodNormal_WithoutSteam  0.01281    0.23284   0.055
Production_methodNormal_WithSteam     4.78816    0.29372  16.302

Correlation of Fixed Effects:
                      (Intr) Prdctn_mthdNrml_WthtS
Prdctn_mthdNrml_WthtS -0.562
Prdctn_mthdNrml_WthSt -0.425  0.324
```

8.1.3 Specific energy

```
Linear mixed model fit by REML ['lmerMod']
Formula: `Electrical + Thermal (SME+STE)` ~ Production_method + (1 | ProductNummer)
   Data: .y

REML criterion at convergence: 1749.5

Scaled residuals:
    Min      1Q  Median      3Q     Max
-3.2204 -0.5740 -0.1300  0.3827  4.4059

Random effects:
 Groups        Name        Variance Std.Dev.
 ProductNummer (Intercept) 43.71    6.611
 Residual                  22.27    4.719
Number of obs: 279, groups:  ProductNummer, 45

Fixed effects:
                                     Estimate Std. Error t value
(Intercept)                           42.5749     1.0998  38.712
Production_methodNormal_WithoutSteam   0.6179     0.6480   0.954
Production_methodNormal_WithSteam      1.6827     0.8289   2.030

Correlation of Fixed Effects:
                      (Intr) Prdctn_mthdNrml_WthtS
Prdctn_mthdNrml_WthtS -0.251
Prdctn_mthdNrml_WthSt -0.159  0.290
```

8.1.4 Durability

```
Linear mixed model fit by REML ['lmerMod']
Formula: Pellet_durability ~ Production_method + (1 | ProductNummer)
   Data: .y

REML criterion at convergence: 135.7

Scaled residuals:
    Min      1Q  Median      3Q     Max
-2.8087 -0.4885  0.2449  0.6810  1.7641

Random effects:
 Groups        Name        Variance Std.Dev.
 ProductNummer (Intercept) 0.2230   0.4722
 Residual                  0.3324   0.5765
Number of obs: 66, groups:  ProductNummer, 20

Fixed effects:
                                     Estimate Std. Error t value
(Intercept)                          98.12775    0.17328 566.291
Production_methodNormal_WithoutSteam  0.33631    0.18007   1.868
Production_methodNormal_WithSteam    -0.01972    0.19612  -0.101

Correlation of Fixed Effects:
                      (Intr) Prdctn_mthdNrml_WthtS
Prdctn_mthdNrml_WthtS -0.537
Prdctn_mthdNrml_WthSt -0.412  0.432
```

8.1.5 Average capacity

```
Linear mixed model fit by REML ['lmerMod']
Formula: Average_capacity ~ Production_method + (1 | ProductNummer)
   Data: .y

REML criterion at convergence: 414.9

Scaled residuals:
     Min       1Q   Median       3Q      Max
-3.13400 -0.44492  0.06503  0.56688  2.08487

Random effects:
 Groups        Name        Variance Std.Dev.
 ProductNummer (Intercept) 0.2542   0.5042
 Residual                  0.1856   0.4308
Number of obs: 279, groups:  ProductNummer, 45

Fixed effects:
                                    Estimate Std. Error t value
(Intercept)                          4.31702    0.08726  49.471
Production_methodNormal_WithoutSteam -0.15263   0.05909  -2.583
Production_methodNormal_WithSteam     0.03078    0.07552   0.408

Correlation of Fixed Effects:
                      (Intr) Prdctn_mthdNrml_WthtS
Prdctn_mthdNrml_WthtS -0.288
Prdctn_mthdNrml_WthSt -0.185  0.292
```