

The Coffee Roast Process

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Traineeship report

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Chapter 1

Introduction

Douwe Egberts is a company that produces among others coffee. For domestic use this is done in a factory in Utrecht. In this factory the green coffee beans are roasted. In the factory are five industrial roasters. These roasters are used to roast the green beans. Of the five industrial roasters, roaster number five is used for this research. Operators control the other four roasters, whereas roaster 5 has fixed settings.

The colour of roasted beans gives a good indication of the taste and flavour. But the colour differs at every batch, whereas the aim is to get the same colour every time and therefore a consistent taste. In this research the causes of the colour differences will be investigated.

The aim of this traineeship is to investigate, whether it is possible to use a controller, based on the measured colour. Therefore the colour of roasted beans will be more uniform than without a controller. For this purpose knowledge about the roasting process is needed. The information on this process is found in literature and through experiments.

Chapters 2 and 3 deal with the origin and the processing of the coffee beans in general. In chapter 4 experiments are conducted, to determine what affects the colour of the roasted beans. The experiments are divided in sources which may cause the differences of the colour. The possible causes are differences between the batches, which are measured before, during and/or after each batch. Unknown factors are assumed to be general disturbances. Other possible causes, such as the wear of the thermocouples and influences of different concoctions, are not investigated, because of the limited time. The results of the test on the industrial roaster will be discussed in chapter 5. Chapter 6 compares the results of chapters 4 and 5. After this the conclusions of this research can be found in the last chapter.

Chapter 2

Coffee

The following section can be found in [1]:

"The coffee plant is a shrub that belongs to the family Rubiaceae, genus *Coffea*. The plant consists of one or more trunks from which stem the primary branches. In the wild the plant grows to a height of 8-10 meters whereas in plantations, to facilitate care and cropping, the plants are kept to a height of 2-2.5 metres. The leaves grow in opposite pairs, are 10-15 centimetres long and oval or lanceolate in shape. They are deep rich green in colour, glossy and fleshy on their surface and overall are not unlike laurel leaves, with the characteristic wavy edge. The flowers are white and always grow in clusters of two or three together, reaching almost 2 centimetres in size.

The fruit which develops from the ovary of the fertilized flower is called drupe or berry; it is about 15 millimetres in diameter and turns bright red when fully ripe. The outer covering of the drupe is a thick pulpy skin, which encloses a layer of jelly-like pulp, about 2 millimetres thick. Inside this are the seeds or beans. They average about 10 millimetres in length, weigh about 0.15 grams each and are green in colour, tinged with shades varying from grey to blue or from red to brown. These beans are the only part of the fruits of the coffee plant that are used: the rest is discarded during the processing

The ideal habitat for coffee plants is in the band between the two tropics, in three main large areas: Central South America, Central Africa and the zone comprising India, the Indonesian Islands and Papua-New Guinea.

Dozens of species of the genus *Coffea* are known, but only two are significant in economic terms: *Coffea Arabica* and *Coffea Canephora*, being the only two that are cultivated on a large scale. The two species are commonly referred to as *Aribica* and *Robusta*.

The green beans are transported straight from their native country to the factory. Most coffee arrive in containers. A small amount of beans are packed in bags of jute in which they travel to their destination. Before the beans are stored in silos, their quality is checked.

Blending serves two purposes: to enhance the quality of coffee and maintain a consistently high standard. As a rule every consignment contains coffee of predominantly one type of taste (for example mild or bitter) and one particular aroma. Blending makes it possible to obtain a balance between the different flavour components (bitter, sour, sweet) and a strong aroma that has a wide spectrum of characteristics. A further consideration, as with all natural products, is that from time to time and from year to year the organoleptic properties of coffee consignments may vary; it is only by adjusting the properties of the different types of coffee that these variations can be remedied and a consistent blend produced. Blending may be done before or after roasting.

Coffee-roasting is a process of pyrolysis which, by increasing the temperature of the coffee from

room temperature to 200-230°C, brings about marked physical and chemical changes in the beans that improve the quality of coffee and make it easier to prepare.

The main physical changes are the loss of weight mainly due to water evaporation and the release of certain heavy gases such as CO₂, which causes the bean to swell, increasing its volume by about 60%. Loss of weight and increased volume are accompanied by a change of in the structure of the bean, which becomes more elastic more brittle (which makes it easier to grind). Its colour changes from green to brown through the caramelizing of the sugar and other carbohydrates and the formation of certain pigmented substances produced by chemical reactions known as Strecker's reactions. These take place only at the highest temperature, so the higher the temperature the darker the coffee.

The main chemical changes however concern the presence of some groups of substances that vary before and after roasting and the formation of new compounds. The explosion of a limited number of cells causes rather popping sounds when the coffee is thus said to be "squeaking". When the cell wall splits through too much pressure, gas is released as well as volatile aromas; this explains why, when increasing of the final temperature of the roast, up to a certain point the aromas increase and then diminish. Not only does the aroma vary in accordance with the temperature but also the corresponding degrees of bitter and acid taste: bitterness increases with the temperature whereas acidity diminishes. The most delicate stage in the roasting process is the final stage: above 200°C the chemical reactions, hitherto endothermic (heat absorbing) become exothermic (heat producing). The increase in temperature of the coffee therefore becomes more rapid.

Roasting is stopped automatically by a temperature gauge. The beans are sprayed with water and tipped into a cooling hopper. Here the beans are continually kept moving in a flow of cold air. When the beans are cooled down, they are grinded. The size of the parts of the grinded beans also has an impact on brewing time as well as extraction.

Grinded roasted beans lose its freshness and aroma within a couple of weeks, when exposed to air. To prevent oxidation and to keep the coffee fresh for longer, the coffee is vacuum packed."

Chapter 3

The roasters

To roast green beans, roasters are needed. Douwe Egberts has two types of roasters: large industrial roasters for production and a small one for experimental use, the pilot roaster. With this roaster it is possible to do tests, which can help to understand the roast process. The next two sections will discuss the roast process and the similarities and differences of these roasters.

3.1 The roast process

A schematic drawing in appendix A.1 represent the pilot roaster. This drawing can also be used to describe to roast proces of the industrial roaster. The following part will help to understand the process. The words between the brackets are the Dutch translations which match the description in figure A.1 in appendix A.1.

A batch of green beans (1, groene koffie) is weighed and transported to a funnel (2, vul-trechter). The funnel fills the roaster (3, roostvat). In a furnace (4, fornuis) air is heated by a flame. The heated air is used to heat the beans. To ensure a uniform roast, a stirrer is used to stir the beans. Gases and the skin of the beans are removed through a fan (5, ventilator) and a chimney. The skins and the gases are separated, after which the gases are burned in an afterburner (6, naverbrander). This is done to prevent a release of smelly gases in the environment. The skins are gathered (7, cycloon). When the beans have reached their desired temperature (T_{final}), the roast process is stopped. The beans are cooled down with water (8, bluswater). Then they are put on a grid (9, koelbak) to cool down some more. When the roasted beans are cooled down, they are stored in a container (10, gebrande koffie).

3.2 The industrial roaster vs. the pilot roaster

There are differences between the pilot roaster and the industrial roasters. These differences have to be kept in mind, while comparing the results of the two roasters. This section will discuss the differences and its consequences.

Size. Roaster number five, Gothot RN 4000 roaster, is build to roast batches of 400 kg, but it roasts 700 kg. The weight of the batches varies with an amount of 30 kg. This is caused by the small time frame in which the blend is composed. The more ingredients a blend consist of, the more inaccurate the weight of the batch is.

The pilot roaster is a small version of the industrial roaster. This roaster, Gothot RN 100, is build to roast 10 kg a time. When the load is weighed automatically, the weight varies about 100 gr. The load of the pilot roaster can also be weighed manually to achieve a precision of 0.5 gr. (The weight of one coffee bean is less then 1 gr.)

The load differences result in a different time-temperature curve, which affects the way the beans are reacting.

Thermocouples. The temperature of beans is an indication of the state of beans during the roast process. This temperature is measured by thermocouples. These thermocouples, which measure the temperature of the beans (and the temperature of air between the beans, this combined temperature is called the product temperature), are sluggish due to size of them. The thermocouples are thick because of the wear caused by the beans and to provide them stiffness. When the beans are green, they are very solid. Their density is similar to stone.

The wear also influences the recorded temperature. The difference between an old and a new thermocouple is about 2°C. Because of the wear the final temperature needs to be adjusted (or the measured temperature needs to be corrected). A good operator gradually adjusts the final temperature. While at the long run test the final temperature will be adjusted after a certain period.

Initial conditions. Before Roaster 5 will be filled with a new batch, it is preheated to a temperature which depends on the final temperature. This is not possible with the pilot roaster. The starting temperature of the pilot roaster is dependent on final temperature of the previous batch. This causes dependency between batches, which are roasted by the pilot roaster, while the batches of the industrial roasters are independent of each other.

Airflow. The roast gas of roaster 5 is recycled. It is used again to roast the beans. The pilot roaster uses fresh and cold air from outside. So the difference of composition of air may influence the roast process.

The temperature of the gases (roast gases) in the chimney and the product temperature are similar, therefore the roast process can be assumed to be ideal mixed process.

Chapter 4

Experiments

The main focus of this research is to find sources, which affect the colour of roasted beans during the roast process. Therefore some experiments are done. These experiments will help to gain some insight in the behaviour of the roasting process. All experiments are done on the pilot roaster.

4.1 Experiment 1: Measuring the colour of roasted beans

The colour of the roasted beans gives an indication of the taste of the coffee. Therefore it is important to get the same colour at every batch. For *Aroma Rood*, the blend which is mainly produced, the desired colour is 60. Batches with colours between 58 and 62 are considered to be in range. When colours are outside the range of 57 and 63, the batch will be rejected. If the colour is between the acceptance and rejection range, the batch will pass. The following batches will be examined closely.

The measurement. The colour is measured, through a device that measures the intensity of light. This light is reflected by the roasted grinded beans. The lighter the beans are, the more light is reflected, so a lighter colour has a higher number. The colour depends on the measuring device, the mill, point in time. Even the way the grinded beans are distributed over the dish. This is one of the reasons why the colour differs, every measurement gives another result. Therefore all experiments are conducted with the same measuring device, the beans are grinded on the same mill.

To get an impression of the differences in colour, the following experiment is conducted. For the experiments the following assumption is made: The deviations of the colour measurement are assumed to be indifferent of the measured colour. The colour of the grinded beans are measured twenty-eight times. Of every four measurements the average is calculated. The dashed line in figure 4.1 shows the results. The averages turned out to differ widely. So the experiment is repeated. Now the colour is measured forty-five times and of every five measurements the average is calculated. The solid line in figure 4.1 shows these average.

The figure shows clearly that the means of five measurements are more alike then the means of four measurements. But the measured colours are scattered. Figure A.2 in appendix A.2 shows a boxplot of all measurements. The range of the measured colours is about 2 and the 50% of the data differ not more than a half point. Moreover both figures show that a considerable number of measurements are needed to get an reliable average.

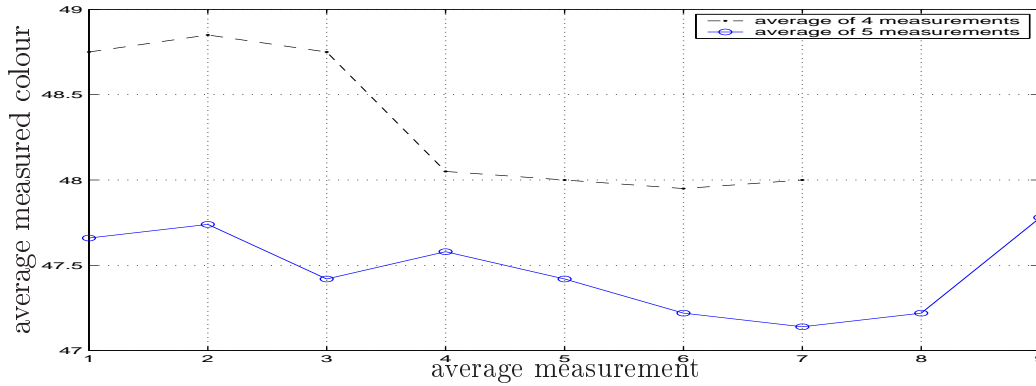


Figure 4.1: Average of the colour measurement

The standard deviation of the measurements is $\sigma = 0.24$. If the distribution of the colours of the roasted beans is assumed to be normally distributed. The following table can be used to get an indication about the effect of the standard standard deviation on a calculated average [3].

$\mu \pm \sigma$	68%
$\mu \pm 2\sigma$	95%
$\mu \pm 3\sigma$	99.7%

Table 4.1: Probabilities associated with a normal distribution

For example one can trust a mean for 99.7%, that the difference between the measured mean and real mean will not exceed $0.72 (= 3\sigma = 3 \times 0.24)$. When an average is taken over fewer measurements, the standard deviation will be larger and therefore also the confidence interval.

In all further experiments the colour of the roasted beans will be determined as the average of five measurements. A part of the standard deviation will account for the deviation ($\sigma = 0.24$) caused by the measurement. These standard deviations are assumed to be indifferent of the colour.

Distributing the grinded beans. The same test is conducted but this time the grinded beans are compressed in a dish. The results, which are shown in table 4.2, clearly represent a dependency on the way the grinded coffee is distributed over de dish. The table shows the differences between compressed and not compressed grinded beans. It is obvious that the colour of the compressed beans are lighter (higher number). The surface is more smooth, so that more light is reflected. Also the standard deviation of the compressed beans is higher, so it is not advisable to compress the grinded beans. This experiment shows that different colours can be measured out of the same batch of beans. Not only the mill and measuring device will have influences on the colour also the way the grinded beans are distributed over the dish.

	mean	standard deviation
not compressed	47.46	0.24
compressed	72.49	1.12

Table 4.2: Mean and standard deviation of experiment 1

4.2 Experiment 2: Freerun testing

To investigate the influences of the disturbances acting on the roasting process, a freerun test is conducted. In this experiment the input is kept constant. The input is the temperature of the heated air and the duration of the roast process. The differences in the output are caused by the disturbances and by the measurement errors. With this information further data can be better interpreted. Figure 4.2 shows the average colour and the standard deviation of each batch.

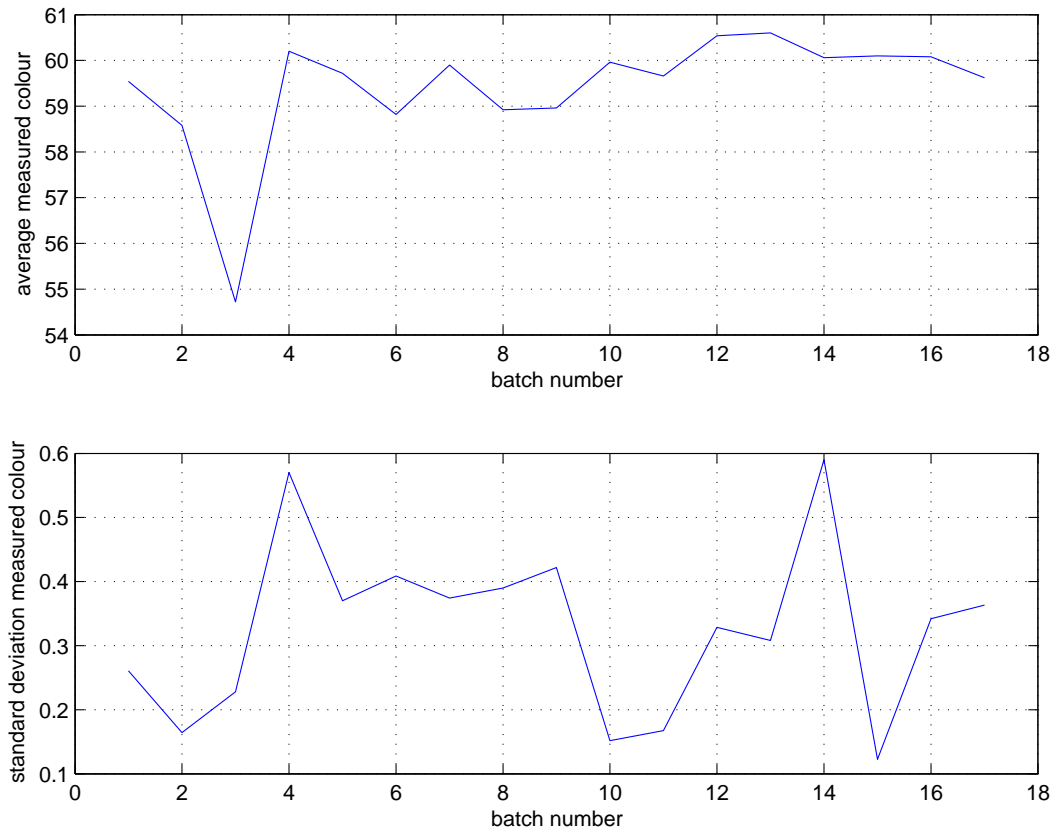


Figure 4.2: Colour measurement of the freerun test

The colour of each batch is the average of five measurements. The first 3 batches differ. This can be explained, as being due to a start phenomenon, for instance heating the furnace and the roaster. Furthermore the result of the third batch is caused due to a double charge load.

In the next figure, figure 4.3, the initial temperature supports the assumption that during the first three experiments the roaster is heated. The influence of the double load is obvious. The figure shows that the start-up effect, due to the heat up of the roaster, only last for three batches.

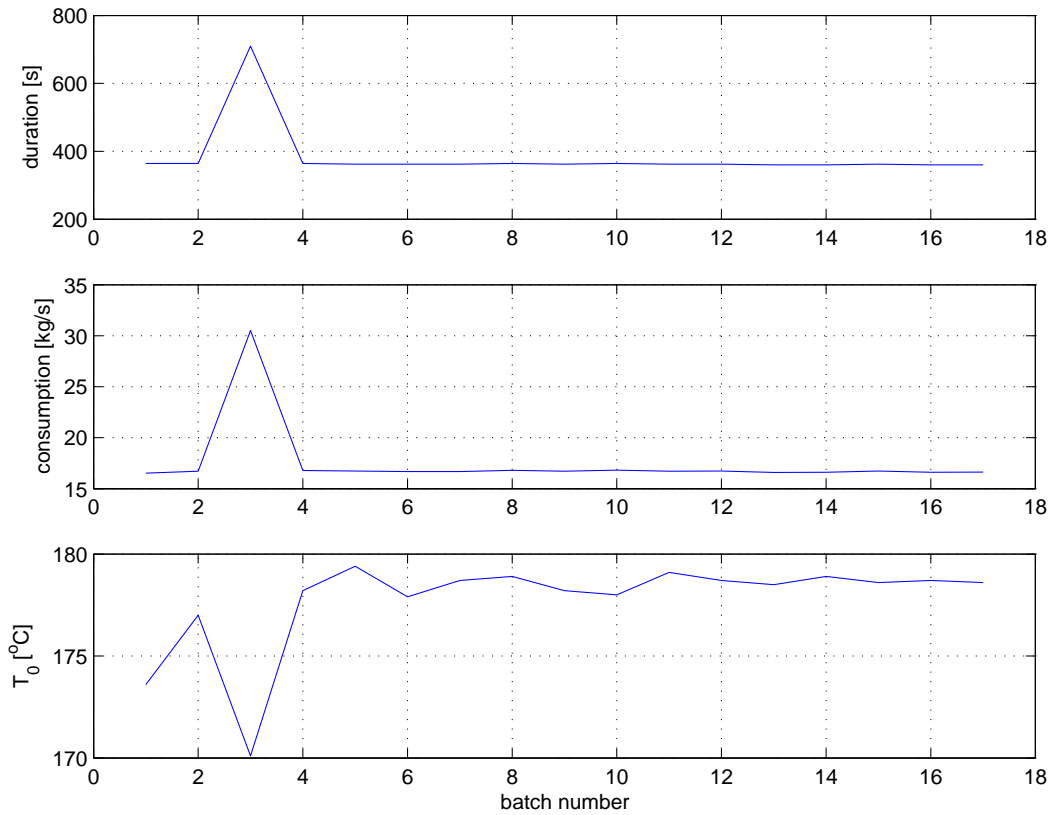


Figure 4.3: Runtime, gas consumption and the initial temperature

The disturbances are assumed to have a normal distribution and have a mean of 0. A part of the standard deviation consists of differences caused by the measurement of the colour. These measurement deviations are assumed to be indifferent to deviations caused by the disturbances. The next equation (4.1) shows the relation between the standard deviations.

$$\sigma_{total} = \sqrt{\sigma_{measurement}^2 + \sigma_{disturbances}^2} \quad (4.1)$$

The results of this experiment, which are shown in table 4.3, show that the standard deviation due to the disturbances is 0.51.

mean	59.80
standard deviation	0.51

Table 4.3: Mean and standard deviation of the freerun test

4.3 Experiment 3: Influence of moisture in the green beans

The moisture content of the green beans differs at each shipment and each season. This is shown figure A.3 in appendix A.3. A difference of 0.10% is equal to 0.7 kg of water. Because of the fact that the evaporation of water out of the beans demands a lot of energy, this could be a major source of disturbance.

This experiment is done following the previous experiment. The settings are kept the same and the same melange of beans is used, the only difference is the moisture. 10 Batches of 10 kg green beans are dried; the initial moisture was 10.03%. The dried beans have moisture content of 3.92%. The load of a batch of "wet" beans has a weight of 10 kg and the load of dried beans have a load of 9.2 kg. This is done to be able to compare the results of the two tests. This statement is supported by weight of roasted beans, as it is shown in figure A.4 in appendix A.3. In this figure the weight of each batch at the start and at the end of the roast process is plotted. Whether wet or dried beans are used, the weight of a batch of roasted beans is the same.

First several batches of "wet" beans were roasted, then 10 batches of dried beans are roasted. The colour of the roasted beans is the average of five measurements. The results are shown in appendix A.3 in figure A.5. The next table summarises these results. These results also incorporate the measurement errors.

	mean	standard deviation
wet beans	59.80	0.51
dried beans	60.78	0.52

Table 4.4: Mean and standard deviation of experiment 3

There are differences in colour, but the standard deviations do not differ. Moreover the roast time decreases by 30% and the gas consumption decreases 27%. Because of the different amount of water, that has to be evaporated, the roast time will differ and therefore the temperature profile will differ also. These results are also shown in appendix A.3 in figure A.6.

The colour of the roasted beans is a rough estimate of the taste of the coffee. Professional tasters are used by Douwe Egberts to determine the taste of the coffee. These tasters tasted the dried and the wet beans. Their unanimous conclusion was that there exists a difference but it is too small to be notable by the average customers. It should be remarked that the roasted beans were roasted by the tasters. As result the beans, wet and dry, had the same colour, when they were tasted. The taste difference indicates that the profile of the temperature influences the taste of the coffee.

So the concentration of water in the beans mainly has effect on the roast time and the gas consumption. The differences of the colour are negligible because the real difference of the moisture content are far less than the difference used in this experiment.

4.4 Experiment 4: Interdependence of the batches

This experiment is done to investigate if batches have influence on each other. The result of this experiment is only used for evaluation of the experiments conducted on the pilot roaster. The industrial roaster is preheated until a certain temperature is reached. So that the initial condition in the roaster is the same for every batch. Therefore the batches will not affect each other.

The temperature of the roast gas, the gas from the furnace, is kept constant during the roasting of a batch of green beans. This is done to avoid possible disturbances, caused by process. These possible disturbances will be investigated in the next section. After a few batches the temperature is changed. The final temperature is kept the same for all batches.

In the first plot in figure 4.4 the roast gas temperatures are shown for each batch, the second plot shows the average colour of each batch and last plot shows the boxplot of the measurements of each batch.

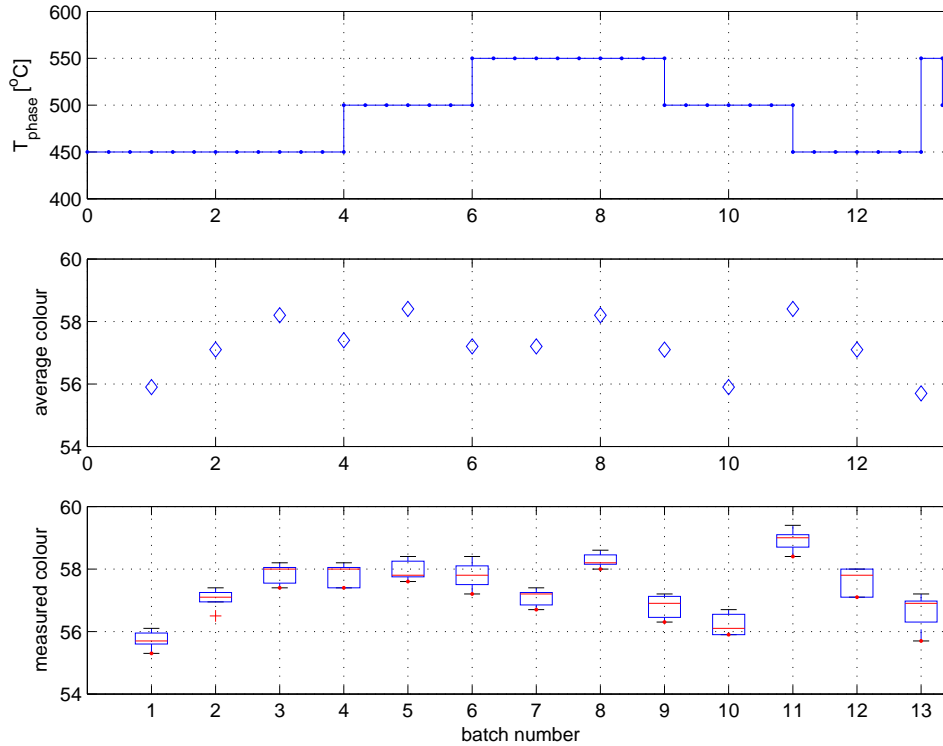


Figure 4.4: Phase temperatures, average colour and boxplots

The first two batches do not represent the process correctly, due to the start-up effect, which is clearly shown in appendix A.4, figure A.8. This start-up effect can be seen in the plot of the initial temperature. This temperature is still rising.

The figures show clearly that the colours differ, but the colour doesn't follow the same pattern as the phase temperature. The boxplots show that the range of many experiments is the same. Thus the assumption, that the batches are mutually independent can be made.

mean	57.54
standard deviation	0.56

Table 4.5: Mean and standard deviation of experiment 4

The standard deviation of this experiment is rather large compared to experiment 2. However the initial temperature of each batch (figure A.8) seems not to be interdependent. Also the temperature-time curve (figure A.9) is independent of the former batches. The only differences

are caused by the temperatures of the roast gas, which determines the duration of the roast process. (A higher roast temperatures will result in a faster temperature rise of the beans.) This should indicate that there is some other disturbance causing this extra deviation.

4.5 Experiment 5: Dependency of the roast temperature

The roasting process is divided in three phases, each will end after a fixed period of time or when the beans reach a certain temperature (T_{final}). The same experiment as the last can be done, but now with different phase temperatures, as shown below.

Now it is possible to investigate possible dependencies of the process on the colour. The average colours of batch 14 to 19 show again, that there does not exist an interdependency between batches.

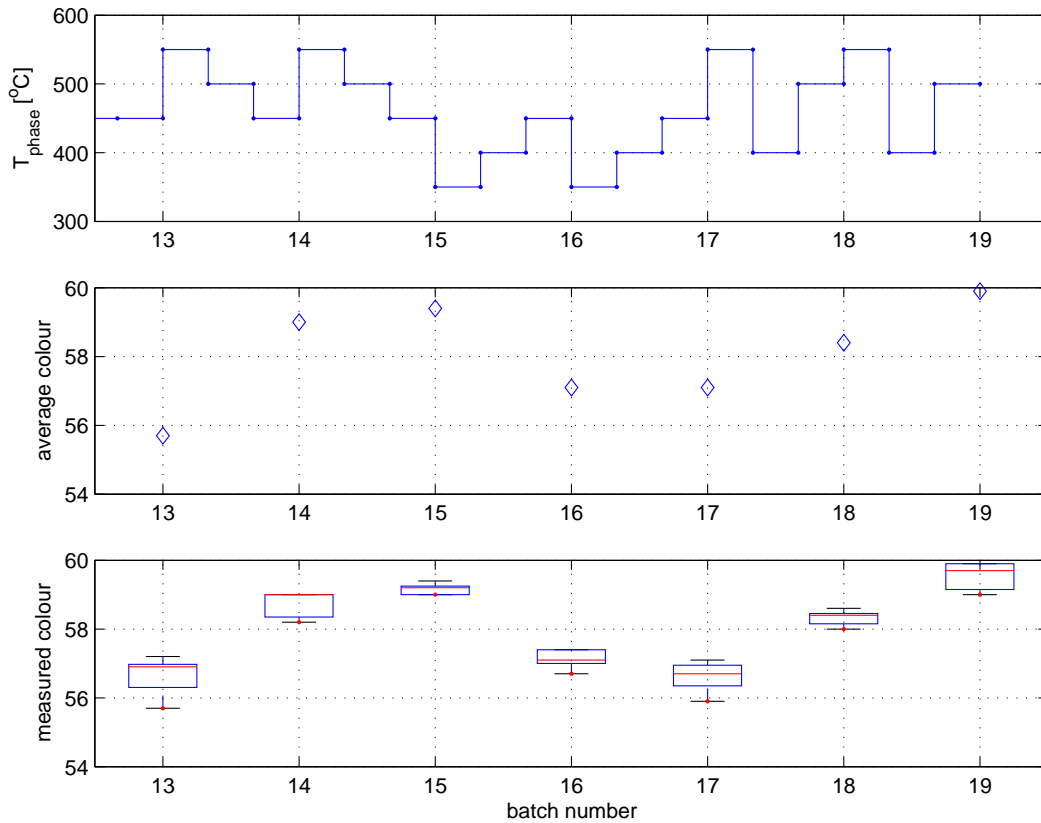


Figure 4.5: Phase temperatures, average colour and boxplots

The furnace and the roaster are well insulated, because of this the roast temperature will change slowly. At large phase temperature changes the roast temperature can not follow the desired path. The heating and cooling of the furnace and roaster are slow processes compared to the length of a phase (40-200 seconds). This causes the large standard deviation.

The results can be seen in table 4.6, which shows the mean and the standard deviation of this experiment.

In comparison with the results of the previous experiment, the standard deviation is very large. This can also be explained by the different range that are used during the experiments.

The range in experiment 4 is from 450°C to 550°C, whereas the range of this experiment is from 350°C to 550°C.

At higher temperature the temperature of the bean will rise faster and therefore it will reach the final temperature in a shorter period. The physical reaction, which causes the colour changes, will have a different result due to the shorter period of time. The colour clearly depends on the way the beans are roasted. High phase temperatures will result in a lighter colour (higher colour number). Therefore only experiment at which the same temperature-curve is followed can be compared.

mean	58.25
standard deviation	1.15

Table 4.6: Mean and standard deviation of experiment 5

4.6 Experiment 6: Final temperature

The colour of the beans is usually controlled by the final temperature. When this temperature is reached the roast process will be terminated. This is done by shutting down the furnace and spraying the beans with water. To determine the relationship between the colour and the final temperature the following experiment is conducted. The phase temperatures and the weight of the batches are the same for all batches, as all other settings. The roast-curve, the curve of the temperatures of the beans, approximates the curve of the industrial roaster. The content of the green beans is a blend of several different beans. Together they should represent the blend of *Aroma Rood*, which is the blend that is used in the industrial roaster. The weight of the batches is 15 kg instead of the usually 10 kg. This is also done for a better approximation of the industrial roasting process. The roast time of the pilot roaster approximates the toast time of the industrial roaster. The only differences between the roasters are the phase temperatures. These temperatures are adjusted to match the roast-curve.

At each final temperature three experiments are done and then the point of the final temperature is increased. The colour of each batch of roasted beans is measured five times. The settings for the final temperatures are chosen so that the colours are between 55 and 65, because 60 is the desired colour and 57 and 63 are the rejection boundaries. In figure A.10 in the appendix the averages of each batch is plotted, together with their final temperatures. The colour reacts immediately on the change of the final temperature. (the first two batches are neglected due to start-up effects).

In the next figure the colour is plotted against the final temperature. This gives an indication about the relation between the final temperature and the colour of the roasted beans.

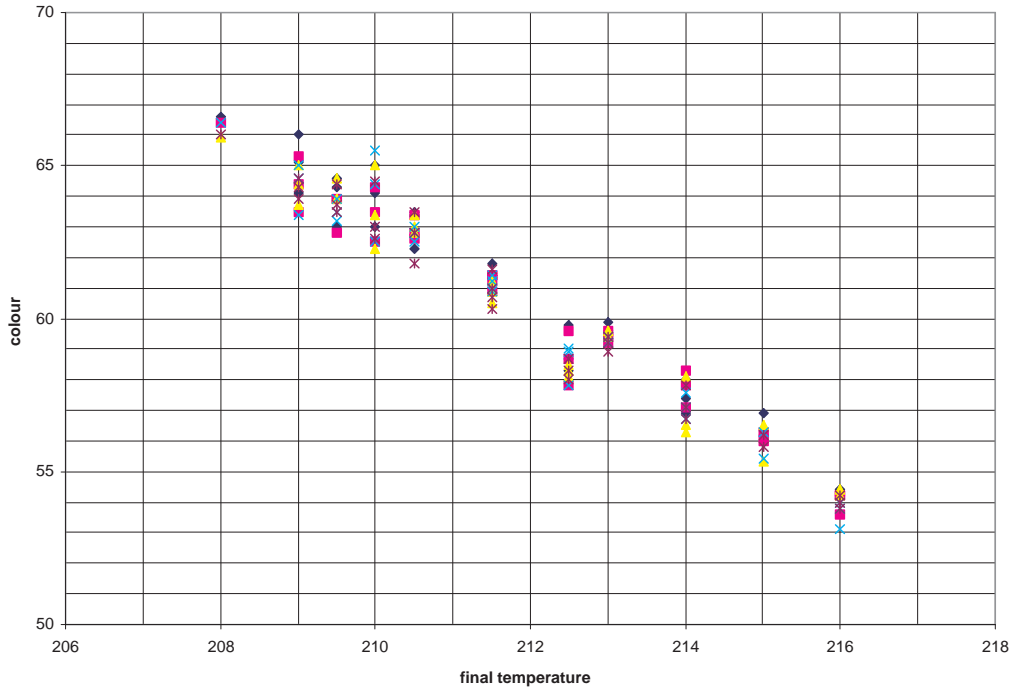


Figure 4.6: Final temperature vs. colour of roasted beans

In a least squares sense a linear fit can be made, furthermore the coefficients of a polynomial can be fitted. The polynomials are fitted on the average measured colour. This done to determine the relation between the final temperature and the colour. These fits (figure A.11) and their mean absolute error (figure A.12) are shown in appendix A.5. The results show there is a linear relation between the final temperature and the colour. This relation holds for the range of the measurements.

$$colour = 374 - 1.48 \times T_{final} \quad (4.2)$$

The colour decreases 1.5 point at every raise of 1°C of the final temperature; this could be used as a rule of thumb.

4.7 Experiment 7: System approximation

The data of the experiments can be considered as a step response, the input is the temperature of the furnace and the output is the temperature of the product (beans and air). The approximation theory [2] provides an algorithm to approximate data with strictly-proper linear system.

In appendix A.6 the figures of these data are shown. The data are from a freerun test, the first 10 batches were heated with a temperature of the furnace of 450°C and the last 10 were heated with 500°C (figure A.13). The second figure (figure A.14) shows the step response of the linear models with the same input as the original data. The models are able to represent the original response. The determine wether the models are able to represent the roast proces the next test is done.

A linear model satisfies the following property:

$$u_3(t) = u_1(t) + u_2(t) \implies y_3(t) = y_1(t) + y_2(t) \quad (4.3)$$

Where $u_i(t)$ is the input and $y_i(t)$ is the output of the model.

If the input of a linear model is the sum of the input of other linear models, then the output of the model can be written as the sum of the outputs of those other models.

This property can be used to determine the response of a batch which is roasted at a different temperature. At this test the response of a model (determined with a roast temperature of 450°C), which had an input of 500°C is compared with the data of the real proces. This test is also reversed. A model (determined with a roast temperature of 500°C) is compared with the data of the freerun test, conducted at a roast temperature of 450°C .

The results are shown in appendix A.6 in figure A.15 and A.16 respectively. When the figures are compared, it turns out that this property does not hold. The linear models are not accurate enough to describe the roast process. In appendix A.6, in figure A.17 and A.18, the bode plots are shown of the two models. The magnitude of the models shows clearly the difference between the models at low frequencies.

4.8 Experiment 8: Influence of change in weight

The weight of each batch is not the same. The load of each batch, used by the industrial roasters, differs about 30 kg, whereas the average load is about 700 kg. This could be a source, which causes colour deviations.

For this experiment data from the industrial roaster is used to determine the influence of weight differences. In the next figure (4.7) the weight of the batches is plotted against the colour of the roasted beans.

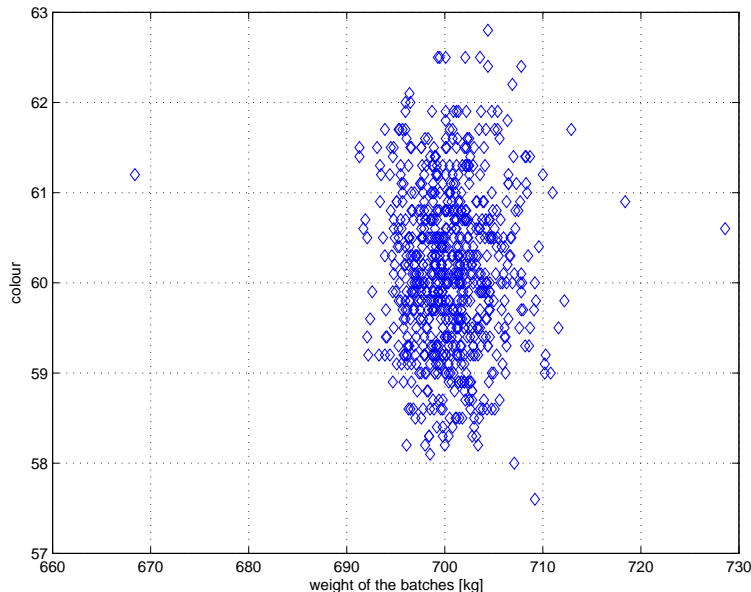


Figure 4.7: Weight of the batches vs. colour

The figure shows there is no relation between the weight differences and the colour of the roasted beans, because different colours are measured for the same weight of the batch.

Therefore it can be concluded, that these weight differences do not effect on the colour of the roasted beans

Chapter 5

The industrial roaster

The industrial roaster number 5 takes part in an experiment. This experiment is done to investigate the influence of the operators on the roast process. In this experiment the settings are fixed and only the blend of *Aroma Rood* is roasted. The results will be compared with the other roasters.

Of every blend the 1st, 5th, 15th, 30th, 45th, etc. batch will be measured. The concoction of the blend changes after several batches. It depends on the quality and the quantity of the available green beans. This could also be an important factor which causes differences in the colour of the roasted beans. But this is not investigated.

This data can be compared with the data of roasters with no fixed settings. The data is also compared with former data of roaster 5. In the next figure the measurements of this test are shown.

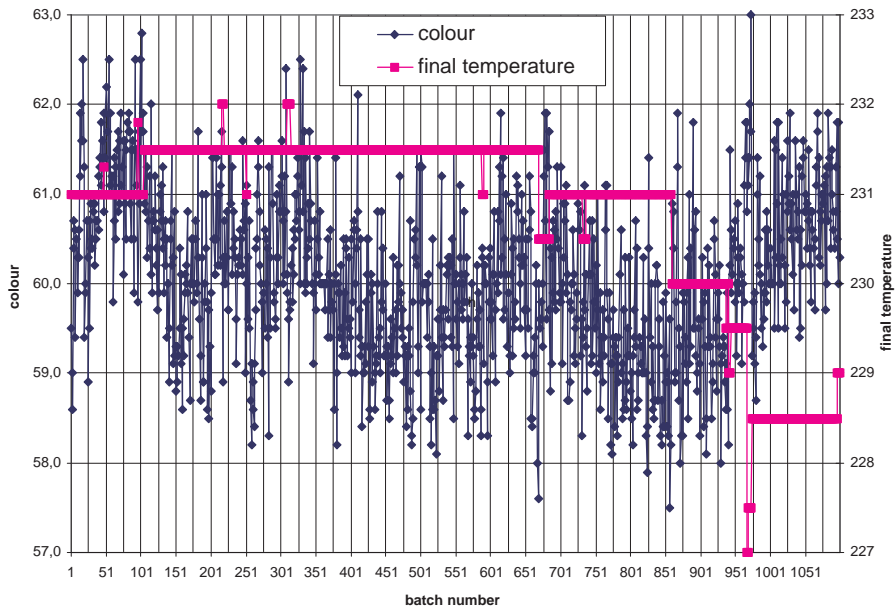


Figure 5.1: Industrial roaster 5

The experiment started on the 16th of February 2004 and will be continued. The data that is used for this report runs from the 16th of February till the 26th of October. (March starts at 93, April at 322, May at 490, June at 597, July at 659, August at 712, September at 837 and October starts at 998.) It seems that there is no trend present, which is dependent of the season. Furthermore there seems to be no differences between days. But this is difficult to detect, because of the limited number of measurement.

In appendix A.7 the measurements of the other four industrial roasters in the same period are shown. Also the measurements of roaster 5 over a longer period are shown.

The wear caused by the thermocouples can clearly be seen. Because of this the wear the thermocouples become less sluggish. The temperature measurement will be more accurate. The final temperature needs to be adjusted to compensate for the wear (the real final temperature of the beans has to be the same to ensure the colour of the roasted beans). In September and October the final temperature is changed for several times. This wear considerable influences the roast process.

To find out whether the test gives better result, the results have to be compared with the results of other roasters. These roasters also roasted the blend *Aroma Rood*. Furthermore a comparison is made with roaster 5 over the same period a year earlier. (This is done because the settings of the other roasters were also fixed more or less). In the next table 5.1 the results are shown. The desired mean is 60. The table makes it evident that the fixed settings give a better result. Their mean approaches better the desired goal and the standard deviation is less.

Figure A.23 in appendix A.7 shows colour measurements of the last two years. At the batch number 1143 the experiment with the fixed settings is started. The figure shows that the deviations of the mean (60) are less during this experiment, in comparison with the previous period.

The difference between the results of roaster 5 this year and a year earlier is obvious. Therefore it can be concluded that fixed settings give better results, in the way that the standard deviation is less.

	mean	standard deviation
roaster 1: 16-02-04 till 26-10-04	60.1983	0.8062
roaster 2: 16-02-04 till 26-10-04	60.1165	0.8415
roaster 3: 16-02-04 till 26-10-04	60.1969	0.9439
roaster 4: 16-02-04 till 26-10-04	60.2839	0.8470
roaster 5: 16-02-04 till 26-10-04	60.0644	0.9392
roaster 5: 16-02-03 till 26-10-03	60.1210	1.2086

Table 5.1: Mean and standard deviations of the industrial roasters

Chapter 6

The standard deviations

The results of the experiments of chapter 4 are compared with the results of the experiment of chapter 5, which is conducted on the industrial roaster.

The standard deviations of the experiment are summarized in the next table 6.1. It should be remarked that all measurements include the standard deviation of the measurement. These measurements deviations are assumed to be indifferent to the other deviations.

Furthermore the results of the dependency tests are not incorporated because the settings of the industrial roaster are fixed for each blend and the roaster is preheated for each batch.

source	standard deviation
measurement	0.24
disturbances	0.51
moist	0
weight	0

Table 6.1: Standard deviations of the experiments

$$\sigma_{total} = \sqrt{\sigma_{measurement}^2 + \sigma_{disturbances}^2} \quad (6.1)$$

$$\sigma_{total} = \sqrt{0.24^2 + 0.47^2} = 0.56 \quad (6.2)$$

The standard deviation of the industrial roasted beans is $\sigma = 0.94$. Thus the sources combined are not sufficient to account for all the disturbances. There are still a number of possible sources which are not investigated.

The wear of the thermocouples changes the measured temperature and therefore the point at which the roast process is stopped. This affects the colour of the beans, what can be seen at experiment 6. The changes of the concoction of the blend and the differences between the green beans are also a source which affects the colour. Furthermore in the factory the colour of the beans is measured once or twice, in the experiments the colour is measured five times this also gives a lower standard deviation. On the other hand the disturbances on the industrial roaster should be less, due to mass of the beans and the roaster.

Chapter 7

Colour control

The test, which is conducted on roaster 5, shows that there is no need for a controller, because the desired goals (a colour mean of 60 and colours within the desired range) are met.

For a controller more data is needed. The colour of each batch has to be measured several times to get an appropriate indication about the colour and more batches have to be measured. This will improve the signal to noise ratio. The controller will only be able to decrease systematic deviations, because the measurements are done, when the roast process has ended. So the controller will not be able to improve the result of the measured batch.

With more measurements a controller can achieve a decrease of the deviations, but the controller will never be able to reduce the deviations to zero. Better knowledge about the effects of disturbances on the roast process will also help to improve the decrease of the deviations.

At the start of the roast proces of every batch the industrial roaster is preheated. The initial temperature depends on the desired final temperature of this batch. This ensures that the colours of the roasted beans are immediately in acceptable range and there is no start-up effect. Experiment 6 shows that little changes in the final temperature has immediately affect on the colour.

Chapter 8

Conclusions and recommendations

The aim of this research was to investigate, whether it is possible to use a controller, based on the measured colour. So the colour of the roasted beans would be more uniform than without a controller. If the colour will be used, the colour measurement has to be more precise. This problem needs to be handled first, because the results of the colour measurements differ too much to design a proper controller. The current range, which specifies whether a batch of roasted beans has the right colour, is too small to make a difference between noise and the real colour.

But the main source of differences in the colour is the way the colour is measured. In this report it is mentioned that there are several sources, which causes differences in the measured colour. Whereas the same batch of grinded beans are measured. Not every batch of a blend is measured, so possible deviations can not be detected on time. This is enhanced because the measurements are done offline.

Another source of disturbance is the wear of the thermocouples. This wear causes differences in the temperature measurement. Therefore the point, where the roast process is terminated, changes during time. Due to the thickness of the thermocouples, which are used to measure the temperature of the beans, the measurement will react slow on temperature changes. During the last phase of the roast process the temperature of the beans rises very rapid.

The roast process is a process that reacts fast on changes of the settings. Changes of the final temperature have immediately effect. So wind-up, will not happen.

The experiment, which is conducted on the industrial roaster, shows that the colour of the roasted beans is within the desired range. The average colour of all batches is also the desired. Therefore it can be concluded that present situation, fixed settings, gives the desired result.

The research about this process should be continued. So a better knowledge of the roast process is gained and to decrease the colour range. Further research of this subject should be mainly focussed on the measurement and processing the colour of the roasted beans. Therefore a model about the roast process has to be developed. To get a better insight how disturbance act on the colour of the roasted beans.

To improve the colour measurements another measuring device is needed or more measurements of each batch are needed. So the standard deviation will be decreased. If systematic deviations have to be detected, the measurements should be more frequently.

The similarities and differences between the pilot roaster and the industrial roasters need to be investigated. This is needed in order to be able to translate results of the pilot roaster to the industrial roast process.

Another way of measuring the bean temperature should be investigated. For instance the roast gas has almost the same temperature and the same temperature characteristic. There are a number of advantages, when this measurement is used. The thermocouple, which measures the roast temperature, is not affected by the wear. Therefore the size of the thermocouple can be smaller and the thermocouple will react faster and more consistent on the temperature changes.

When a reliable temperature measurement is used, the roast process can also be controller through the use of temperature profile. This is could *curve roasting*. The product temperature is prescribed, because of this the colour of the roasted beans will be more uniform and within a smaller range.

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Appendix A

A.1 Schematic drawing of the pilot roaster

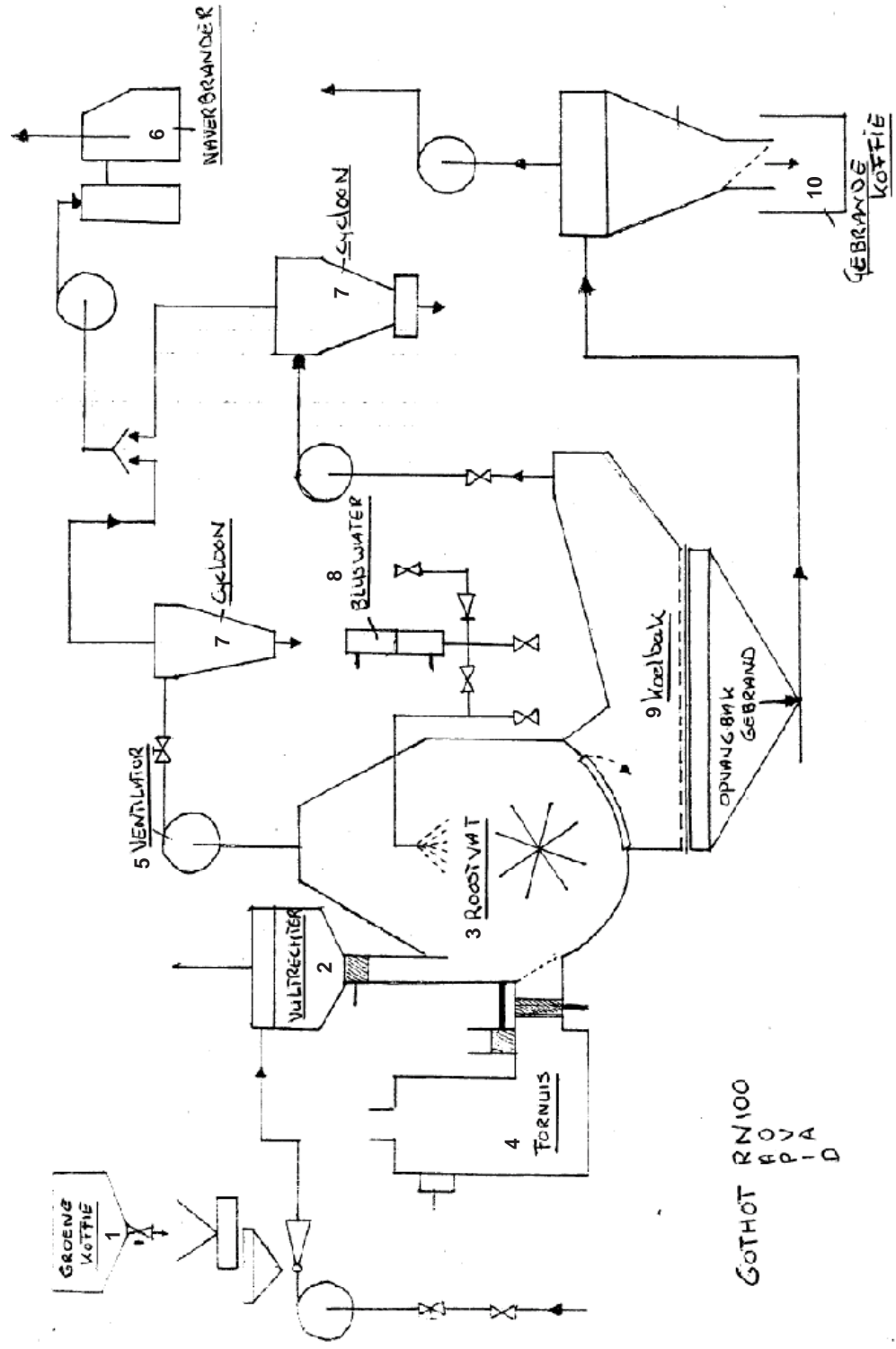


Figure A.1: Schematic drawing of the pilot roaster

A.2 Experiment 1

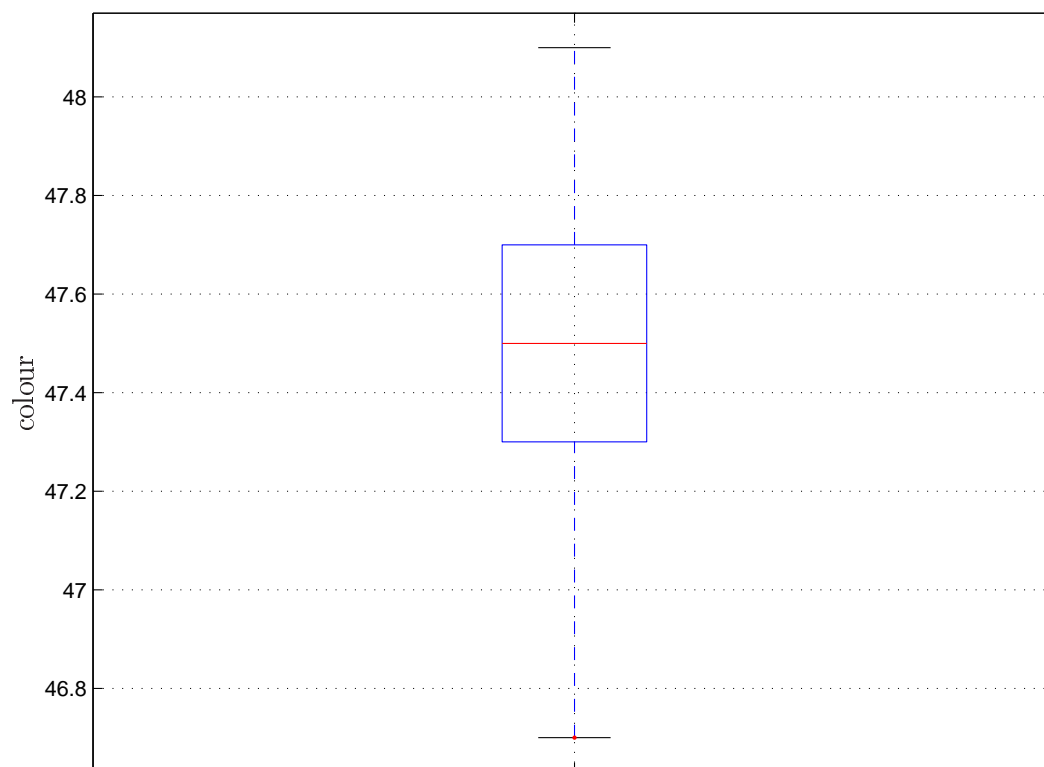


Figure A.2: Boxplot of all colour measurements

A.3 Experiment 2 & 3

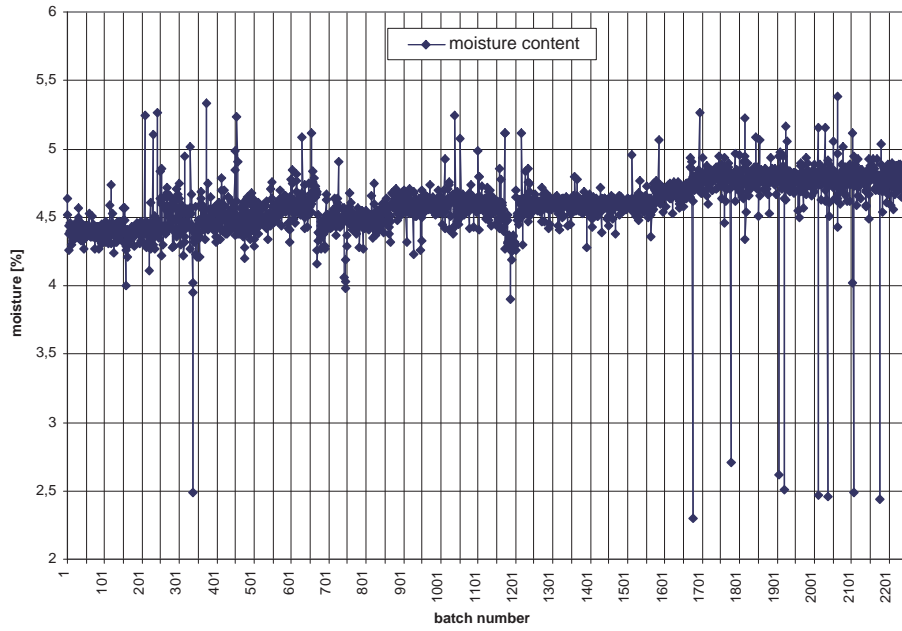


Figure A.3: Moisture content of the batches of roaster 5 during the past 2 years

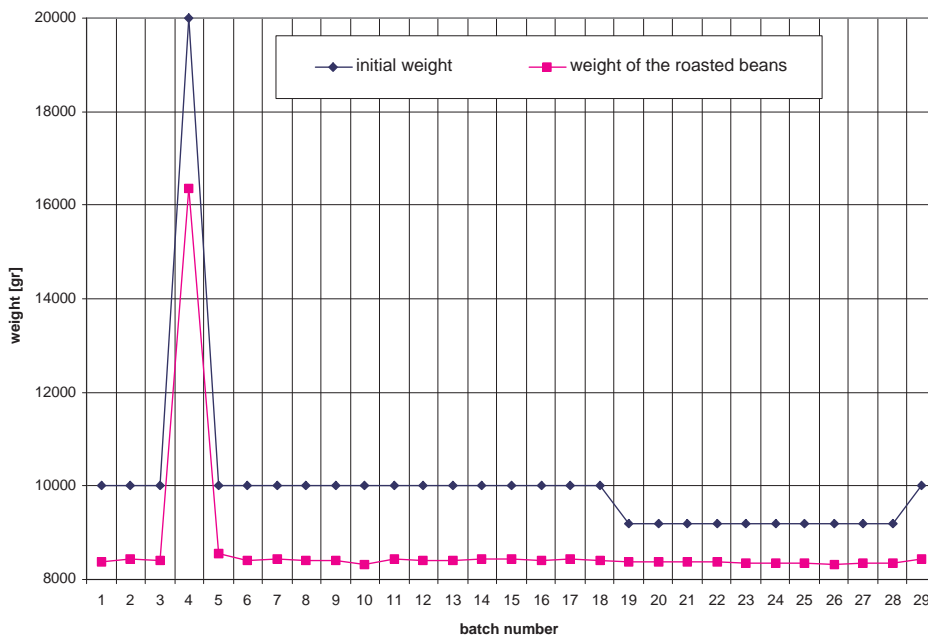


Figure A.4: Weight of the batches

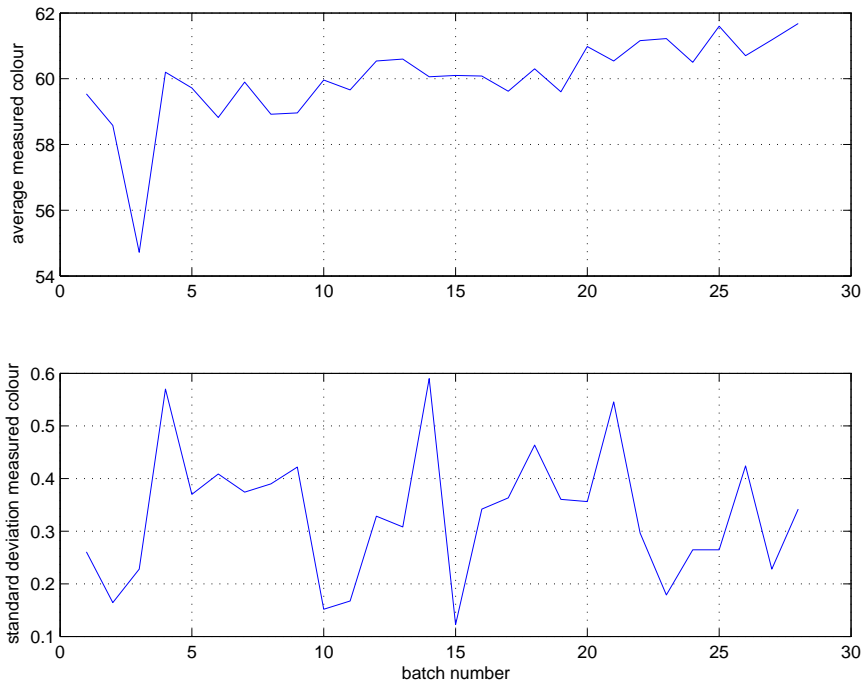


Figure A.5: Freerun moist vs. dried beans

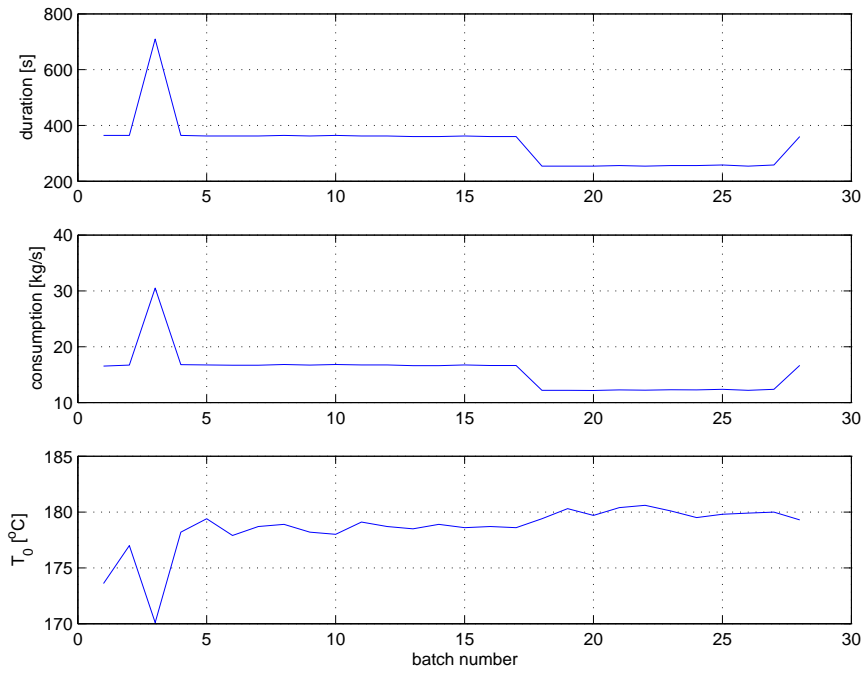


Figure A.6: Runtime, gas consumption and the initial temperature of moist vs. dried beans

A.4 Experiment 4 & 5

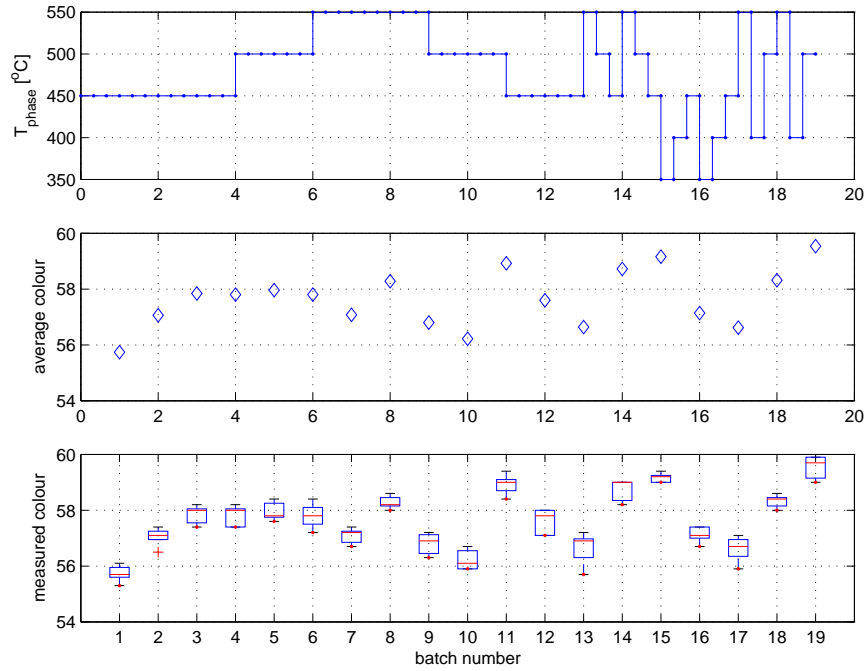


Figure A.7: Phase temperatures, average colour and boxplots

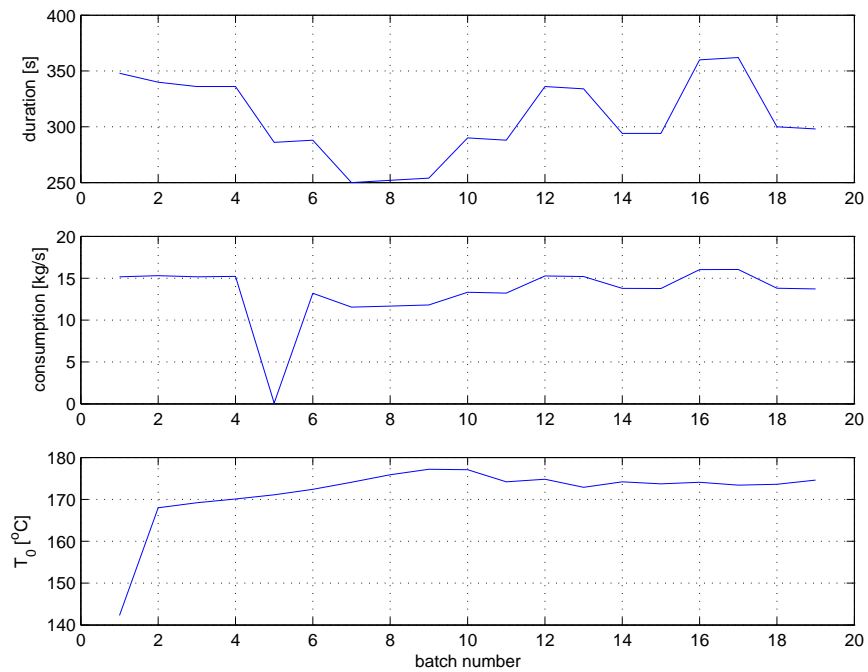


Figure A.8: Runtime, gas consumption and the initial temperature

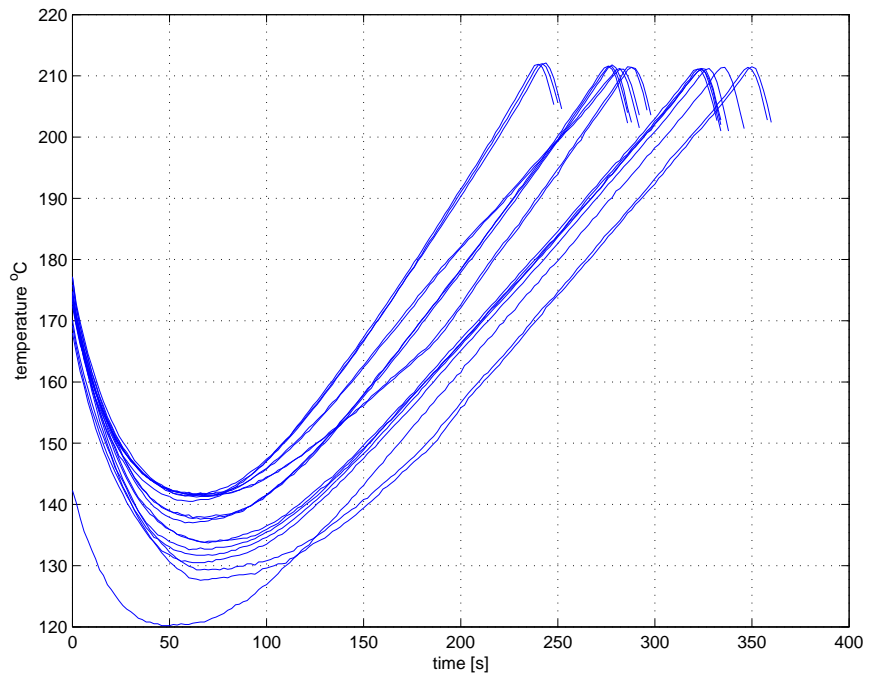


Figure A.9: Temperature curve

A.5 Experiment 6

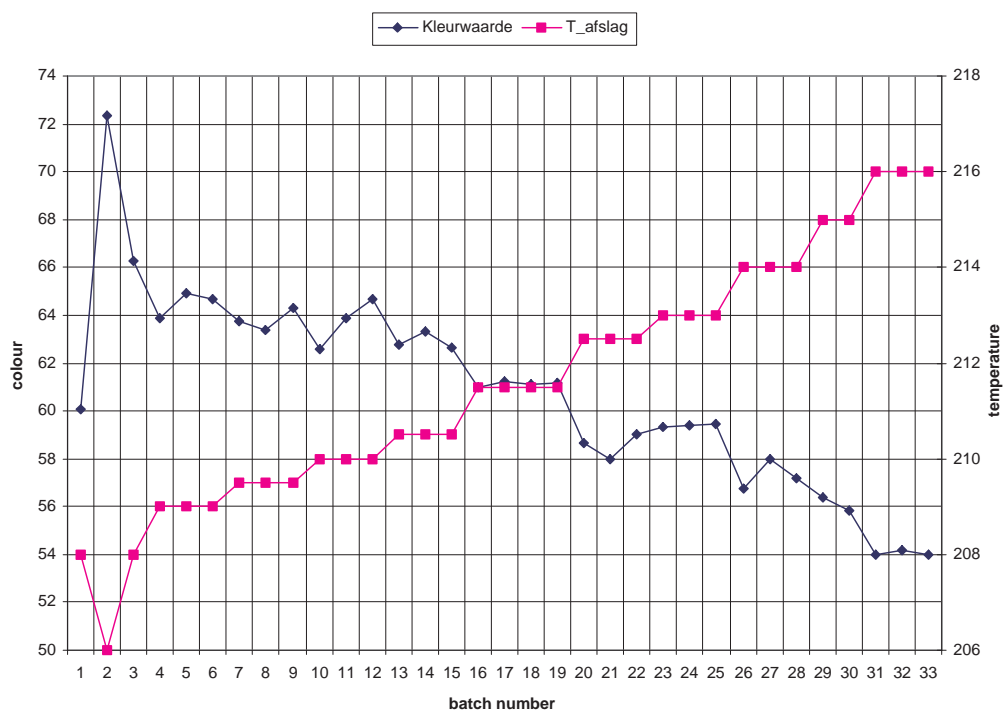


Figure A.10: Final temperature vs. colour

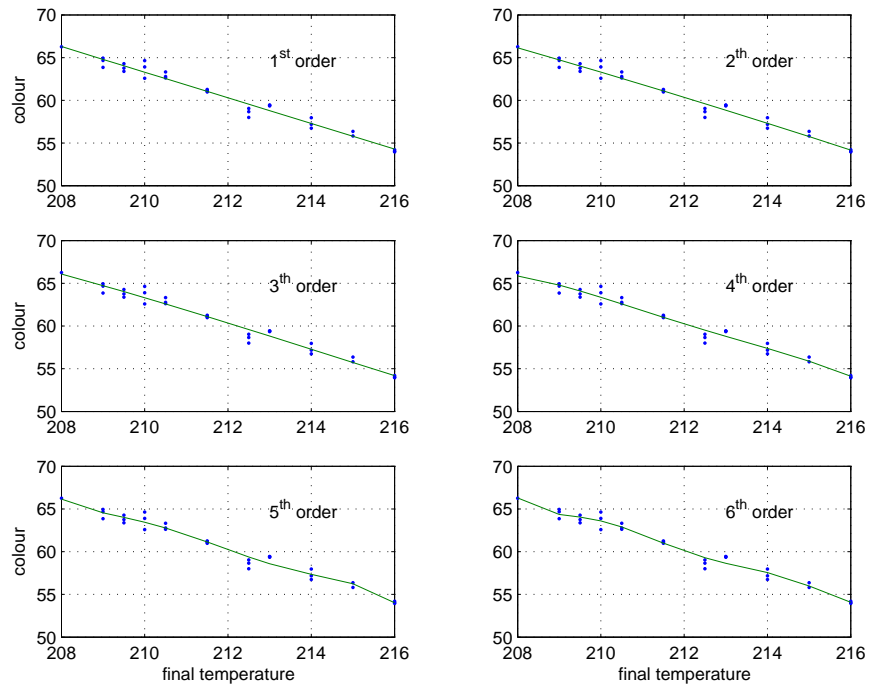


Figure A.11: Polynomial fits and data

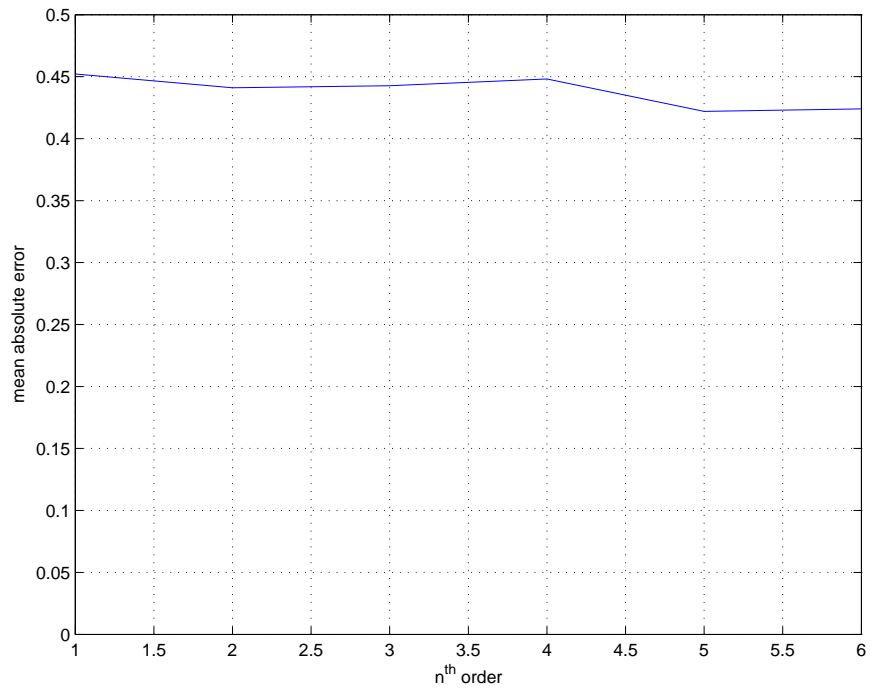


Figure A.12: Mean absolute error of polynomial fit of data

A.6 Experiment 7

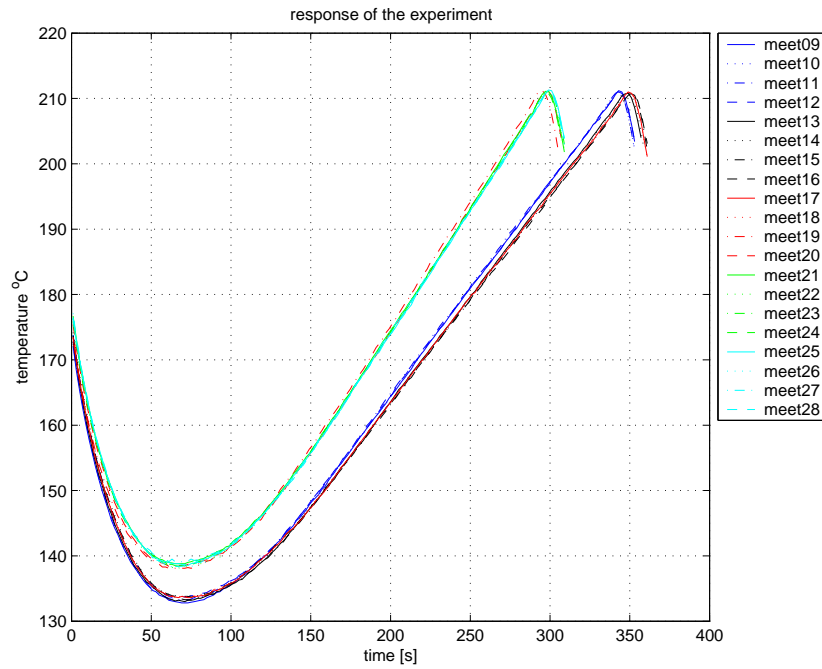


Figure A.13: Data experiment

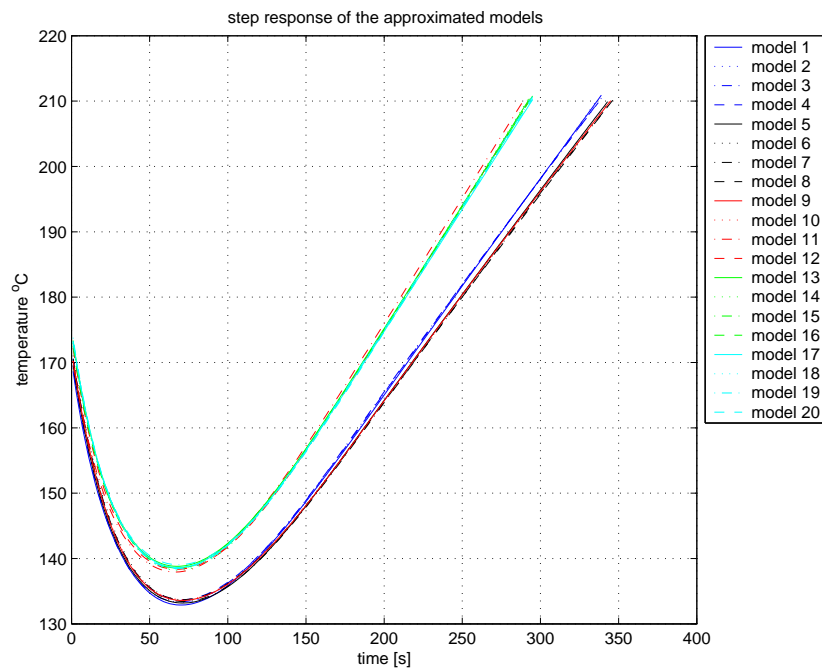


Figure A.14: Data step response of models

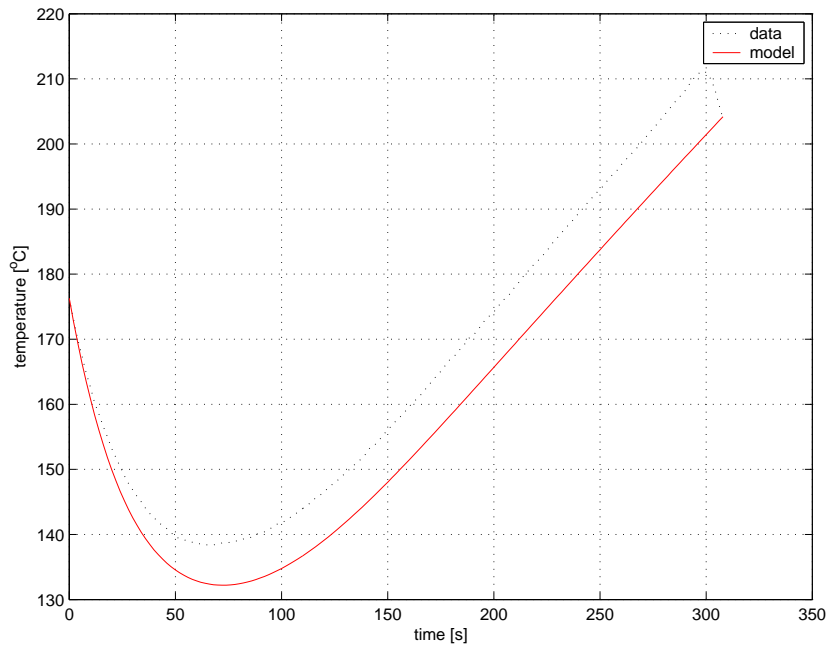


Figure A.15: Data 500°C and response model

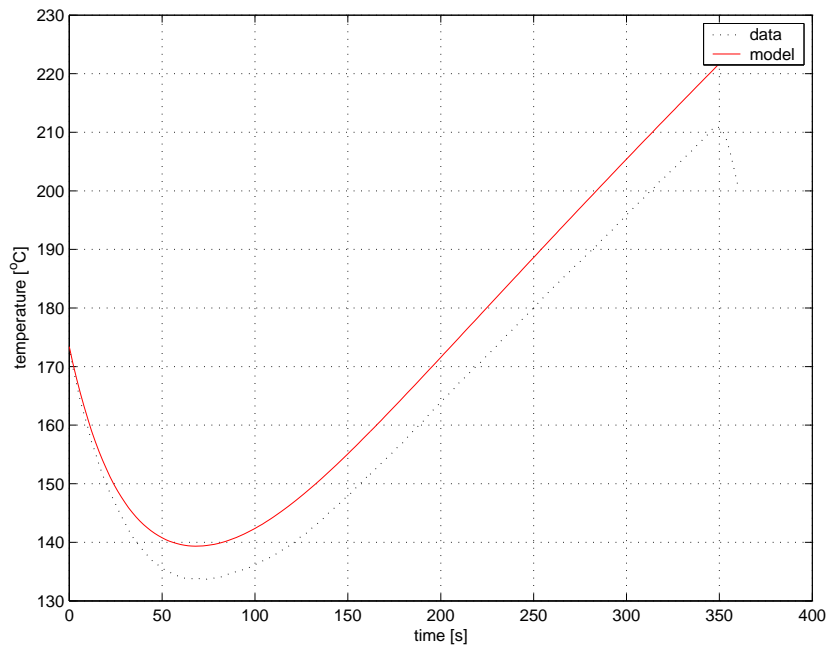


Figure A.16: Data 450°C and response model

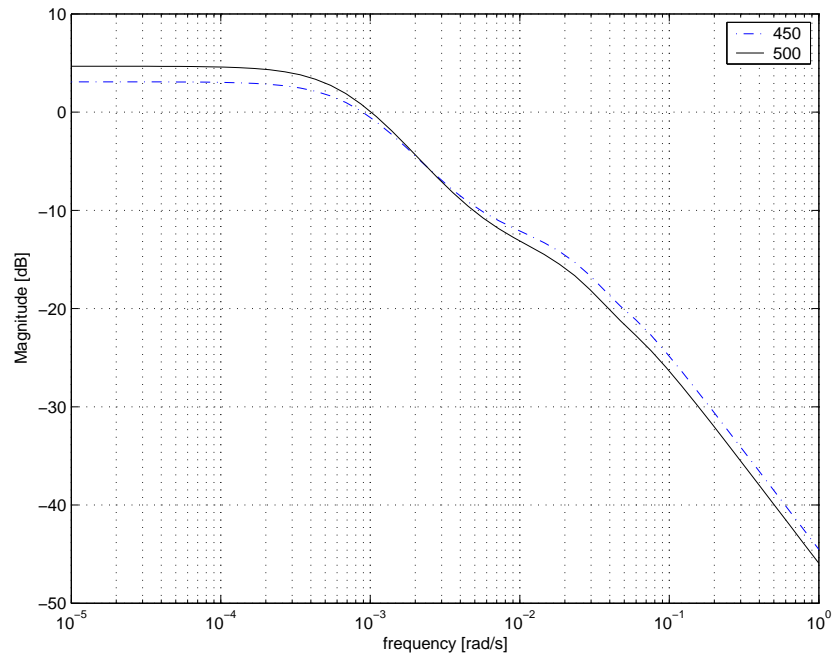


Figure A.17: Magnitude of the bode plot of data 450°C and 500°C

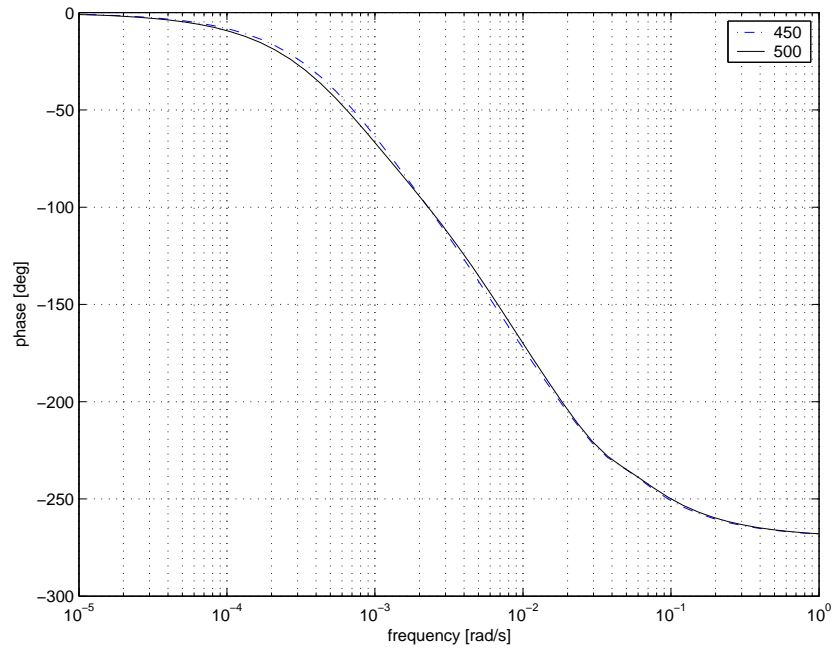


Figure A.18: Phase of the bode plot of data 450°C and 500°C

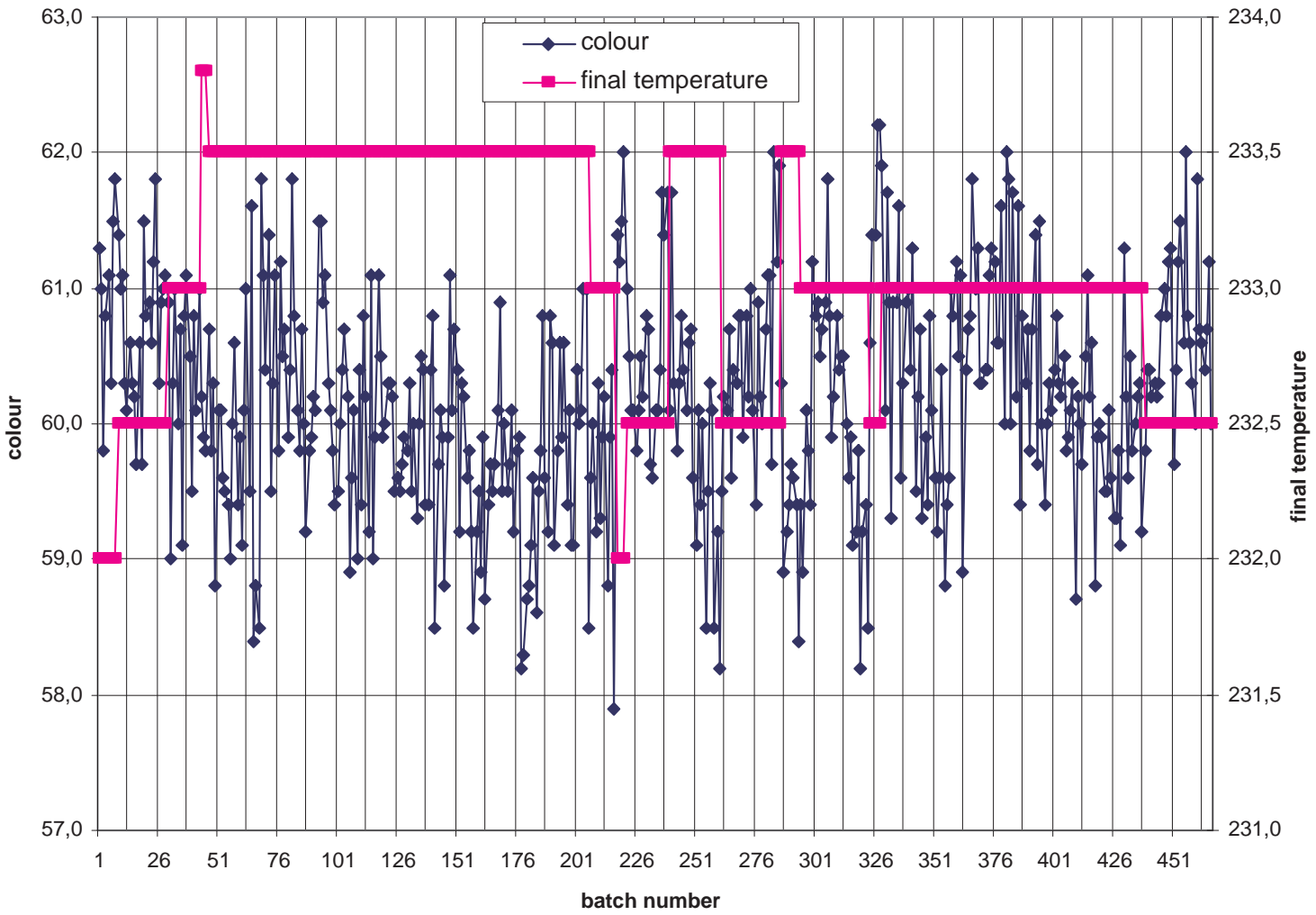


Figure A.19: Data roaster 1

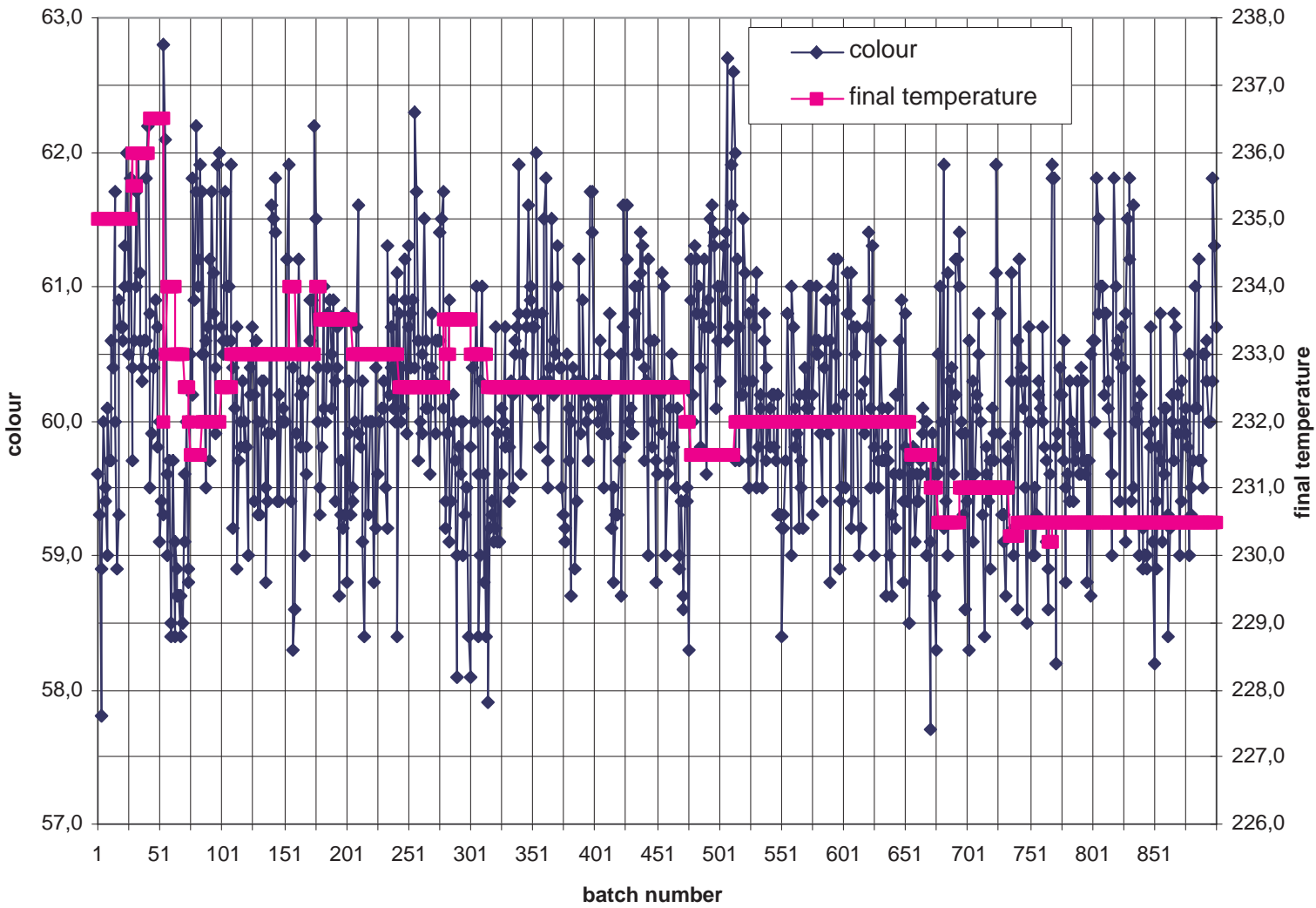


Figure A.20: Data roaster 2

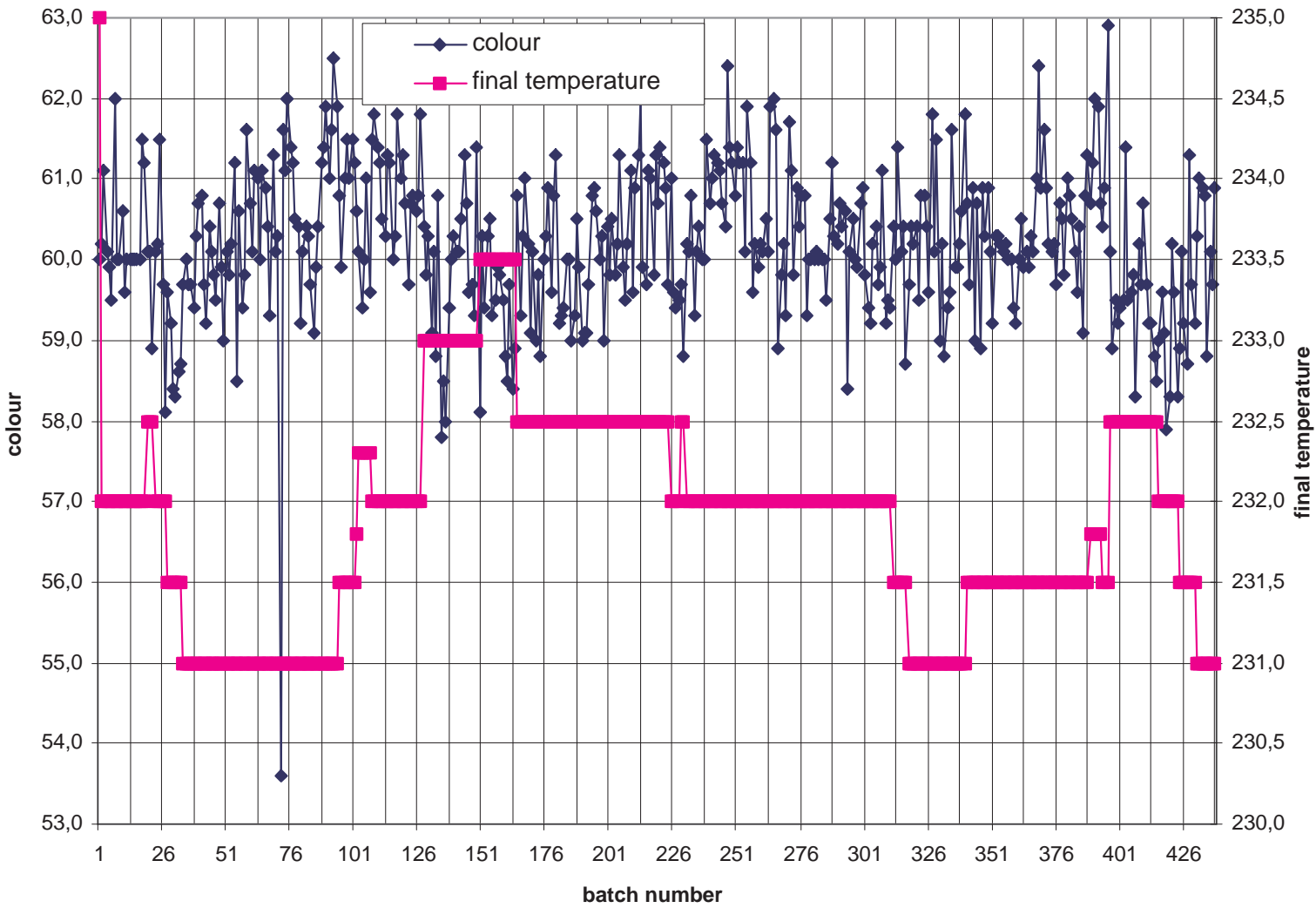


Figure A.21: Data roaster 3

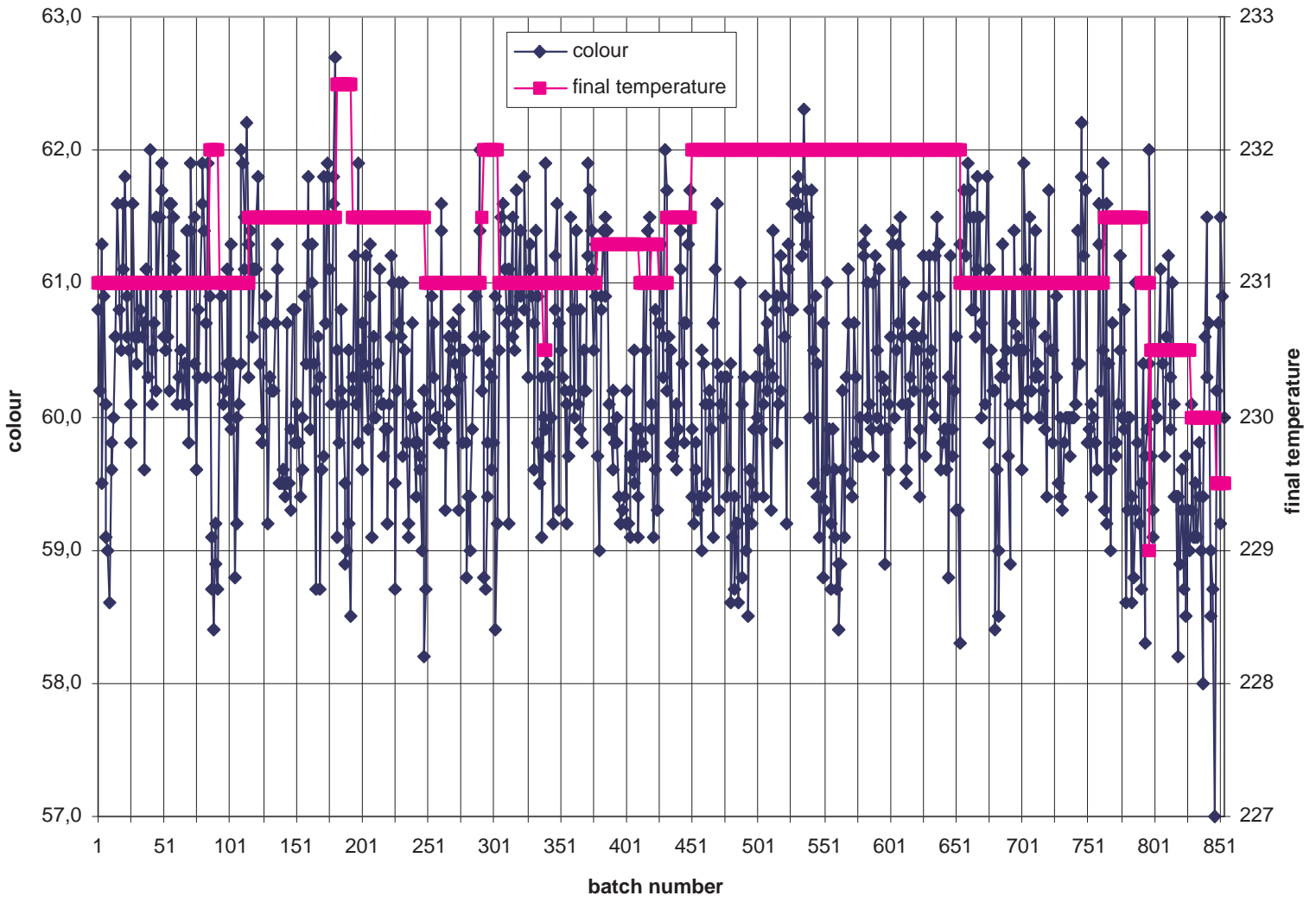


Figure A.22: Data roaster 4

Figure A.23: Data roster 5 of last two years

