UNIVERSITY OF SOUTHERN QUEENSLAND
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THE MECHATRONIC BAKERY

A Thesis submitted by

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Abstract

Large-scale bread bakeries generally exist as 'Islands of Control' – a long line of processes interrelated, but not interconnected in terms of their control systems. To successfully implement a control system that encompasses the entire bakery, much information must be gathered and processed in such a form that process and control engineers can deduce control algorithms.

This project involved the instrumentation of an entire bakery with a view to providing production reports that merge the processes. New methods of tracking products through the entire process were investigated and tested. Methods were also proposed and tested to log temperature/humidities of various bakery processes and align with products passing through to produce a loaf/time/temperature profile.

CERTIFICATION OF THESIS

I certify that the ideas, experimental work, results, analyses, software and conclusions reported in this thesis are entirely my own effort, except where otherwise acknowledged. I also certify that the work is original and has not been previously submitted for any other award, except where otherwise acknowledged.

SIGNATURE OF CANDIDATE DATE

ENDORSEMENT

SIGNATURE OF SUPERVISOR/S DATE

Acknowledgements

John Billingsley, who has been the official supervisor of this project. Who would have thought one person could have so many whacky, yet brilliant ideas.

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Tako, my faithful Siamese Fighting Fish for his hours of company and team spirit in the office at USQ. May he rest in peace.

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Chapter 1 – Introduction

A bakery is not the most obvious example of a Mechatronic system. In its usual form a bread bakery is simply a series of processes that are unrelated in terms of control. Bakery operators oversee their section of production and use predetermined empirical settings for the process. Adding instrumentation to each process and deducing advanced control algorithms will improve operation. However each process still operates on its own, with no information from other parts of the bakery.

If information from every process is combined into one main computing centre, a step towards a mechatronic system is achieved. The information must then be processed in an intelligent way that integrates effects from all baking processes. Once control strategies are implemented using the processed data, all the requirements to create a mechatronic system are satisfied.

Using information gathered from all parts of the bakery, this project aimed to produce information of use to bakery operators that cannot currently be obtained. This included calculating weight loss information, developing product following techniques and producing summary reports showing general production information for the production managers.

Rather than focusing on one aspect of the baking process, this project seeks to gain a better overall understanding of techniques that may be applied to better control the overall process. Several of these techniques were developed and applied in a bakery, providing information that was not previously available to production managers. As a result, many projects focusing on smaller aspects of bakery control will also be defined.

1.1 Achievements of this Project

The architecture for a complete bakery control system has been developed and implemented. This system gathers data from all parts of the bakery and combines it in one central computer.

Several methods of product following were developed and tested. These methods enable the production staff to know where different product types are in the system. Additionally, this allows various bakery process values to be set in preparation for an imminent product change.

Techniques to calculate the weight loss of loaves were developed. These used the product following methods as well as additional mathematical techniques. During this process some shortcomings in the bakery processes were identified.

A major achievement was to determine the actual temperature experienced by loaves passing through the oven. This was achieved by using sensors placed throughout the oven and correlating these with temperatures experienced by a sensor travelling through the oven like a loaf of bread.

Further work aimed to correlate loaf temperature history to weight loss. This was approximately achieved in certain cases.

Using the complete bakery data acquisition system, as well as the techniques developed above, the creation of daily production reports was achieved. These give the production managers access to baking process data that had not been available before.

1.2 Baking Bread

A large bread bakery may produce thirty to sixty thousand or more loaves of bread per day. These may include up to thirty different varieties, each requiring different ingredients and baking conditions. Total production time for each individual loaf is in the order of three hours.

Large bakeries generally use the Rapid Dough method of baking bread. This method is shown in Figure 1.1. There are thirteen separate processes that the bread must pass through. Bread baking involves manipulating a living organism - the yeast in the dough. If the cultures are treated incorrectly in any of these processes, there may be adverse effects on the resulting product.

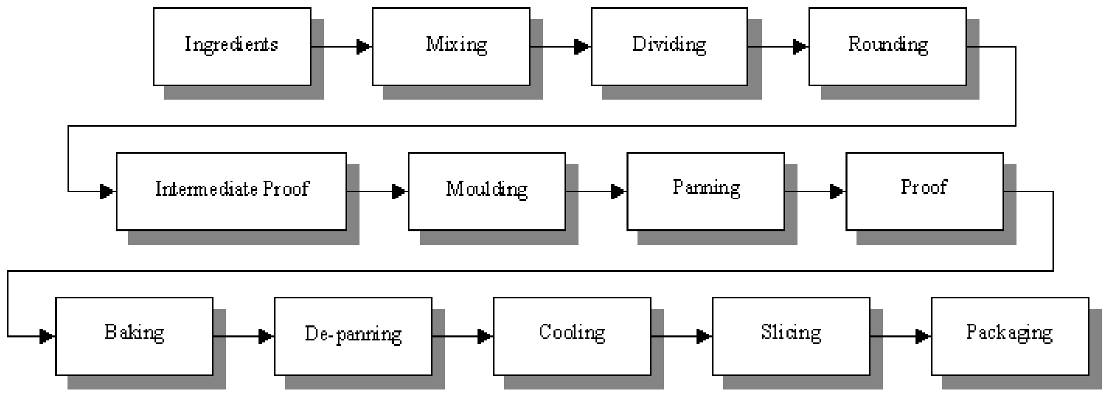

Figure 1.1: Rapid Dough Method of Baking Bread

Producing bread in large-scale bakeries using the Rapid Dough Method is not a simple, straightforward task. Assuming the dough has been mixed properly and suitable ingredients have been used, there is still a multitude of other problems that may occur.

Control systems found in large bakeries generally involve simple direct control of processes. Set-points for products are not necessarily optimised and few other factors are taken into account.

1.3 Problems Faced by Bakeries

1.3.1 Loaf Weights

The weight of loaves is one of the major issues confronting bakeries. Generally, loaves are packaged into bags that have the loaf weight pre-marked on them. Legally, a bakery is required to ensure that any loaf may be no less than 5% below nominal weight. Also, the average of any 12 loaves picked at random may not be below nominal.

1.3.2 Consistent Loaf Quality

Another major issue for bakeries is maintaining product quality. There is significant variation in the quality of loaves. This could be due to a plethora of different factors, and these must be isolated to determine the cause.

A loaf's quality is determined by observing several factors including the colour of the crust, the texture of the crumb, the shape, size and of course, flavour. These are discussed more thoroughly in 0.

A picture of a slice of bread with the crust and crumb labelled is shown in Figure 1.2.

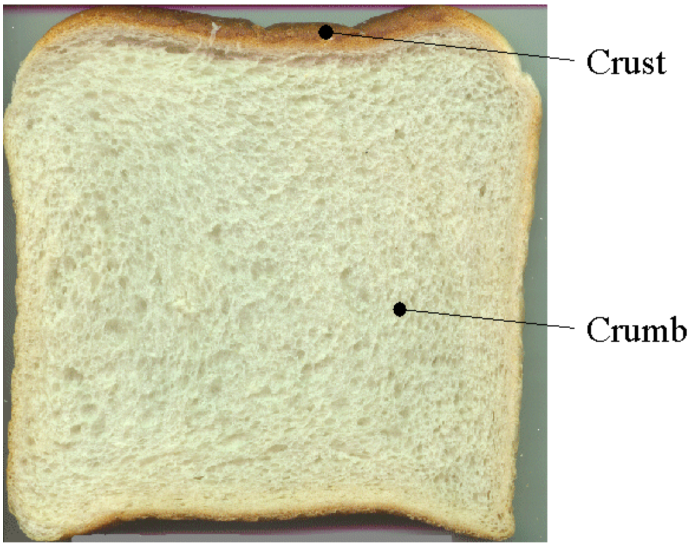

Figure 1.2: Sample slice of bread

1.4 Improvements Possible using a Complete Control Solution

There are many possible advantages to be gained by developing a complete control system for a large-scale bakery. Here, each section will be discussed in turn, with possible applications and benefits discussed.

1.4.1 Production Schedule Optimisation

At the bakery, the orders would be received and an optimal production schedule determined. This production schedule would have to take into account several factors.

Strap type would have to be considered. Straps are the containers that the bread is baked in. There are generally either 2, 3 or 4 tins per strap. Larger loaves will require larger tins for baking and consequently less loaves fit in a strap. If a product requires a different strap type, operators must manually remove all old straps and place the new ones on the production line. (This process may be automated in the future.)

Replacing straps is a time consuming, manually intensive operation and is preferably performed a minimal of times during the day. The production schedule must take this into account.

Another factor to be considered when optimising the production schedule is the oven temperatures required by each product. A product requiring an oven temperature of 230°C should not be preceded by a product requiring an oven temperature of 190°C since it would take up to half an hour to increase the temperature of the oven by the required amount. Determining and maintaining the correct oven temperature is quite an involved subject and is investigated in Chapter 5.

When the product is required is an important factor as well. If 8000 loaves of a certain variety are required to be made one day, it may not be the best option to bake them all first thing in the morning. A better option may be to bake 4000 early in the morning and deliver them, then bake the rest later in the day so they may be delivered fresh later on. This would also depend on when the bread retailers actually want the bread.

After all of these factors are considered, an optimal production schedule may be produced automatically by the central computer.

1.4.2 Ingredients and Mixing

Recipes may be stored on a central computer. According to the production schedule, this computer automatically accesses the mixer. Ingredients are automatically measured out and mixed. According to the variety, other factors such as length of time the bread is mixed and speed of mixing are altered.

Automatically measuring ingredients out gives the added advantage that the accuracy of measurements are known. It eliminates human error from this part of the baking process.

If an ingredient is running low, a new order may be electronically sent to the distributor/manufacturer of that ingredient.

An advanced addition to the control of the mixing process involves the automatic altering of critical ingredients such as yeast levels. The levels of these ingredients may be altered depending on such factors as the ambient temperature and humidity levels on that particular day. Algorithms within the control software may also optimise these values by altering them slightly each day and monitoring the results in the product.

1.4.3 Dividing and Rounding

This section involves dividing the dough into the correct size portions and rolling them into shape. The divider is a crucial element in the baking process because any variation experienced in the initial weight of dough placed into the process cannot be subsequently reduced.

An optimum divided weight will be one that produces loaves of bread at the end of the process that correspond exactly with the marked weight of the loaves. This is one of the major challenges one is faced with when attempting to optimise the baking process. Implications of having weights that are not within specification are discussed in Section 1.3.1, “Loaf Weights”.

The divided weights for each product may be stored in the central computer. These may then be fine tuned automatically as data is gathered about each product and optimal baking conditions are developed.

Variation in weights at the divider is experienced due to the mechanical operation of the machine. Ideally the divider would produce loaves that are all of equal weight, however due to the physical characteristics of the dough, it is quite difficult to achieve.

An advanced option may be to alter the divided weights depending on factors such as gaps in production. The loaves immediately after a gap may be divided at a greater weight. This would allow for the extra baking they would receive in the oven due to the lower thermal load during the gap. Ideally intelligent oven control would solve the problem, eliminating the need for dealing with the problem of unevenly divided loaves.

1.4.4 Intermediate Proof

Intermediate proving is used as an initial rise period for the dough. Currently the humidity, temperature and time of proving are not accurately controlled. The end effect of this on the bread is not yet fully understood.

1.4.5 Moulding and Panning

In this section, the dough is sent through a roller and directed into the tins. It is a purely mechanical process and works reasonably well. Occasionally the dough does clog in this section, suggesting that sensors to spot this may be useful. However usually the operator will notice the jam almost immediately, and it is a result of poorly cleaned machinery. Sensors that detect machinery getting progressively more obstructed may be possible.

1.4.6 Proofing

Proofing allows the dough to rise via the yeast activation process. It is here that the volume and cell structure of the dough is developed for baking. Optimum proofing conditions are thought to consist of a temperature of approximately 40°C and a relative humidity of approximately 85%.

A cause of variation in the proofed height of bread is the temperature of the tins in the prover. The tins that doughs are placed in may be either hot or cold - the hot ones having recently been used in the oven. Sometimes the tins are all hot or all cold. For example, when a change of tins from 3-strap to 4-strap is done, all the new tins will be cold. Sometimes there are only a few cold tins. This happens when there is a lack of tins ready for dough to go into and an operator must place some new tins on the assembly line.

This is a difficult occurrence to deal with. The best response may be to simply have some method of ensuring the tins are all the same temperature and the yeast levels in the mix should be set to deal with that.

1.4.7 Baking

The oven, where the bread is baked is the most important process apart from the mixing of ingredients. Many avenues for control and optimisation are possible in this section of the bakery.

The oven is specifically covered in more depth in Chapter 5, but a control summary will be presented here.

Ideally, the oven would be divided into 4 to 8 separately controllable zones. Oven temperature would be controlled according factors such as loaf variety, oven thermal load and ambient conditions. The temperature histories of loaves passing through the oven could be customised according to an ideal setting for that variety and considering the settings required for the next variety.

1.4.8 De-Panning and Cooling

After the loaves are removed from their tins (de-panning), they enter a cooler where they remain for around an hour. This procedure is necessary because after the loaves have left the oven, they are still losing moisture to the atmosphere. If they are placed in bags straight away, condensation will collect inside the package. This then has adverse effects on the bread. Also, there are problems with slicing of loaves if the bread is too hot.

1.4.9 Slicing and Packaging

This is the final section in the bread production process. It has much significance in the overall control system.

Final weights are taken here. These weights are fed back to the main computer and analysed to calculate new improved set-points and ingredient levels for the next day's production. With the ability to track particular products through the bakery, bags for each variety may be automatically changed, or alternatively operators may be warned, as a variety change is about to occur.

The slicer provides an opportunity for image analysis to be used on the loaf grain.

1.4.10 Maintenance

Although completely beyond the scope of this project, an added aspect that may be pursued when developing an advanced bakery control system is automated maintenance warnings. Maintenance at a bakery, as at any manufacturing plant, is extremely important. Any loss in production time due to breakdowns is costly and possibly dangerous.

Using sensors already in place for other purposes in the control system (eg sensors that track oven movement), the amount of work that certain motors, chains etc do may be logged. When predefined limits have been reached, warnings may be produced either by on-screen prompts, printed reports, emailing the appropriate employee or a combination of these.

In addition since the communications infrastructure is already set up in the bakery, it should be easier to add other sensors. These may sense values such as vibration in motors and set an alarm state when a critical level is passed.

1.5 CDROM Contents

Included, as an appendix to this dissertation is a CDROM. This contains the entire text of the dissertation in several different formats. It also contains much extra information directly related to the project. This includes colour photos of bakery processes as well as screen shots of the Product Performance Indicator (PPI) software, source code for the PPI software and several other programs, presentations and a paper presented during the project, Microsoft Excel macros used for sorting data and producing reports, data logged in the bakery, other relevant documentation for the PPI and useful Internet links.

Chapter 2 – Background of Baking and Measuring Loaf Quality

Control of the baking process depends on the ability to measure the quality of a loaf of bread. There are a variety of factors that can give an indication of loaf quality.

Some of the measurements that have been taken in the past include “Baker’s Score”, Crust colour, Colour ratio, Loaf softness/sponginess, Side wall caving, Weight Loss, Loaf Height, Loaf Shape, Volume, Bubble Size/Texture and Flavour.

Each of these will be discussed here. It is important to note that these qualities are dependent on a complex combination of factors including dough composition, oven conditions (temperature, air velocity, humidity), proving conditions, and cooling conditions.

2.1 Controlling the Baking Process

Little literature on overall control systems for large-scale bakeries is available. This is due to the fact that up until this point, all studies found have concentrated on control of separate processes – usually the oven. Practical work in bakeries has also focussed on individual processes rather than the system as a whole.

An interesting introduction to the world of automating complex processes that are ordinarily controlled by experienced human operators, using the specific example of a bread bakery, is “The Knowledge Based Sensor System – A Novel Measurement Approach”, (Wide, 1995).

There are many studies that investigate the processes that occur inside the oven and explore possibilities for control. Related papers are discussed in Section 5.1.

2.2 Bakers Score

A ‘Baker’s Score’ is the traditional method that bakers use to assess a loaf of bread. It is typically based on an arbitrary numerical scale that assigns certain maximum values to specific loaf attributes (Pyler 1988). Since bakers score is such a subjective method, qualities such as loaf colour, crumb cell size/uniformity/shape, loaf shape and various others may not be reliably and consistently measured.

Until recently, bakeries have been obliged to use bakers' score since it was the only realistically available method of determining loaf quality. There are several methods of more objectively determining loaf quality, especially with the advent of image analysis techniques. Ideally, baker's score would be completely replaced with more objective techniques.

2.3 Crust Colour

Crust colour is one of the most obvious indicators of loaf quality to the naked eye. It has direct consequences with regard to the flavour of the loaf as well.

Colour may be measured in several ways. There are commercially available 'colour meters' such as the Hunterlab ColorTrendTM HT that has been used by BRI Australia Ltd in several projects (Varma 1998). This is shown in Figure 2.1.

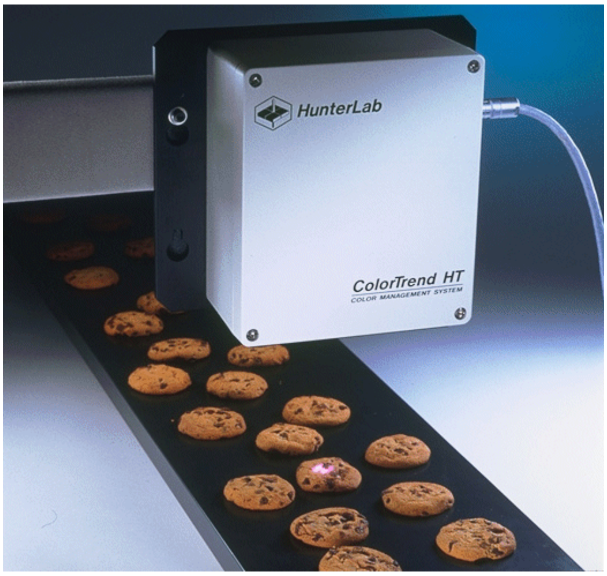

Figure 2.1: The Hunterlab ColorTrendTM HT (From the Hunterlab website, http://www.hunterlab.com)

Image analysis provides a more adaptive method of measuring colour in that more detailed analysis of separate loaves may be performed. In its simplest form, the loaf may be isolated from a captured image and an averaged 'brightness' value may be calculated. The ambient lighting must be taken into account here as well - if the lighting level changes, a different brightness will be measured.

In Kim and Chun (1997), a loaf is monitored during baking via a CCD camera. Using red, green and blue colour histograms, the bread colour development was observed. If an ideal 'colour development' is defined for a particular product, conditions may be controlled to produce this result.

In the long term, measuring the colour of loaves while they are in the oven is not necessarily the best approach. It is more of a research exercise to study what is actually happening within the oven. Once the loaf is in the oven, the large time constant of the oven dictates that it is too late to change the oven temperature to accommodate that particular loaf. Instead enough needs to be known about the bread and the conditions it is experiencing to have the oven set suitably before the loaf enters.

2.3.1 How to Quantify Colour

Quantifying colour may be done in several ways. A widely used method is the L * a * b colour space devised in 1976 by the CIE (Commission Internationale de L'clairage, or the International Committee on Illumination). This represents colour as a colour space in which equal distances approximately represent equal colour differences. 'L' is the brightness value, 'a' is the red/green value and 'b' is the blue/yellow value. A diagram of this is shown in Figure 2.2.

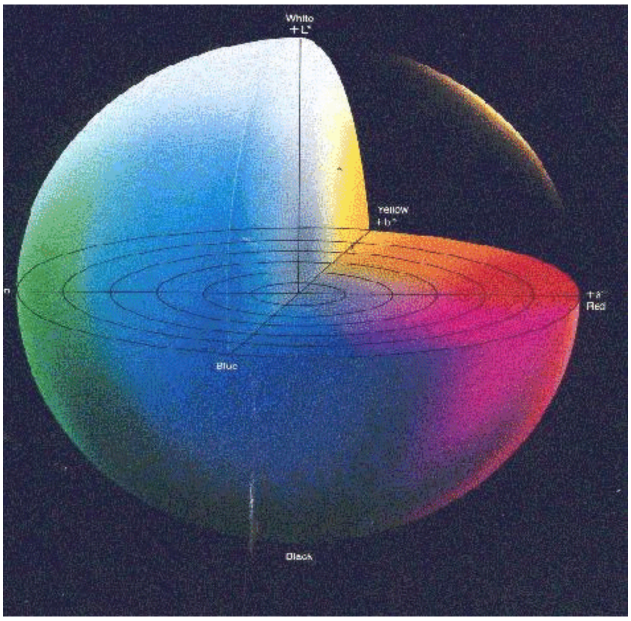

Figure 2.2: Colour solid for L * a * b colour space

If using this method for bread, only the 'L' value really needs to be used since brightness is the main indicator. However, if a measure of how constant the colour is over the loaf surface is required, image analysis is probably the best option.

2.4 Colour Ratio

This is a value proposed in Adamczak and Kallitsis, (1997). It was proposed as a result of the problem identified in industry of variation in colour between the top/bottom and sides of the loaf. The colour ratio (CR) is a ratio of the sidewall colour to the average loaf colour.

Generally, problems in industry involve a low CR, meaning that the sidewalls are lighter than the average colour. This is not only visually unappealing, but results in weaker sidewalls that may cause the loaf to collapse during slicing or transport. A low CR indicates uneven heat flow around the loaf and therefore uneven baking. In Adamczak and Kallitsis, (1997), the conclusion was to increase the air flow and/or gap between tins. If done correctly, this would result in a CR of close to unity.

2.5 Loaf Firmness/Softness/Sponginess

Since a customer will often test the 'freshness' of a loaf by squeezing it, it follows that this could be done after baking to test the quality of the loaf.

An 'Instron Universal Testing Machine' has previously been used (Adamczak and Kallitsis, 1997) to determine the compressibility of a whole loaf. An example of such a machine is shown in Figure 2.3. In (Adamczak and Kallitsis, 1997), this compression was found to depend on the moisture content and crust properties of the loaf. This testing was performed 24 hours after baking, so results may not be exactly applicable to loaves during the baking process. Testing was done both on whole loaves and on separate slices to test the firmness and recovery of the crumb.

Figure 2.3: An example of an Instron Universal Testing Machine (from the Instron website, http://www.Instron.com)

Testing the firmness during production would require a slightly different approach. The firmness, when related to loaf quality may be fed back to bakery operators (or an adaptive control system) to monitor production. A drawback may be the fact that a firmness test might damage the loaf. This would have to be considered with any testing method.

Using firmness as an indicator of loaf quality was not pursued in this project, the focus being more on loaf weights.

2.6 Weight Loss

Weight loss is not one of the qualities a consumer would look at when determining loaf quality, however it has much value for use in a bakery. These uses are discussed more thoroughly in Chapter 4, “Weight Loss”, but will be quickly listed here.

Legal reasons are important. The connection between initial weight and final weights is useful because legal requirements must be met when labelling and selling loaves.

It has been found that the weight loss of a loaf has a linear relationship with other factors such as loaf colour and firmness (Adamczak and Kallitsis, 1997). If a bakery can minimise weight loss while maintaining loaf quality, great savings in ingredients may be made.

Complications in accurately determining weight loss during production have limited the study of its use in a bakery in the past. Chapter 4, “Weight Loss” looks at this in more detail.

2.7 Loaf Height, Shape and Volume

Loaf height, measured after proving is a function of ingredient levels (particularly yeast) and prover conditions. These values may be monitored from here.

The shape of a loaf of bread after baking is very important from a consumers point of view. A common problem in industry is the caving of the bread sidewalls and also caving of the top and bottom of the loaf. This was studied in Adamczak and Kallitsis (1997). It was found that caving is related to the firmness of the loaf as well. A less firm loaf will be judged as ‘fresher’, but is more likely to experience side wall caving.

Caving may be measured as a ratio of the minimum distance across a loaf compared to the maximum distance or tin width. This is shown in Figure 2.4.

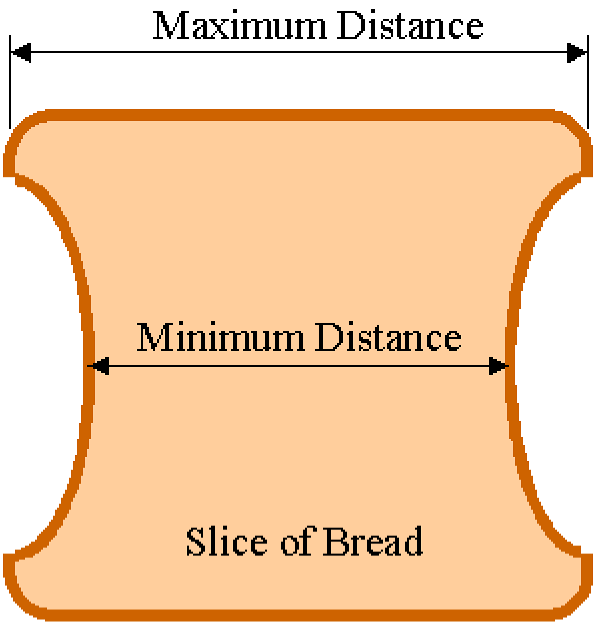

Figure 2.4: A diagram of side wall caving

Measurement of sidewall caving during production may not be effective since caving usually occurs during or after slicing/bagging or during transport and handling. It is desirable however, to produce loaves that are not prone to caving. This quality may be linked with the colour ratio as discussed in Section 2.4 above. A low colour ratio indicates less baking on the sides of the loaf that may make the loaf more susceptible to caving. This would have to be verified.

2.8 Slice Texture, Cell Attributes

There have been several studies done to determine the quality of a slice of bread by using image analysis on the crumb grain (Wang and Coles, 1997; Zayas and Chung 1996, 1997; Sapirstein, 1995). A photograph of the crumb grain is shown in Figure 2.5.

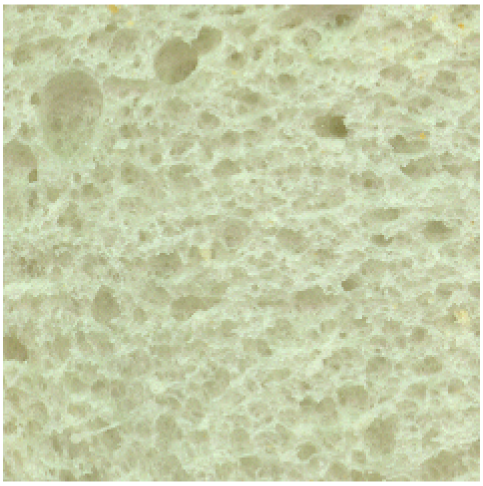

Figure 2.5: A photograph of the crumb grain of a loaf

The main considerations used when human experts assess crumb texture are cell size, uniformity of cell size and thickness of cell walls (Wang and Coles, 1997). Usually this is done by comparing slices with a photograph of agreed standards. This is a very subjective method since one photograph is not enough to represent a wide range of textures that may all be acceptable. It is also repetitive and time consuming.

A commercial 'Bread Quality Imaging System' (BQIS) was developed in (Wang and Coles, 1997). This uses edge-detecting algorithms to produce information about the cells.

Although useful, the BQIS has limited application on-line in a bakery because it requires special attention by an operator and needs separate slices from the loaves. A better method would be to measure the crumb texture during production. The obvious place to do this would be at the slicer. A possible configuration is shown in Figure 2.6.

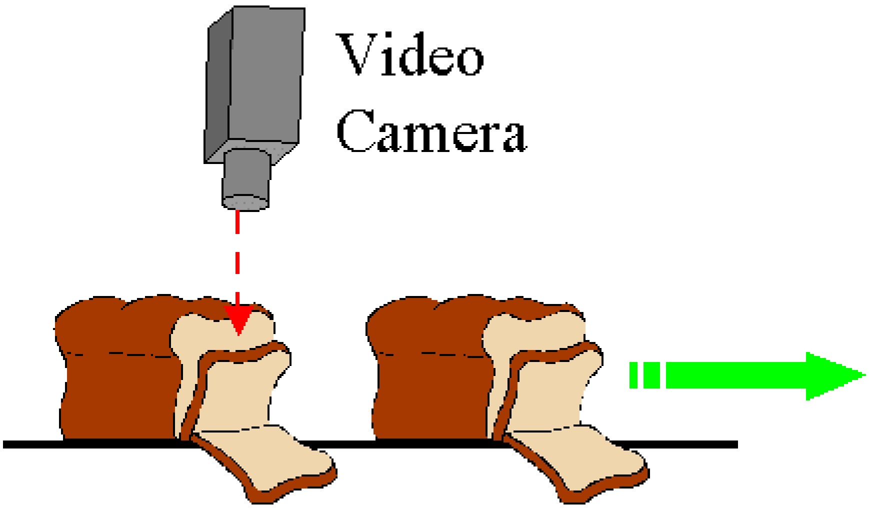

Figure 2.6: A diagram of how image analysis may be used on-line in a bakery

2.9 Flavour

Flavour is a very subjective measure of loaf quality that cannot easily be measured at the bakery. A better solution is to somehow relate the general consumer's opinion of flavour with other indicators of loaf quality discussed here.

Ingredients and the particular variety of loaf have much do with the measured flavour. These need to be taken into account separately from other factors. That is, assuming the same variety and basic ingredients, how do changes in baking conditions affect the flavour of a loaf of bread. At some stage, ingredients do have to be taken into account, but this is more of an issue for the product development scientists, not for a bakery control engineer.

2.10 Summary

Several methods of measuring loaf quality have been outlined here. Weight loss is one of the most interesting and under-utilised. Weight loss will be the method most focussed on in this project.

Chapter 3 - Data Collection and Processing

To begin assessing methods of improving control and optimising a bakery's processes, a data collection system had to be set up. Initially, several small short term field trips were completed. These generally involved placing a minimal number of proximity sensors and the logging of weight files from the scales at a bakery.

These trips allowed product following techniques using gaps between loaves and loaf counts to be assessed. They also allowed factors such as product loss and basic weight losses to be determined.

It was quickly realised that a larger, more permanent data acquisition system was required. The hardware and software used in this larger system will be discussed here, along with how it interfaces with bakery operations.

3.1 Overview of Product Performance Indicator Setup

The combination of software and hardware used to collect, process and display data for this project was named the 'Product Performance Indicator', or 'PPI'. The main aims of the PPI were as follows:

- To determine, by experimentation, what data would need to be recorded from a bakery in a commercial control system.
- To develop methods of processing and displaying data from the bakery by post-processing and real-time processing in a way that gives bakery personnel information they have not previously had access to.
- To build up an archive of data from the bakery that may be used to determine long-term trends.

3.1.1 Factory Automation Software and PLCs

Earlier data collection systems used for day trips to a bakery consisted of a PC data acquisition system utilising a DL205 PLC base from 'AutomationDirect' connected to a PC via Ethernet. Although the terminology 'PLC' is used, it is not strictly operating as a ‘Programmable Logic Controller’ because the PC controls all operations through a base controller module.

Software was originally written in ‘Think & Do’, a graphical programming language by AutomationDirect for the DL series of PLCs. The software simply logged data as it was coming in. The PPI still uses Think & Do to communicate with the PLC bases, but uses Visual Basic 6.0 for the Graphical User Interface.

3.1.2 Scan Based System

The central PC collects data from the PLCs usng a scan-based system. This means that every specified period (*x* ms), all the I/O points are scanned. In order to sense individual loaves passing by, the scan period must be small enough to guarantee sensing of the gaps. It was found that this was not practical however, because at some points (most notably, after de-panning), the loaves were extremely close together, even to the point of touching each other.

Some quick calculations demonstrate the limitations. At the de-panner, 24 loaves may pass in 10 seconds. If these loaves are all 10cm wide with 1 cm in between them, they are travelling at a speed of around 0.264 m/s. At this speed, a gap of 1 cm would pass in 37.9 ms. With a scan period of 40 ms, this gap may not be sensed. Figure 3.1 shows this limitation with a 50ms scan time.

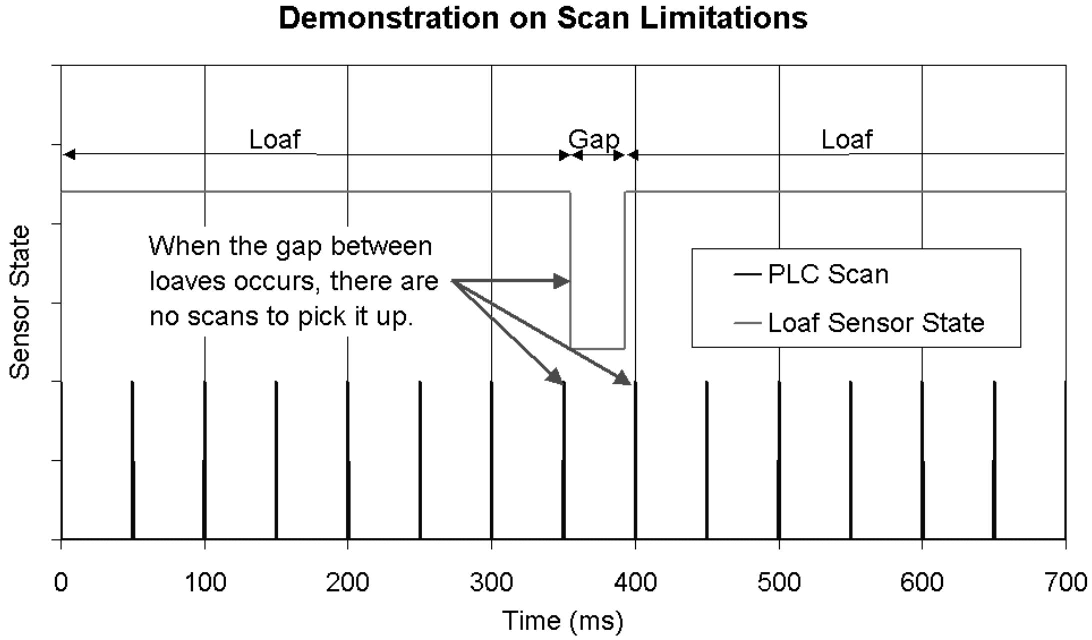

Figure 3.1: Demonstration of limitations of a scan based system

The simple solution is to decrease the scan period to a very low value such as 5 ms. However, very small scan periods cause problems with other program operations performed by Visual Basic such as serial communications with the oven temperature controllers. Therefore the scan period needed to be increased to about 40ms. It may have been preferable to use Think & Do for all serial communications, but most code had already been written in VB before the problem was discovered. Additionally, VB was the preferred language due to its versatility.

3.2 Microsoft Visual Basic

The GUI and most data processing algorithms were programmed in Visual Basic. Data was imported into Visual Basic continuously using both 'Dynamic Data Exchange' (DDE) and 'Component Object Model' (COM). These are both computing standards that have been developed to allow communication of data between different software applications. Application of DDE and COM is a feature of both Visual Basic and Think & Do.

3.3 Loaf Weights

One of the most important values that is logged by the PPI is the weights of loaves. There were already three sets of scales in place at the bakery - one at the beginning of production and two (one on each branch of the conveyor) at the end of production. The scales used are Ramsey-RCCI Checkweighers, Model WDD - Version 5. A photo of the checkweigher at the beginning of production is shown in Figure 3.2.

Figure 3.2: First checkweigher - after loaves are divided and rounded

Data is acquired from the checkweighers via separate RS-422 serial communications lines. Every time a checkweigher senses a loaf, ASCII data is automatically sent along the serial line. Serial communications were programmed directly in the Visual Basic module of the PPI.

A separate PC run by the bakery also logs weights from the final two checkweighers using the 'AutoView' software produced by Ramsey-RCCI. This software is used by production managers to determine average weights of products and other details such as number of underweight loaves. This information is now automatically produced by the PPI.

All the checkweighers have product details stored inside them. The bakery operator selects the appropriate product when required. The initial checkweigher rejects underweight loaves, but overweight loaves are allowed to pass. There is a system in place that feeds back a control signal to the divider to automatically set the weights of loaves. Due to unsatisfactory operation of the current weight control, bakery operators usually adjust the divider manually.

As well as rejecting underweight loaves, the final checkweighers also incorporate a metal detector that rejects any loaves with metal in them.

The data that is resolved by the PPI includes (for each loaf), the product number, the weight and whether it was overweight, underweight or passable. If the loaf was rejected due to a metal detection, that is logged as well.

Product names are stored in the checkweigher but are not transmitted with the data from the checkweighers. The PPI has a list of product numbers and names that is updated from the checkweigher every time a product changes. In this way, the product name may be displayed on the PPI screen.

3.4 Loaf Heights

An ultrasonic proximity sensor measures the height of loaves as they exit the prover.

Figure 3.3 shows the positioning of the height sensor. It is a PCU Series Ultrasonic Proximity Sensor from Electro Corporation with a 4-20mA output. Its sensing range is about 200 - 1800 mm.

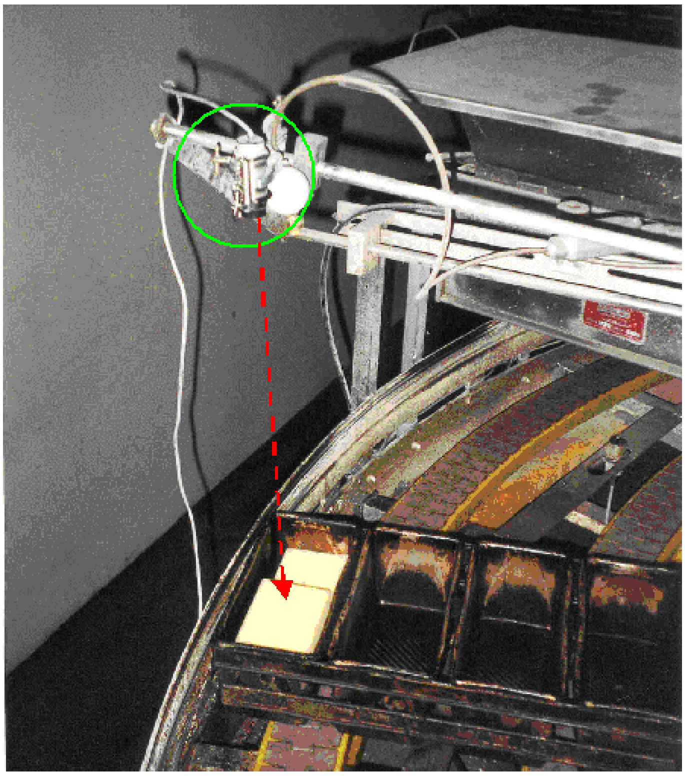

Figure 3.3: Photo of height sensor positioning (sensor is circled and sensing direction is shown with an arrow.

To calculate the height of a loaf, the average of all the readings taken across that loaf is calculated. It is assumed here that the PLC scan period is 40ms (25 readings per second), the conveyor speed is approximately 0.3 m/s and the tins are about 30cm long.

When the loaf is being sensed, it is probable that the tin will be sensed as well, giving an average height for that loaf that is inaccurate (See Figure 3.4. To guard against this interference, before the average of all the readings is taken, the first and last entries are eliminated.

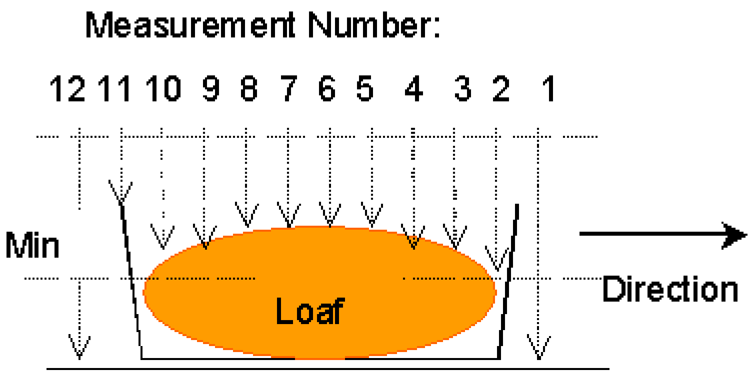

Figure 3.4: Demonstration of tin interfering with loaf height measurements

Placement of the sensor must be done carefully so as to ensure that all types of strap (2,3 and 4 tins) are sensed properly. This means that the sensor will not sense every type of loaf along the centre line. This is not a problem - as long as it is known what the recommended heights of loaves should be along the particular section being measured. If an accurate measure of the height is required, a different approach must be taken.

Figure 3.5 shows how validation of the height sensor operation was performed. A low density foam 'pattern' was used of known dimensions. The foam had to have some flat plastic placed over the top of it so that the ultrasonic sensor could work satisfactorily.

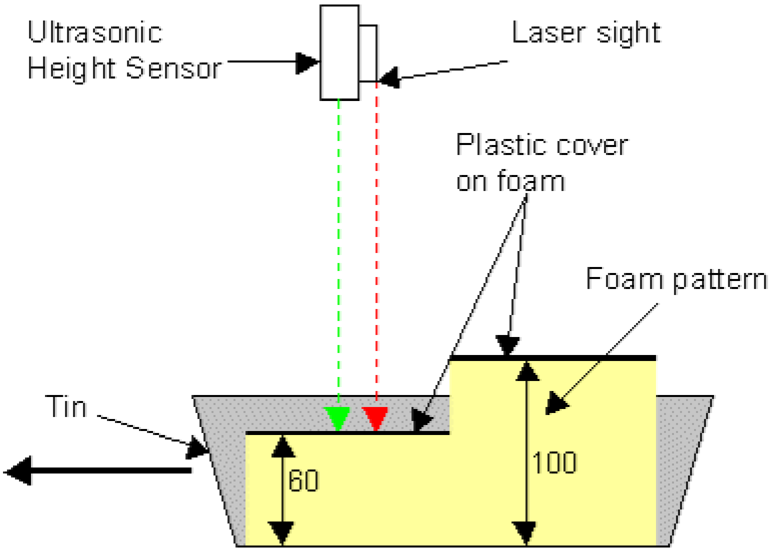

Figure 3.5: Foam pattern used to configure height measurement

Firstly, static measurements were taken on both the 60mm and 100mm sections to check that the sensor was configured. Once this was done, moving checks could be performed. It was found that the height sensor would measure accurately to about 2mm.

An example of the averaging in practice is shown in Figure 3.6. The plot shows the instantaneous readings from a group of 12 tins passing the sensor. It can be seen that an average is taken only 6 times during the 12 tins. This is because there are small gaps between tins and these are not always sensed. The averaging that does occur is sufficient to give an indication of the trend in loaf height during a production run.

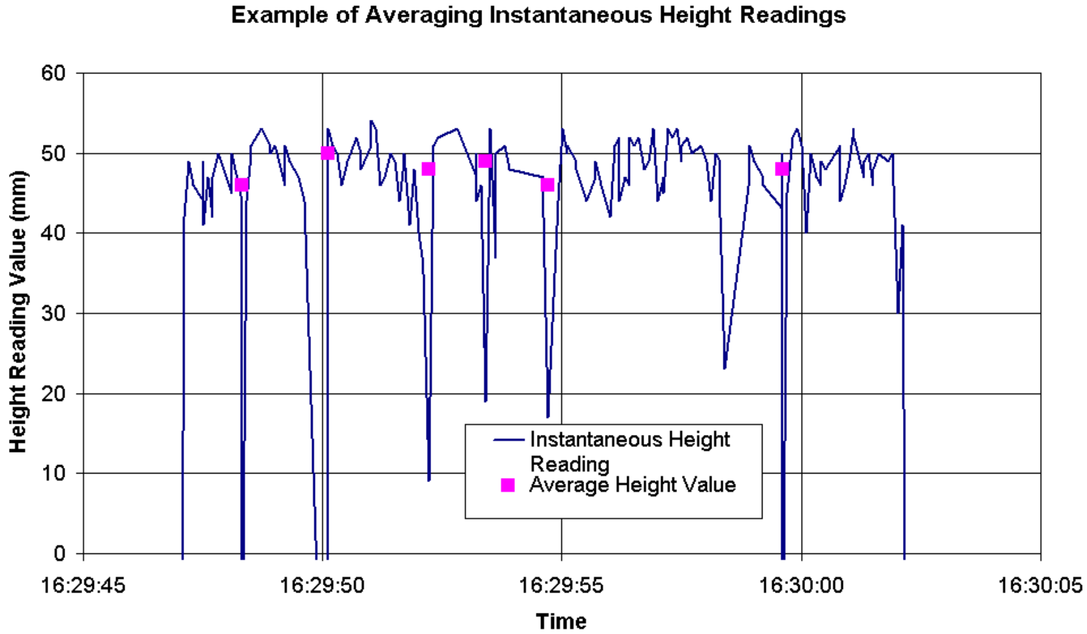

Figure 3.6: Example of averaging instantaneous height readings

3.5 Temperature and Relative Humidity

The temperatures and relative humidities of several processes are measured. Logging frequency is configurable upwards from a minimum of once every 2 sec.

3.5.1 The Intermediate Prover, Prover and Cooler

Temperature and relative humidity are measured in the intermediate prover, the prover and the cooler. There is one temperature and RH sensor in the intermediate prover and two of each sensor in the prover and the cooler. In the prover there is one on the left and one on the right side, giving a balanced measure of the values. In the cooler, there is one inside and one in the inlet air duct. This allows the effect of the temperature of the air entering the cooler on the cooler temperature to be determined. The humidity sensors used are capacitance type sensors made by Vaisala.

The temperature sensors used are RTD (resistance-temperature detector) type, with the voltage being converted to a 0 - 1 Volt signal corresponding to -40 to 60°C.

3.5.2 The Oven

Oven temperature measurement is analysed in greater detail in Section 5.5. All sensors in the oven are thermocouples connected to the main PC via either a thermocouple module in the PLC (4 Inputs) or a 'SmartReader Plus 7-Channel Temperature Logger' by ACR Systems Inc (7 channels + ambient). This is connected to the main system by an RS-485 connection.

Thermocouples are type 'K' thermocouples and are exposed to the oven air with no thermal shielding.

There are two temperature controllers for the oven, each controlling a separate burner. These controllers are 'CAL 9400 Dual Display Autotune Temperature Controller. Each is connected to a single thermocouple that has thermal shielding around it, slowing down response time to temperature changes. This reduction in response time is necessary due to physical constraints of the burners. The burners should not be allowed to switch on/off too quickly or the flame is in danger of extinguishing. This constraint on the oven is one reason why accurate temperature control is so difficult.

Figure 3.7: Front display of the CAL 9400 Temperature Controller (from the CAL website, http://www.cal-controls.com/)

Data is acquired from the temperature controllers via an RS-485 serial line using the MODBUS RTU protocol. This protocol is designed as a standard that allows many different types of device communicate over one serial cable. These serial communications are programmed in the Visual Basic part of the PPI. Each controller has its own ID address and returns data when it is requested by the PPI. Data that is returned includes the measured temperature, the oven set-point, the output state (Normal output On/Off and Alarm output On/Off). The alarm output is always set about 4 degrees below the set-point. If the temperature reaches this low, the burner is set on ‘High’. During normal output the burner is set on ‘Low’.

3.6 Proximity Sensors/Digital Inputs

Each PLC has a digital input card. These inputs are used to connect to proximity sensors and to relays that respond to the movement of processes. Optical proximity sensors are located at various points to sense the passage of loaves. Also, digital inputs are taken from other processes to indicate their movements.

A final configuration for the placement of sensors has not been reached. Current sensor placements and future suggestions are discussed here.

3.6.1 The Divider

The first proximity sensor is located just before the checkweigher, after the dough is divided and rolled. This sensor is quite reliable although the operator’s hands may interfere with it sometimes.

The second sensor is located directly after the section where underweight loaves are rejected. This loaf count from this sensor is not completely reliable because the dough rejection system is not completely reliable. Sometimes the rejection system attempts to reject a piece of dough, but does not succeed. The sensor will not sense this piece of dough, yet it is in the intermediate prover.

The location of these sensors is shown in Figure 3.8. Both of these sensors would not be required if the dough rejection system could be made 100% reliable. Instead, the weights registered by the checkweigher would be used for exact loaf count data. After comparing the readings from these proximity sensors with the weight readings, it was decided to rely on the latter for most calculations. However when loaf-by-loaf calculation of weight loss is to be pursued, reliability will need to be increased here (See Chapter 6).

Figure 3.8: Proximity sensors at initial checkweigher (after divider). Sensors are circled.

3.6.2 Intermediate Prover Operation

The shelves in the intermediate prover move forward every time a shelf is full. This movement is the source of a digital input. The input goes 'On' when the shelves are moving. The operation of the intermediate prover is shown in Figure 3.9.

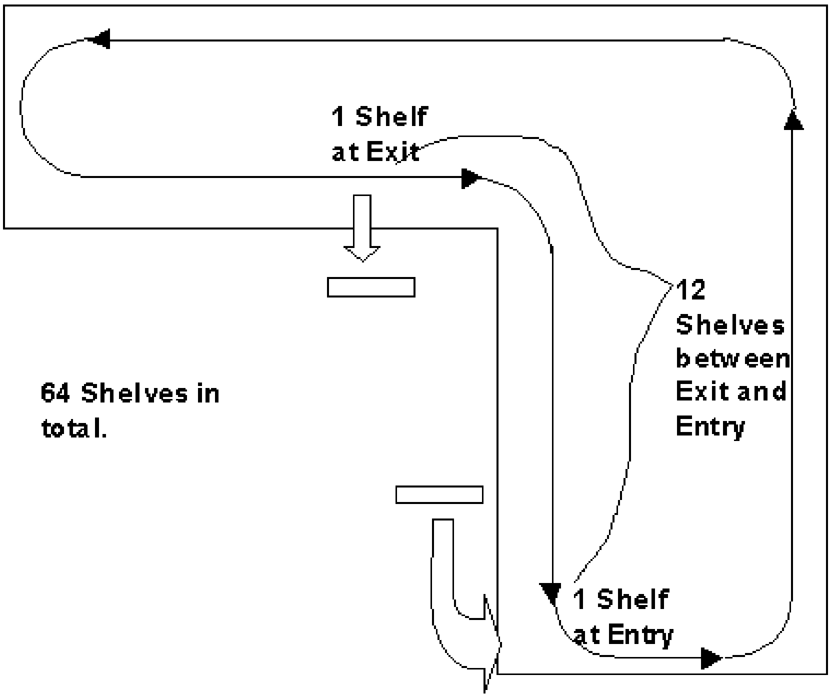

Figure 3.9: Intermediate prover operation

Additionally, a digital input that senses the forward movement of the pockets as they enter the prover may be useful to allow precise tracking of loaves through the intermediate prover. The operation of the prover loading is shown in Figure 3.10.

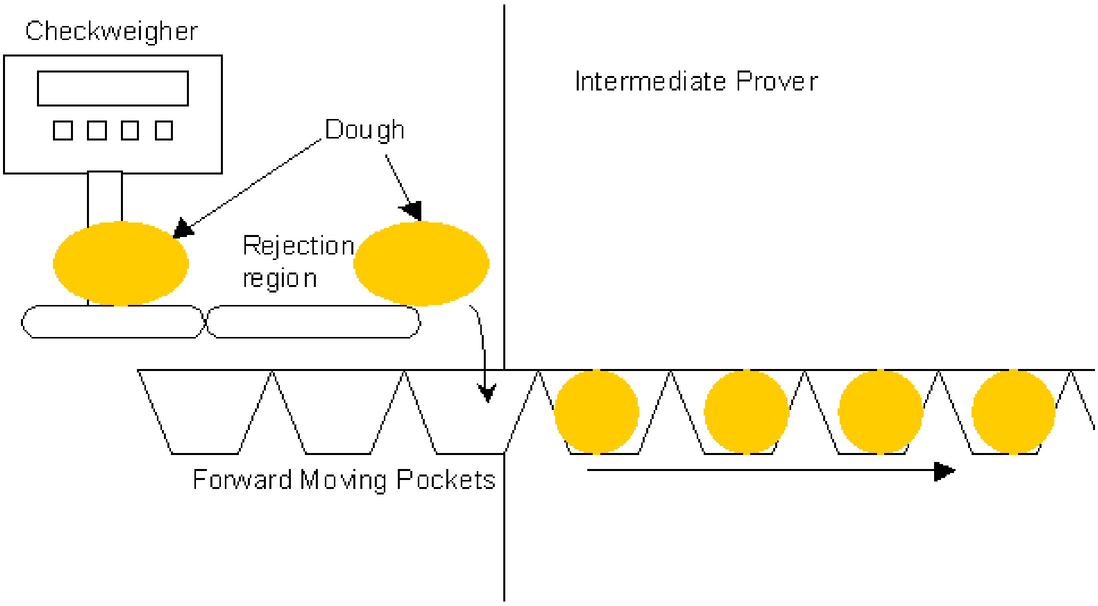

Figure 3.10: Diagram of pocket movement in intermediate prover

3.6.3 Into Tins

After being rolled, the pieces of dough are put into tins. A digital input is taken from here. It reliably goes 'On' when a piece of dough enters a tin.

3.6.4 The Prover

A digital input is connected to a relay that operates when the loading arm at the prover operates. This loading arm will only load the prover with tins when there are 12 tins ready to load, or when the operator manually activates it (More about this in Chapter 6. The relay goes 'On' when the arm is in operation.

A digital input is also connected to a relay that operates when the shelves in the prover move. This relay goes 'On' while the shelves are moving.

3.6.5 The Oven

There is a proximity sensor located between the prover exit and oven entry. It senses individual straps as shown in Figure 3.11. This sensor originally had some problems with being obstructed by dust since it was located close to where 'toppings' are put on the bread (eg flour or sesame seeds). It had to be cleaned regularly. A new position was found closer to the oven entry as shown. Cleanliness of the sensor has been improved but it still has to be wiped every few days to ensure reliable operation.

Other future options may be to place a inductive proximity sensor here or to do away with this sensor altogether and rely on the a relay connected to the loading arm for the oven. This would be okay since most shelves passing through the oven/prover section are full of 12 tins. Or, if they aren't full, this can be sensed when they enter the prover.

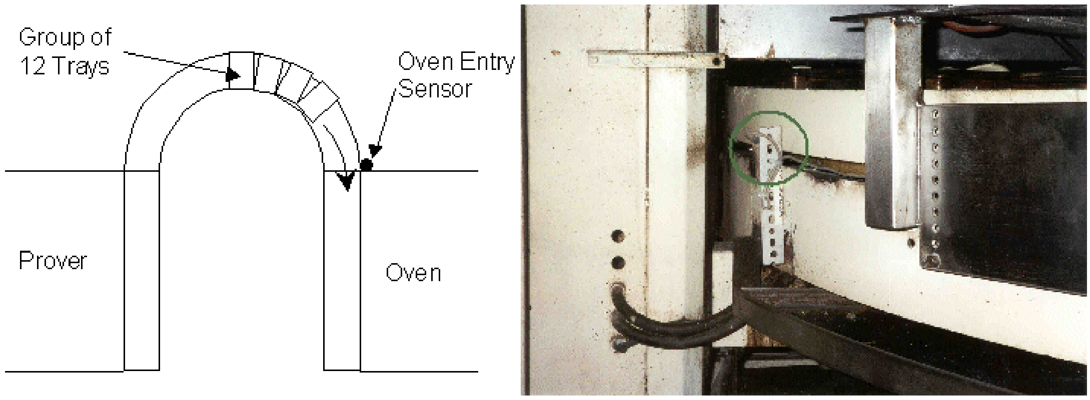

Figure 3.11: Oven strap sensor location

As with the prover, a digital input is connected to a relay that goes ‘On’ when the oven shelves are moving.

3.6.6 The De-Panner

A digital input is taken from a sensor that is part of the de-panner. This sensor turns ‘On’ as each loaf is removed from its tin. However currently the counts being recorded are not accurate. This is because at the point the sensor is located, the loaves are extremely close together. The gap is too small to be sensed with the current scan times being used.

There is also a proximity sensor located just after the loaves have been separated from their tins. The counts performed by this sensor are not fully reliable either due to the gaps between loaves being too small. However it is more reliable than the previous sensor. Its placement is shown in Figure 3.12.

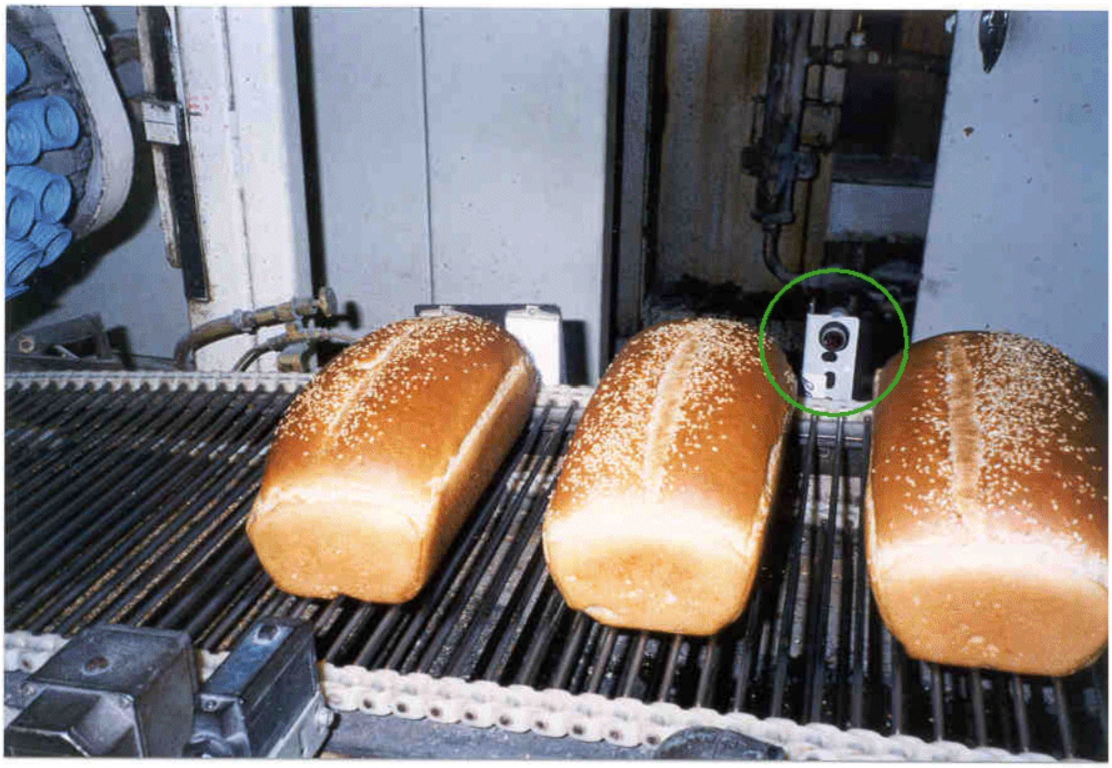

Figure 3.12: Proximity sensor after depanner

3.6.7 The Cooler

There are three digital inputs from the cooler section of production. The first goes 'On' when the cooler shelves are moving. The second is connected to the cooler loading arm and goes 'On' when the loading arm is in operation. This sensor is used to decide when to log cooler shelf weight.

The third sensor is a proximity sensor placed after the cooler exit, before the conveyor split. It senses individual loaves, but the count is not accurate since many of the loaves are very close together.

3.6.8 Conveyor Split

There is a proximity sensor located on each conveyor split above the conveyor. Their placement relative to one another is shown in Figure 3.13. A photo of one of the sensors is then shown in Figure 3.14. The loaf counts from these are fairly reliable but may not be 100% accurate.

Sensors in this region are needed to be able to re-calculate the order of loaves entering the slicers. Before each slicer is a buffer where the loaves queue. This means that the order in which the loaves leave the cooler are not necessarily the order they are sliced (and weighed) in.

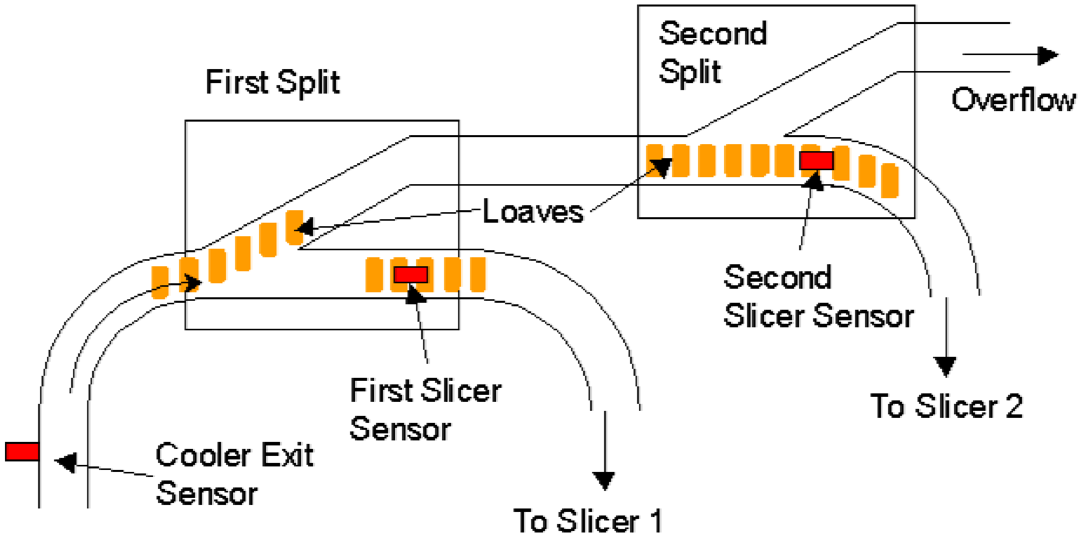

Figure 3.13: Locations of sensors around conveyor split. (Including cooler exit sensor)

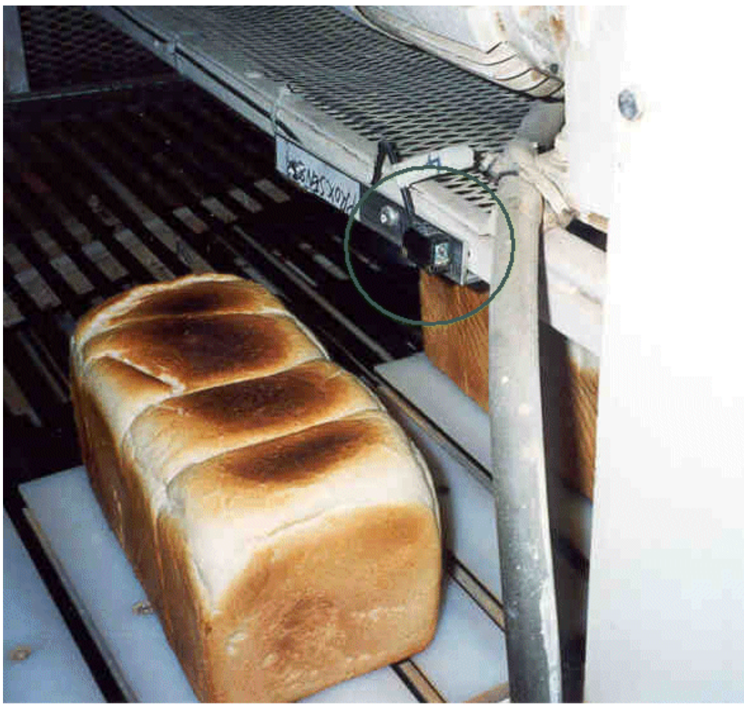

Figure 3.14: Photo of one of the overhead loaf sensors at the conveyor split

3.7 Oven and Prover Loading

Calculating the thermal load in the oven and prover was a major objective of the project. However, many difficulties have been encountered that make accurate calculation very difficult.

Currently, the approach taken involves expressing the oven load in terms of a percentage of the maximum number of straps the oven or prover can hold.

3.7.1 Calculating Prover Load

Prover load is calculated by using the input from the prover loading digital input and the prover shelf movement digital input.

When the prover loading arm operates, it is assumed that a full shelf of loaves has entered the prover. It is known that the prover has 147 shelves. Two of these shelves are always outside the prover (at the entry and exit), so the maximum load is the number of shelves inside the oven, multiplied by the maximum number of straps on each shelf. For the prover here, the maximum load is 1740 straps.

The number of straps on each shelf are stored in an array in the PPI. Each time the prover moves forward one shelf, the new load is calculated and expressed as a percentage of the maximum load.

Ideally, the exact number of straps on each shelf would be known. This may be achieved by placing a proximity sensor at the prover entrance (as is done with the oven). This may be done in the future.

3.7.2 Calculating Oven Load

Oven load is calculated in a similar way to prover load. Two digital inputs are used. One is the proximity sensor that senses straps entering the oven. The other is the digital input signifying shelf movement in the oven.

The oven has fifty shelves, two of them being outside (the entry and exit). Each shelf can hold a maximum of twelve straps, so the maximum load is 576 straps.

Unlike the prover load calculations, the precise number of straps on each shelf is counted by the proximity sensor. The number of straps on each shelf is stored in an array in the PPI. Each time the oven moves forward one shelf, the new shelf is added to the load and the old shelf is taken away.

As well as total oven load, the load in each of the zones inside the oven is calculated. The particular zone that a shelf is in is known because all shelf movements are tracked and the first twelve shelves are in the front zone, the next 24 are in the back zone and the final twelve are in the front zone. The nature of this design means it would be quite difficult to optimise the temperatures experienced by the loaves as they pass through.

Additionally, the front zone (Zone 1) is divided into two separate zones (‘a’ and ‘b’). Zone 1a is the first twelve shelves and zone 1b is the last twelve shelves

In addition to load, the baking time is also logged. This is calculated by subtracting the entry time stored for this shelf from the exit time.

An example of the oven load data logged is shown in Figure 3.15.

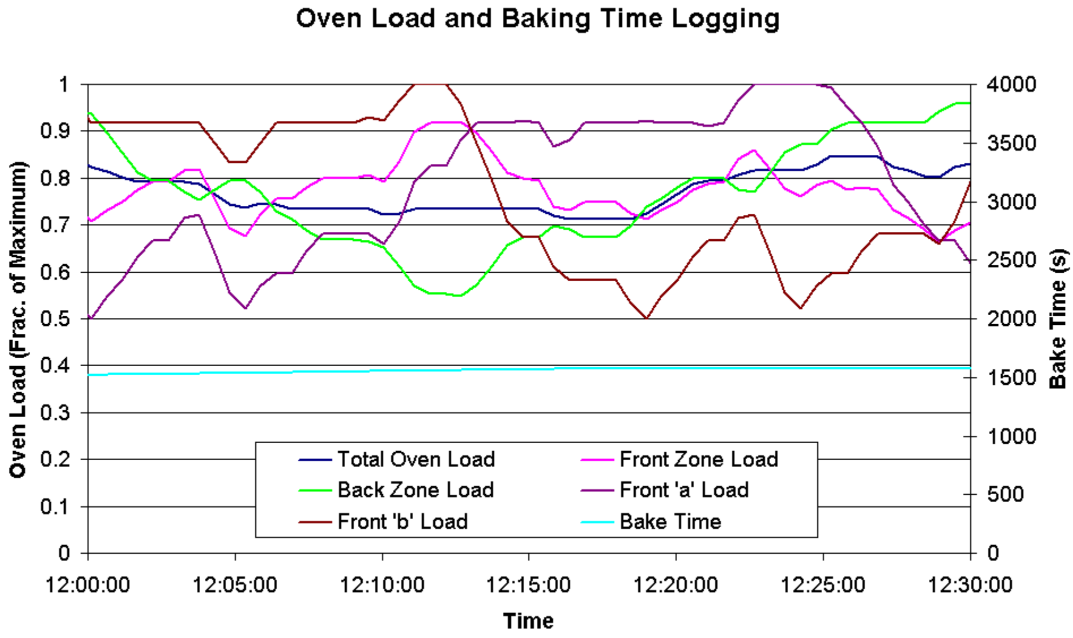

Figure 3.15: Example of oven load and baking time data

3.7.3 Predicted Oven Load

Since the load in the prover is known, it follows that the load in the oven should be able to be predicted in advance. Theoretically, the load is able to be predicted 147 shelves in advance. This translates to over one hour, which should be ample time to prepare the oven for any thermal load change.

Predicted load is still in its development phase, but would be an important part of a final control system.

3.7.4 Calculation of Thermal Load

The oven load calculations discussed here should provide a rough indication of the thermal load. However the calculations do not take into account the actual weight and thermal properties of the dough and tins as well as the rising temperature of the dough and tins as they travel through the oven. That is, a loaf that has been in the oven for ten minutes will contribute much less to the thermal load than a loaf that is entering the oven cold. Possible approaches for taking this into account are discussed in Chapter 5.

One addition that may help estimate thermal load more accurately is to be able to sense what sort of straps are entering the oven. There are three type of straps - those that hold four loaves, those that hold three normal loaves and those that hold three extra-long loaves. The weights of loaves in each type of tin are similar (to within approximately 50 grams). So if each type of tin could be sensed, an approximation of the weight of loaves in them could be performed.

It should be possible to determine the difference between normal length 3 and 4 loaf straps and the extra long 3 loaf strap. This could be achieved by measuring the length of time either the height sensor or the oven entry sensor is on.

3.8 Cooler Shelf Weight

Load cells were placed on the cooler entry shelf to measure the weight of loaves on that shelf. This is the shelf that loaves are conveyed onto before entering the prover. Taking the weight of loaves here is useful because it will allow calculation of the relative amounts of weight loss in the oven and in the cooler. Although most weight loss occurs in the oven, moisture is still being lost to the atmosphere as the loaves cool. Cooling time and conditions affect this amount of weight loss.

A photo of two of the load cells on the shelf is shown in Figure 3.16. A diagram showing how they are placed is also shown Figure 3.17.

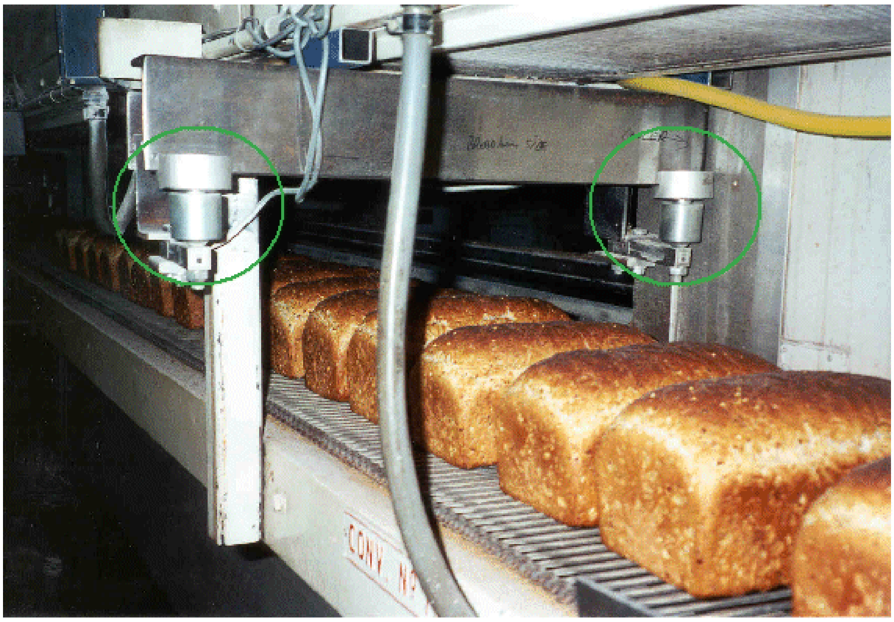

Figure 3.16: Photo of two of the four load cells on the cooler entry shelf

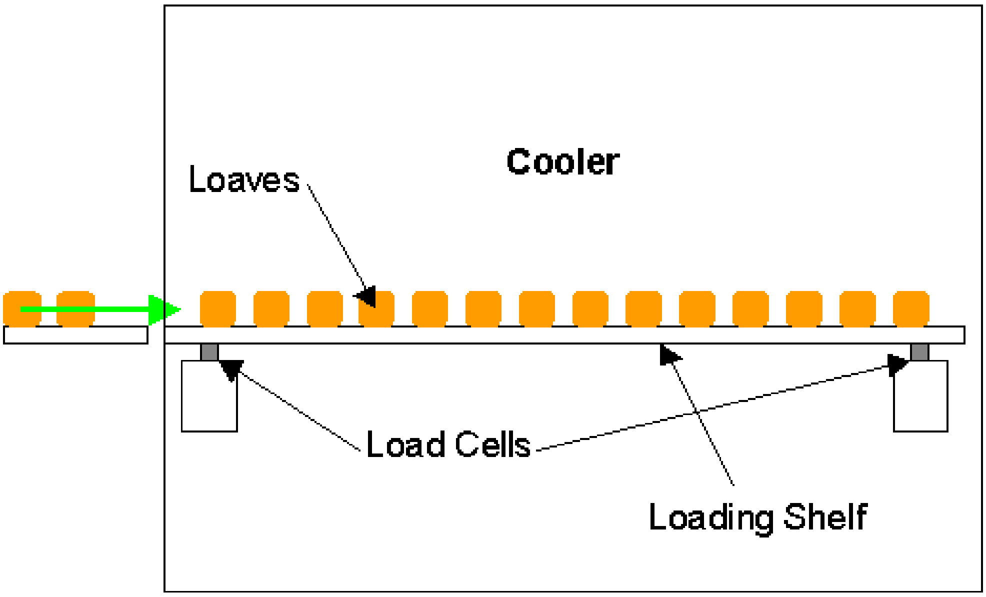

Figure 3.17: Diagram of how the load cells are placed at the cooler loading shelf

The exact time to record the weight from the load cells must be known. A digital input from the cooler loading arm is used. When the input turns on, it means the loading arm is in operation, therefore the shelf must be full of loaves. The last reading prior to the shelf loading is taken as the correct weight of the shelf. A diagram of how this works is shown in Figure 3.18.

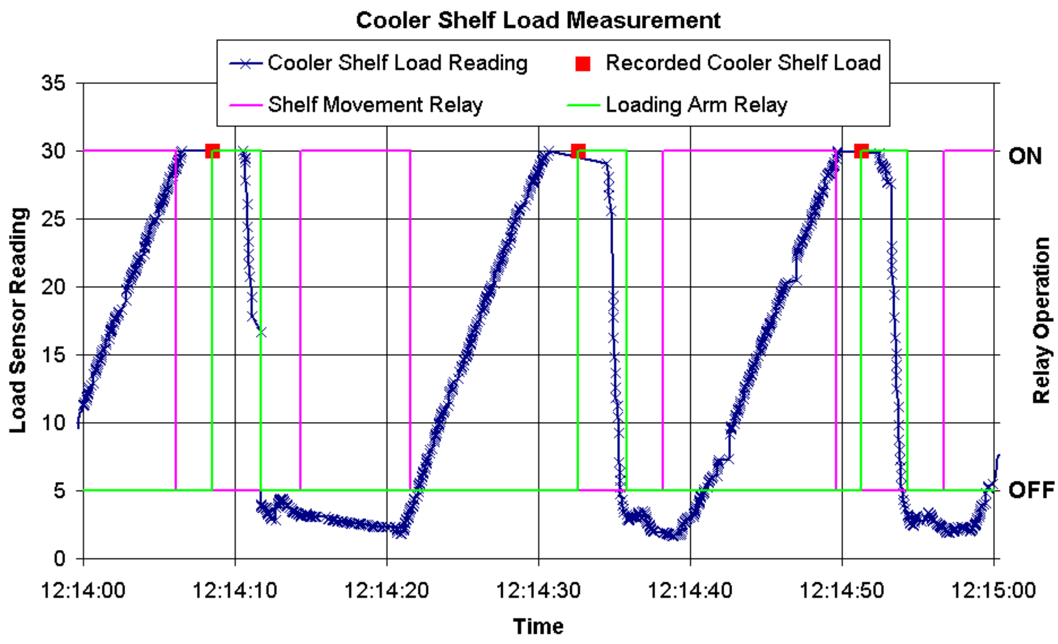

Figure 3.18: Plot of load cell readings, sensor readings and logged shelf weight

No verification was done on the accuracy of the load cells when measuring the shelf weight. The purpose of their inclusion in the PPI was primarily with a view to use the data to determine weight loss in the cooler at some point in the future.

3.9 Image/Video Capture

Image capture has been added to the PPI currently as an archiving tool. Images can be captured to file either every *x* minutes during the day or manually by clicking on a button in the PPI. There is also the possibility of triggering the image capture as a result of some other event occurring such as an extra high/low group of loaves or after exceptionally high/low oven temperatures.

The images are captured immediately after the de-panner. The camera used is a CCD video camera providing composite video output. It is connected to the main PC via a video capture card. Images are then captured to file in Visual Basic using a simple, easy-to-use ActiveX control called ‘EZVidCap’ written by Ray Mercer.

An example of a captured image is shown in Figure 3.19. The quality of these images were kept low to save disk space.

Figure 3.19: Captured image of loaf for archiving

3.10 Stoppage Detection at All Points

An added feature of the PPI that has been partially implemented is stoppage detection. It is useful for the production manager and maintenance staff to have a view on the computer monitor of when there is a stoppage in production. This feature has been implemented to display a stoppage when it occurs at any of the following points:

- Initial checkweigher
- Into tins
- Prover loading
- Oven loading
- Depanner sensor
- Cooler exit
- Both final checkweighers

Each of these is displayed with an indicator next to it showing whether there is a stoppage or not. The number of seconds that the stoppage has been current is shown next to the indicator.

With extra inputs from various relays and other sensors around the bakery, this feature could become an extremely valuable part of the PPI. It could alert production managers of any out-of-place events in the bakery. Also, technical personal could have a record of operations of different machines and a maintenance schedule could be accurately adhered to.

3.11 Product Reporting

The Product Performance Indicator software has the ability to access a report generation macro written in Microsoft Excel. A brief description of how this is achieved is included here.

3.11.1 Startup

When the PPI starts up, Microsoft Excel is started. A file is opened in excel that contains the report generation macro. The user selects a day to produce a report for and the PPI issues commands to Excel. After setting several values in Excel cells, the macro 'DATAPROCESSBYWEIGHTS' is run. If an error occurred during the running, a message box is displayed that shows the cause of the error.

3.11.2 Updating Product Data

Whenever product data is updated at the checkweighers, this updated data is sent along the serial line. The PPI captures this data then enters the new data into the appropriate place in the Excel data file.

3.11.3 New Product

When a new product starts at any of the checkweighers, the product name is retrieved from Excel and displayed on the screen. Additionally, when a new product arrives, the PPI automatically requests the product data (name, over-weight, under-weight and pass-weight) for that product from the checkweigher. The data is updated in Excel as discussed above in 'Updating Product Data'.

3.11.4 Future Developments

One of the disadvantages with using Excel to produce the product reports is that the workbooks may be changed by a person using the computer. This means a person may (knowingly or unknowingly) alter data in the files that are needed by the PPI.

This may be solved by running excel in 'Invisible' mode, but it needs to be visible when the Product Report is shown. An alternative approach is to open a separate version of Excel, or the product report could be sent to the printer and not displayed on the screen.

Another issue with using Excel is that transferring the data processing to another program seems unnecessary. Visual Basic has all the abilities to process the data, so in the future a data base may be used in Visual Basic to log bakery data. All the data processing would then be done in Visual Basic. Alternatively, an Access database may be accessed from within Visual Basic.

3.12 Summary

Instrumentation has been fitted to the bakery. This includes sensors on most processes connected to a central computer. Data from this system may be remotely downloaded and will allow further study of bakery processes. Additionally, various automatic reports are produced to provide summarised information on production. Further features such as stoppage detection are being tested.

Chapter 4 - Weight Loss

The importance of weight loss was introduced in Section 2.6. Its significance will be discussed more thoroughly in this chapter. Methods of determining the weight loss of loaves will also be presented.

4.1 Significance of Weight Loss

4.1.1 Legal Requirements and Product Giveaway

One of the major reasons for the importance of weight loss is the unwillingness of the bakery to produce under or overweight loaves. Underweight loaves are illegal to sell and the bakery must satisfy the following requirements from the Trade Measurements (Pre-packed Articles) Regulation 1997 under the Trade Measurements Act 1989:

- No loaf may be less the 5 % below nominal weight.
- The average weight of any 12 loaves picked at random may not be below nominal weight.

Over weight loaves are also undesirable, since this means that the bakery is 'giving away' dough. Current product giveaway levels are in the order of 1.5 to 2 % of the total product. Figure 4.1 shows an example of this. For this product, the total product giveaway level is 2.3 %. Using conservative estimates, a bakery producing 35 000 loaves of bread a day with an average weight above nominal per loaf of 10 grams would be giving away about 130 tonnes of dough each year. This is the equivalent of over 200 000 loaves of bread, translating into hundreds of thousands of dollars. If product giveaway levels can be reduced, the bakery stands to save a significant amount of money.

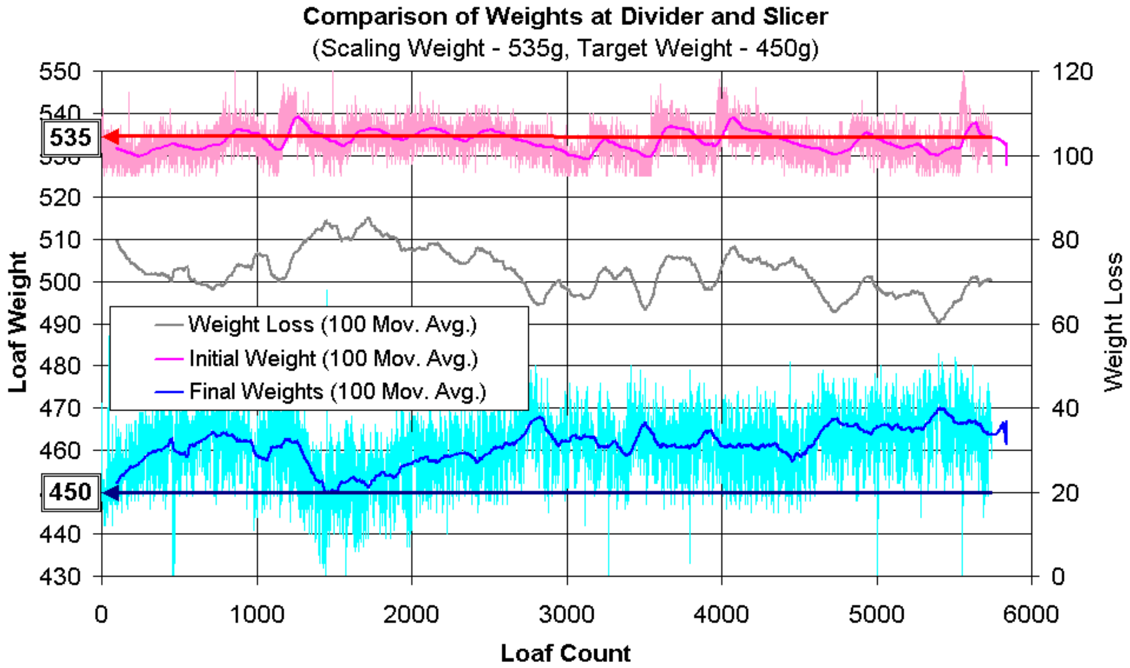

Figure 4.1: Example of Weight Loss Variation (Schultz, Billingsley et al. 2000)

To enable the final weight of loaves to be accurately controlled, it is necessary to establish a relationship between the initial weights and the final weights in terms of the ingredients and the conditions the loaves encounter.

One of the difficulties with decreasing product giveaway is that currently there is a large spread of loaf weights at the end of production. In Figure 4.1, the initial standard deviation is already 4 grams. By the end of production, this has increased to over 8 grams. To decrease the average final weight to a value close to the nominal weight means that many loaves will be under weight, increasing the chance of contravening the legal requirements stated above. This is why bakeries currently operate at such high product giveaway levels.

Using better control methods, not only may the average weight loss be better controlled, but the spread of weights may also be decreased, allowing the final weights to be closer to nominal.

4.1.2 Relation to Loaf Quality

In (Adamczak and Kallitsis 1997), a report compiled at BRI Australia Ltd, several relationships between weight loss and other indicators of loaf quality were established through experiments in controlled circumstances. Figure 4.2 shows a linear link between colour, firmness and weight loss.

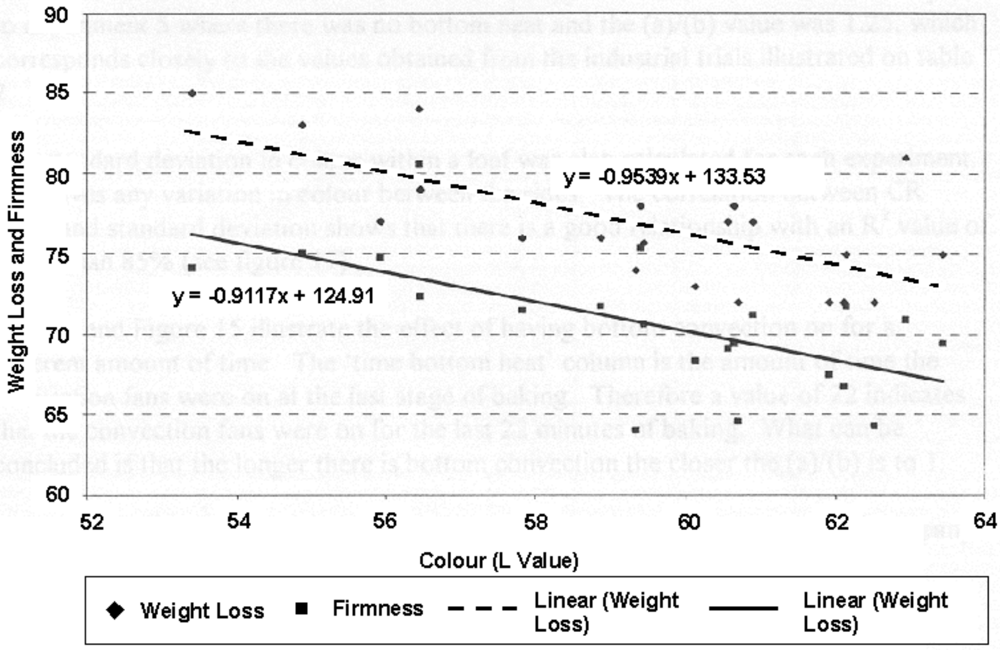

Figure 4.2: Relationship between colour, firmness and weight loss

If the link between weight loss and loaf quality can be verified in practice at a bakery, and a reliable method of calculating weight loss during production developed, new avenues for bakery control will be opened. Relating weight loss to oven conditions is discussed more thoroughly in Chapter 5.

4.2 Estimation of Weight Loss Using Only Weight Files

This method of calculating weight loss involves using the initial and final weight files and relying on the product numbers they provide. The files are ‘lined up’ next to each other and the weight loss calculated loaf by loaf. A moving average of the resulting values is then taken as the approximate weight loss. This is the simplest way to calculate weight loss since it does not involve exact product following.

There are several problems with this method however. Firstly, the final product numbers are not always accurate since the bakery operator does not always know exactly what product is passing through. Before calculating weight loss it is recommended that a simple mathematical check be done that confirms that the final weight file starts at approximately x minutes after the initial weight file, where x is the average total production time for that product. A similar check may be performed to confirm that the ends of the weight files are legitimate.

Also, to produce the 'final weight' file, the separate files from each final set of scales must be combined. This was generally done according to the time loaves were weighed. Although this would not result in the exact order loaves were baked, it is accurate enough for these calculations.

Another problem is that loaves are lost during production. This means that there are less final weights logged than initial weights. A method of 'lining up' the loaves must be decided upon. Two methods were investigated.

4.2.1 Alignment by Beginning/End/Middle

The simplest way to align the loaves is to simply line up the first initial weight with the first final weight, then the second initial weight with the second final weight etc. This would allow a weight loss calculation to be made, but would result in initial weights being 'left over' at the end. An example of beginning alignment is shown in Figure 4.3.

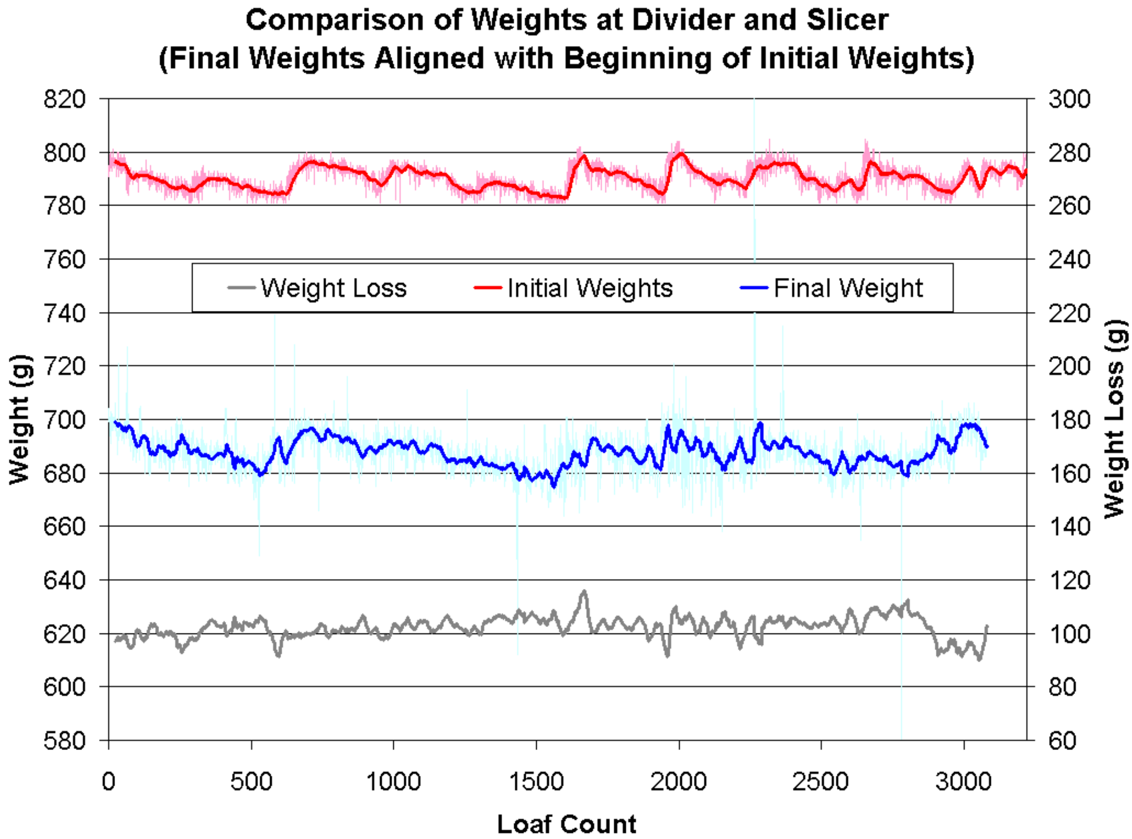

Figure 4.3: Alignment of weights by beginning.

There are 137 more initial weights than final weights recorded for this product, so by the end of the process, the accuracy of the weight loss would only be within approximately 250 loaves when the inaccuracies in final weight alignment are included. The data line shown is based on a moving average of 25 loaves. This is less than the accuracy of the loaf-alignment, so the small fluctuations in weight loss in the figure are probably not accurate.

Similarly, the end of the initial and final weights may be aligned (i.e. last initial weight with last final weight etc). An example of end alignment is shown using the same data as above in Figure 4.4.

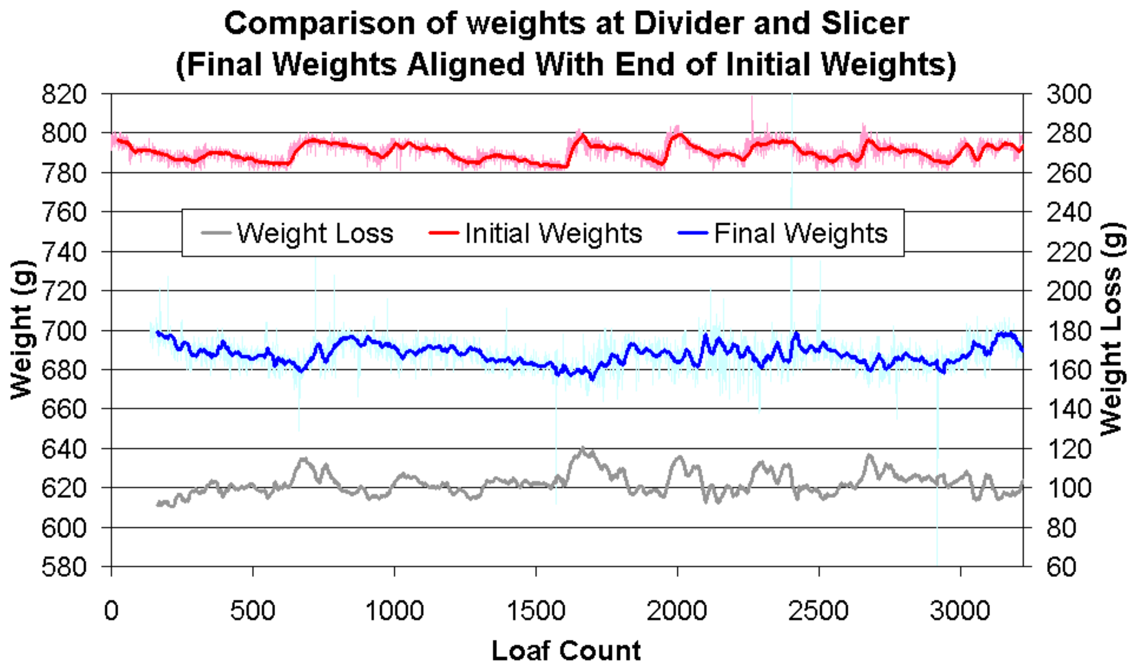

Figure 4.4: Alignment of weights by end

It can be seen from Figure 4.3 and Figure 4.4 that changing weights from being lined up at the beginning to being lined up at the end completely changes the resulting weight loss plot. Similarly, when weights were centrally aligned, the weight loss plot changed again. The changes to the weight loss plot indicate that this alignment method is not satisfactory.

4.2.2 Alignment by Extending Final Weights

Another method proposed to align initial and final weights is to extend the final weight data series so that there are the same number of entries in it as the initial weight series. If this is done, then a loaf-by-loaf calculation of weight loss may be performed. It may not be entirely accurate, but should show a marked improvement over alignment by the beginning or end.

A suitable approach for extending the final weight series must be developed. Initially, it was decided to ignore time altogether and simply use product counts. Using the time that loaves passed each of the scales would help line up weights more accurately, but would make processing much more complicated.

There are then only two series to work with - the initial weights for the product and the final weights. It is assumed that these can be resolved from the entire weight series logged from production.

A Microsoft Excel macro “ExtendFinalWeights” has been written that uses linear interpolation to match the final weight series with the initial weight series. Figure 4.5 gives some idea of what this macro does. A plot showing the resulting weight loss is shown in Figure 4.6.

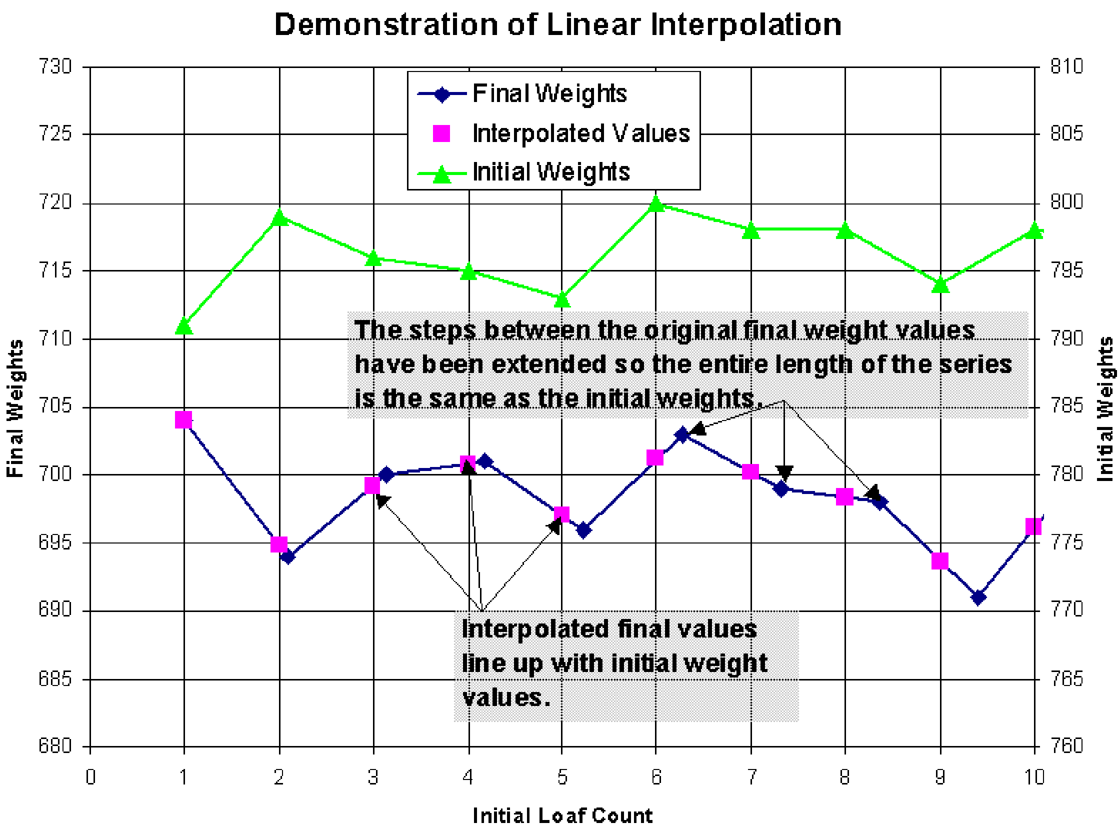

Figure 4.5: Explanation of how linear interpolation approach works. The interpolated values are simply placed on the straight line joining two final weights of an extended final weight series.

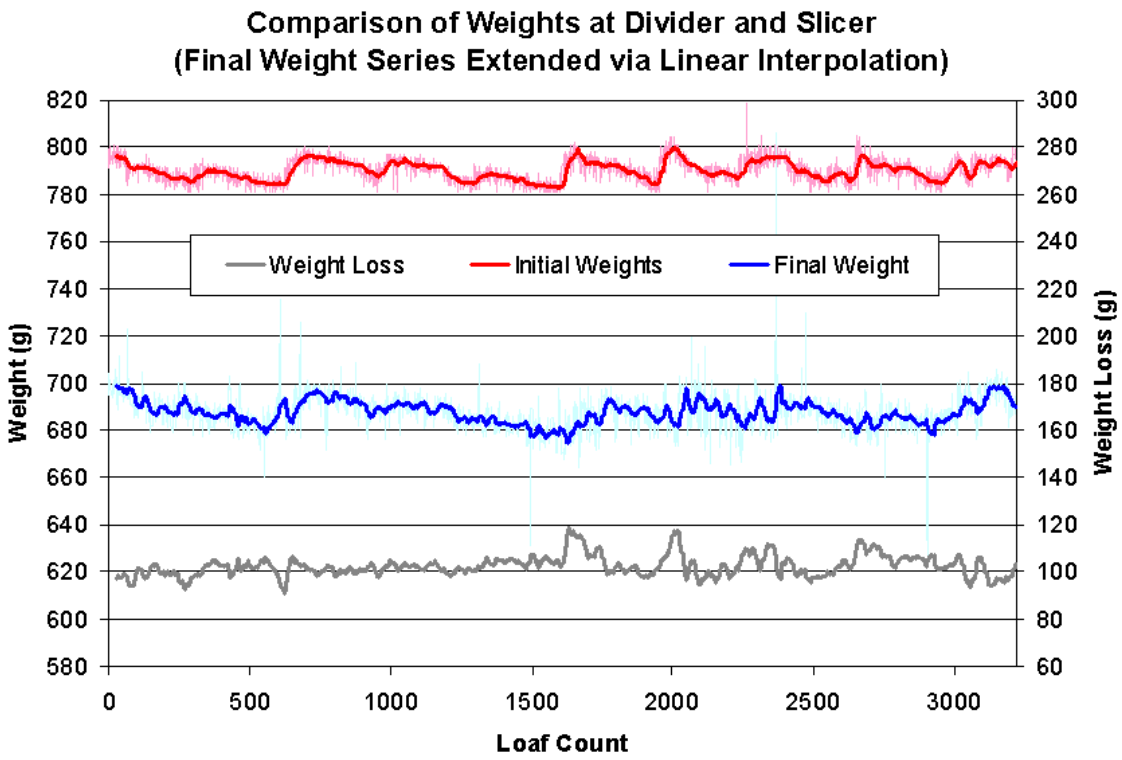

Figure 4.6: Alignment of weights by Linear Interpolation.

The linear interpolation method of lining up weights is the best approach to take without additionally taking into account time. It can give some idea of the variations in weight loss over a product run or from day to day. Fluctuations in the weight loss that only occur for a short period cannot be depended on as being accurate though since there is still an inaccuracy of up to a few hundred loaves in the calculations.

4.2.3 Description of Weight Loss Calculations Macro

Using Visual Basic in Microsoft Excel, a data processing macro was written that calculates weight loss by either beginning alignment or extending the final weights. Its main purpose is for obtaining a quick idea of weight variation within a product run. The file containing the macro is called 'ProcessWeights.xls' and is included in the accompanying CD.

It is also useful for the purpose of summarising all the weight data for a particular day. It has the ability to produce a plot of all initial and final weights and product numbers.

The basic concept is that the macro accesses the weight log files and moves them into a new weight summary file. It then searches the data to find the required product, and begins a new file that contains only the information for this product. Here it plots the weights and weight loss. Before running the macro, the user must enter various pieces of information such as the production date, initial and final product numbers and the location of the log files. Operation instructions are included in the macro.

In the future, an adapted version of this macro could be included within the Product Performance Indicator software package to allow operators to quickly and easily view plots of weight loss for various products.

4.3 Loaf By Loaf Calculation of Weight Loss

The ideal method of expressing weight loss would be by calculating it for every separate loaf. In practice, this is very difficult to achieve since it would require the lining up beginning and ending weights exactly. To do this, extremely accurate product following is needed. Approaches to this are discussed in Chapter 6.

Currently, product following techniques are not advanced enough to enable loaf-by-loaf following, however they do offer improvements over the alignment by weight data technique discussed in Section 4.2 above. Currently, using weight data is the best option because of its ease of use.

If achievable, the advantages of accurate loaf-by-loaf calculation of weight loss would be enormous. Weight loss specific to that loaf may be correlated with other loaf qualities such as bubble size/texture and crust colour. The relationship between the two could then be verified. Once this is achieved, other measurements of loaf quality would ideally be unnecessary.

4.4 Weight Variation at Divider

Weights of divided loaves vary quite significantly at the divider. The divider in use at Buttercup Bakery in Canberra is typical of dividers in most bakeries in Australia. It separates four pieces of dough at a time. These are dropped onto a conveyor that then feeds them into a roller.

The divider is designed with automatic weight control. This uses a checkweigher to weigh pieces of dough and feed a control signal back to the divider. This signal adjusts the divider so that the required weights of dough are produced. Operation of this automatic control is generally unsatisfactory and bakery operators usually turn it off and adjust the divider manually.

A plot showing typical weight variation at the divider is shown in Figure 4.7. It can be seen that not only is there instantaneous variation between weights, but that the moving average varies quite markedly as well. Sudden changes in the moving average are usually caused by the operator changing the setting on the divider. The gradual change in the moving average is either from the operator making gradual changes or is more likely due to 'drift' in the settings of the divider. This was verified by simple observation.

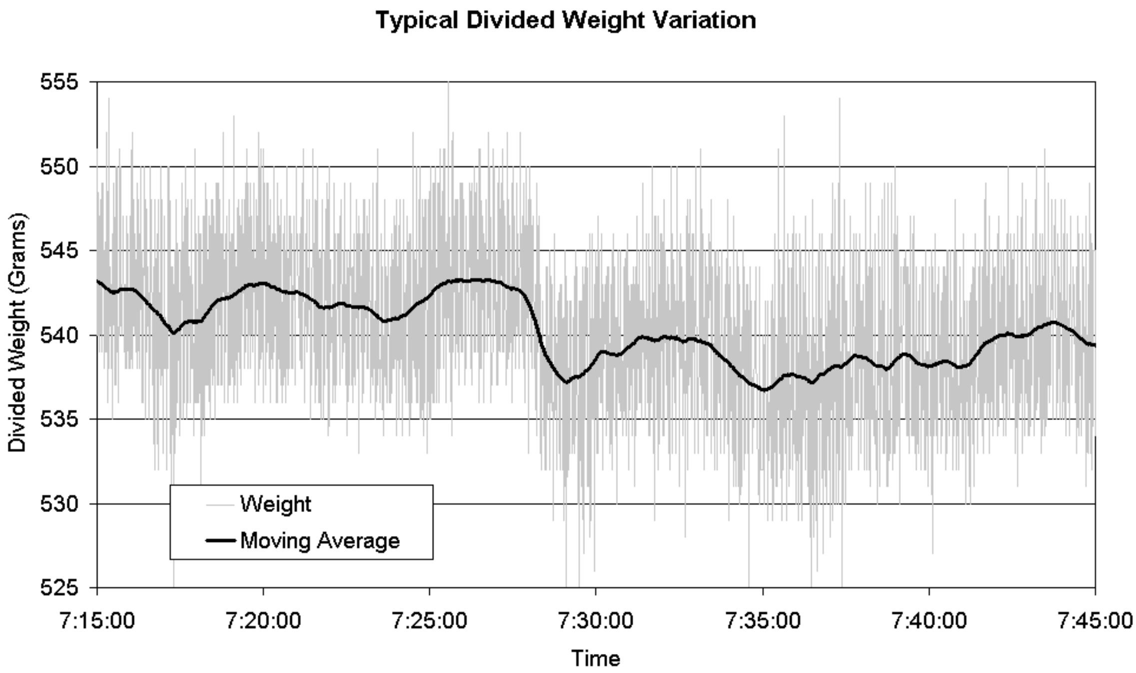

Figure 4.7: An example of the variation in divided weights within a single variety.

Even if the moving average is not drifting, there is still a great deal of variation in the divided weights. The amount of variation was calculated by subtracting the actual weights from the moving average and calculating the standard deviation of the result.

This was done for the time period shown in Figure 4.7. The resulting plot is shown in Figure 4.8. The standard deviation for these weights can be seen from the plot to be 4.99.

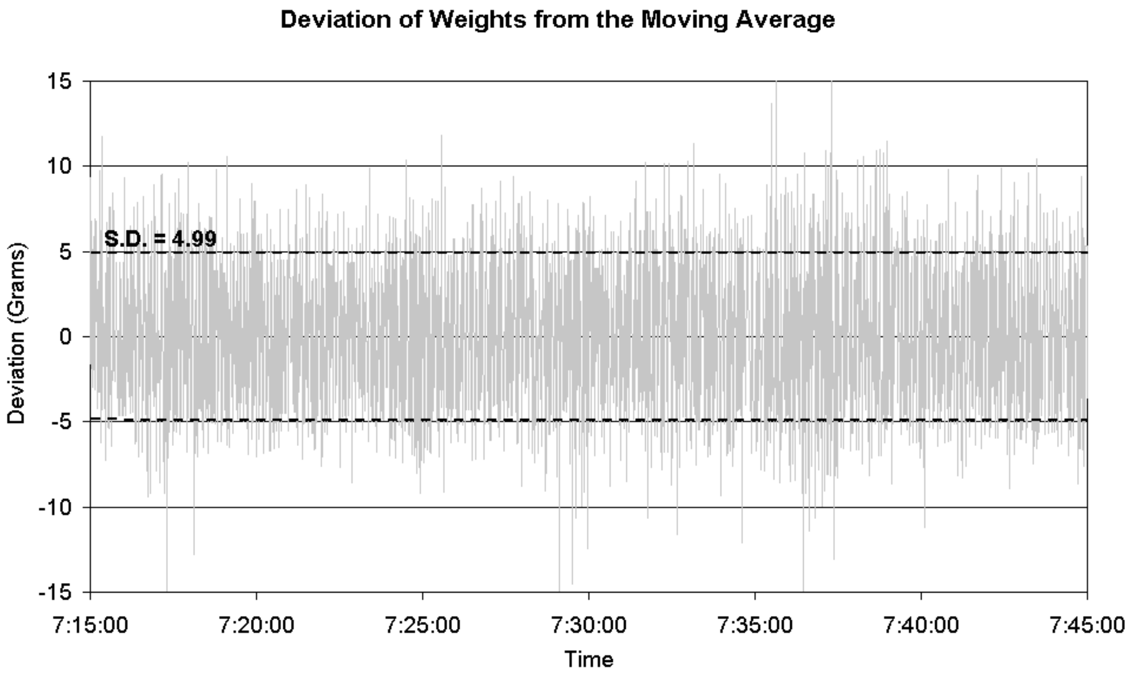

Figure 4.8: The deviation of weights from the moving average with the standard deviation shown.

It was thought that a significant amount of this weight variation may be due to the four separate pieces of dough produced each time differing by a constant amount. A macro was written for Microsoft Excel which stepped through the initial weight file and separated every fourth weight into a separate series. The results are shown in Figure 4.9.

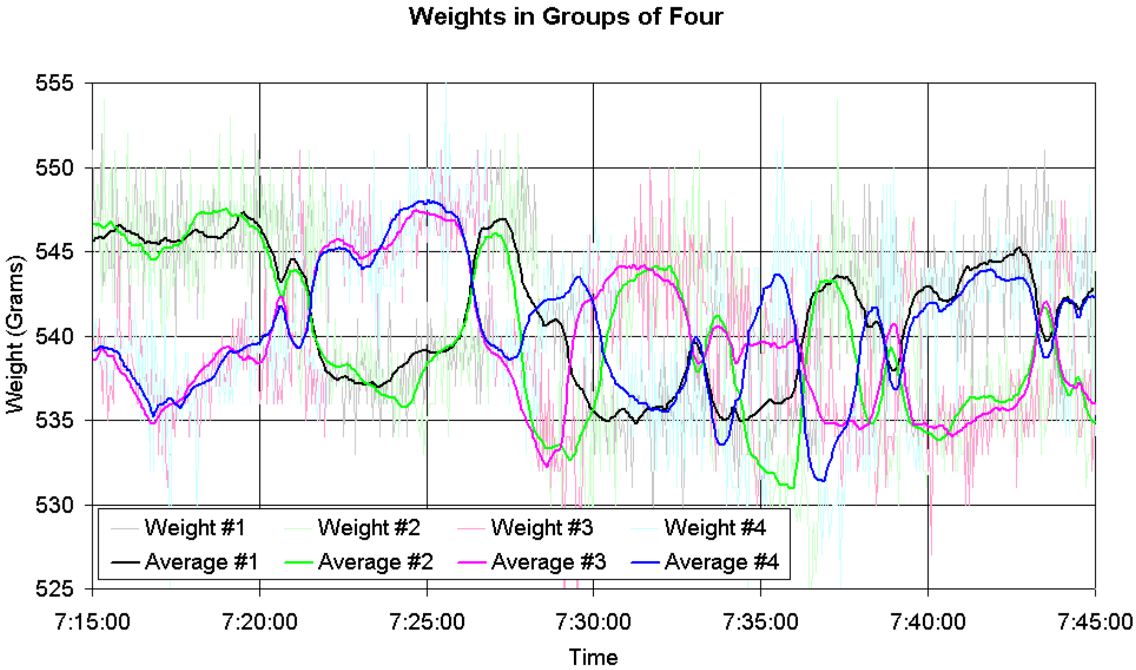

Figure 4.9: The deviation of weights from the moving average with the standard deviation shown.

It is obvious from the plot that there is quite a large difference in divided weights between the four parts of the divider. The reason that the moving averages 'cross over' every so often is that occasionally, dough pieces are removed from the conveyor between the divider and the checkweigher. This is usually because the operator sees a loaf that is obviously too large/small or so a temperature check or manual weight check may be performed on the dough.

A comparison of the standard deviation of all weights to the standard deviation of the separated weights gave some idea of the improvements that may be gained by improving the operation of the divider. It was decided to calculate this standard deviation from 7:15am to 7:20am with the data shown in Figure 4.9 since this was before the first 'cross over' due to dough removal. It was found that with all loaves considered, the standard deviation for this time period was 4.95. Taking each set of grouped dough weights separately, standard deviations of 2.56, 2.89, 2.16 and 2.76 respectively were calculated. These results are displayed in Figure 4.10.

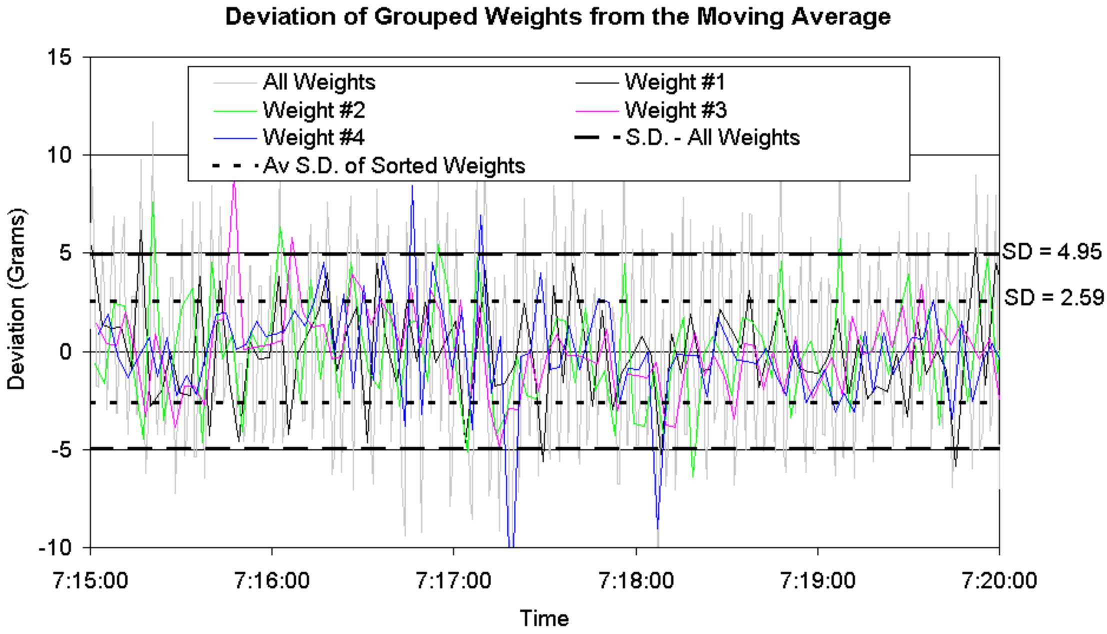

Figure 4.10: The deviation of grouped weights from the moving average with the standard deviation shown.

If this problem with the divider can be rectified, a significant reduction in initial weight spread should be observed. A corresponding reduction in final weight spread should also result. The production manager and bakery technical support staff were notified of this problem and were intending to rectify it. At the time of writing there was no new data to show whether improvements had been made.

4.5 Weight Variation Through Oven

The oven is the section of the bakery where most weight is lost from the loaves. It is also the area where most variations in weight loss occur. Variations in weight loss mean that different loaves lose different percentages of weight. For a single variety of bread, this weight variation (and corresponding quality variation) occurs in several ways:

- Variation across the oven shelf
- Variation during the production run
- Variation between product runs on different days

These will each be discussed in turn below.

4.5.1 Weight Loss Across Oven Shelf

Due to the complicated design of the oven, heat flow to the loaves is not constant across the shelf. Both convective heat transfer and radiant heat transfer vary across the shelf, affecting the loaf quality and weight loss in different ways. (For more explanation on the relative effects of radiant and convective heat transfer to the loaves, see Chapter 5.

In the past, during 'bakery audits', an estimation of the weight loss across the oven shelf has been determined by manually weighing loaves after they have exited the oven. This is a very labour-intensive operation and the accuracy is doubtful since it can only be done a few times. However the results from such an operation are enough to show that there is a constant difference in the weight loss across the shelf. An example of this is shown in Figure 4.11. This plot was not produced at the Canberra bakery studied in this project, however the ovens are of similar operation, so results should be similar in Canberra. It may be seen that the loaves on either end have lost more weight. It is thought that this is due to the extra radiation these loaves receive from the oven walls.

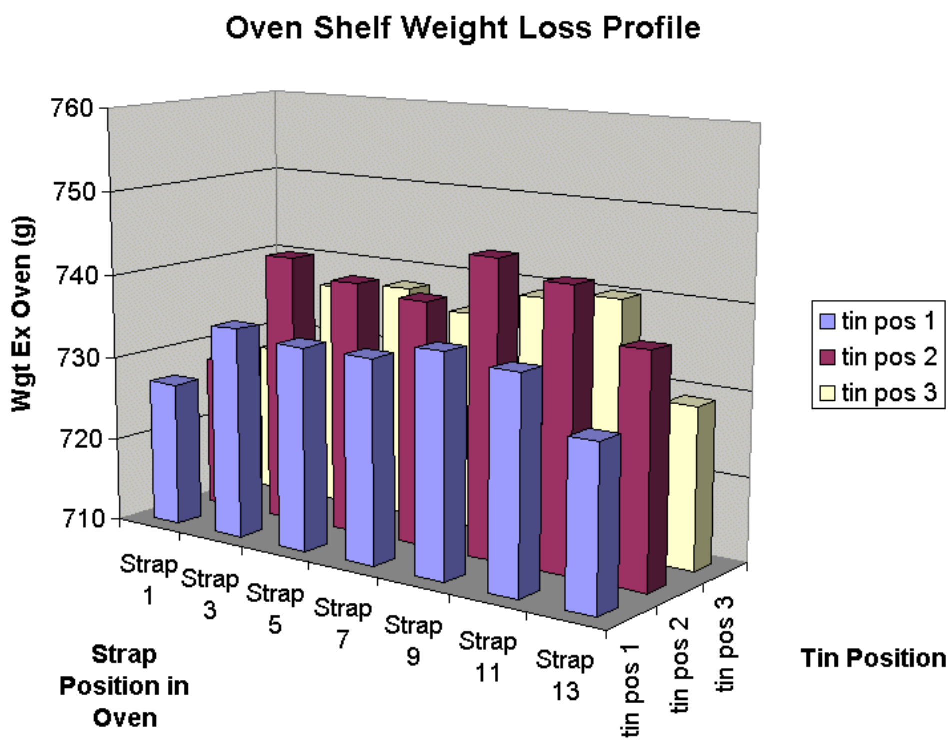

Figure 4.11: Oven shelf weight loss profile determined manually

No manual test has been done at the Canberra bakery, but it has recommended that at some stage this is performed. A shelf weight loss profile that is constant amongst all varieties and baking temperatures may become apparent. If not a constant profile, the profile should at least be directly related to oven temperature and loaf variety.

If this profile can be predicted, it may be used for several reasons. Initially, it should allow better prediction of the final weight loss variation. Knowing the shelf weight loss profile may also be used to help line up loaf final weights with initial weights. This is discussed further in Section 6.8.

4.5.2 Accurately Determining Weight Loss Variation Across the Oven Shelf

To manually determine weight loss variation across the oven shelf is an extremely labour intensive task. The loaves must be manually weighed before oven entry and then immediately after oven exit, removing them from the conveyor each time in order to do this. Realistically, this can only be performed a small number of times - possibly not enough to build up a reliable ‘shelf weight loss profile’.

Ideally, this ‘shelf weight loss profile’ would be known very accurately. The best way to determine it would be to calculate the weight loss of each individual loaf after baking. As discussed in Section 4.3, this is extremely difficult and is currently not possible.

Another possible way to approach this problem uses simple image analysis to track loaves. Several tins may be ‘embossed’ with a particular pattern - possibly a company logo or some other symbol that would not alarm consumers. This pattern would then appear on the loaf after baking. Several different patterns could be used, and would be distributed throughout the bakery. This embossing technique is shown in Figure 4.12.

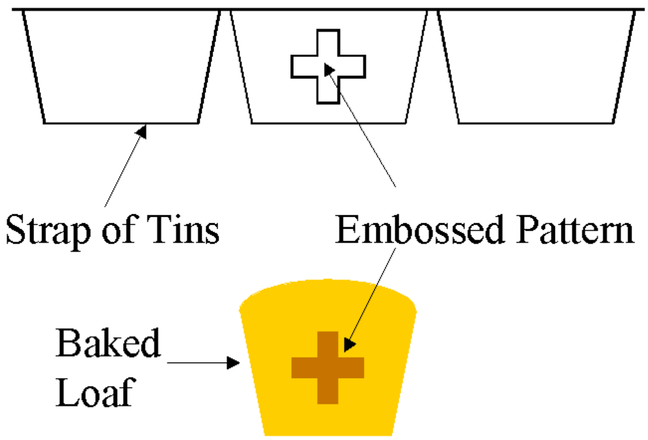

Figure 4.12: Embossed pattern on loaf for recognition by image analysis

Using a basic frame-scan camera setup, at the point where loaves enter the tin, the embossed tin would be recognised and the weight of the loaf entering the tin would be recorded.

At the entry to the oven, another frame-scan camera setup would be used to ascertain the time that the strap entered the oven and more importantly, the position of the strap on the shelf.

The final camera setup would be before the final scales. The loaf would be detected and its weight recorded. The weight loss of that particular loaf may then be calculated, since both its initial and final weights are known.

Over time, a profile of the weight loss at different strap positions on the oven shelf would be built up. Improvements to the oven could be made according to this. It would also aid in predicting the variation of weights to be expected through the oven.

4.5.3 Weight Loss During Single Product

Weight loss also varies during the production run of one product. This was shown at the beginning of this Chapter in Figure 4.1. From a simple observation of this plot, it is apparent that the final weights do not vary in the exact same pattern as the initial weights. There is significant variation in the experienced conditions of loaves passing through the bakery.

It is thought that the conditions experienced by the loaves in the oven are the most likely cause of these variations. As discussed in Chapter 5, these conditions are not easily determined. Using techniques presented there, if the loaf entry time is known, the temperature experienced by the loaf during baking may be determined. This may then be compared to the weight loss for that particular loaf. If performed for enough loaves, a pattern should emerge.

4.5.4 Weight Loss Variations from Day to Day

Weight loss of loaves also varies significantly over different days production. An example of this is shown in Figure 4.13. On one particular day (19-Sep), the weight loss was much higher, indicating different conditions experienced on that day.

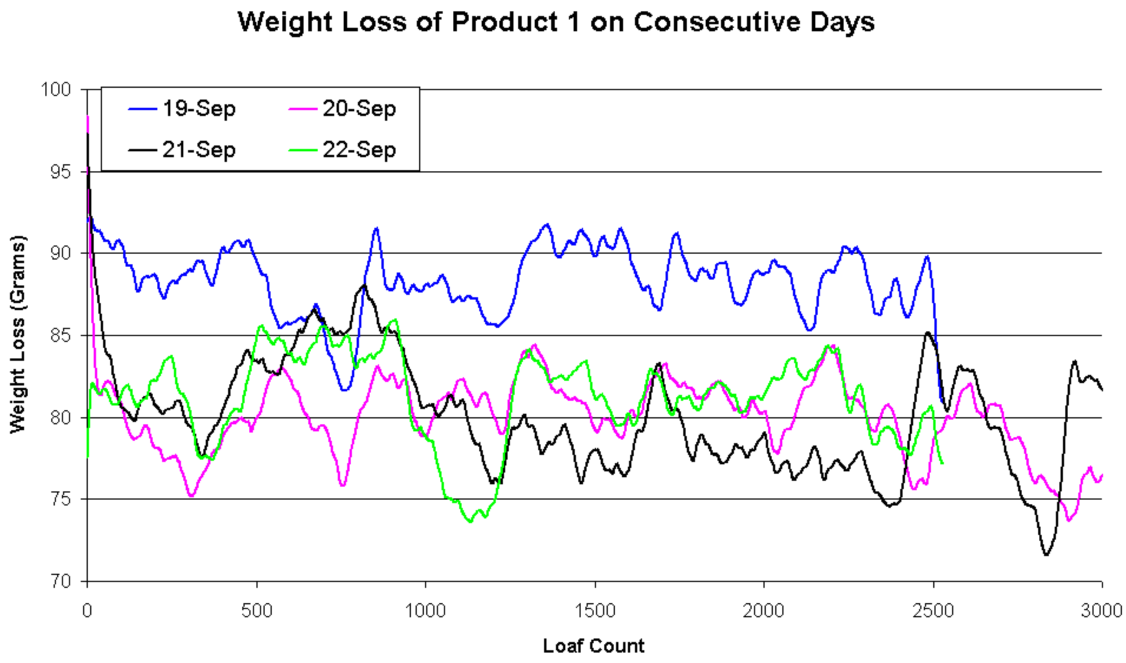

Figure 4.13: Plot demonstrating variations in weight loss from day to day

Figure 4.14 shows final loaf weights corresponding to the weight losses shown in Figure 4.13. It can be seen that although the average from the 19-Sep is below the others, it is still above the target weight. However, as the average is closer to the target weight, many more individual loaves are below target. The individual loaf weights are displayed for two of the products so that this is apparent.

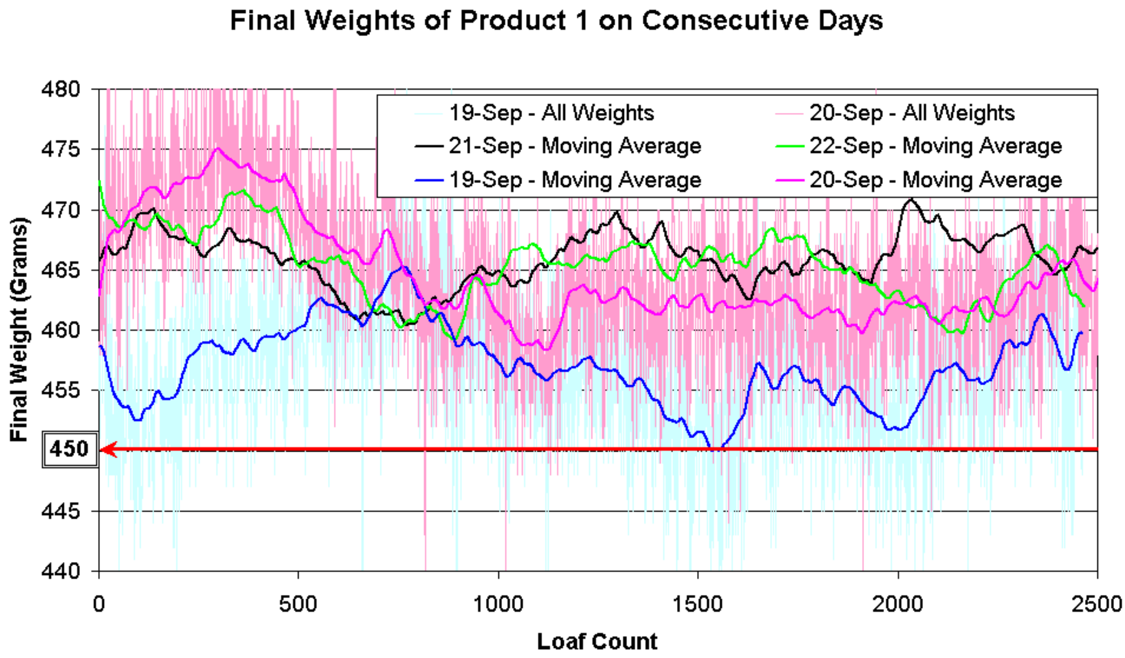

Figure 4.14: Plot demonstrating variations in final weights from day to day

4.6 Summary

Several methods of measuring weight loss have been put forward and tested. Using nothing but the weight data to do this gives a limited degree of success. Ideally other data needs to be combined with the weights to give a satisfactory result. A method of following products through the bakery process is needed and will be discussed later.

Chapter 5 - The Oven

Apart from the mixing of appropriate ingredients, the oven is the most important baking process. This is because most changes to the loaves occur here. In this project, oven operation was examined more closely than any other section of the bakery.

5.1 What Happens to Bread During Baking

The processes that take place during the baking of bread are very complex. Physical, chemical and structural changes occur to the loaf. These are generally caused by temperature and moisture gradients through the dough (Zanoni, Peri et al. 1997). Moisture transport occurs as a result of several factors (Thordvaldsson and Skjöldebrand 1998). Starch gelatinisation absorbs water, protein denaturation releases water and the temperature rise at the surface of the loaf transports heat and moisture to the centre of the loaf. Additionally, the relative importance of the various transfer mechanisms varies between different stages during baking (Carvalho and Martins, 1992).

Studies (De Cindio and Correra, 1995; Fahloul, Trystram et al, 1994) have shown that it is difficult to develop reliable models that correlate the physical characteristics of the product with the operating conditions it encountered. Nevertheless, this correlation is extremely important when developing a control strategy for the oven.

Additionally, the studies were done using conventional small baking ovens where the bread is stationary. These ovens are much less complicated in operation than the industrial ovens used in large-scale bakeries.

5.2 Oven Operation

If oven operation can be optimised and controlled perfectly, considerable savings are to be made in energy consumption and improved product quality. However the oven is a complex piece of machinery, so approaches such as finite element modelling or finite difference equations have severe limitations with current levels of modelling technology (although they do provide some potential).

The type of oven used in the bakeries investigated during this project were gas fired, radiation, indirect heating (through heat exchanger) ovens. These may consist of one, two or more separately operated ‘zones’. A separate natural gas burner heats each zone. The gas burner heats air in a duct. This duct then passes heated air to heat exchangers in the main oven cavity. Some of the heated air (less than 10%) is passed directly into the oven cavity. The operation of a single zone is shown in Figure 5.1.

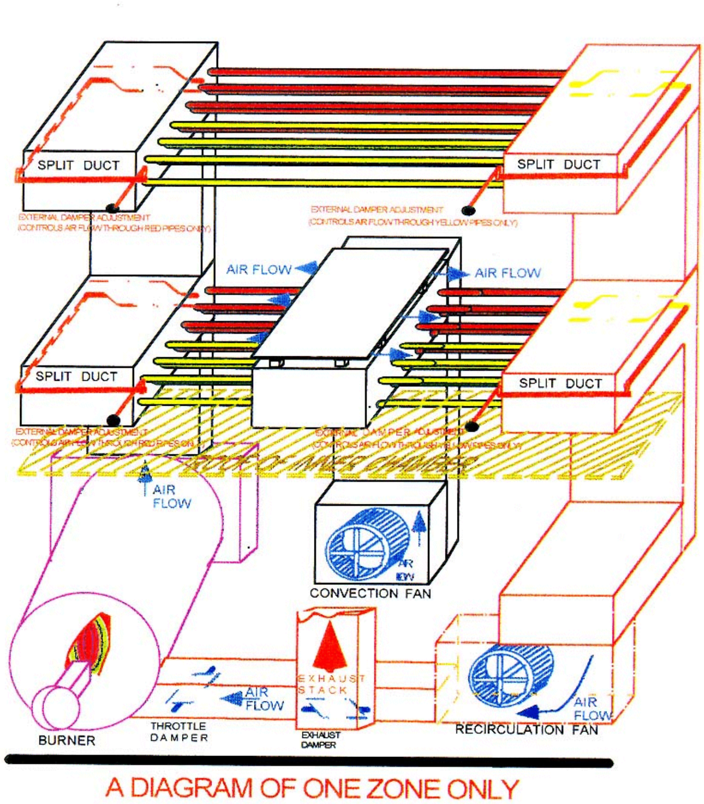

Figure 5.1: Diagram of operation of a single oven zone

The specific oven investigated consisted of two separate zones. The loaves enter in shelves containing 12 straps. Each strap may hold 2, 3 or 4 tins. The shelves pass through the oven, moving through the front zone first, then the back zone and back into the front zone again. This is shown in Figure 5.2 below.

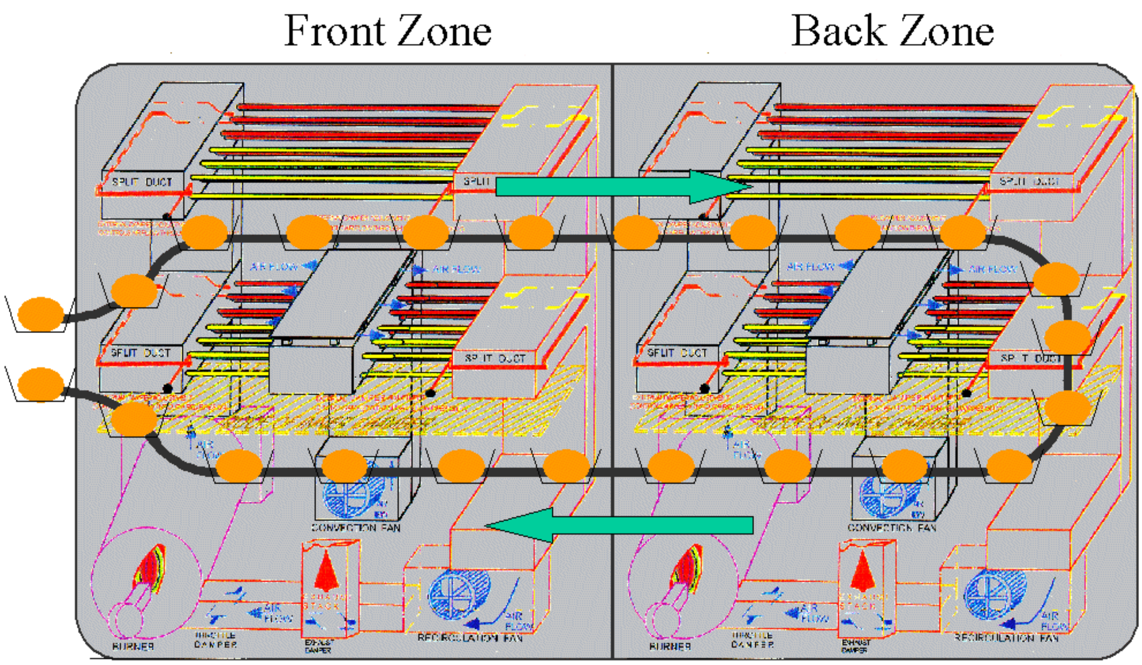

Figure 5.2: Diagram of oven operation

Currently the oven is controlled by using a simple On/Off controller for each zone. A thermocouple in each zone provides the input for the controller. This thermocouple is placed inside a metal tube and is located at the top in the middle of each zone. The effect of the metal tube is a ‘low pass filter’ to the oven temperature. This slows the response of the thermocouple, removing temperature spikes and causing the temperature measured to change more slowly. This is required to limit the switching rate of the burners. The switching rate must be kept fairly low (once every 2 - 5 minutes maximum) for reasons inherent to the burner design. If switched too quickly, the burner may be extinguished completely. If this occurs, a seven minute ‘purge’ time is required, by which time all the loaves in the oven would usually be wasted.

The controller has three output states (so calling it an On/Off controller is not completely accurate). The states are Off (Pilot), Low Fire and High Fire.

Off (Pilot) - This mode is not completely off. It keeps a pilot flame going so the entire oven does not have to go through a ‘purge’ sequence of 7 minutes when the burner is switched on again. The heat produced when the ‘Off’ mode is around 5% of that produced when the burner is on Low Fire.

- Low Fire - This is the mode that is used during most 'normal' operation of the burner.
- High Fire - In this mode, more gas is supplied to the burner to increase oven temperature faster. Generally, this mode is entered when the measured temperature of the oven is more than 4°C below the set-point.

Bakery technical personnel may manually set the rate that gas is consumed in each mode of operation. The rates cannot be adjusted during normal oven operation. Heat generated by the flame is proportional to the volume of gas consumed per minute.

The table below is an example of real values used in an oven at one stage during the project.

	Front Zone	Back Zone
Pilot	≈ 0.04 m^3/min	≈ 0.04 m^3/min
Low Fire	≈ 0.38 m^3/min	≈ 0.59 m_3/min
High Fire	≈ 0.67 m^3/min	≈ 0.74 m^3/min

5.2.1 Shortcomings of Current Oven Design and Control Strategy

There are several shortcomings of the oven design and current control methods.

First of all, the actual temperature set-point for each value has not been optimised. They have been chosen empirically based on operator experience and factors such as loaf size. These set-point temperatures need to be optimised for each variety.

Due to various factors, the set-points are not conformed to. A typical plot of oven temperature compared to the set-point is shown in Figure 5.3. The operation of the oven burners is also shown. It is obvious from the plot that the temperature in the oven does not accurately match the set-point. There are other factors besides the burner states that are affecting the temperature. Possible factors include changes oven thermal load (due to gaps in production and different varieties) and changing ambient conditions.

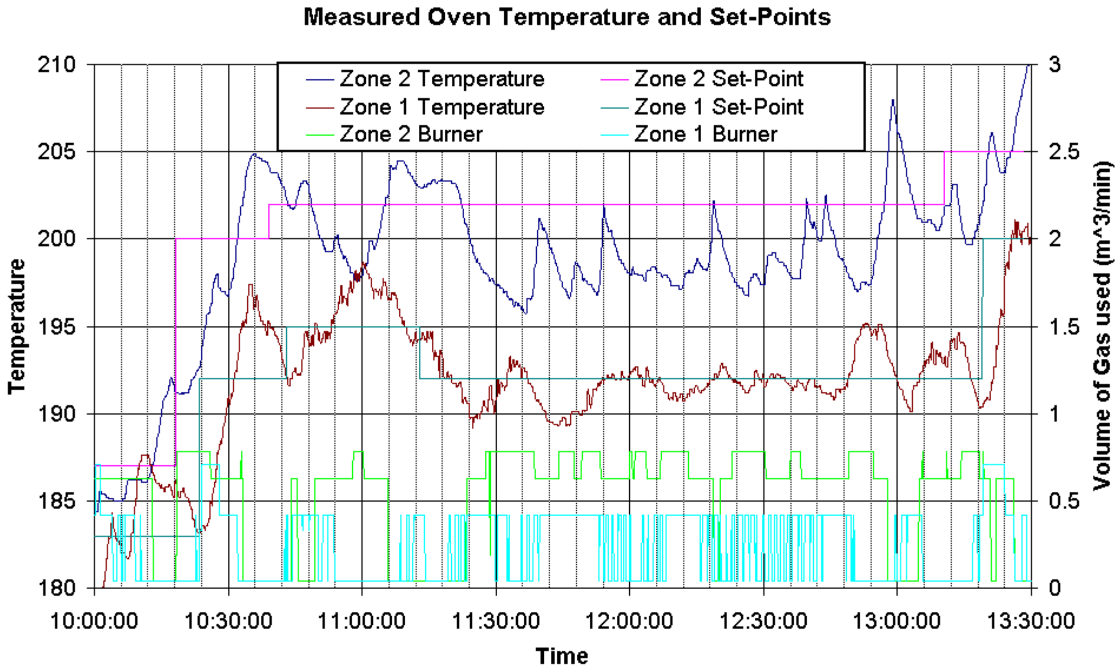

Figure 5.3: Plot of measured oven temperature, set-point and burner operation in both zones

Much oven control discussion has been focused on controlling the temperature measured by the thermocouple connected to the oven temperature controller. This temperature may not in reality be an accurate indicator of the parameters that affect loaf quality and weight loss. The current sensor position was chosen empirically without much regard for its relevance to the quality of the bread. It shows temperature at one point in the oven and has a delayed response due to the sensor's construction.

5.3 Factors that Influence Oven Temperature

The various factors that influence the temperature in one zone of the oven are discussed here.

Burner Status is the most obvious factor that influences oven temperature. The temperature depends directly on the status of the gas burner in that particular zone.

The thermal load of the oven is affected by several factors. The most important of which is the thermal load provided by the loaves of bread and the tins in which they reside. This is the most important factor because it is dynamic - the load is changing all the time.

The material that the oven is made of provides most of the thermal load. However, since this load is not changing, it is most significant only during start up. Once the oven has reached operating temperature, it should lose heat through the walls at a fairly constant rate. The aspect of the thermal load that most affects the oven temperature then, is the loaves and tins that are entering the oven. Every time a new shelf enters the oven, the loaves and tins are cold and must be heated up. If this were a constant disturbance, with a full load of equal loaves on every shelf, it may not be such an issue. However there are often empty shelves passing through the oven. These are due to gaps in production.

5.4 Oven Temperature Theory

For industrial baking ovens, there is never one average temperature value that accurately describes the state of the oven at a particular time. The temperature varies throughout the oven due to changing air velocities and radiation values. The oven actually has a temperature function that depends on spatial position and time.

$$\theta(x,t)$$

Where θ is the oven temperature, *x* is the spatial position in the oven and *t* is time

The spatial position in the oven may be given as an (x,y,z) co-ordinate, however for modelling purposes it is easier to ignore the width and regard the oven as being two dimensional. It is known that there is a certain amount of temperature variation experienced across the shelf in most ovens. The effects of this are discussed in Chapter 4. However it should be small enough to ignore here. Spatial position may then simply be expressed as ‘shelf position’. There are 48 different shelf positions in the oven that was studied here.

The temperature experienced by a loaf travelling through the oven may be expressed as a function of time, L(t). This 'perceived' temperature is reliant on the loaves position in the oven at a particular time. That is,

$$L(t) = \theta(x(t), t)$$

5.4.1 Oven Temperature Profile Customising

The loaf 'perceived' temperature function determines the quality of the loaf of bread, as it is linked directly to the loaf surface temperature, $T_s(t)$ and the loaf inner temperature, $T_i(t)$. If L(t) can be controlled and customised, there are many advantages to be gained. These include savings on energy consumption as well as improved transition between varieties requiring different set-points.

Generally, in small ovens the temperature that bread is baked at is kept at a constant value throughout baking. This is not necessarily the best approach however. As discussed in (Kim and Cho 1997), as bread is baked, rising occurs first. As this slows, browning occurs, until during the last half of baking, there is very little rising at all.

The oven temperature required for rising is not as high as that required for browning. Therefore, if the temperature is kept slightly lower during the first half of baking, then increased for the second half to assist browning, energy savings are possible while still maintaining a quality loaf.

This is good in theory, however there are difficulties in putting this into practice in a two-zone industrial oven such as the one studied in this project. This is because the loaves have to pass back through the lower temperature front section on the way out, making it difficult to have an increased temperature for the whole second half of baking.

One possible solution to this is to further divide the oven up into zones that are controlled separately from each other. This is the ideal solution, and would allow quite localised customisation of the temperatures. However the required modifications are quite extreme and would require much research and planning, as well as bakery downtime.

So using the current two zones, a temperature profile must be defined that allows for the fact that loaves exiting the oven are experiencing a similar temperature as loaves entering.

5.4.2 Product Transitions

Another ideal application for oven temperature history customising is when there is a change of variety entering the oven. Often, the new variety will require a different set-point in the oven. With proper production schedule optimisation, the magnitude of the set-point change should not be excessive (certainly no more than 10 degrees). However the change still has to be made.

Usually, the set-point in the front zone is changed when the first loaves of a product are entering the oven. The back zone set-point is changed when the operator thinks the first shelf of the new product has reached the back zone.

Obviously, in this set of circumstances, not every loaf is going to receive the same conditions as the others in its product. Consider the following scenario. Assume a constant baking time of 28 minutes. Variety 'A', requiring set-points of 200 and 205°C for the front and back zones respectively, enters the oven at 0 minutes and continues until 28 minutes. Variety 'B', requiring set-points of 205°C and 210°C, starts at 30 minutes.

A plot of the set-points experienced by a loaf of variety 'A', entering at 26 minutes is shown in Figure 5.4, compared to the recommended set-points for this variety. It can be seen that the temperature actually experienced by this product is well over what it should be. This would probably result in an over-cooked product that at best may be passable, or at worst may be burnt and/or underweight.

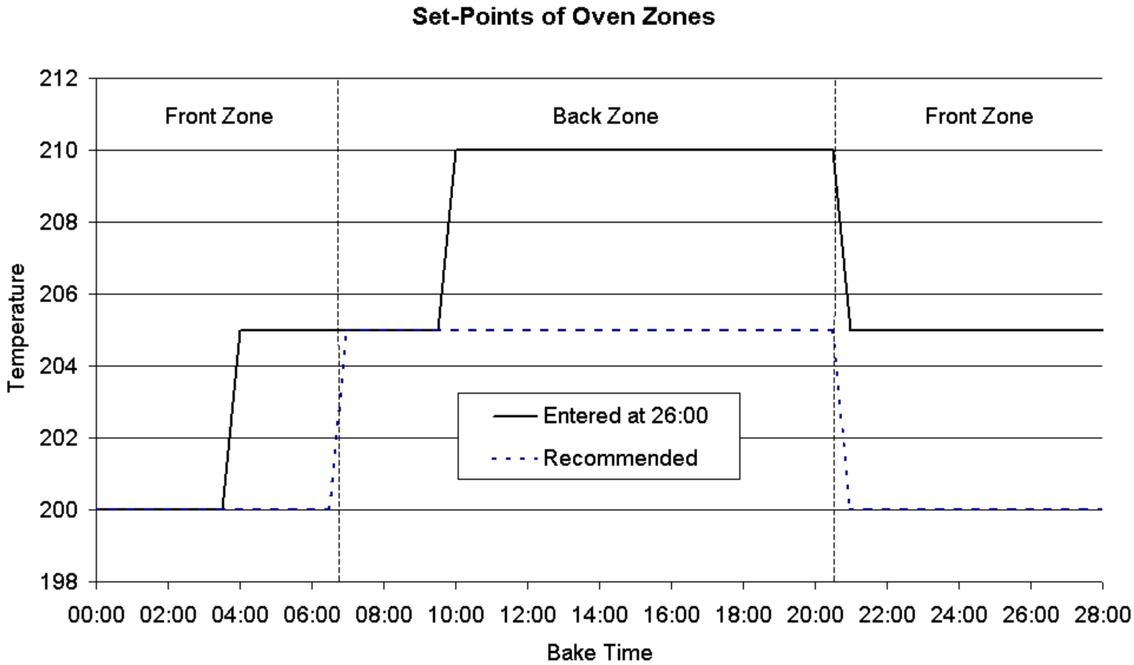

Figure 5.4: Set-points experienced by a loaf of Product 'A' entering at 26 minutes compared to the recommended set-points.

Figure 5.4 shows the set-points that the loaf experiences; however in reality these are very different from the actual temperatures experienced. The set-point of the oven is often a very inaccurate indicator of the temperatures loaves are experiencing, especially with current oven control methods.

With the very best control methods, the time taken to raise the oven 5ºC would still be in the order of three to five minutes.

The gap experienced between changes in varieties also affects the oven temperature. Generally, when several shelves enter without loaves on them, the temperature in the oven will increase. The remaining loaves inside the oven will receive more heat and this may result in an overcooked product.

5.5 Relating Oven Temperature to Loaf Temperatures

As stated earlier, the temperature actually experienced by the loaves of bread travelling through the oven is quite different from the temperature measured by the thermocouple connected to the oven temperature controller.

To view this difference, it was desirable to obtain an accurate time-temperature profile of a loaf passing through the oven. Probably the most obvious way to achieve this is by placing a temperature sensor with a loaf as it passes through the oven. This sensor would then need to be connected to a data logger that is travelling with the loaf. The logger would have to be designed to withstand temperatures of between 180ºC and 300ºC. Fortunately, BRI Australia Ltd produce a product called the 'Bakelog', which is a data logger, about the size of a loaf of bread. At the oven entry, the Bakelog may be placed in a tin in place of a loaf. Temperatures are then logged as the tin passes through the oven. A photo of the Bakelog in use is shown in Figure 5.5.

Figure 5.5: The Bakelog in use.

Several Bakelogs were sent through the oven, at different positions on the shelf and at different oven temperature set-points. A typical example of the Bakelog temperature compared to the measured oven temperature is shown in Figure 5.6.

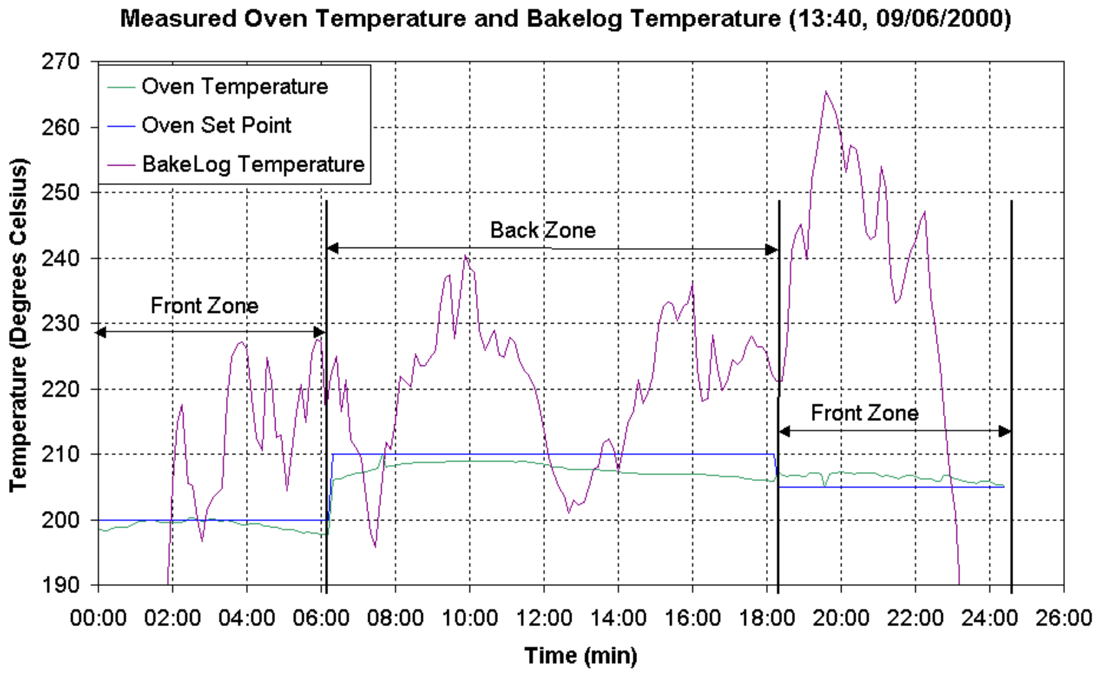

Figure 5.6: Plot comparing the measured temperature in the oven to the actual temperature experienced by the loaf

From the plot it can be seen that the measured oven temperature varies much less than the Bakelog temperature. In one zone, the oven temperature seems to vary less than 5ºC whereas the Bakelog temperature varies by 45ºC or more. This may be explained in part by the fact that the thermocouple used to measure oven temperature is placed in a metal pipe that delays its response. However, the variation is probably mostly due to the different temperatures experienced by the Bakelog in different parts of the oven.

If this variation throughout the oven is constant all the time, it may be related back to the measured oven temperature so should not be a problem. However this is not strictly the case. Another plot is included (Figure 5.7) to show that the Bakelog temperature profile differs from Figure 5.6. It can be seen that there are some rough similarities between the two plots (eg the dip after 10 minutes). However the two do not relate to the measured temperature enough to make this a reliable way of estimating the real temperature experienced by the loaves.

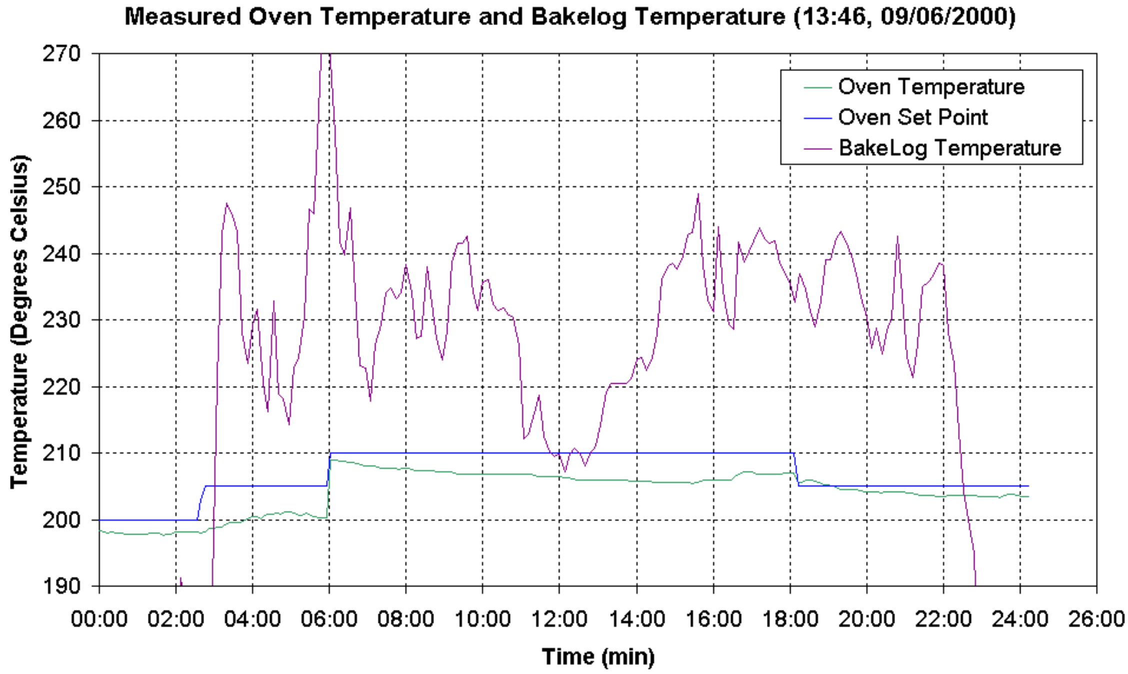

Figure 5.7: Another plot comparing the measured temperature in the oven to the actual temperature experienced by the loaf.

5.5.1 More Temperature Sensors

A method needs to be determined to accurately estimate the temperature experienced by loaves in the oven. One way would be to install temperature sensors on each shelf. This would provide an accurate temperature reading experienced by the shelf. However installing a sensor on each shelf and setting up the hardware so that the signals may be received while the shelves are moving would be quite difficult (although this option may be pursued at some point). A simpler option to implement is to install extra temperature sensors around the oven. It can be determined where a shelf is at a particular time, so a suitable temperature should be able to be resolved to correspond with that shelf.

Duct temperatures are also worth measuring for several reasons. The temperatures experienced by the loaves are directly related to duct temperatures due to radiation from the heat exchanging rods. Air from the ducts passes into the oven, so this is an intermediate temperature measurement in that regard. Also, the duct temperature is a very important variable for automatic oven control.

The diagram below shows sensor placement in the oven. Sensors 9 and 10 are located in the heating ducts at the bottom of the oven. These ducts carry air throughout the oven as shown in Figure 5.1 but are only shown at the bottom in Figure 5.8 since that's physically where the sensors are located.

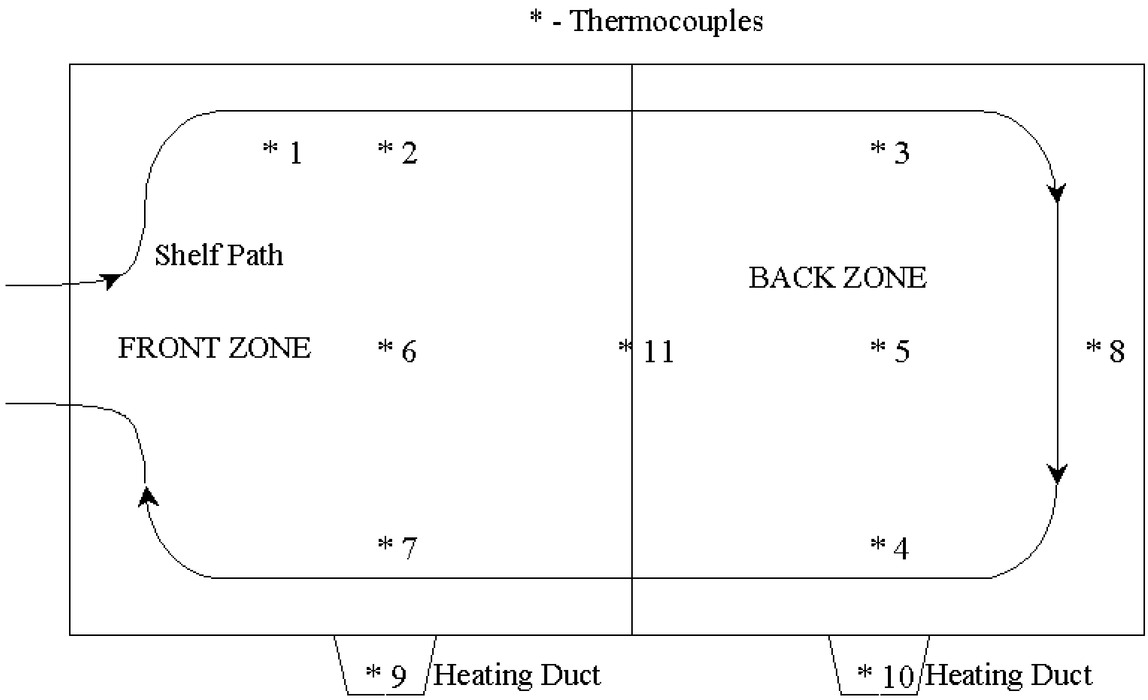

Figure 5.8: Diagram of thermocouple sensor placement in the oven.

It can be seen that as a shelf of loaves passes through the oven, the temperature experienced should be related closely to certain sensors at different times. The thermocouples currently used for oven control are located near sensors 2 and 3 in the diagram. The resulting temperature should only be correct when the shelf is in this region.

Ideally, it would be desirable to be able to relate the temperature experienced by the loaves to one measured temperature. This would reduce complexity of the control system. This is not possible, so the best thing to do would be to get a reliable estimate by combining results from several sensors.

Equations may be developed to relate the oven temperatures experienced by the loaves to the temperatures measured by the thermocouples in Figure 5.8. This may be done at any number of points around the oven. The equations for calculating the actual experienced temperature at a certain point would have the format shown in Eq 5.1.

$$[T_{pos}(t)] = [F_{1pos}] * ([C].[T_{TC}(t)]) + [F_{2pos}] \qquad \text{Eq 5.1}$$

Where:
$[T_{pos}(t)]$ is the array of calculated loaf-perceived temperatures at particular defined point in the oven.
$[C]$ is an array of coefficients that describe the relative weighting that each sensor has on the oven temperature at each point.
$[T_{TC}(t)]$ is an array containing the temperatures measured by the thermocouples at the time 't'.
$[F_{1pos}]$ is a multiplication coefficient particular to this position.
$[F_{2pos}]$ is a constant to be added to the final result, particular to this position.

The coefficient *F1* is not strictly necessary since it may be included in the factors in [*C*]. However, if the relative effects of various thermocouples are known, then *F1* may be easily used to fine-tune the model, rather than re-calculating every coefficient each time.

An example equation for the temperature at shelf 24 is shown in Eq 5.2.

$$T_{24}(t) = F_1 * (C_{3,24} * T_{TC3} + C_{4,24} * T_{TC4}) + F_2 \qquad \text{Eq 5.2}$$

From observing the positioning of the sensors in Figure 5.8 above, it was thought that it might have been possible to obtain a reliable estimate of the temperature experienced by loaves by taking measured temperatures from sensors 2, 3, 4 and 7 at the appropriate times. The fewer sensors used, the better since it keeps the whole process simple. However localised temperature fluctuations mean that these sensors are not indicative of temperatures at all points around the oven. Therefore, all the sensors were considered when determining the temperature.

5.5.2 Bakelog Matching by Geometrical Calculation

A technique had to be developed that would take temperature data from various sensors and produce from them a plot of the temperature experienced by a loaf.

First of all, an estimate of the required accuracy had to be determined. This was arbitrarily decided to be +/- 7°C. If this type of accuracy can be achieved, then an attempt can be made to correlate the loaf experienced temperature profile with factors such as weight loss.

There are 48 different shelf positions in the oven. Conceivably, a separate temperature could be calculated for every shelf position, but this is probably not necessary. If the temperature is calculated for around 8 of the positions, this should be enough to develop a usable temperature profile.

Initially, nine shelf positions were studied. These are shown in Figure 5.9.

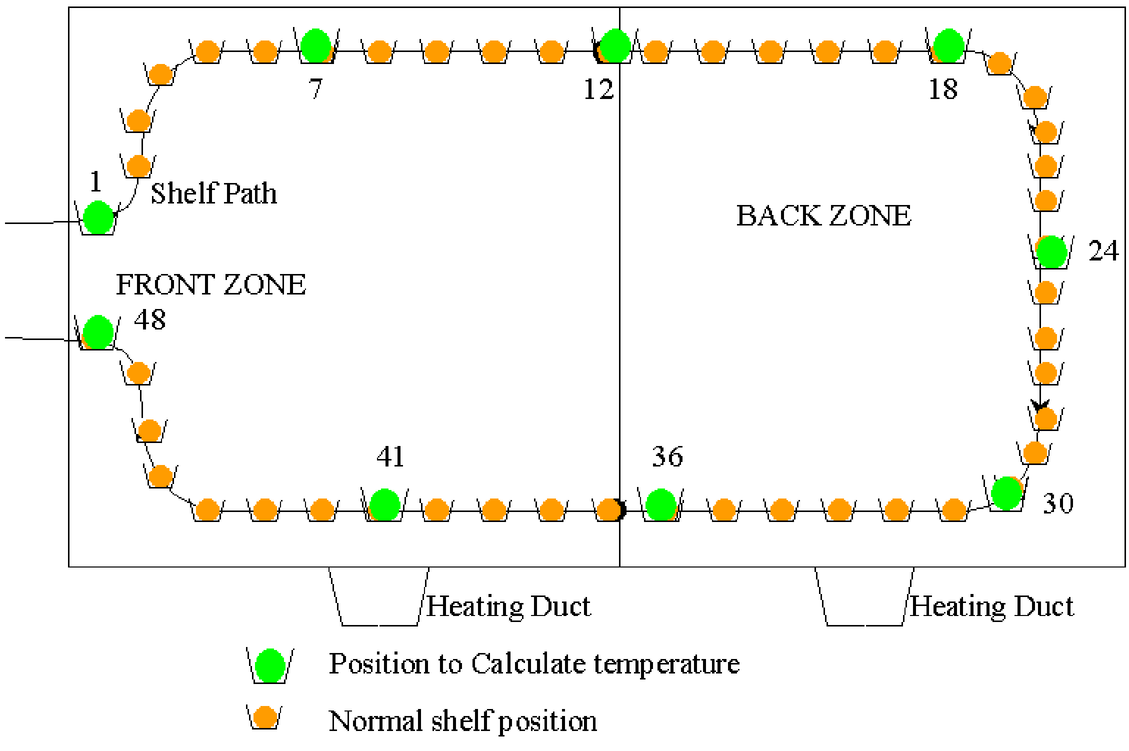

Figure 5.9: Shelf positions

Equations must then be deduced to describe the temperature at the various positions in terms of the measured thermocouple temperatures (as in Eq 5.1). This was initially done by looking at the geometry of the oven. Some optimisation of the equations was performed by further experimentation.

One issue that was considered was whether to include oven thermal load and burner operation in the equations or not. Currently, since no firm estimate of oven thermal load can be made, it was not practical to include it. Additionally, the thermal load should be reflected in the measured temperature values. That is, if the load decreases, the temperatures should increase. Therefore, the thermal load is, in effect, being considered.

Burner operation may be included in the equations by way of including the duct temperature. Since duct temperature is directly related to the burner operation, there is no need to further include it. In these initial estimations, duct temperature ignored as well.

The results of these equations were not entirely satisfactory, which is why the regression technique was investigated later (see Section 5.5.3).

Shelf Position 1

This is the temperature experienced at the initial shelf position. The temperature is still rising very steeply, so it is difficult to produce an accurate solution. It seemed that the best approach was to take the reference (ambient) temperature, then add a proportion of TC 2 (See Eq 5.3).

$$T_1 = T_{REF} + 0.2 * T_{TC2} \qquad \text{Eq 5.3}$$

Shelf Position 7

Sensor TC 2 is placed exactly where shelf 7 is (see Figure 5.8), so it follows that the temperature experienced here should be the same as that measured by TC 2.

$T_7 = T_{TC2}$ Eq 5.4

Shelf Position 12

This shelf position is on the border between the Front Zone and the Back Zone. It should be related to several sensors in fixed proportions. It is assumed that the effect of the temperature measured by the other sensors on the temperature at the shelf 12 position decreases in proportion to the square of the distance from the other sensors. That is, looking at the distances involved as shown in Figure 5.10, thermocouples 6 and 5 will only have half the effect of thermocouples 2, 3 and 11. Additionally, the effect of all temperatures should add up to one.

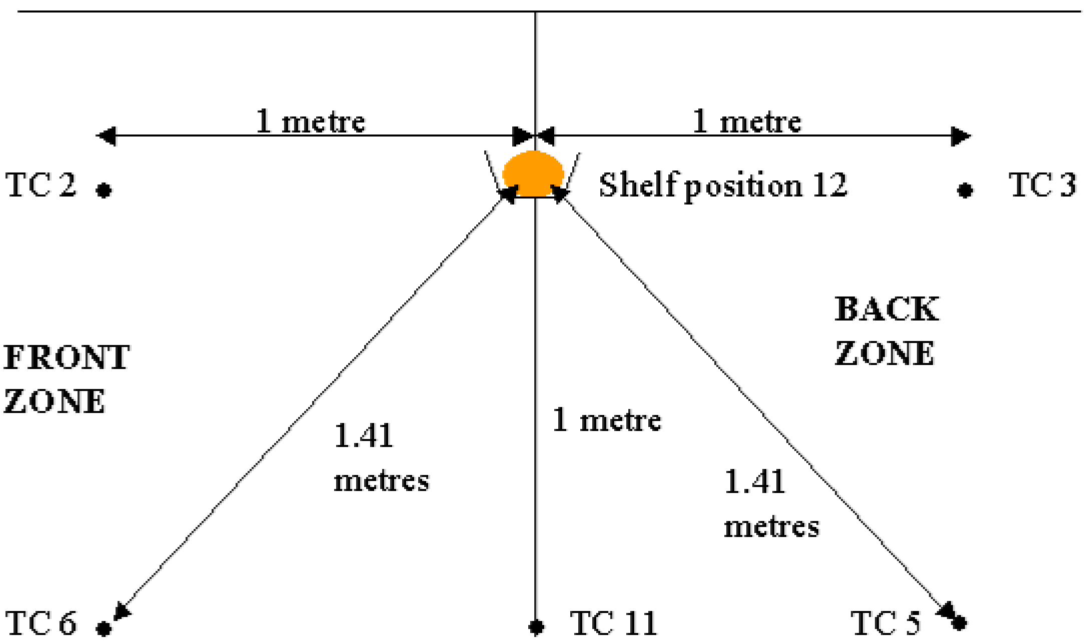

Figure 5.10: Diagram of thermocouple sensor placement around shelf position 12.

So the equation for this position may be expressed as follows. (The '5' constant at the end was deemed necessary to produce an accurate result.)

$$T_{12} = 0.25(T_{TC2} + T_{TC3} + T_{TC11}) + 0.125(T_{TC5} + T_{TC6}) - 5 \qquad \text{Eq 5.5}$$

Shelf Position 18

Sensor TC 3 is placed exactly where shelf 18 is (see Figure 5.8), so it follows that the temperature experienced here should be the same as that measured by TC 3.

$$T_{18} = T_{TC8} \qquad \text{Eq 5.6}$$

Shelf Position 24

Sensor TC 8 is placed exactly where shelf 24 is (see Figure 5.8), so it follows that the temperature experienced here should be the same as that measured by TC 8.

$$T_{24} = T_{TC8} \qquad \text{Eq 5.7}$$

Shelf Position 30

Sensor TC 4 is placed exactly where shelf 30 is (Figure 5.8), so it follows that the temperature experienced here should be the same as that measured by TC 4. In reality, it was found that a slight correction (minus 12˚C) was necessary.

$$T_{30} = T_{TC8} - 12 \qquad \text{Eq 5.8}$$

Shelf Position 36

This shelf position is similar to position 12 discussed above. In this case, the equation would be as follows.

$$T_{36} = 0.25(T_{TC7} + T_{TC4} + T_{TC11}) + 0.125(T_{TC5} + T_{TC6}) \qquad \text{Eq 5.9}$$

Shelf Position 41

Sensor TC 7 is placed exactly where shelf 41 is (see Figure 5.8), so it follows that the temperature experienced here should be the same as that measured by TC 4.

$T_{41} = T_{TC4}$ Eq 5.10

Shelf Position 48

This is the temperature experienced at the final shelf position. The temperature is falling very steeply, so it is difficult to produce an accurate solution. It seemed that the best approach was to take the reference (ambient) temperature, then add a proportion of TC 7.

$T_{48} = T_{REF} + 0.2 * T_{TC7}$ Eq 5.11

5.5.3 Using Multiple Regression

A more mathematical way of establishing a relationship between temperatures is to use a Multiple Regression method. Regression analysis is a statistical tool used to evaluate the relationship of one or more independent variables to a single dependent variable (Kleinbaum, Kupper et al. 1998).

It was decided to use the 'least-squares method'. In this method the sum of squares of the distances between the observed responses and those predicted by the fitted model are minimised.

In matrix form, the equations for a set of n observations of the variables X and Y can be described as follows in Eq 5.12. There are *p* independent variables.

$\mathbf{Y}_{n\times 1} = \mathbf{X}_{n\times(p+1)}\beta_{(p+1)\times 1} + \mathbf{E}_{n\times 1}$ Eq 5.12

Where:

$Y_{n\times 1}$ is the vector of observations of Y, the dependent variable. In the oven case, this is the Bakelog temperatures.

$X_{n\times(p+1)}$ is the matrix of independent variables (the measured temperatures). In this case, a constant term is included in the equation, meaning the first column of this matrix is made up of ones.

$\beta_{(p+1)\times 1}$ is the vector of parameters.

$E_{n\times 1}$ is the vector of random errors.

For the least-squares solution, the vector β must be found that minimises the error sum of squares, given as:

$$(\mathbf{Y} - \mathbf{X}\hat{\beta}).(\mathbf{Y} - \mathbf{X}\hat{\beta}) \qquad \text{Eq 5.13}$$

The solution is obtained using matrix calculus. The result is the following formula (Kleinbaum, Kupper et al. 1998).

$$\hat{\beta} = (\mathbf{X}'\mathbf{X})^{-1}\mathbf{X}'\mathbf{Y} \qquad \text{Eq 5.14}$$

In addition to the measured temperatures, it was decided to include the zone set-points in the calculations. This was because, although they are not a direct measure of oven temperature, the target temperature of the oven may assist in regression calculations.

5.5.4 Low Pass Filtering

First of all, it was decided to use a low pass filter on both the Bakelog temperatures and measured temperatures. This removes spikes from the readings. Since the temperature would only be calculated at only 9 points anyway, using the low pass filter means that average values are being used to calculate this.

The low pass filter was in the form of Eq 5.15.

$$T_{LP(n+1)} = 0.8 * T_{LP(n)} + 0.2 * T_{n+1} \qquad \text{Eq 5.15}$$

Where:

$T_{LP(n+1)}$ is the new low pass value at reading n+1

$T_{LP(n)}$ is the last calculated low pass value - taken at n.

T_{n+1} is the new value to include in the equation.

The result of this low pass filter will be skewed to the left on a plot, so it is applied twice - once in each direction to negate this effect. A Microsoft Excel macro was written to achieve this called “LowPassFilter”. The same macro may be adapted to produce a 'moving average' type plot for any data. If a high pass filter is required, the low pass data may be subtracted from the original data.

The values for the coefficients (0.8 and 0.2) were chosen after trying several values and finding one that seemed to remove smaller fluctuations, but allowed the general trend to remain. These values must also add up to 1.

This low pass filter had to be run on entire oven temperature log file to produce a new version of the file. The filter was not applied to the oven controller set-points though since they do not fluctuate like the temperature measurements. The macro written to do this is called "ApplyLowPassOven".

5.5.5 Summarising Data and Conducting Regression

The next step was to summarise the data into tables for each shelf position that was to have an equation calculated. A set of macros was written for this purpose and is included in the Excel file 'LoafTempMatch1.xls' in the accompanying CD.

Once the data was summarised, multiple regression could be used to determine an equation that would link the logged values with the Bakelog values. Initially, some experimental analyses were performed using Matlab. However, Microsoft Excel has a 'Data Analysis' add-in that includes a least-squares regression function. This produced the same result as Matlab, as well as providing other useful data such as an ANOVA table. Consequently, Excel was used for all analyses.

For each shelf position, regression was applied using different combinations of sensors and set-points as well as with and without a constant added to the result. For each position, the combination that produced the smallest standard error was chosen.

The resulting equations were as follows:

- Shelf 1: $T_1 = 196.7173292 – 0.628156011 * T_{FrontSet}$
- Shelf 7: $T_7 = 5.387972164 * T_{TC1} - 4.156714473 * T_{TC2} + 0.148774445 * T_{TC6} - 0.238491854 * T_{TC9} - 0.09388347 * T_{TC11}$

- Shelf 12: T_{12} = -211.0229395 - 1.578279887 * T_{TC2} + 0.496360054 * T_{TC3} + 1.011703726 * T_{TC5} + 0.879038101 * T_{TC6} + 0.780982166 * T_{TC9} + 0.09005394 * T_{TC10} - 0.386066117 * T_{TC11} - 1.646295499 * T_{Ref} - 0.530395111 * $T_{Front\ Set}$ + 1.097334762 * $T_{Back\ Set}$
- Shelf 18: T_{18} = -108.0199655 + 0.016949662 * T_{TC3} - 0.977398943 * T_{TC5} + 0.996672884 * T_{TC8} + 0.703653912 * T_{TC10} + 0.574331447 * T_{TC11}
- Shelf 24: T_{24} = 0.75245021 * T_{TC3} - 0.904595329 * T_{TC4} + 0.68884679 * T_{TC5} + 0.85409769 * T_{TC8} + 0.524199217 * T_{TC10} - 4.171901864 * T_{Ref} - 0.426291532 * $T_{Back\ Set}$
- Shelf 30: T_{30} = 113.6870379 - 0.027495679 * T_{TC4} - 0.256318066 * T_{TC5} + 0.458104141 * T_{TC8} + 0.197856776 * T_{TC10} + 0.097264111 * T_{TC11}
- Shelf 36: T_{36} = 80.15941214 + 1.094484134 * T_{TC4} - 0.123331581 * T_{TC5} + 2.108730678 * T_{TC6} - 0.846431646 * T_{TC7} + 0.017477456 * T_{TC9} - 0.375953275 * T_{TC10} - 1.124735383 * T_{TC11}
- Shelf 41: T_{41} = 0.712016997 * T_{TC7} + 0.241042267 * T_{TC9}
- Shelf 48: T_{47} = 1.707543343 * T_{Ref} + 0.333720741 * $T_{Front\ Set}$

These equations obviously bear no resemblance to the equations determined by geometrical methods in the previous section. This should not be a problem, as long as the predictions made by them are acceptable.

As stated above, the standard error was used to determine the best fitting equation. The standard errors for each shelf are included in the following table.

Shelf	Standard Error
1	16.72
7	7.19
12	4.39
18	5.66
24	5.66
30	5.36
36	2.78
41	6.69
48	15.26

Table 1: Standard errors of calculated shelf temperature s

It can be seen that the standard errors for the first and last shelves are significantly higher than the others. This is to be expected since the temperature is changing at a great rate here. However, the inaccuracy of the estimation at these points is of little consequence since the lower temperatures experienced will not affect the loaves as much as at other points in the oven.

All the other standard errors seem to suggest that the equations are working acceptably.

5.5.6 Applying the Equations

Once suitable equations have been defined to express loaf perceived temperature, the next step is to apply these equations. This was done using a set of macros for Microsoft Excel. These macros may be applied from 'Sheet 1' of 'LoafTempMatch1.xls' on the accompanying CD.

The approach taken was to enter all relevant data on the worksheet (i.e. date, time and equation definitions). The macros then obtain the data from here and produce a new file that plots the estimated loaf perceived temperatures, as well as other oven temperatures.

The macros also allow the ability to apply equations to other shelf positions in the oven. This is achieved by selecting 'TRUE' or 'FALSE' at the beginning of the equation definition rows.

5.5.7 Discussion of Results

A few months after the initial Bakelog samples were taken, a few more runs were performed to check the accuracy of both the geometrical and regression predictions of loaf perceived temperature.

Included here are two plots, Figure 5.11 and Figure 5.12. Each shows the low passed Bakelog recorded temperatures, along with the temperature calculated using both the geometrical and regression formulas. These have all had curves fitted by Microsoft Excel.

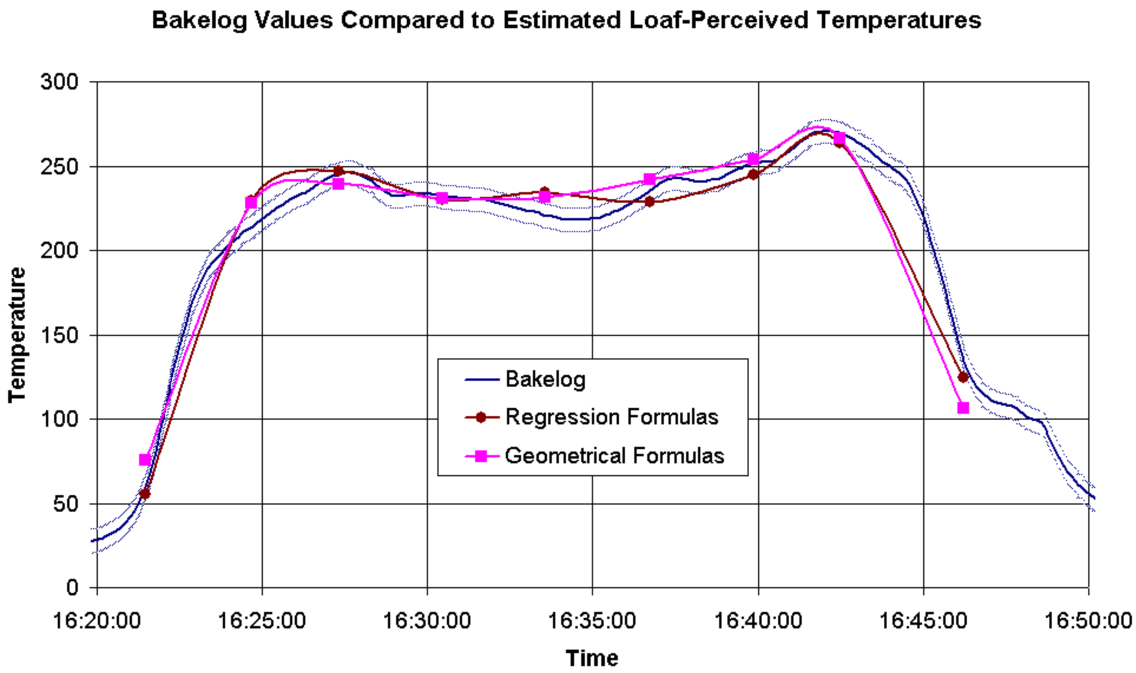

Figure 5.11: Bakelog values compared to estimated loaf-perceived temperatures – Test 1. (The light blue lines are arbitrary and assist with estimating closeness of the two estimated values)

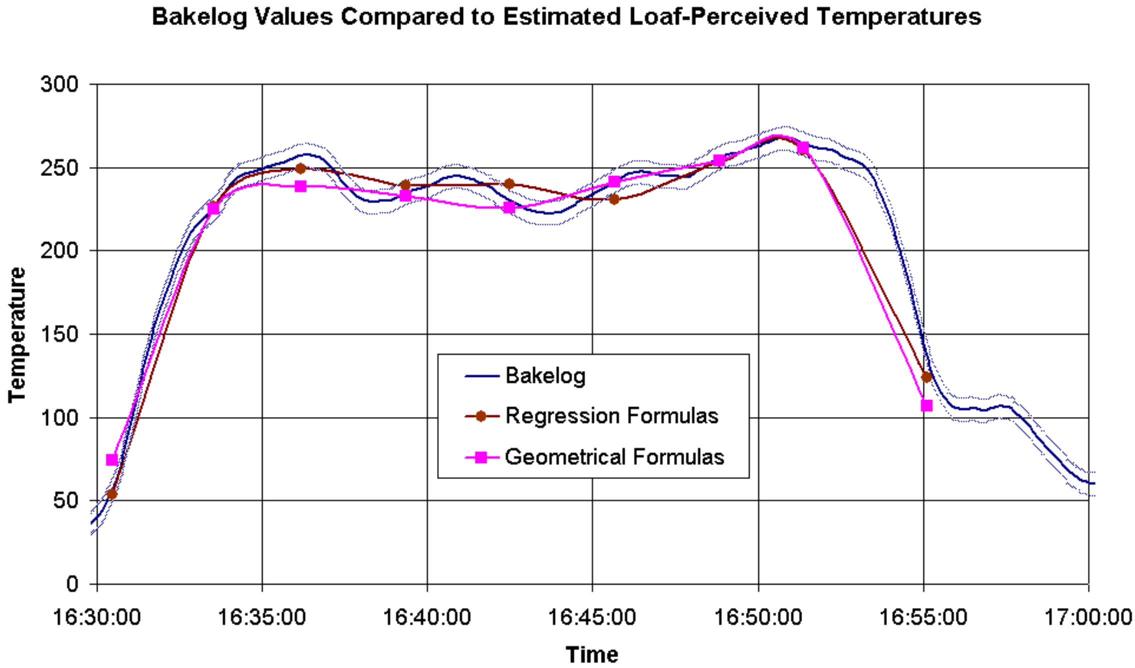

Figure 5.12: Bakelog values compared to estimated loaf-perceived temperatures – Test 2. (The light blue lines are arbitrary and assist with estimating closeness of the two estimated values)

It may be seen form the Figures that both estimates perform reasonably well. In both cases, there is little difference between the performances of the different formulas. The original aim was to be able to predict oven temperature to within ±7°C. This has been successful over most of the range.

It is suggested that to produce an accurate loaf-perceived temperature profile, more Bakelog runs would have to be performed. Additionally, a regression analysis should be performed at more points inside the oven. This would be relatively easy to do, using the macros already included in 'LoafTempMatch1.xls'. With more Bakelog data and more oven points, an accurate solution that aids in the linking of oven conditions to weight loss should be forthcoming.

5.6 Matching Loaf Temperatures to Weight Loss

Once a reliable method has been developed to calculate the temperatures experienced by loaves passing through the oven, these temperatures must be related to the loaf quality. The way this project seeks to achieve this is through loaf weight loss. Methods of determining weight loss are discussed in Chapter 4.

As an example, the weight loss and loaf-perceived temperatures were calculated for various shelves during the first product run on 03/10/2000 at Buttercup Bakery, Canberra. A plot of the percentage weight loss for the first one thousand loaves is shown in Figure 5.13. The percentage weight loss is used because it should negate the effects of different sized loaves.

Figure 5.13: Weight loss for the first one thousand loaves of Product 1, 03/10/2000. The numbers on the Wt Loss series refer to the shelf number.

The weight loss in the plot was calculated using ‘Alignment by Beginning’ of the weight data files (See Section 4.2.1). It was done this way in preference to ‘Alignment by Extension of Final Weights’ (Section 4.2.2) because the calculations needed to be as close to loaf-by-loaf as possible. Although the alignment by beginning method becomes more inaccurate over the product run, the effects of this were ignored since only the first one thousand loaves were used. The entire product run consisted of 2768 loaves. There is still a potential inaccuracy in the weight loss calculation of about forty loaves (or about one shelf). For this reason, only general trends in weight loss were investigated.

Using the data logged from the sensor at the oven entrance sensing straps entering the oven (See Section 3.6.5), the entry time of each shelf may be approximately determined. This is achieved by looking at the gaps between sensor operations. If the gap is more than about 5 seconds, the gap is too large to be considered part of the same shelf, so a new shelf is assumed. The last time before the larger gap is assumed to be the approximate time that the shelf entered the oven. In reality, this will be several seconds before the shelf enters the oven as sensed by the oven shelf movement relay. This approximate entry time was then used as the time of entry for the loaves in the macro discussed in Section 5.5.6 above.

The equations used to calculate temperatures were those determined by geometrical calculation in Section 5.5.2 above. These calculations were performed for the shelves marked in Figure 5.13.

The results for some of these shelves are displayed in Figure 5.14. It can be seen that the weight loss does not correlate with the temperatures experienced. This is not unexpected for several reasons. These are discussed below in Section 5.6.1. Oven load may need to be considered as well.

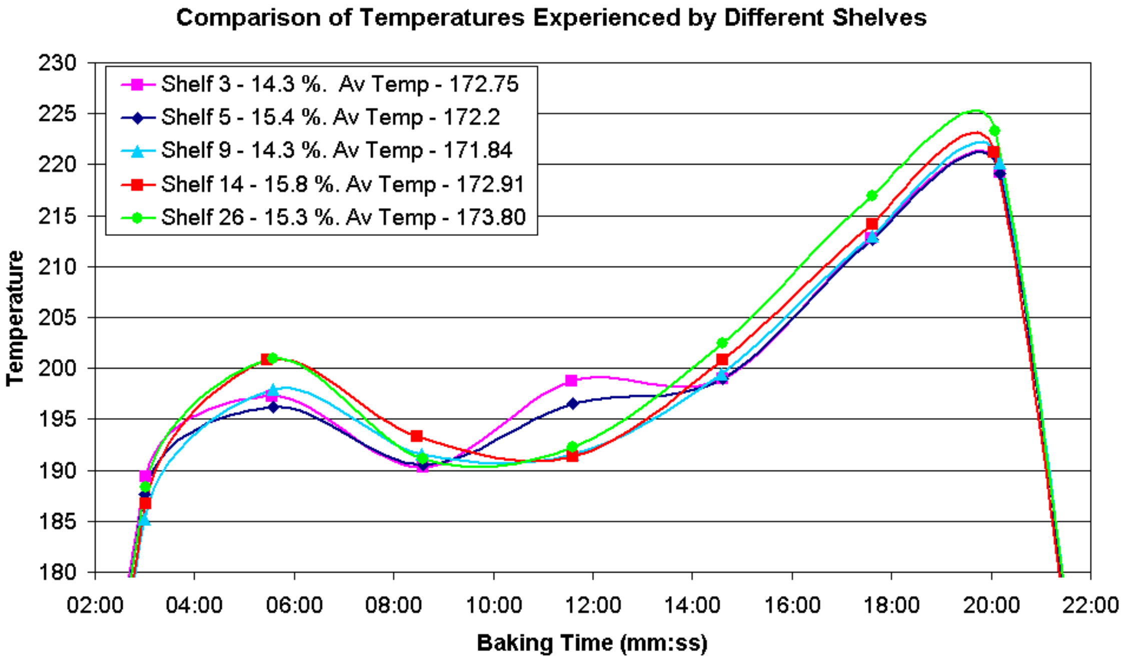

Figure 5.14: Weight loss compared to loaf-perceived oven temperature for several shelves.

Figure 5.15 shows the percentage oven zone load against the weight losses for the same shelves. This is the percentage of full load (in terms of number of tins) for the zone that the loaf is in. As a summary, the data is also tabulated below.

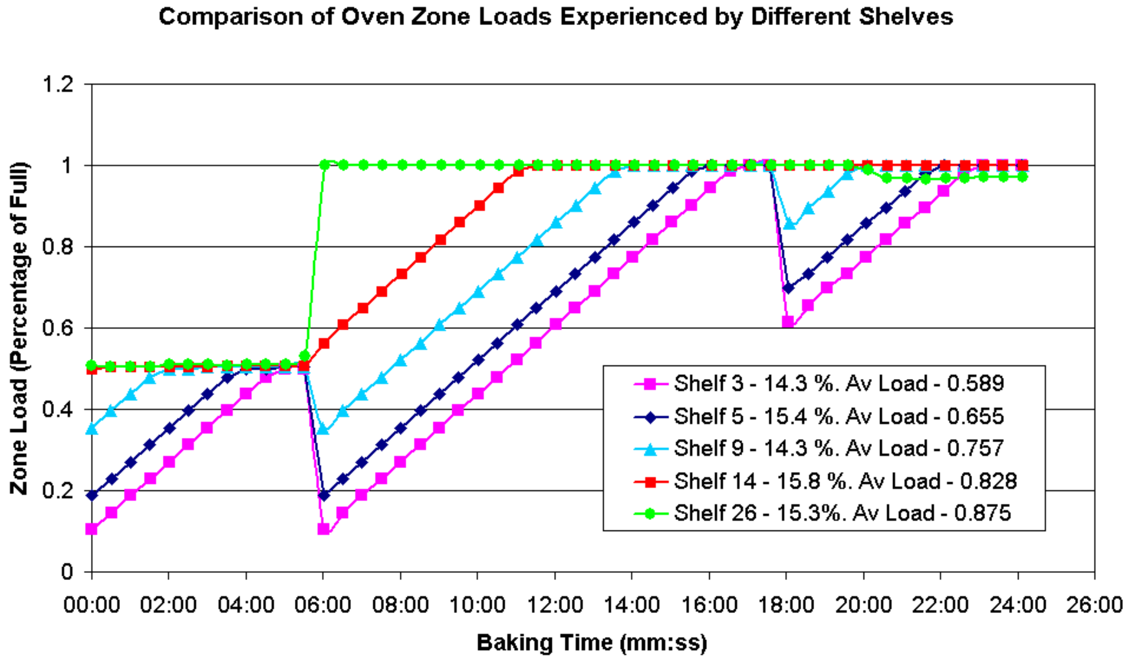

Figure 5.15: Weight loss compared to oven zone load for several shelves

Shelf Number	Wt Loss	Wt Loss (grams)	Ave Temp (°C)	Ave Load (%)
2	14.3	79.8	173.2	55.2
5	15.4	83.9	172.2	65.5
9	14.3	78.3	171.8	75.7
16	15.8	88.6	173.2	84.5
26	15.3	83.7	173.8	87.5

Table 2: Weight loss compared to oven zone load for several shelves

A regression analysis was performed on this table to see if there was a relationship between the load, temperature and weight loss, but a standard error of 0.77 was the result. This is too high to assume a definite relationship when differences in the percentage weight loss of only 1.5 % are observed.

5.6.1 Possible Causes of Errors

As mentioned above, it was not unexpected that the weight loss did not correlate with oven temperature. In addition, including percentage oven load did not improve the correlation. There are several reasons that may be the cause of this.

Firstly, the above analysis was performed at the beginning of the day's production. When the first shelves were entering the oven, the oven was almost empty. This may have had an effect on the result. It would have been better to perform the analysis on a product in the middle of normal production. This was undertaken, however results were comparable, with no definite correlation between weight loss, temperature and percentage zone load.

The weight losses used in the analyses may not be entirely accurate. An effort was made to minimise any errors by only using the first 1000 loaves in the product. However there was no way of telling whether a large number of loaves had been removed from the production line, or even whether the oven entry times were entirely reliable. This is especially the case for products in the middle of production since their oven entry time was determined by simply observing the gaps at the initial checkweigher and at the oven and trying to align the two.

The loaf-perceived temperature profiles used may have errors. This was discussed earlier this chapter in Section 5.5.

Even though oven load was taken into account, the method used is not a completely accurate indication of the thermal load in the oven. If the true thermal load was taken into account, it is likely that the results would be better. Oven thermal load is discussed more thoroughly in the next section.

The method presented here has much potential to discover the link between oven conditions and loaf weight loss. To improve results, the errors discussed above should be minimised and many similar analyses carried out. With the use of data processing macros in Microsoft Excel, the analyses should be able to be almost fully automated.

5.7 Oven Thermal Load

Calculating the thermal load in the oven is a very important step for control purposes. It is thought that the thermal load affects the temperature extensively, yet it is not taken into account during day-to-day operation of the bakery. It is quite common that if there is a large gap in production and many empty shelves enter the oven, loaves on either side of the gap are often over cooked.

A simple way to estimate the oven thermal load has been used during this project. By having a sensor counting loaves as they entered the oven, sensing the shelf movements in the oven and knowing how many shelves the oven has, the load can be calculated. This is expressed as a percentage of full load (in terms of the number of straps in the oven). This is shown in Eq 5.16.

$$L = \frac{\sum_{i=1}^{m}(n_i)}{M} \qquad \text{Eq 5.16}$$

Where:
m is the number of shelves in the oven.
n is the number of straps on a particular shelf.
M is the maximum number of straps in the oven.

The shortcoming of this approach is that all loaves are regarded as having the same effect on oven thermal load. In fact, the loaves nearing the exit of the oven, being fully heated would constitute a much smaller thermal load than the loaves just entering the oven.

Additionally, the oven consists of a huge amount of material, constituting a large thermal load. This part of the thermal load is most relevant when the oven is heating up. Once the oven is at operating temperature, the thermal load of the oven itself plays a smaller part since it is very hot already compared to the cold loaves and tins entering. This still does need to be quantified however.

The heat energy required to heat an object is expressed in Eq 5.17.

$$Q = m.c_p.\Delta T \quad \text{Eq 5.17}$$

Where:
Q is Heat in kJ
m is the mass of the object in kg
c_p is the specific heat at a constant pressure
ΔT is the change in temperature of the object.

There are several ways this may be applied to the oven thermal load. First, the properties of the loaves and tins must be investigated.

5.8 Thermal Load from Tins

The baking tins are made from steel. This has a specific heat of 0.473 kJ/kg.°C. Tins are arranged into 'straps'. These may contain 2, 3 or 4 tins. The calculations here will be done with a 3 tin strap. The weight of the strap is taken to be 4.35 kg. During baking, it is assumed the tin will rise in temperature from its entry point of around 40°C to nearly the oven temperature.

$$Q_{tin} = 4.35 * 0.473 * (180 - 40) = 288kJ \quad \text{Eq 5.18}$$

So it would take about 288 kJ to take the temperature of one strap from 40°C to 180°C. There are twelve straps on a shelf, so to raise the temperature of a whole shelf would require 3456 kJ.

5.9 Thermal Load from the Dough

Thermal properties for dough are more difficult to estimate than for the tins. The properties of the dough change according to bake time, temperature and spatial coordinate. To include the actual physical properties at every point in the dough at every temperature, an approach such as a finite difference method would be needed (Zanoni, Pierucci et al. 1994). In the case here, what is required is not a complete model of heat transfer within a piece of dough. What is required, is to have some idea of how much heat will be needed to bake the bread, and what this rate of heat usage will be at different stages during the baking process. Therefore, a more straightforward approach will be taken.

5.10 Simple Approach Using Effective Properties

Carvalho and Martins (1992) gives the following values for effective thermal properties of dough. All properties are given from 30.0°C to 100.0°C. Thermal conductivity is 0.2 to 1.2 J/°C.m.s, product bulk density is from 110 to 82 kg/m3 and specific heat is from 4500 to 5300 J/°C.kg.

The properties of the crust are not included in the above values since it makes up such a small proportion of the entire volume.

5.11 Modelling Oven Temperatures (Proposed Method)

As discussed above, producing a mathematical model of the oven would be extremely difficult to do accurately due to the complicated nature of the oven's construction and operation. A simplified model can be produced which may give some useful information about the oven's operation. It may even be tuned. A simple approach to modelling the oven is shown in the diagram below. There are two state variables, the temperature in the duct and the temperature in the oven. One of the major assumptions made in this model is that the temperature of the oven is taken to be constant throughout the oven. In reality there are many variations due to air flows and movements of loaves inside the oven.

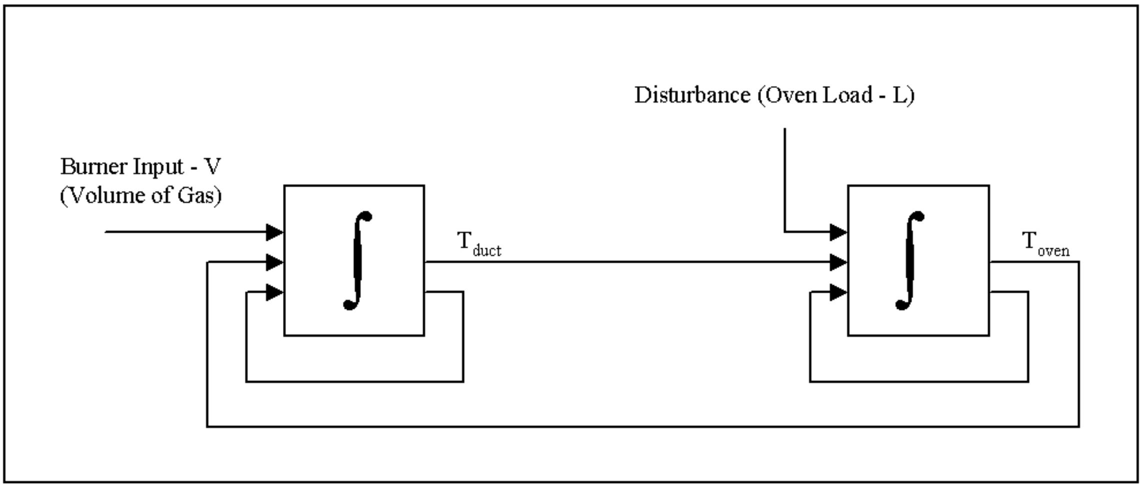

Figure 5.16: System diagram of typical bakery oven

The rate of change of the duct temperature is proportional to several factors as shown in the following equation.

$$\frac{dT_{duct}}{dt} = -a.(T_{duct} - T_{oven}) - b.(T_{duct} - T_{ambient}) + c.V \qquad \text{Eq 5.19}$$

Where a, b and c are constants depending on the oven characteristics. V is the volume of gas in m^3/min consumed by the burner.

Similarly, the rate of change of oven temperature is also proportional to several factors.

$$\frac{dT_{oven}}{dt} = d.(T_{duct} - T_{oven}) - e(T_{oven} - T_{ambient}) + f.L \qquad \text{Eq 5.20}$$

In the diagram, T_{oven} represents the temperature in the oven and T_{duct} represents the temperature in the main duct. Disturbances are mainly due to the changing load in the oven. It should be remembered that this is quite a simplified representation of oven operation, but one that should meet the control requirements. Traditionally, oven control consists of a simple on/off controller that measures the internal oven temperature. An operator sets the target temperature manually. Baking temperatures for different varieties are not optimised and disturbances such as changing oven load are not allowed for. Using such recorded oven values, and the model in Figure 5.16, a set of state equations may be derived which result in the following.

$$\frac{dT_{duct}}{dt} = a.V - b.T_{duct} + c.T_{oven} \qquad \text{Eq 5.21}$$

$$\frac{dT_{oven}}{dt} = d.T_{duct} - e.T_{oven} - f.L \qquad \text{Eq 5.22}$$

Where a, b, c, d, e and f are constants depending on the particular oven, V is the volume of gas in m^3/min and L is the oven load. Instead of the current method of controlling oven temperature, an improved approach would be to control the duct temperature T_{duct} according to a demanded value of oven temperature T_{oven}. The actual position that the measurement is taken from should be optimised as well. Feed-forward and feedback control are the two apparent methods to improve oven control. These methods involve not only maintaining a target temperature, but also calculating what the value of the target should be. Problems with traditional feedback methods of control arise due to several factors. Many varieties only run for a short time - around ten minutes. Baking time is around 30 minutes, so if product quality is measured at the end of baking, it is too late to feed back data that may improve oven conditions. In practice, feed back times can be further increased because the product generally undergoes an hour of cooling before qualities may be measured.

Results of the above method had not been determined at the time of publication.

5.12 Conclusion

The oven is a pivotal process in the bakery. Several ideas for customising and optimising loaf-experienced temperatures for different products have been proposed. A method of correlating loaf temperature with measured oven temperatures has been proposed and tested with limited success, re-iterating the difficulties in predicting oven behaviour. Some initial attempts were made to correlate oven temperatures with weight loss of loaves. It was realised that many more factors had to be considered. One of these was thermal load in the oven, which was investigated. Finally a simplified mathematical model was proposed, but has not at this point been tested.

Chapter 6 - Product Following and Reporting

In this chapter, the topic of following products through the bakery and compiling the resulting data into reports is discussed. Out of the techniques tested, the technique showing most promise is the post-production logical processing of data. With a few additions outlined, it could become a very useful tool in bakeries.

6.1 Why Follow Products and Loaves?

There is much potential information to be logged in a bakery. For example, weight of loaves, temperatures, relative humidities and loaf counts, just to name the basic ones. This data has limited use unless it can be related to data from other points in the system. For example, the difference between initial weights and final weights of loaves may be calculated to obtain weight loss - an extremely useful variable. Weight loss may then be related to oven conditions, baking time, yeast levels and other measurements.

To calculate values accurately, such as oven temperature for a certain loaf of bread, the position of the bread in the bakery at a certain time must be accurately known. Since different loaves and products can look very similar, it is very difficult to tell which loaf or product is where.

6.2 Product Following Software

Products are 'tracked' through the bakery via data processing algorithms. Initially, in the development phase, product following software was written as a macro in Microsoft Excel and utilised pre-recorded data from the bakery. The macro read each file separately and placed the resulting processed data into a summary file.

Microsoft Excel was chosen as the software to manipulate the data because the use of macros makes data processing extremely easy. The language used to write the macros is Visual Basic - a simple language that is also used in other aspects of the project. Also, a graphical or tabular summary of the data is easy to produce and manipulate in Excel.

Several methods of tracking products through the bakery have been investigated. The first three are post-processing methods. That is, the processing is done at the end of the day with a view to produce a summary report. The last method involves real-time processing of the data.

6.3 Post Production Estimation Exclusively Using Weight Data

This technique of processing the bakery data uses the initial and final recorded weights of loaves. The initial product numbers are used in all processing methods to describe which variety is at the beginning of production. These can be regarded as accurate. At the point where final weights are measured, a bakery operator enters the product number in the scales, according to which product is passing through. This value is usually accurate and may be used 'line up' weights from the beginning and end of the bakery. The approximate delay times between processes are known, and these approximations may be used to calculate process conditions when products were passing through.

Advantages:

- Avoids much of the complicated data processing required of other methods (eg correlation of gaps (Section 6.4) and Post-Production Logical Processing (Section 6.5)
- Results should not be as prone to processing errors due to unusual occurrences such as product removal.

Disadvantages:

- Final product numbers are not always accurate due to the operator's difficulty in determining exactly which product is at the divider.
- Estimations of times that the product entered processes will always be at least slightly inaccurate.

This approach is good for calculating average weights at the beginning and end, as well as average weight loss for a product. The data it gives for the other processes (oven, prover etc) is not very accurate. It has been used during the project to produce basic summary reports at the end of production. This method was used since the actual 'Product Tracking' software was not yet fully developed.

6.3.1 Product Reporting Macro File - 'Produce Report Generator 1.xls'

This is the Microsoft Excel file where all the macros for processing data via 'Post Production Estimation Exclusively Using Weight Data' are located.

The workbook contains three sheets - 'Products0' – containing product data from the divider checkweigher, 'Products1' and 'Products2', containing product data from the two final checkweighers. 'Products0' also contains several other pieces of information.

The product data stored for each checkweigher is – Product Number, Product Name, Under Weight, Pass Weight, and Over Weight. 'Products0' also contains the number of loaves in a strap for each product and the corresponding final product numbers.

A selection of 'Products0' is shown in Figure 6.1. It shows the product data for the initial checkweigher. The user of the software must enter data for columns 'F' and 'I', the 'Loaves in Strap' and 'Final Product Number'. The 'Loaves in Strap' value is simply the number of loaves in the type of strap used for that particular variety. This is used when numbers of loaves are to be calculated from the number of straps that were counted. This value is not required for report generation at the moment since product counts at mid-way points in the production process are not being calculated. It will be necessary for when they are though. The 'Final Product Number' is the corresponding final product number to that product's initial product number. This is used to match up products at the beginning and end of the process.

	A	B	C	D	E	F	G	H	I
1	Product N	Product Name	Initial Target	Under Weight	Over Weight	Loaves in Strap			Final Product Num
2	1	MEAL-SPLIT	536	526	556	***4***			2
3	2	WHITE SPLIT	533	523	553	***4***			1
4	3	HEL D-RYE---	787	777	807	***3***			4
5	4	HEL-MEL -GRN	959	949	979	***3***			8
6	5	JUMBO-MEAL -	1029	1019	1049	***3***			10
7	6	JUMBO-WHITE	1025	1015	1045	***3***			11
8	7	UT-GOLD	774	764	794	***3***			12
9	8	0	0	0	0	***3***			12
10	9	UT GRAIN	783	773	803	***3***			13
11	10	UT SOY-LIN	831	821	851	***3***			14
12	11	HI-Q	853	843	863	***3***			14
13	12	W-WHITE	824	814	844	***3***			17
14	13	MEGA-MEAL	865	855	885	***3***			18
15	14	MOLE	882	872	902	***3***			19
16	15	MOLE-SOY-LIN	896	886	916	***3***			20
17	16	MULTI-HB	804	794	824	***3***			22
18	17	W-MEAL-HB---	802	792	822	***3***			23
19	18	600-W-WHITE	712	702	732	***3***			24
20	19	WHITE-H-B	796	786	816	***3***			25
21	20	MAX	760	750	780	***3***			26
22	21	MULTI HB	806	796	816	***3***			22
23	22	PRITIKIN	809	795	820	***3***			
24	23	W-MEAL HB	809	799	819	***3***			23
25	24	WHITE HB	799	789	809	***3***			25
26	25	A5	480	470	490				
27	26	RITE GRN	840	830	850	***3***			
28	27	HI Q	849	839	859	***3***			15
29	28	HEL-LIGHTRYE	788	778	798	***3***			3
30	29	HEL-DARK-RYE	788	778	798	***3***			4
31	30	JUMBO-MEAL	1048	1038	1058	***2***			10

Figure 6.1: Part of sheet 'Products0' in 'Product Report Generator 1'.xls

6.3.2 Matching Initial and Final Weight Product Numbers

In order for this product reporting macro to be successful, the corresponding product numbers at the beginning and end of production must be known.

It is not always straightforward to match final product numbers with their corresponding initial products. This is because product names at the beginning and the end of production are not stored in the checkweighers as the same name and also, the order of storage is different.

A recommendation for the bakery is to create a standard method of entering data into the checkweighers. Each product should be spelt the same at the divider and the slicer checkweighers. Also, the product numbers should be corresponding. (i.e. product 1 at the divider is product 1 at the slicer etc.) If this recommendation were applied, entering the final product number data would be unnecessary.

6.3.3 Other Data

There are also several other items that are to be entered. If the product report is to be generated through the Product Performance Indicator software (discussed below), then these items do not need to be entered as the PPI enters them automatically. However if the product report generator is to be used directly from Excel, their values should be checked.

	M	N	O	P	Q
1	Date	LogDir	Success?	Reason	Report Pattern Directory
2	30_10_2000	D:\BRI\Downloaded Canberra\	TRUE		D:\BRI\VisualBasic\PPI\21_08_2000

Figure 6.2: Other data to be entered in sheet 'Products0' in 'Product Report Generator 1'.xls

6.3.4 Data to be entered:

The date that data is to be processed for is to be entered in cell 'M2'.
The directory where the data is logged is to be entered in cell 'N2'
The directory containing the file that is the pattern of the report to be generated is entered in cell 'Q2'.

Cell 'O2' states whether the product report generation was successful or not in terms of macro operation. If there were any errors, this cell's value is 'FALSE' and the reason for failure is entered by the macro in cell 'P2'.

6.3.5 Manually Running the Macro

To run the macro form within Microsoft Excel, press Alt+F8 or 'Run Macro'. Run the macro entitled 'DATAPROCESSBYWEIGHTS'. This is the main macro that calls all other sub procedures that do the data processing. For precise operation information, all of the procedures are commented within the macro (see accompanying CD). A basic flowchart showing the operation of the macro is shown in Figure 6.3.

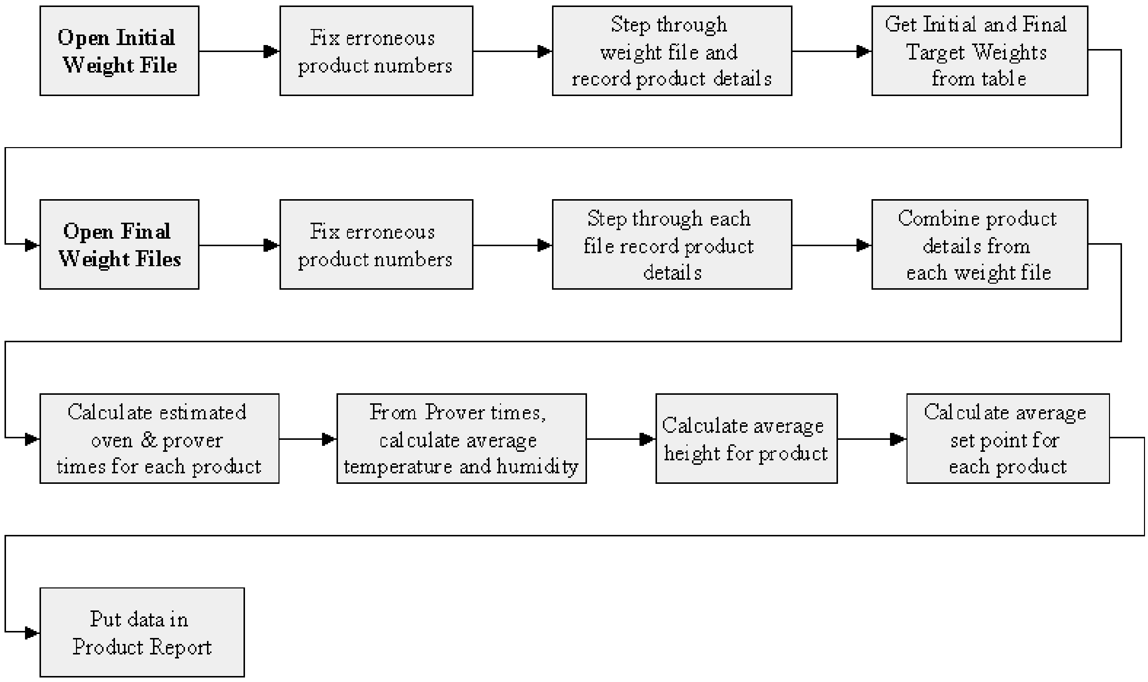

Figure 6.3: Flow chart of data processing algorithm to produce production report

The step in the flow chart entitled 'Fix erroneous product numbers' is necessary because for an unknown reason, an ASCII character may not be received in the product number part of the data sent from the checkweighers. For example, during product '19', a product number of '9' or '1' may be recorded. Fixing the erroneous product numbers consists of looking at the product number in the weight entry before and after every entry. If they are both the same, but different from the current entry, the current entry is changed.

6.3.6 Running the Macro from the PPI Software

The Product Performance Indicator software has the ability to access the report generation macro in 'Product Report Generator 1.xls'. A brief description of how this is achieved is included in Section 3.11. The PPI also updates product data in the workbook whenever data is updated at the checkweighers.

6.3.7 Resulting Product Report

An example of a report produced is shown in Figure 6.4. Most of the product counts suggest that the reporting is being done quite accurately. There are several products for which the product counts are not accurate though. For example, there are no final weights for product 14. This is because of mistakes in the setting of product numbers at the final checkweighers at the bakery.

Also, for product 13, there were no product heights recorded. This was a very short production run, so a slight inaccuracy of time calculations means that the wrong heights or no heights would be recorded.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y
4		Initial weight (g)				Final weight (g)			Wt loss (%)		Prover oC	%	Height (mm)		Yeast (%)		Oven set-point (oC) Current		Recom		Counts (No)				
5	Prod No.	Ave	Stan Dev	Target	Target Rec	Ave	Stan Dev	Target	Ave	Target	Temp Ave	R.H. Ave	Current	Target	Current	Rec	Front	Back	Front	Back	Makeup Plant		Slicer	Lost	U.wgt
6																									
7	6	1030	6.2	1025		912	15.0	900	11.5		42.5	74.9	72				202	195			507		489	18	1
8	5	1029	7.5	1029		901	55.0	900	12.5		42.6	74.1	75				202	195			122		120	2	7
9	7	777	6.4	774		694	9.3	680	10.7		42.3	64.2	91				202	195			5005		4937	68	6
10	9	793	5.2	783		699	6.4	680	11.8		42.0	64.5	80				205	199			1586		1540	46	0
11	10	836	6.6	831		730	13.3	720	12.7		42.7	61.9	89				205	200			1547		1272	275	5
12	12	835	7.9	824		731	16.2	700	12.4		42.1	60.0	91				212	208			3818		2463	1355	0
13	14	886	6.9	882		0	0.0	750	100.0		40.8	58.3	90				225	211			547		0	547	0
14	15	903	6.4	896		776	8.5	750	14.0		40.9	58.3	99				215	219			247		156	91	0
15	13	871	4.9	865		745	20.2	700	14.5		40.8	58.6	0				226	219			85		123	-38	1
16	16	808	5.6	804		689	10.1	680	14.8		40.9	58.7	78				228	225			757		738	19	1
17	17	807	5.7	802		700	10.0	680	13.2		41.0	58.5	73				227	227			1094		1061	33	1
18	18	715	8.7	712		614	12.2	600	14.1		41.0	58.7	66				227	227			275		268	7	1
19	19	801	6.6	796		698	13.4	680	12.9		41.1	58.0	63				227	227			4326		4189	137	8
20	20	765	6.3	760		665	13.3	650	13.1		41.6	56.6	62				227	227			5874		5902	-28	5
21	19	798	5.8	796		696	11.3	680	12.7		41.9	55.9	67				198	224			400		237	163	0
22																					26190		23495	2695	36
23																									
24																									

Figure 6.4: Example of product report produced by macro in 'Product Report Generator 1.xls'

6.4 Correlation of Gaps

Correlation is a well-known mathematical method of determining the relationship between two sets of data. The method may be applied to gaps between loaves to determine product change gaps at various points in the system.

Advantages:

- Mathematically sound approach
- Can eliminate problems due to production stoppages and loaf removal

Disadvantages:

- Data must be post-processed, i.e. no real time correlation may be easily done
- Takes much more processing time
- If stoppages and removals are too frequent, the correlation will not work.

6.4.1 Description of Gap Correlation Approach

Some example plots of the gaps experienced in a bakery are shown in Figure 6.5. It can be seen that there is a similarity between gaps experienced at the Divider and the Prover entry. This occurs even though the gaps being sensed at the Prover are between tins whereas the gaps sensed at the Divider are between individual loaves.

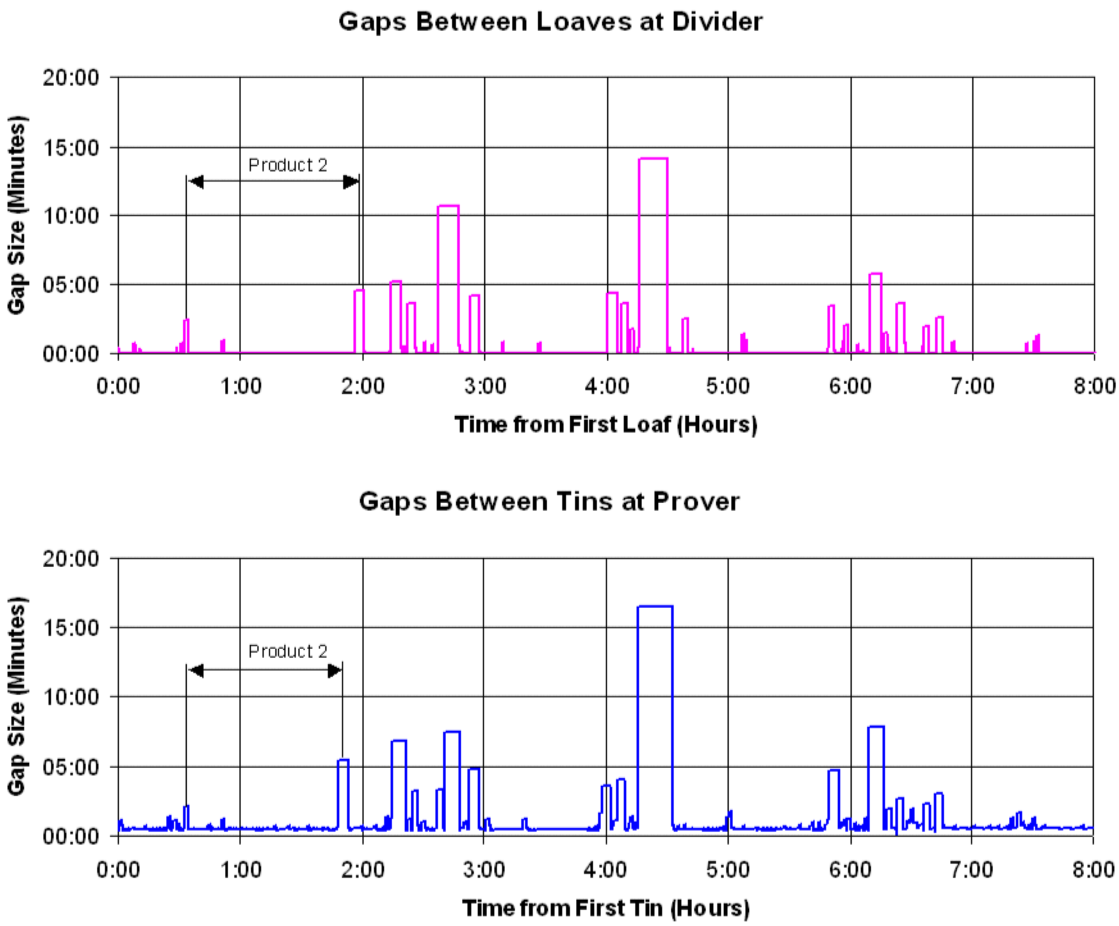

Figure 6.5: Plots showing gaps between loaves/tins at the divider/prover.

The correlation product tracking technique seeks to establish a relationship between product change gaps by correlating the gaps at a point in the system with gaps measured at an earlier point. If this is done for several points throughout the bakery, product change times should be calculated accurately.

In Figure 6.5, Product 2 is marked both at the Divider and the Prover. If this product's starting and finishing times are known at the Divider, then the times at the

Prover are obvious from visual inspection of the plot. This may not be the case for all products however.

As an example of the correlation technique will be discussed for Product 2. First of all, the data needs to be sorted correctly. The data that is recorded directly from the bakery is logged every time a loaf/tin passes the sensor. This means that the array of sensor times will be a different size for each sensor, and the gap between entries will change. For correlation, gap arrays need to be of the same length, and the time between entries must be the same.

So a standard time array must be produced. In this case, the standard time array used had an entry every 5 seconds. This value was chosen because it is small enough to allow all gaps to be recognised but large enough to minimise processing time. (Longer arrays require more processing time). An example of the raw data is shown below.

:	:
0:51:16	0:00:01
0:51:18	0:00:01
0:51:18	0:00:01
0:51:19	0:00:01
0:52:13	0:00:54
0:52:15	0:00:02
0:52:16	0:00:01
0:52:16	0:00:01
0:52:17	0:00:01
0:52:18	0:00:01
0:52:19	0:00:01
:	:

A macro was written to match the sensor data to the standard time array. An example of the type of output it provides is shown below.

:	:
0:51:15	0:00:01
0:51:20	0:00:54
0:51:25	0:00:54
0:51:30	0:00:54
0:51:35	0:00:54
0:51:40	0:00:54
0:51:45	0:00:54
0:51:50	0:00:54
0:51:55	0:00:54
0:52:00	0:00:54
0:52:05	0:00:54
0:52:10	0:00:54
0:52:15	0:00:01
:	:

Once the gap data has been matched to a standard time array, it must be decided how to do the correlation. It is known when a product starts at the Divider since the product number is recorded. The approach then used was to take the start of the gap at the product change as the beginning point in the correlation. The end point of the correlation was taken as 2000 samples after this. The 'Divider Gaps' series in Figure 6.6 shows all values that were correlated to the Prover values.

It was decided that taking 2000 samples for correlation was better than using only the samples from the particular product being analysed. This is because some products only run for a short time, meaning there may be as few as 60 sample periods with which to correlate - not enough to produce a reliable result. Taking 2000 samples means that about 2 3/4 hours of data is correlated.

Before conducting the correlation, the estimated time that the product is expected at the next point should be calculated. In the example case shown here, loaves are expected at the Prover between 5 and 15 minutes after they have been recorded at the Divider. This approximate arrival time at the prover is shown in Figure 6.6.

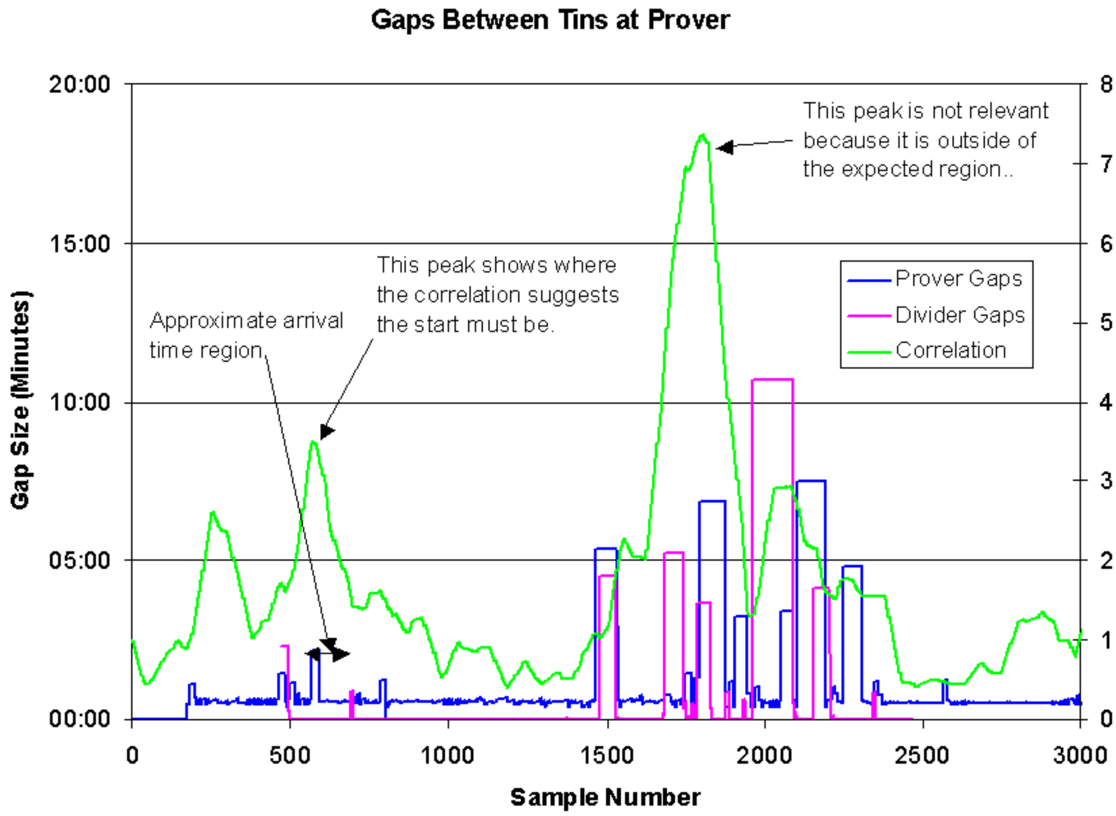

Figure 6.6: Plot showing how correlation can show where the product change gaps occur

The green line in Figure 6.6 shows the correlation that was performed . The peak that occurs in the approximate arrival time region is the one that the correlation suggests is the start of the product at the Prover. In this case, the correlation has proven successful with an accurate result.

The problem with the approach used here is that it creates difficulties for correlating the final products. That is, products that occur within 2000 sample periods of the final product will not have 2000 loaves to be correlated with. In this case, it may be better to go ‘backwards’ with the correlation group. The final sample in the correlation group would be where the product change is. The first sample would be 2000 entries before this. When the correlation is performed, the resulting peak will be 2000 entries before the actual start time.

6.4.2 Other Correlation Issues

Correlation of gaps has a great deal of potential to assist with product tracking in a bakery. It does need to be used carefully however, with the addition of other information.

When compared to techniques such as Post-Production Logical Processing (see Section 6.5), correlation involves more processing time, but has the advantage that it can remove some inaccuracies due to stoppages that were not sensed and product removal. This is because the correlation may be done using data from many hours of production. Using this much data to determine one time can overcome small inaccuracies due to product removal.

Short stoppages may also not affect the result significantly since the variation in production time due to a short stoppage will only last until that section of bread has finished production. If correlations are done for times of 4 hours or more, these should be eliminated. On a particularly 'bad' day, stoppages and removals may cause correlation to fail, but on these days most other forms of product following would probably fail as well.

One concern with the correlation approach is that 'coincidences' may occur, causing false peaks to be taken as the product change time. The extent of these coincidences is not known and would require much more testing to determine. Using other data such as that discussed in Section 6.5 should eliminate this.

6.5 Post-Production Logical Processing

This is the approach where data is read in from the log files and processed according to a logical set of rules that are defined according to the behaviour of the actual baking process. For example, when a product is produced at the divider, its estimated time at the prover is calculated. The gaps at the prover are monitored around this estimated time until a gap that looks approximately like the expected one arrives. This is then regarded as the product change.

This method is open to some errors because not every action in the bakery is monitored. If product is removed from the conveyor or if a stoppage occurs that is not sensed, errors in the calculations will occur.

6.5.1 Deterministic and Non-Deterministic Events

Events in the bakery may be divided into two categories - deterministic and non-deterministic. The deterministic events follow a logical pattern, or may be easily sensed to show how bread is flowing through the system. For example, the oven, prover and cooler are all deterministic, because a shelf movement may easily be sensed, so the position of a loaf of bread in the oven may accurately be known (as long as the loaf's precise entry time is known).

Non-deterministic processes are those such as slicers and baggers where there is a buffer for the bread, or those processes whose operation is not, or cannot be sensed. For example, at the bagger, the throughput rate depends on the skill and speed of the operator. It is very difficult to correlate between a loaf that enters the bagging section and the same loaf being weighed at the end of the section.

6.6 Detailed Description of Technique

The approach taken to attempt to track loaves of bread through the system will now be discussed. As well as tracking, it describes methods used to produce useful statistical data from the logged information.

The general approach taken is to follow the 'gaps' through the system. The data is processed in the order of production. So, starting from initial weights, the data is processed and some information such as gaps and average product weights etc is stored. Each point in production where data is sensed is called a node. At each node, a new estimated time for the next node(s) is calculated.

Figure 6.7 shows all nodes in the system. It also includes two extra pieces of data that are not classified as nodes. These are the oven shelf data and prover shelf data.

Theoretically, once the tins have entered the prover, that shelf should be able to be tracked accurately until it exits the oven using the oven and prover shelf data. The nodes between which, loaves may be tracked accurately and deterministically are joined with a dashed line.

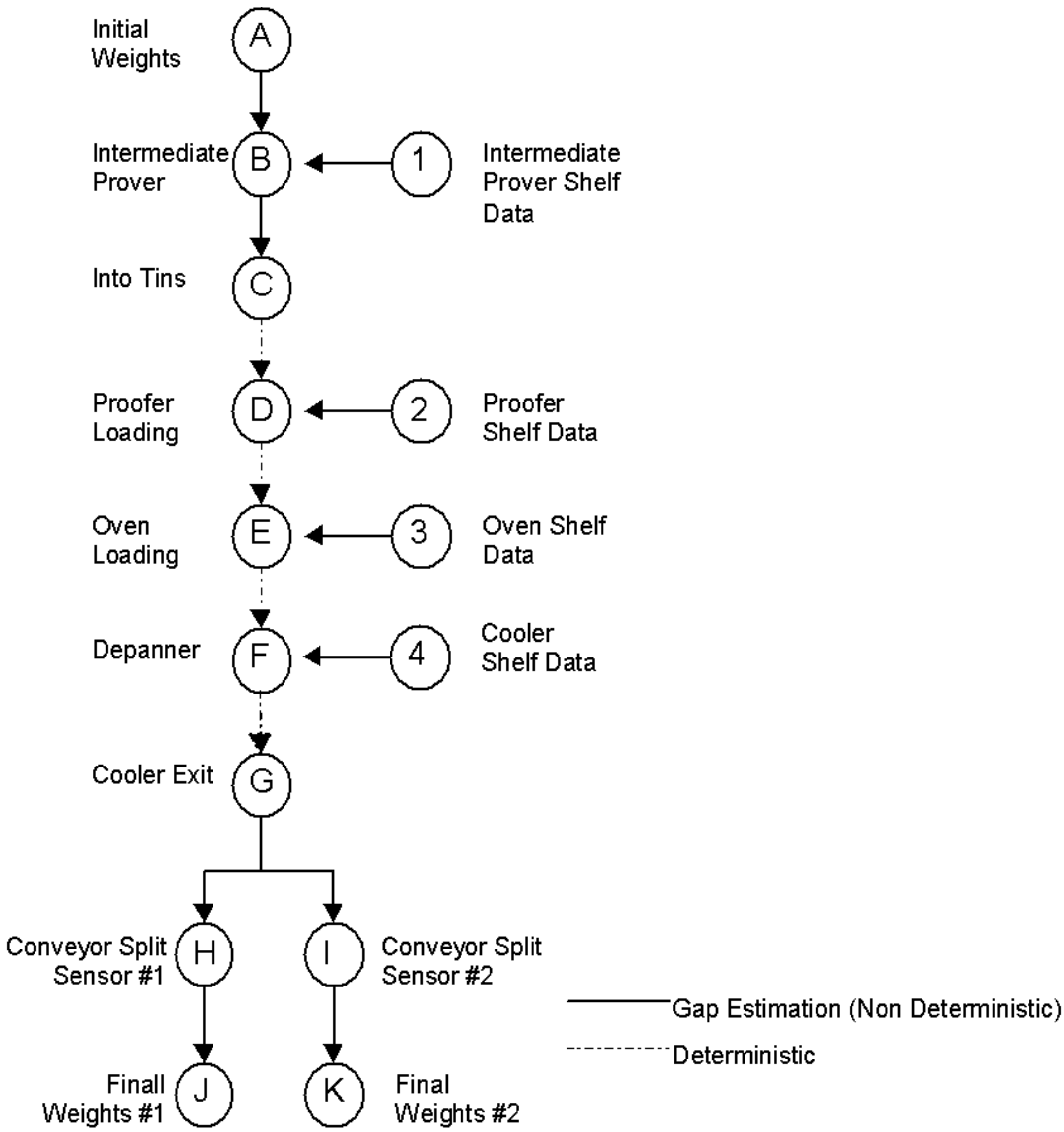

Figure 6.7: Node diagram of the bakery

Each section above will now be described in greater detail. Since the rules and conditions are different for different nodes, each will be discussed separately. However there are some general approaches that are common for most nodes. Many of the techniques described are put into practice in macros included with the file

‘Product Gap Tracker.xls’ on the accompanying CD. These macros are discussed during the description of each node further below.

During development, the system was designed so that calculations at any particular node could be omitted, and the data processing would continue. For example, while calculations at Node B, ‘Intermediate Prover’ were not working properly, they could be omitted, and the estimated times calculated at Node A would be used for Node C.

The main control sub procedure is named ‘ProductReport’. It calls all other sub procedures.

6.6.1 Node A: Initial Weights

The initial weight file is the logical place to start processing. It is read sequentially with data being stored for each product.

Data that is obtained from this file is as follows:

- Product Start Time
- Product End Time
- Product Number
- Gap size at start of product (i.e. the size of the gap between the last loaf of the last product and the first loaf of the new product)
- Average initial loaf weight for each product
- Standard deviation of weights for each product
- Number of loaves passed
- Number of under-weight loaves
- Estimated times to the other nodes are calculated.

The sub procedure that achieves this is ‘InitialWeights’.

6.6.2 Node B: Intermediate Prover

There is only a small gap between when the dough is weighed at Node A and when it enters the intermediate prover, however this is one area where some interesting events occur. Sometimes, due to sensing mistakes, two pieces of dough may end up in one pocket of the prover. Usually the operator then removes both loaves. Events such as this cause problems with product tracking.

This node has not yet been utilised in the product tracking software. A sensing approach that reliably detects which loaves have entered the prover needs to be developed.

6.6.3 Extra 1: Intermediate Prover Shelf Data

The sensor here senses the movement of shelves in the intermediate prover. The shelf moves whenever it is full of loaves. Each shelf contains eight loaves.

This sensor is not truly a 'node' in the system, but it is more than an 'extra data' indicator. The prover moves forward every time 8 loaves have been loaded into it, or when it has been sitting still for a specified period. Combining the shelf movement data with the initial weights should then give quite an accurate estimation of when loaves will be exiting the prover. This then allows a good estimate of the time that the loaves will reach node C, 'Into Tins'.

A possible reason that the accuracy of estimation to node C may be decreased is stoppages in the rolling/shaping section. If these occur, they will not be able to be sensed accurately and the time taken for the loaves to reach node C will be extended, or the loaves may not reach the node at all.

This node has not been included in the tracking software at this stage.

6.6.4 Node C: Into Tin

The sensor here senses each loaf as it enters the tin. An accurate loaf count may be made here, as this is not an optical proximity sensor prone to errors. It is connected to a relay that is part of the production line.

The technique used is to recognise the gaps between products when they reach here. An estimated time of arrival is known. This is the quickest time a loaf can get here. All gaps are monitored, and the first one that is of the approximately correct size after the estimated time of arrival is regarded as the product change gap.

The main problem with this approach is that there is still quite a large margin for error. Since the loaf count here is accurate, it too may be used too ensure that the gap chosen is the correct one. That is, once too many loaves have passed, it would be certain that the required gap has already passed.

If node B or extra 1 were not in operation, average conditions in the intermediate prover may be calculated. (i.e. temperature and humidity) experienced by loaves in the intermediate prover may be calculated.

The sub procedure that achieves this is 'IntoTins'.

6.6.5 Node D: Prover Loading

The prover is loaded whenever there is a full compliment of 12 straps ready to enter it or when the operator makes it load by pressing a button. This creates a buffer of sorts, since only 6 straps may have reached the prover before a gap occurs. These straps would normally remain until the first 6 straps after the gap have arrived. This causes a processing problem since it 'blurs' the gap between varieties. Figure 6.8 shows this diagrammatically.

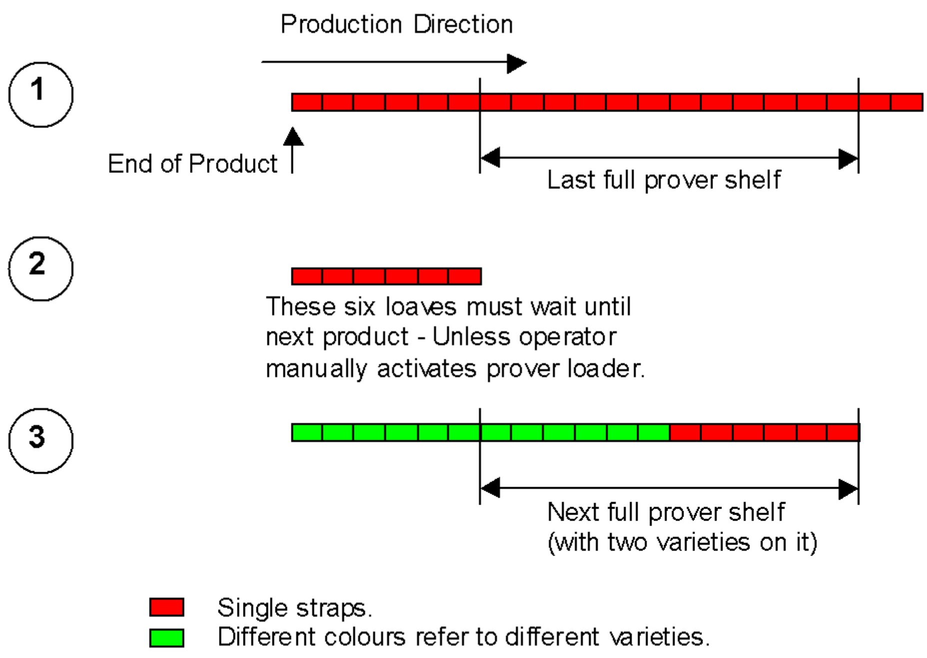

Figure 6.8: Mixing up of products at prover entrance

If an operator sees that there is a large gap and there is not a full shelf ready to enter, or if he knows there is a product change he will manually start the shelf loader so a shelf with less than twelve straps on it will pass through. Currently there is no sensor in place to know how many straps are on a shelf. A sensor that senses individual straps should be installed in the future.

At this node, exact prover entry times are calculated. Estimates of loaf times at other points in the system are also calculated. The sub procedure that uses data from this node is 'ProverEntry'.

6.6.6 Extra 2: Prover Shelf Data

The three 'Extra' data nodes extras 2, 3 and 4 are extremely useful because the extra information they give causes the system to be deterministic until the next node. This node is connected to a relay that operates every time the shelves in the prover move.

Slight inaccuracies are sometimes introduced because the shelf may start moving then stop for an unknown reason. Unless the data processing software is conditioned for this, it will register as two shelf movements instead of one. Since this is a very rare occurrence, it was mainly ignored. However if it is to be eliminated, an approach could be taken to 'filter' the prover shelf data file so that any entries too short to be a full shelf movement are combined.

There are 147 shelves in the prover. Using the data from Node D, 'Prover Loading', the loading time is known. Using this extra information, it is known that once the prover has moved forward 147 times, the loaves will be exiting. Thus, quite an accurate estimated exit time may be computed. The only problem with this is that if a 'false move' as described above occurs, the shelves will only have moved forward 146 times. This should not be a problem since it will mean the oven entry estimated time will be a shelf earlier than it should be.

The sub procedure that processes the prover shelf data is 'ProverShelfStore2' which is called from 'ProverEntry'.

6.6.7 Node E: Oven Loading

The oven loading node senses differently to the prover loading node. This node consists of an optical proximity sensor that senses individual straps as they enter the oven. This sensor is sometimes unreliable because it is placed in a position where it accumulates dust which can obstruct its view of the loaves if not cleaned often. It may also be falsely tripped if operator's hands get in the way of it (unlikely).

Using the estimated oven entry times determined at node D (with Extra 2), gaps are monitored until the correct one passes. This is then regarded as the exact oven entry time.

Once the exact oven entry times are known, loaf height data from the prover exit may be processed to calculate the average height for a product. Prover conditions (temperature and humidity) may also be determined.

Also, since the exact oven entry times for each product are known, oven conditions may be calculated. Currently only the oven set-point is averaged. A future step would be to use the calculated entry time to produce a loaf-perceived temperature plot as discussed in Chapter 5.

The sub procedure that process data from this node is ‘StrapsIntoOven’.

6.6.8 Extra 3: Oven Shelf Data

This node is similar to Extra 2, ‘Prover Shelf Data’. It is connected to a relay that operates when the shelves in the oven progress. Thus, each time the relay turns ‘On’, it may be assumed that the oven has moved forward a shelf. This information is used along with Node E, ‘Oven Loading’ to reliably predict when the loaves on a particular shelf are going to exit the oven.

Problems may occur if the sensor goes ‘On’ twice during one shelf movement since this will be recorded as two shelf movements. This is a very rare occurrence however and may be ignored.

The sub procedure that processes the shelf data is ‘OvenShelfStore’ which is called from ‘StrapsIntoOven’.

6.6.9 Node F: Depanner

There are currently two sensors being experimented with at this point.

A proximity sensor was originally placed immediately after the loaves exit the depanner. This has worked fairly well, however occasionally at this position, loaves are touching or too close together to be sensed separately (see Section 3.1.2). Although this does not affect product tracking, it does mean the loaf count is not entirely accurate.

A new input that may replace the proximity sensor operates via a relay connected to the depanner. Every time a loaf is depanned, the relay operates. Currently scan times of the PLCs (Section 3.1.2) are not small enough to detect every loaf.

Loaves may be tracked accurately through the oven because its movements are known according to Extra 2, 'Oven Shelf Data'. However, the time taken for loaves to cover the short distance between the oven exit and this node (F) is quite variable because of the depanner. Occasionally the depanner will jam, causing a stoppage. Also, the occasional loaf may not be successfully removed. An operator may remove this loaf and place it back on the assembly line at a later point.

So this short section negates to an extent, the deterministic nature of following loaves through the oven. The answer may lie in adding extra sensors. A proximity sensor could be placed at the oven exit to sense loaves as the exit, however since their exit time is known anyway, this should not be needed. It may also be possible to take a digital input from the depanner itself that indicates whether it is operating or not.

Currently, using the estimated oven exit times, gaps are monitored at this node until the appropriate gap for a product change appears. New estimated product times for the slicer are calculated here.

The sub procedure that processes data from this node is 'Depanner'.

6.6.10 Extra 4: Cooler Shelf Data

This node is similar to extra nodes 2 and 3. It is connected to a relay that operates when the shelves in the cooler progress. Thus, each time the relay turns 'On', it may be assumed that the cooler has moved forward a shelf. This information is used along with Node F, 'Depanner' to reliably predict when the loaves on a particular shelf are going to exit the cooler.

See sub procedure 'CoolerShelfStore' where the shelf information is loaded into an array. This data is then used in sub 'Depanner'.

6.6.11 Node G: Cooler Exit

This node is located after the loaves have exited the cooler and before the conveyor splits into two. The node consists of an optical proximity sensor that senses individual loaves. The loaf count recorded here is not entirely accurate since many loaves are too close together to be sensed separately (See Section 3.1.2).

This is the last time the loaves are sensed before entering the conveyor split. The gaps are monitored here and when correct product gaps are sensed, the calculated slicer time is the gap time at this node, plus 48 seconds. This was done, rather than observing gaps between loafs at the slicers to eliminate problems caused by having the split in the conveyor.

A better way to calculate slicer times in the future would be to have separate calculated product times at the cooler exit and the final checkweighers. This is discussed further below.

The sub procedure 'SlicerTimes' processes data from this node.

6.6.12 Node H/I: Split Sensors 1 and 2

There are two nodes located just after the conveyor split. They are fairly reliable at sensing individual loaves. Using the data from these sensors, it should be possible to determine which loaves went down which side of the split in the conveyor. The weight files below may then be resolved into the actual order that the loaves were baked in.

6.6.13 Node J/K: Final Weights 1 and 2

The final nodes are the final checkweighers. Each of these record weights, times, product numbers and Over/Under/Pass messages for the loaves.

6.6.14 Further Discussion

Several non-deterministic events in this region reduce the accuracy of product following.

Sometimes overweight loaves may be rejected by the system. Operators often place these back on the conveyor so they will go through the checkweigher again. This causes problems because the weight of that loaf will have been recorded twice.

Often, loaves may be rejected here for other reasons such as metal being detected in the loaf. These are then removed either manually by operators or simply automatically removed from the conveyor by the nature of the fault. Since these losses are not sensed, calculation errors may be caused when attempting to line up loaves exactly.

Notwithstanding the above problems, there are enough loaves to get some basic data from.

Final weights may be averaged to produce the average weight loss for the product. A moving average of weight loss may also be determined - for example, an average for every 100 loaves. A few loaves of inaccuracy either way here should not make much difference to the result.

Currently, at this node, the calculations done for each product are average weight, standard deviation and average weight loss.

The sub procedure 'FinalWeights' processes data from these nodes.

6.6.15 Results

The product tracking software that as been written has demonstrated that the types of techniques being discussed definitely have the potential to reliably track products and loaves through the bakery. Much work must be done on the system before it becomes completely reliable however.

The effectiveness of the current software may be observed by looking at loaf counts at various points through the bakery. These counts are placed in a table in Excel when processing is complete. An example of these results is shown in Figure 6.9.

Product Counts at Various Points - 14/09/2000

Prod No	Divider	Into Trays	Prover	Oven	Depanner	Cooler Exit	Slicer
1	2873	2873	2880	2901	2769	2736	2759
2	6968	6963	7056	6594	6204	6693	6759
3	183	200	180	144	999	581	518
4	383	397	396	861	480	496	485
6	458	533	612	507	21	68	38
5	112	51	36	30	64	121	76
7	6370	6369	6444	6030	5834	5742	5739
9	2685	2704	2700	4839	5003	4992	4925
10	2138	2146	2160	471	5492	6962	7031
13	172	189	180	6096	17	-1	27
12	6303	6367	6372	36	383	272	212
14	722	735	720	735	1019	294	261
15	271	289	252	738	140	343	266
16	802	817	612	252	27	133	93
17	1205	1231	900	942	489	715	686
18	341	5327	4032	4368	2481	5486	5665
19	4883	778	576	1332	718	1665	1684
20	5749	5452	4104	3030	1570	3847	3966
19	404	1	0	321	180	398	359
Totals:	*43022*	*43422*	*40212*	*40227*	*33890*	*41543*	*41549*

Figure 6.9: Product counts at various points resulting from product tracking

If product tracking was working perfectly, one would expect to see loaf counts for each product that decrease slightly at each section (due to product losses) or remain the same. In reality, product counts at the prover and oven cannot be regarded as completely accurate since they are calculated by multiplying the number of straps counted by the number of loaves per strap. Since not all tins may have a loaf inside them, the recorded count here may be too high.

Also, as can be seen from the total count at the depanner, many less loaves were sensed here. This is due to the scan period of the sensors as discussed earlier.

The loaf counts of the first seven products of the day are charted in Figure 6.10. (Note - the product numbers shown in the legend refer to the product number code in the initial checkweigher, not the order of production.) This chart seems to suggest that product tracking was working very well for the first two products. After that, the accuracy of the loaf-counts generally decreased as small errors combined and the more difficult sections of the bakery were encoutnered.

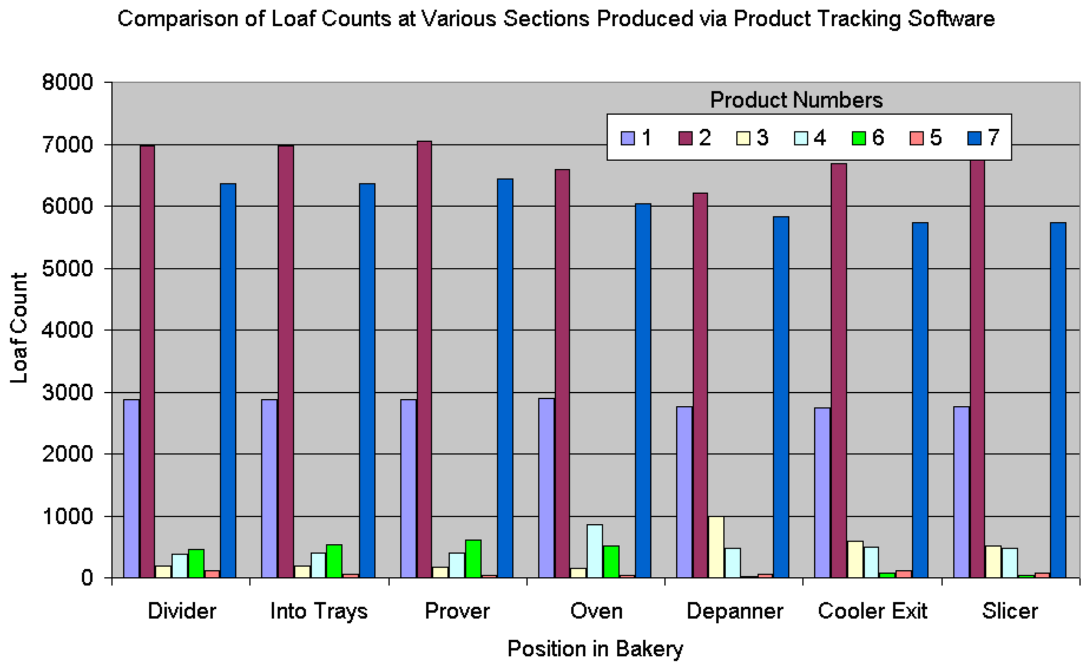

Figure 6.10: Chart of product counts at various points resulting from product tracking

6.6.16 Methods of Improving Results

To improve on these results, there are several other factors that may be taken into account.

Initially, a more modular software approach could be taken. Since the current software was developed along with the technique, there are several improvements that may be made. This will be done in the next iteration of product following software.

Currently, to detect a product change, the first gap that is in the expected range is taken to be the product gap. The 'expected range' was generally set as larger than a minute and smaller than 1.35 times the same gap size at the previous section. The '1.35' figure was chosen after examining normal gap size changes during production. To improve on this, a better approach would be to store all gaps and times at each point in the system. The most likely gap could then be chosen as the product change rather than simply the first one that fits the requirements.

Additionally, rather than only keeping tracks of the gaps between products, all gaps over a certain size should be kept track of. This would be quite difficult due to the changeable nature of the gaps, however if it can be achieved, could improve product-tracking accuracy.

Another way of improving tracking would be to develop more accurate methods of counting loaves. This is especially relevant for the product counts at the prover and oven entries and the depanner. At the prover and oven, a method should be developed that counts how many loaves are actually in each strap. This could involve setting up an ultrasonic proximity sensor that measures distance, or using a linescan camera device to observe the straps. This would also determine what type of straps were entering the oven/prover (ie 2, 3 or 4 loaf straps).

At the depanner, a digital input is already in place that should be able to sense individual loaves, however the scan times of the PLCs need to be decreased to make it more accurate (see Section 3.1.2).

6.6.17 Future Possibilities

Once the exact entry and exit times of products for bakery processes are known, these may be stored in a separate file for that day. When data is to be further analysed, macros may be written to access this data and automatically produce plots of conditions experienced by the loaves.

This may be further extended to include plotting of specific conditions for individual (or small groups) of loaves.

6.7 Real Time Logical Processing

This method of following products would use approaches similar to those discussed in ‘Post-Production Logical Processing’ above. However the same types of rules are applied in real time to data that is currently being registered by the bakery. This makes the processing more complicated, but it should be possible. Also, the processing would most likely be done directly in Visual Basic instead of via an Excel macro.

6.8 Using Pseudo-Random Sequences to Accurately line up Loaves

Lining up initial and final weights so that a loaf-by-loaf calculation of weight loss can be done is the 'holy-grail' of this project. The benefits of doing so are discussed in Chapter 4. Loaf by loaf product following has not currently been achieved in a commercial bakery setting. The benefits of doing so are great.

Loaves entering the bakery from the divider do so in the form of a Pseudo-Random sequence (using the change in weights (delta-weight) as the pseudo-random variable). At the end of the baking process, it may be possible to line up loaves again by looking at this sequence and correlating it with the loaves at the beginning. Before correlating, the loaves would have to be lined up as accurately as possible using other methods described in this chapter. After the approximate lining up, smaller groups (50 or 100) of final weights would be correlated with initial weights to find a match. Once the match is found, individual weight losses may be determined.

Although this all sounds straightforward, there are many difficulties with completing this accurately. These difficulties are discussed here.

6.8.1 Loaf Losses and Order Changes

During baking, there are often several points in the system where the loaf order changes. In the bakery studied during this project, an order change occurred at the exit of the oven/prover section. Loaves, in straps containing 2, 3 or 4 loaves enter the section facing one way and exit facing the other way. This is not a problem in itself, because the final loaf weights may simply be 're-ordered' before doing correlation.

The main problems occur because of loaves lost during production. It is difficult to sense when a loaf is lost because it may simply involve an operator removing a burnt or deformed loaf from the conveyor.

Other times, a loaf may be removed at one point and replaced further on in production. This is quite rare except at the De-panner where a loaf often is not removed from the pan. The operator then removes it by hand and places it on the conveyor with another group of loaves. This problem may be overcome by suitable data processing. If a suitable correlation is found, then the correlation is suddenly out by one loaf, it is known that a loaf has been added or lost.

6.8.2 Re-ordering Loaves After Conveyor Split

An extra problem in realigning weights is caused by conveyor splits. In the Canberra bakery, there are two slicers, so at a point before them, the conveyor splits in two and there are two final sets of scales. The two sets of scales do not weigh the loaves in the same order as they approached the conveyor split, because there is a 'buffer' section where loaves wait to be sliced. So there has to be some method of 're-aligning' the loaves.

Using proximity sensors to count loaves passing seems to offer the best solution. Loaves are sensed just before the conveyor split, then loaves on each branch are sensed also. By using this data, the correct order of loaves may be rebuilt.

There may still be problems with product losses in the slicers and baggers, but these may be dealt with as discussed above.

6.8.3 Effect of Unequal Weight Losses Across Oven Shelf

During baking, all loaves lose weight in the form of moisture. This weight loss is not the same for all loaves due to unequal baking across the oven shelf. This phenomenon is discussed further in Section 4.5.1.

The variations experienced across the oven shelf may be up to ten grams. This is an estimate from experiences at other bakeries. This is more than enough to cause unreliability in the results of the correlation calculation of final weights.

To overcome this problem, the oven shelf weight loss profile needs to be determined. A method of achieving this is discussed in Section 4.5.1. Once this profile has been determined, it may be applied to the final weight data.

To determine exactly where to apply the profile is the next problem. To place the profile exactly across a group of loaves that constitute a shelf would require exact loaf-by-loaf product following. If this type of product following were possible, the pseudo-random sequence method of determining weight loss would not be required! At best, only an estimate can be made to determine where to place the profile. This should be able to be done quite accurately. After this, various correlations may be done to determine the correct placement.

6.9 Conclusions

Product following is important if oven control methods are to be improved. Three methods of following loaves through the entire bakery were proposed and tested. Post-production logical processing shows the most promise in the short term. Real time logical processing would be ideal to enable information to be used as the loaves are being baked. This was investigated. Finally, a novel approach to following loaves using pseudo-random sequences was proposed.

Chapter 7 - Conclusions and Recommendations

This project has identified various shortcomings in large-scale bakery processes and introduced new methods of dealing with these.

A complete bakery data acquisition system was developed and implemented. This system gathers data from all parts of the bakery and combines it in one central computer.

Methods of product following were developed and appraised with varying degrees of success.

Weight loss calculation techniques were developed. These were tested and production reports made available to the production manager at a bakery.

Algorithms and approaches were developed to calculate 'loaf perceived temperature' through the oven. Although improvements to this technique must be made, it allows the temperature profile for individual loaves to be displayed.

Methods to correlate loaf temperature history and weight loss were discussed.

Daily production reports were automatically produced, using information from the whole data acquisition system. This provides data that has not been previously available to the production manager.

To bring these improvements to the production line, various smaller projects, focussing on particular areas of the bakery may be defined.

7.1 Future Projects

7.1.1 Weight Processing Software

Software exists for logging weights from the checkweighers (Ramsey RCCI's 'AutoView'). It also produces various statistics and plots of data however it does not combine data from both the beginning and end of production.

A separate project is to produce a software package that collects data from checkweighers at the beginning and end of production and collates it. A product database could be maintained on a central PC that includes the product names and target weights for the beginning and end of production. Currently these are stored separately on individual checkweighers.

Using the 'Alignment by Extending Final Weights' method described in Section 4.2.2, weight loss reports could be produced for every product, with various plots available for display. These could include initial weights (and moving averages) with target weights, final weights with target final weights, weight loss with target weight loss, product giveaway charts, production costs, rejection charts and possibly others.

This software package would give production managers a great deal of data that is currently not available to them.

7.1.2 Product Following

Product following is one of the most pressing issues to be followed up. Basic methods of following products have been presented in Chapter 6. It is thought that the approach with the most potential would be 'Real Time Logical Processing' (see Section 6.7). This is an extension of 'Post-Production Logical Processing which was covered in depth in Section 6.5.

Work on this may be performed as a separate project, simply using sensor inputs to determine where products are at certain times. If a reliable system of following products can be developed, the way is paved for many other resulting projects.

Specifically, oven control relies heavily on product following. Weight loss can only be determined accurately and automatically once product following is working successfully. Once accurate weight loss may be reliably produced, oven conditions may be linked to this. Optimum oven conditions may then be developed for different products.

Calculating the thermal load of the oven also depends on knowing what products are entering the oven and how much they weigh. This can only be done accurately through product following.

7.1.3 Bakery Operator Early Warning System

Once a reliable method of product following has been developed, a logical subsequent project is to apply the it in a system that warns bakery operators when a new product is approaching.

One specific application is at the end of production where products are bagged. Knowing exactly what product is coming and when makes knowing which bags to have ready much easier. This may also be applied to the oven section where the operator may be advised when a new product is coming and what temperature to set the oven to.

Also, since operators already have specific set-points that the oven should be set to for different products, having an indicator of what product is approaching would be very useful.

7.1.4 Oven Modelling and Temperature Control

An important project involves further modelling of the oven. This is a very important project if automatic oven control according to loaf variety/oven load is to be applied at a later stage. The temperature inside the oven needs to be controlled more accurately than it currently is. This could involve both simple mathematical modelling to produce an accurate system model. Thermal flow modelling software has made great advances in recent years. The use of such software will allow accurate modelling of all that is going on inside the oven and allow accurate temperature control to be achieved.

This project would not necessarily focus on producing the ideal temperature for a particular product. Before that can be achieved, the oven needs to be able to be controlled at a constant temperature during normal operation. This would need to include simple calculations of thermal load depending on the entry of loaves into the oven.

The ideal result of this separate project would be an oven that, when set to a certain set-point, remains at, or very near to that set-point, for a constant thermal load.

7.1.5 Oven Redesign

There are many improvements that may be made to the oven itself. The temperatures that loaves are experiencing at every point during baking need to be known. The current oven makes this very difficult, as was discussed in Section 5.5.

To enable heat to be better controlled as it flows throughout the oven, one approach may be to add more separately controlled zones. This would enable the temperature that loaves experience to be much more closely controlled.

An extension of this project would be to develop custom time-temperature profiles (as discussed in Section 5.4) for the loaves. It is thought that using an optimum loaf temperature history energy could be saved and the quality of loaves maximised.

7.1.6 Determining Optimum Baking Conditions

To successfully control the baking process, the required oven conditions must be known. If a method of automatically controlling the oven is applied, neural networking methods may be used to develop optimal baking conditions. Records of baking conditions, proving conditions ingredients and loaf quality (in terms of weight loss and other values) would be kept automatically by the computer control system. The resulting data would be added to a database, from which methods may be used to calculate optimum values. This is obviously quite an advanced project and a fully installed and proved product following data acquisition system would be required.

7.2 Another Approach – Determining Customer Satisfaction

In addition to weight constraints that must be satisfied, the final characteristics of a product must meet the consumer's approval. In order to determine what consumers want, correlation of the final characteristics of a product with consumer acceptability should be performed.

Does every consumer want a loaf of bread that is exactly the same shape, colour and texture as the next one? It is more likely that each customer may have an individual preference pertaining to a particular type of loaf (i.e. crunchy, doughy, darker or lighter brown etc). The process of determining the qualities of the `ultimate' loaf is an exercise involving both marketing and engineering. Objective measurements taken from the loaves need to be translated into a set of states to describe the product (eg crispness, firmness, and moisture content). These then need to be related to subjective measurements obtained from consumers (eg taste, texture and appearance).

To achieve this, a consumer survey program would be commenced. This would involve measuring a quality (or qualities) of a loaf as it is being packaged. For example, image processing may be used to produce a coefficient that indicates the brownness of a loaf. This coefficient would be printed on the seal of the loaf. The packaging would have a survey form on it that asks the consumer to give their opinions on the loaf in several categories (eg colour, texture and taste). The consumer would be required to include the seal from the loaf when returning the survey. The consumer data gathered could then be correlated with actual quantifiable loaf qualities. Consumers generally will not return survey forms just to be helpful however. Some sort of reward must be offered to entice the return of surveys. For example, for every 5 forms completed and returned, a free soft toy or loaf of bread could be given to that consumer.

7.2.1 Quality Variation

In the end, the aim of controlling a bakery may not be to produce a result where every single loaf is identical, meeting exacting standards. Variation is healthy - to a point. Of course certain considerations must be met - such as the weight of the loaves. Legally, loaves must satisfy what their label claims their weight is. But even this may be negotiable - underweight loaves, instead of being discarded may be labelled as underweight and offered to the consumer at a suitably reduced price. This concept may also be extended to labelling other out-of-specification loaves with their characteristics (eg extra crunchy, extra chewy etc.). Marketing techniques may then be used to 'sell' their particular features. This means that consumers will still purchase the product and be satisfied, which, after all, is the aim at the end of the day.

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Appendix A: General Logging Details for the Product Performance Indicator Software Package

This appendix describes how data is logged from the Product Performance Indicator software.

All values are logged in default folders under the 'D:\PPILOG\dd_mm_yyyy' directory, where dd - date, mm - month and yyyy - year (eg 'D:\PPILOG\26_06_2000'). The 'D:\ PPILOG' part is able to be set manually in the options screen however. The values are logged with an accuracy of 0.1 seconds.

A.1 Loaf Weights

Checkweighers installed at the bakery output product weights automatically as ASCII text. The PPI captures the text and decodes it to display weight, product number and whether the loaf was overweight, underweight or passable.

The PPI can take inputs from 3 separate checkweighers on separately configurable serial ports. Serial ports may be configured from the 'Options' screen.

Filename	W_*c*.csv
What it logs	The weights, product number and Over/Under/Pass of loaves. *c* - The Checkweigher Number (0,1 or 2)
Typical Entry	"09:38:8.9", 460, "P", 1, 16, 7.472, "467.0", "462.4", "10.4"
What the entry means	- "09:38:8.9" is the time. - 460 is the weight in grams (if a '-1' is logged, it means that a loaf with metal in it was detected.) - P specifies Over (O), Under (U) or Pass (P). - 1 is the product number. - 16 is the production rate in loaves per minute. - 7.472 is the load rate in kg per min. - "467.0" is the average weight in grams. - "462.4" is the average weight for this product. - "10.4" is the standard deviation for this product.

Production rate, load rate and average weight are calculated using the last minutes worth of data. If no weights are being received, the screen is updated every 5 seconds, and the updated production rate and load rate are logged in "WGap_0.csv"

A.2 Loaf/Tin Counting (Proximity Sensors) and Relay Sensors

Proximity sensors are placed at various points around the bakery. These sense the passing of loaves or tins. Some sensors are also placed in positions that sense the passing of shelves into the oven. The count of each sensor is logged and displayed.

Filename	S*x*.csv
What it logs	Digital input operation
Typical Entry	"08:01:40.4"
What the entry means	The time that the input went from 'Off' to 'On' (0 to 1)

A.3 Temperatures and Relative Humidity

Temperatures of the oven, prover and cooler may be measured using thermocouples connected through the DL205 PLC. The log interval may be altered from a minimum of one second to an unlimited maximum.

Filenames are "IntProver.csv" (for the intermediate prover temperatures), "Prover.csv" (for the prover temperatures), "Oven.csv" (for the oven temperatures) and "Cooler.csv" (for the cooler temperatures.

Filename	Cooler.csv
What it logs	Cooler temperatures and relative humidities
Typical Entry	"08:26:6.9",26.5,30,15.1,69.9
What the entry means	Time, Temperature 1, Relative Humidity 1, Temperature 2, Relative Humidity 2

Filename	IntProver.csv
What it logs	Intermediate Prover temperatures and relative humidities
Typical Entry	"13:54:8.2",25.2,82
What the entry means	Time, Temperature, Relative Humidity

Filename	Oven.csv
What it logs	Oven temperatures and oven controller temperatures, setpoints and operation.
Typical Entry	"08:41:32.3", 205.9, 203.5, 273.9, 286, 28.5, 201.7, 236.5, 224.2, 225.8, 234, 213.8, 237.4, 202.7, 202, 0, 198, 0, 195.9, 195, 1, 191, 0
What the entry means	Time, TC 2, TC 3, TC 10, TC 9, Ref, TC 1, TC 4, TC 5, TC 6, TC 7, TC 8, TC 11, CALTemp0, CALSet0, CALOutStat0, CALAlSet0, CALAlStat0, CALTemp1, CALSet1, CALOutStat1, CalAlSet1, CALAlStat1(Note: CAL 0 is in the Back zone and CAL 1 is in the Front Zone) (See other Appendix for further information on sensor locations etc.)

Filename	Prover.csv
What it logs	Prover temperatures and humidities
Typical Entry	"10:17:41.5",41.3,40.8,40,84
What the entry means	Time, Temperature1, Temperature 2, Humidity 1, Humidity 2

All temperatures are in Degrees Celsius and Relative Humidity is expressed as a percentage.

A.4 Oven Temperature Controllers

CAL brand temperature controllers are used at the oven and the prover in the bakery. They are connected to the master PC via an RS-485 network using the MODBUS/RTU protocol. The PPI reads several values from these:

- Temperature
- Normal Set-point (Set-point and Alarm Set-point)
- Output Status (Low Burner and High Burner)

These values are logged at the same time and in the same file as temperatures from the thermocouples. However, since this file logs only every *x* seconds, there is also a log file which logs the exact time that the state of the burners changed.

Communications options are adjustable via the ‘Options’ screen. This includes setting the address of each controller. The controllers themselves also need to have this address set.

Filename	See thermocouple temperatures and also Out_x.csv
What it logs	Oven controller values. In the filename, *x* is the controller number (i.e. 0 is the Back Zone Controller and 1 is the Front Zone Controller)
Typical Entry	“05:12:48.8”,82.3,190,1,186,1
What the entry means	Time, Temperature (°C), Set-point (°C), Low Burner State, Alarm Set-point (°C), High Burner State

A.5 Loaf Height

Loaf height is logged via an ultrasonic proximity sensor connected to an analog input module on the PLC. Setting the ‘Minimum Height Threshold’ and the ‘Conveyor to Sensor Distance’ in the ‘Options’ screen configures this sensor. The PPI takes the average height for each loaf and logs it. The sensor is located at the prover exit.

Filename	H.csv
What it logs	Loaf height exiting the prover
Typical Entry	“07:51:37.3”,33
What the entry means	Time, Height (in mm)

The height value logged is an approximate average height for that particular loaf.

A.6 Oven and Prover Loading

This is an advanced logging procedure that is still very much in its development stage. Values are logged for the Prover and for the Oven. Currently, the value logged is a fraction of the maximum number of tins that can fit inside. For example, a load value of 0.5 means that it is half full. (Or half empty, depending on whether you are an optimist or a pessimist). This is not a very accurate indicator of the thermal load in the oven however, since loaves that have been in the oven for longer offer less of a thermal load than cold loaves entering.

Filename	ProverLoad.csv
What it logs	Prover Load
Typical Entry	"08:04:46",.3655172
What the entry means	Time, Load

Filename	OvenLoad.csv
What it logs	Oven Load
Typical Entry	"09:12:20.7", .5711806, .7569444, .3854167, 1604, .75, .7638889, .2916667, .7083333
What the entry means	Time, Oven Load, Front Zone Load, Back Zone Load, Baketime (Seconds), Zone 1 Load A, Zone 1 Load B, Predicted Front Zone Load, Predicted Back Zone Load.

NOTE: Currently (28/09/00), the final 4 entries above are still being developed. Their entries are not to be taken as completely accurate.

A.7 Cooler Shelf Weight

There is a load cell placed at the cooler that measures the weight of loaves on the shelf. This load is recorded for every shelf.

Filename	CoolerShelfWght.csv
What it logs	Cooler shelf weight
Typical Entry	"07:08:3.8",11.612
What the entry means	Time, Weight (kg)

A.8 Image and Video Capture

Images are captured approximately every five minutes (configurable) during production and whenever the manual image capture button is pressed. Video may also be captured manually. The images are stored in .jpg format. The video is stored as an AVI file.

The captured image filename is '*\Images\hh_mm_sspic.jpg*' where the image is captured at the time 'hh_mm_ss'.

The captured video filename is \Images\hh_mm_ssvid.avi where the file was finished being captured at the time 'hh_mm_ss'.

Appendix B: Bakery Process Photos

This appendix consists of various photos of bakery processes that were not included in other parts of the dissertation. Note that these photos are included in full colour in the accompanying CDROM.

B.1 Mixing/Dividing

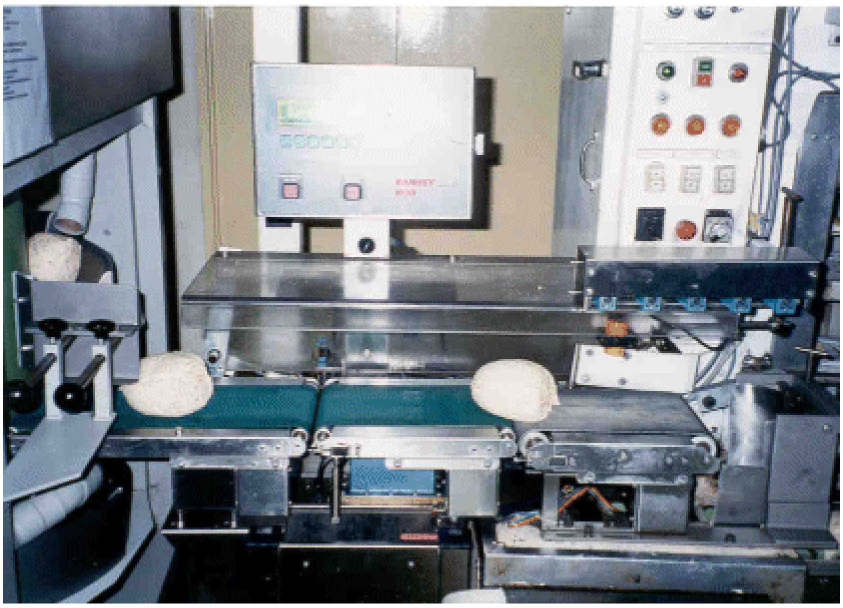

Figure B.1: Checkweigher after Mixer, Divider and Rounder

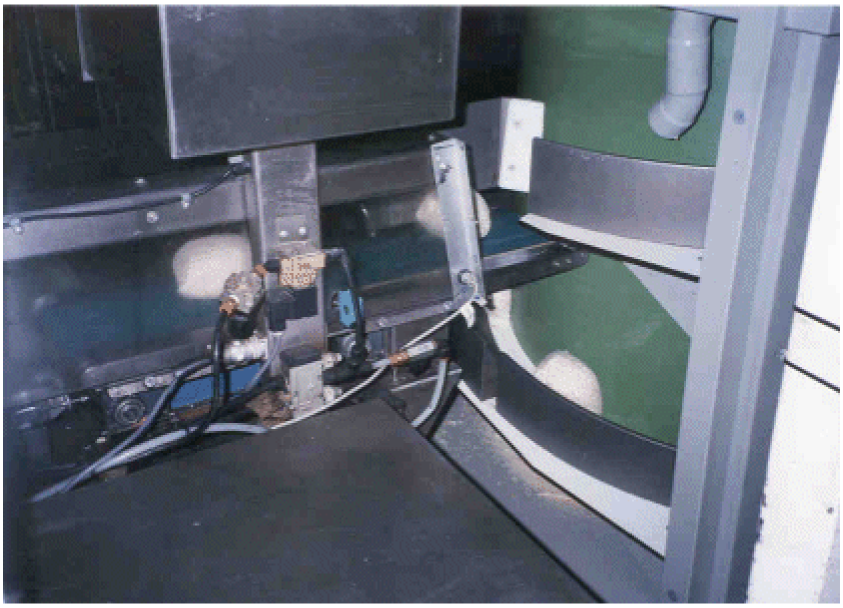

Figure B.2: Divider checkweigher from behind, showing dough entering conveyor from roller.

B.2 Intermediate Prover

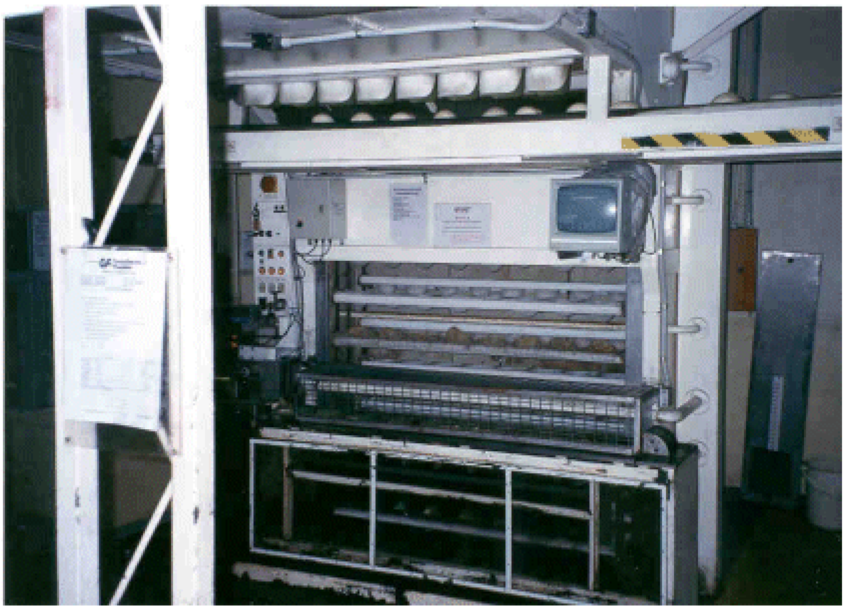

Figure B.3: The Intermediate Prover

B.3 Rolling/Shaping and Into Tins

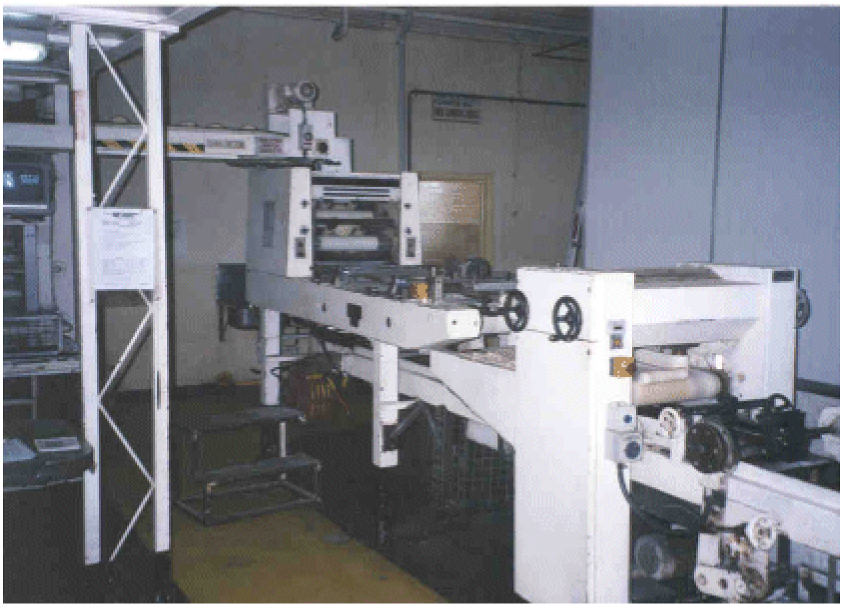

Figure B.4: Dough rolling and shaping section

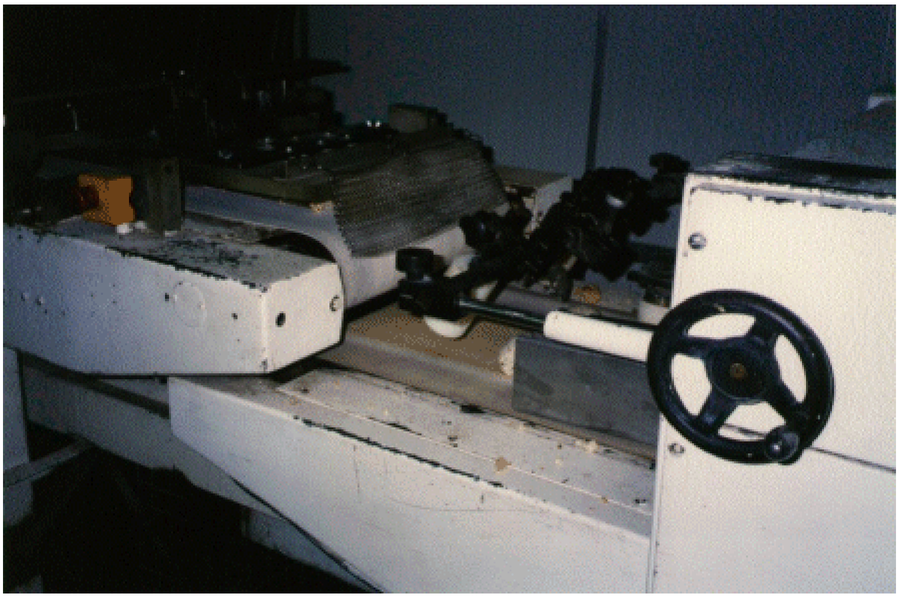

Figure B.5: Rolled dough is 'twisted'

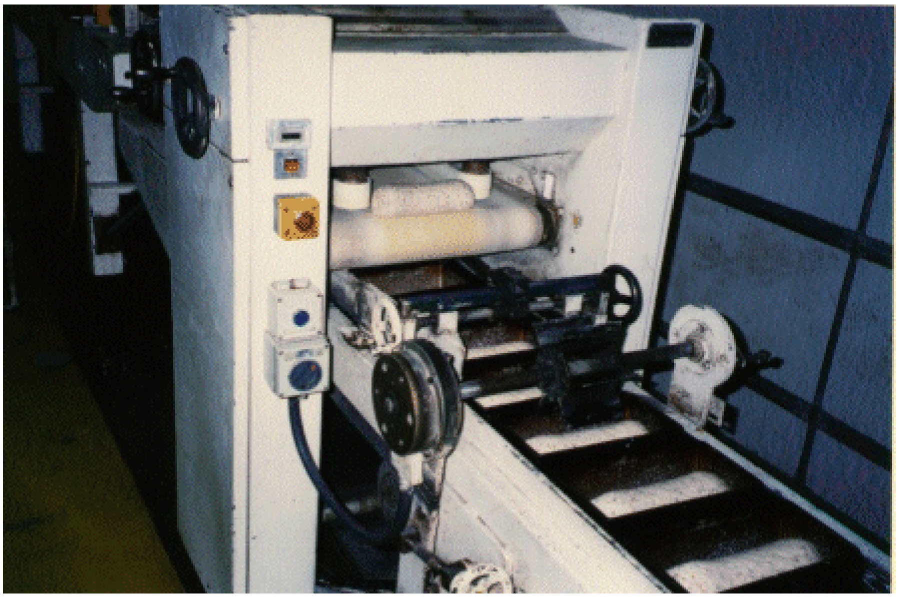

Figure B.6: Into Tins

B.4 Prover

Figure B.7: Conveyor towards prover

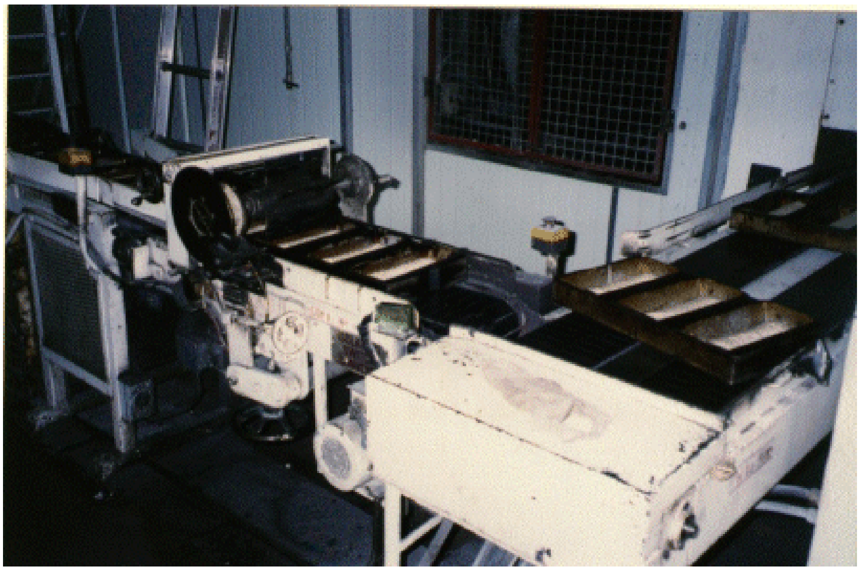

Figure B.8: Tins entering prover loading section

Figure B.9: Prover/Oven control panel with prover in background

Figure B.10: Tins exiting prover

B.5 Oven

Figure B.11: Oven entry and exit section

Figure B.12: Tins exiting oven

Figure B.13: Tins exiting oven and moving onto conveyor

B.6 De-panner

Figure B.14: Tins approaching depanner

Figure B.15: Loaves exiting depanner (tins are on conveyor below

B.7 Cooler

Figure B.16: Cooler loading arm in operation

Figure B.17: View of shelves inside cooler

B.8 Conveyor Split and Slicers

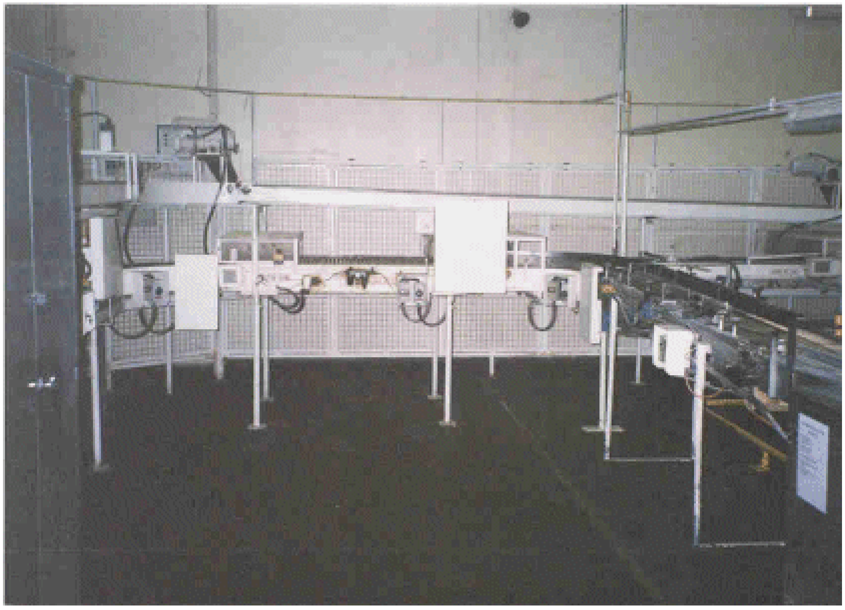

Figure B.18: Conveyor split

Figure B.19: Loaves cornering after conveyor split

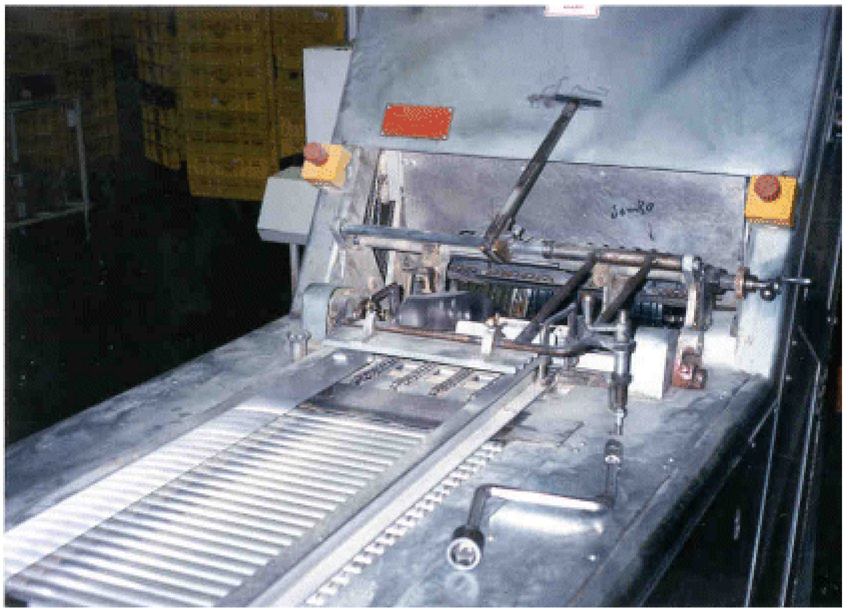

Figure B.20: Slicer Entrance

Figure B.21: Final Checkweigher

Appendix C: Product Performance Indicator Screen Captures

Included here are screen captures of the PPI software. For larger, full colour images, see the accompanying CDROM.

C.1 Bakery at a Glance

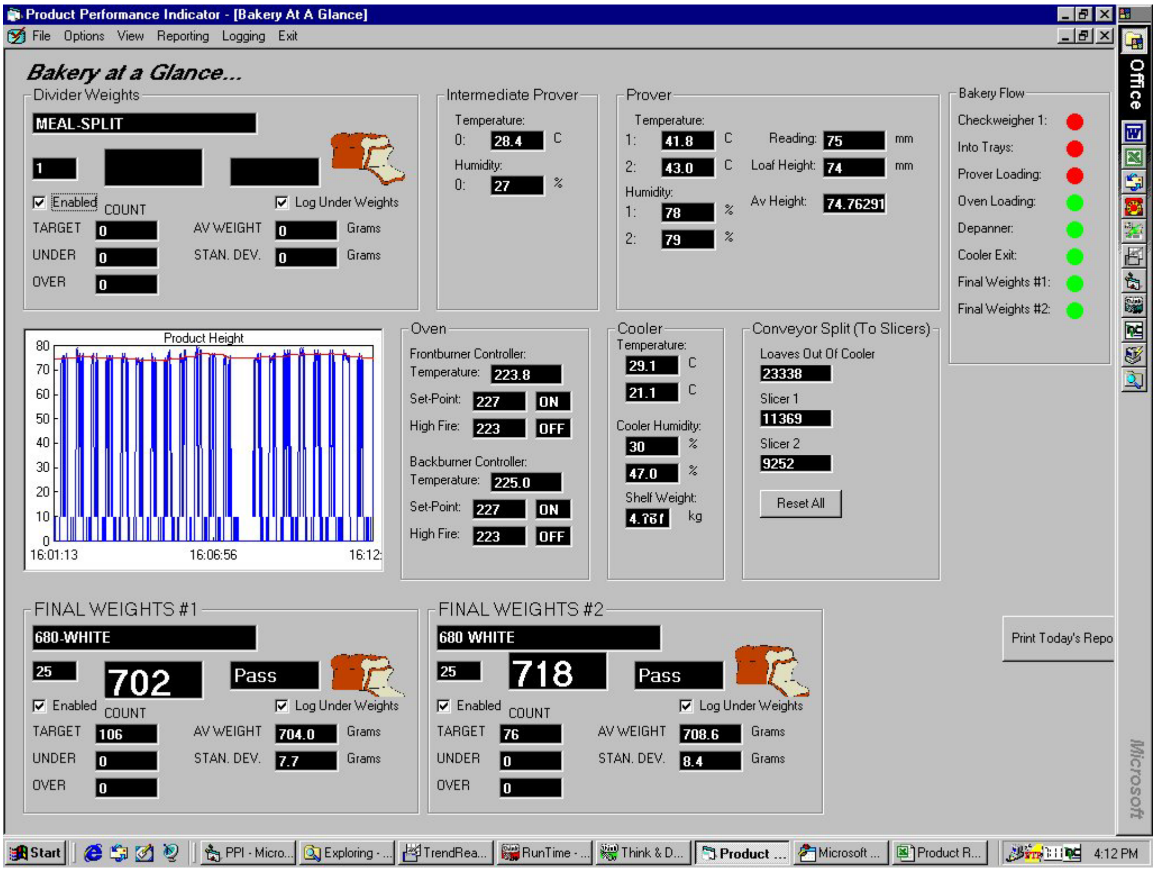

Figure C.22: "Bakery at a Glance" screen

This screen is the main screen for the PPI, showing information from around the whole bakery. The production manager may use it to gain an overall view of what is going on around the bakery. Information displayed is fairly self explanatory from the screen capture. For more information on specific items, see the 'Data Display' section below.

This screen also includes a button labelled "Print Today's Report" which may be used to start data processing macros that produce reports on the days production.

C.2 Data Display

The following screens display data arriving from various points around the bakery. This allows the production manager or engineer to have a more detailed view of specific processes.

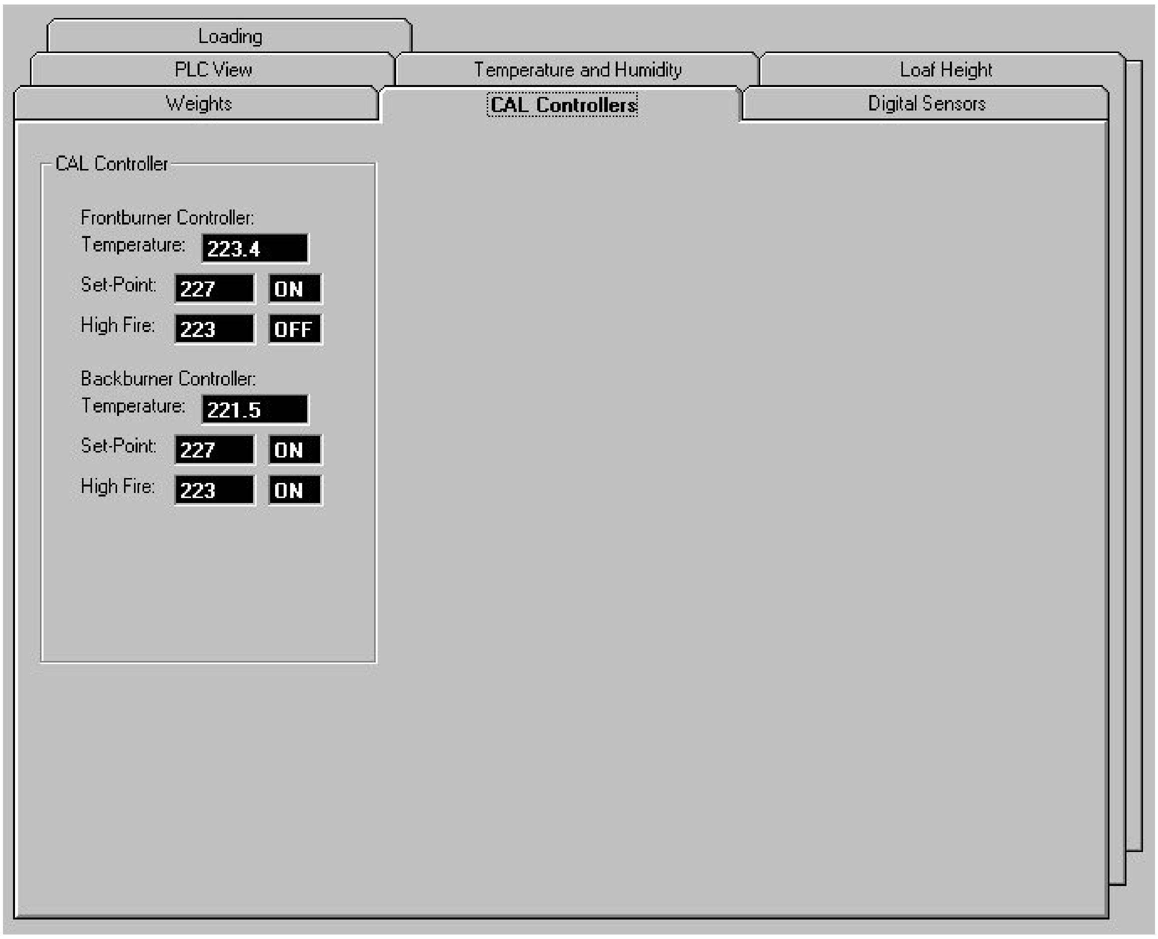

Figure C.23: Oven Temperature controllers

This screen shows the status of the oven temperature controllers. Information displayed is as follows for both the front burner controller and the back burner controller.

- Current oven temperature
- Current set-point for that controller
- The status of the normal burner (beside the 'Set-Point')
- The set-point for 'High Fire' – the temperature at which more power is sent to the burner
- The status of the 'High Fire' burner

Figure C.24: Digital Sensors

This tab monitors the state of all the digital sensors in the system (In the frame 'Digital Inputs'). Additionally, if stoppages are detected at various points, a red circle is shown under the 'Bakery Flow' frame. The number after the red circle indicates the number of seconds that the sensor has been inactive for.

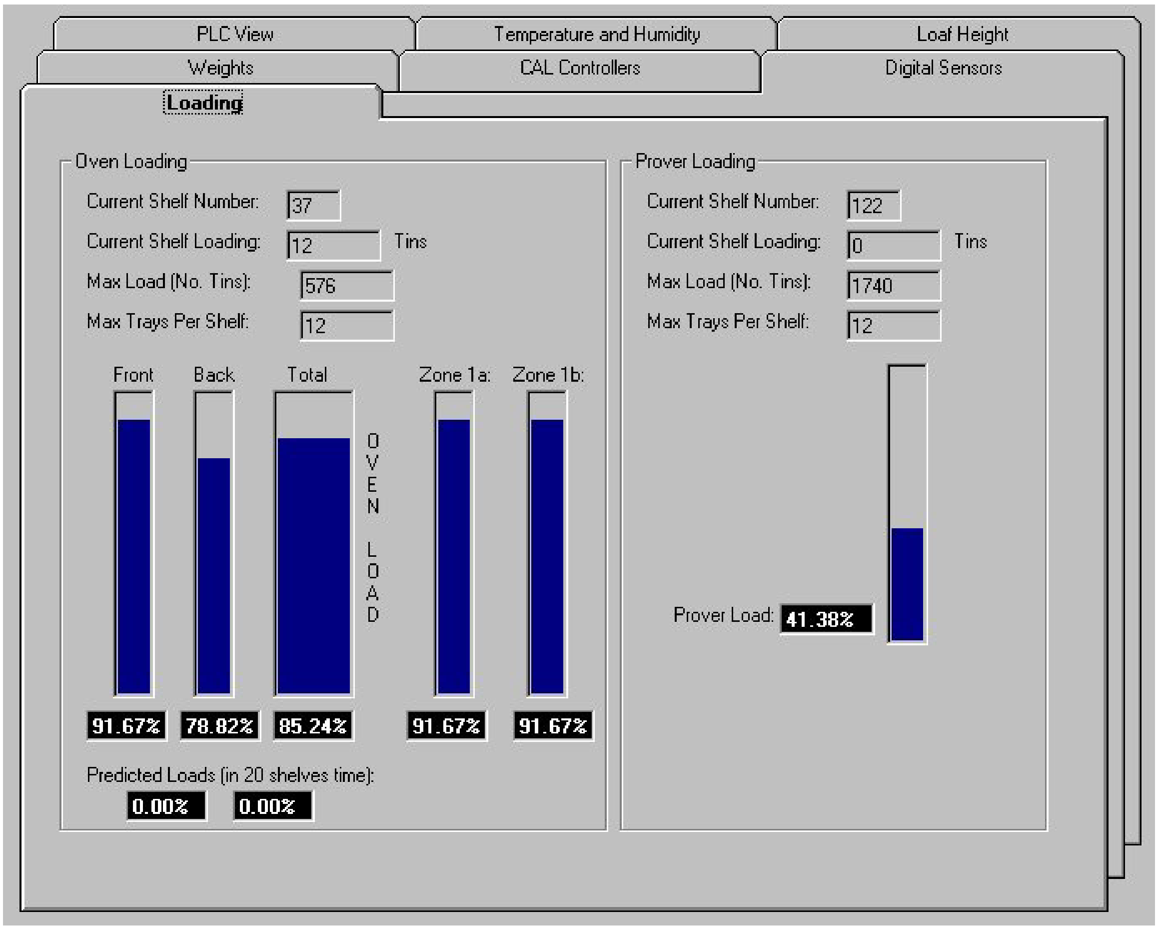

Figure C.25: Loading

This tab monitors the oven and prover loading. Using the digital inputs in the previous screen, the percentage of total load of the oven and prover may be calculated and displayed. Additionally, the percentage load in each zone may is displayed. Predicted loads may also be calculated and used to control the oven burners in time for changes in the oven load. This has not been implemented yet however.

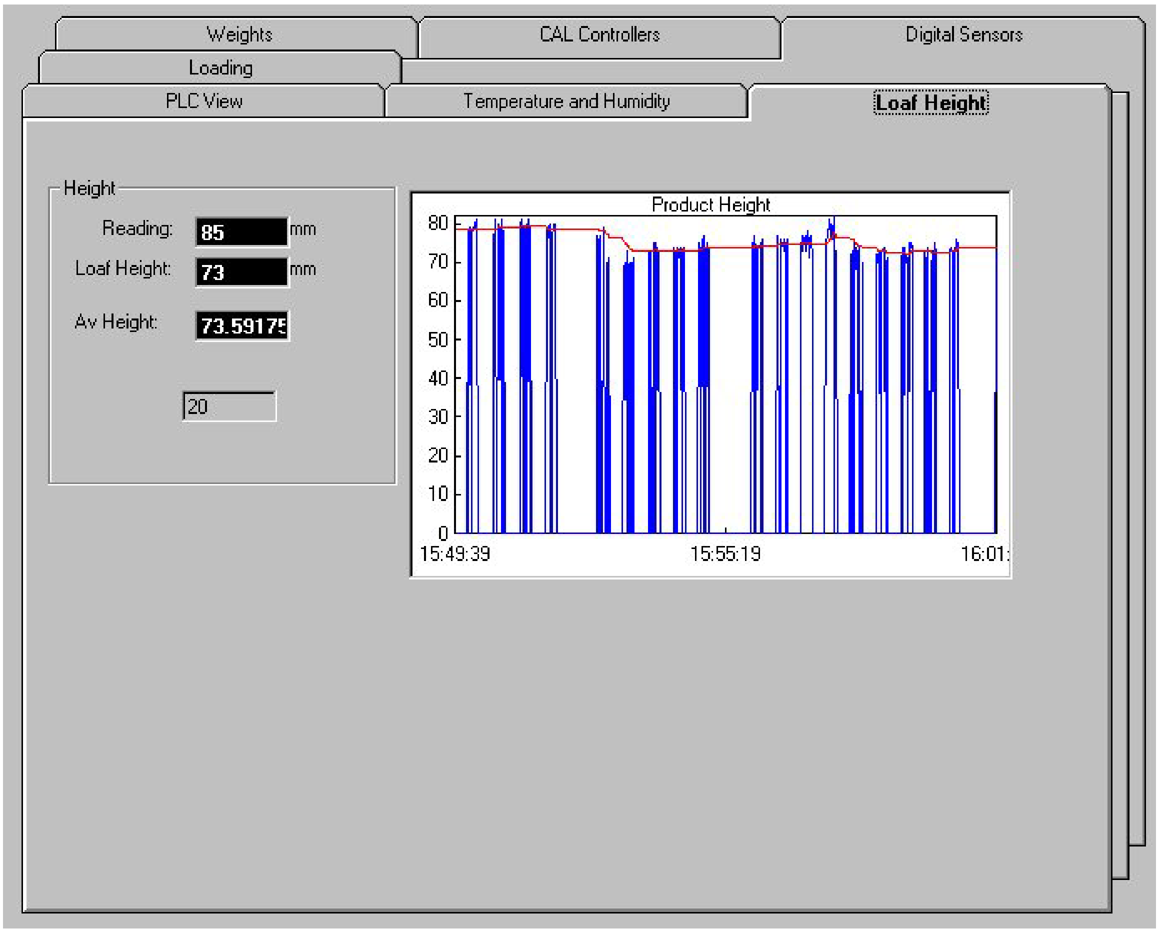

Figure C.26: Loaf Height

This tab displays the height of loaves passing through the height sensor (between the prover and oven). ‘Reading’ displays the current reading of the sensor. This value changes very quickly. ‘Loaf Height’ displays the calculated height for that particular loaf. ‘Av Height’ displays a moving average of loaf heights. A plot of heights is also shown.

Figure C.27: PLC View

This tab displays the two PLCs that have been installed as part of the PPI. It shows the raw values being read by each PLC in real time. It also shows the status of the Ethernet connection to these PLCs. This is provided as a diagnostic tool for the engineer.

Figure C.28: Temperature and Humidity

This screen displays data from all temperature and humidity sensors around the bakery. Again, this screen is provided mainly as a diagnostic tool for the engineer. There are two values for each sensor. The one on the left is the temperature or humidity value (in degrees Celsius for temperature and percentage relative humidity for humidity). The value in the grey box on the right is the raw value from the sensor.

Also included is the output from the cooler shelf weight load cell (‘Shelf Weight’).

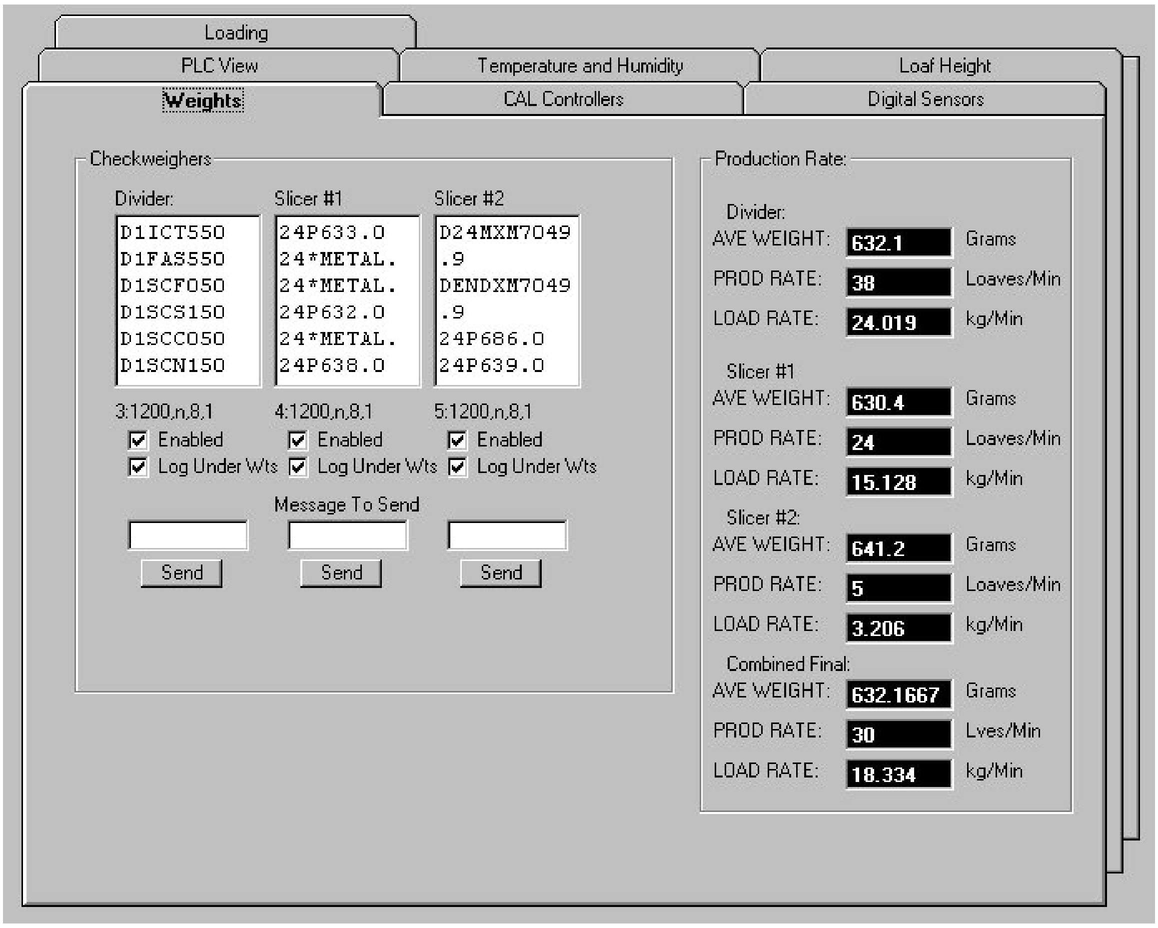

Figure C.29: Weights

This tab displays weight information from the three Checkweighers in the bakery. Under the frame ‘Checkweighers’, the raw serial data from the checkweighers is displayed. Additionally, the user may specifiy whether the particular checkweigher is enabled and whether to log weights that are classified as being ‘underweight’ (an option of interest if not all underweight loaves are rejected due to mechanical malfunction). If a particular setup function is to be sent to the checkweigher, it may be entered in the ‘Message to Send’ boxes followed by pressing the ‘Send’ button.

The frame on the right displays the production rates at the divider, each the slicers and a combination of the slicers. The production rate is expressed as an average rate, loaves per minute and also kilograms per minute.

C.3 Options

The following screens show various options that may be set in the PPI.

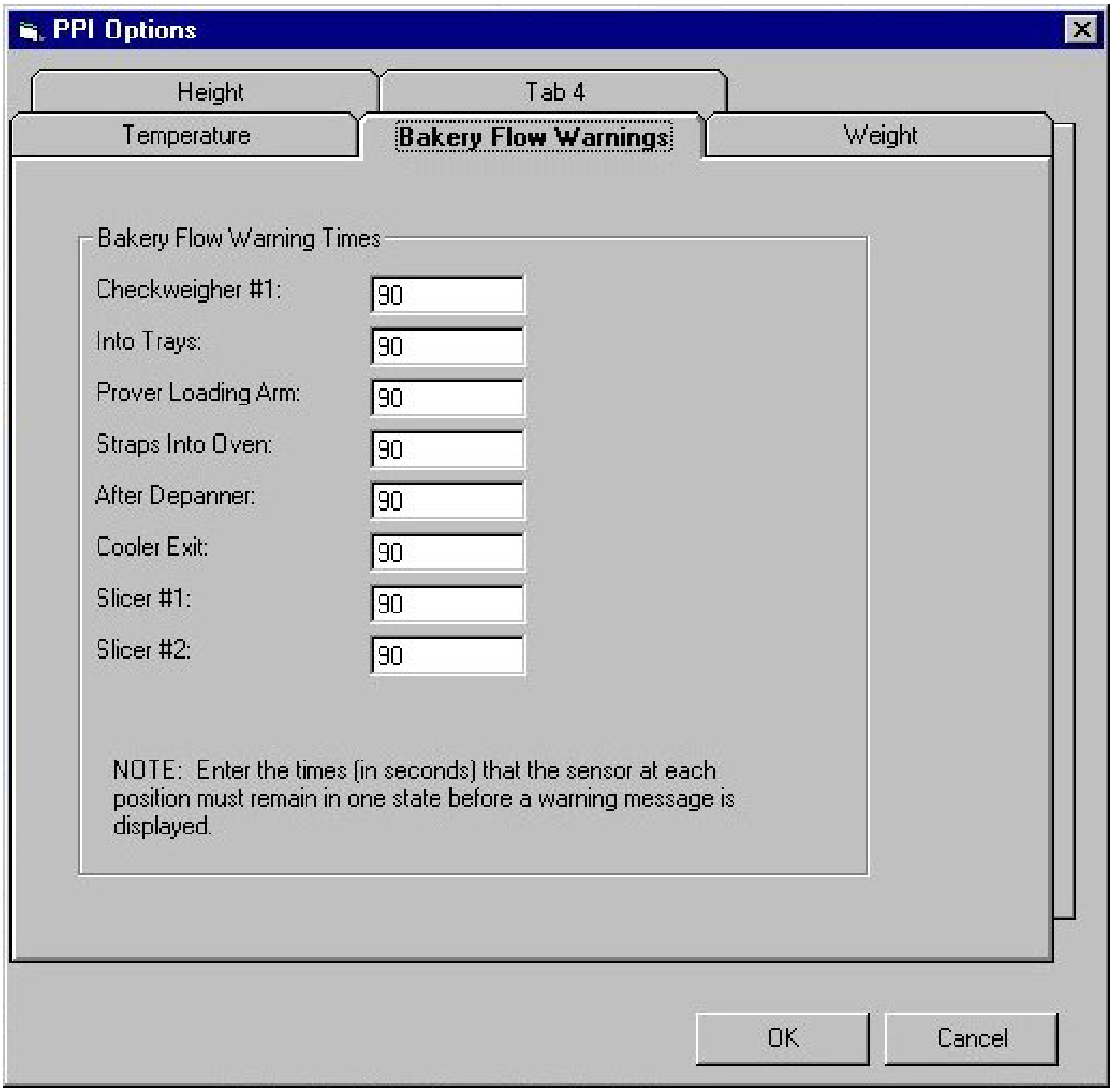

Figure C.30: Bakery Flow Warnings

This tab allows the customisation of the times (in seconds) before stoppage alarms will become active in the PPI. The time may be set separately for the eight sensors displayed.

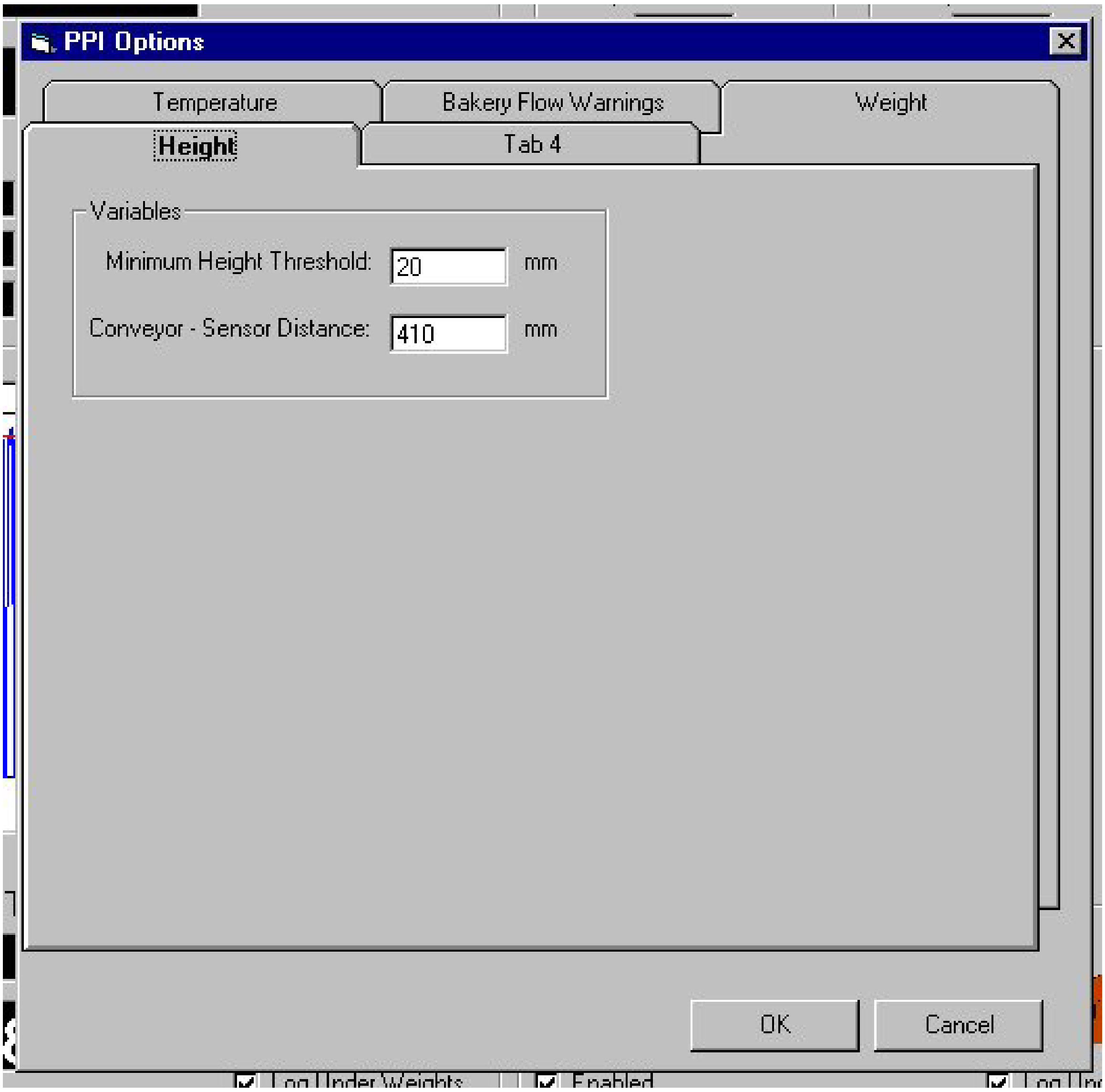

Figure C.31: Height

In this tab the user may set two height settings. The first is the 'minimum height threshold', which is the minimum height at which the program will regard the sensor as sensing an actual loaf. The 'conveyor – sensor distance' is the distance between the conveyor belt and the sensing head, required for calculation of loaf height.

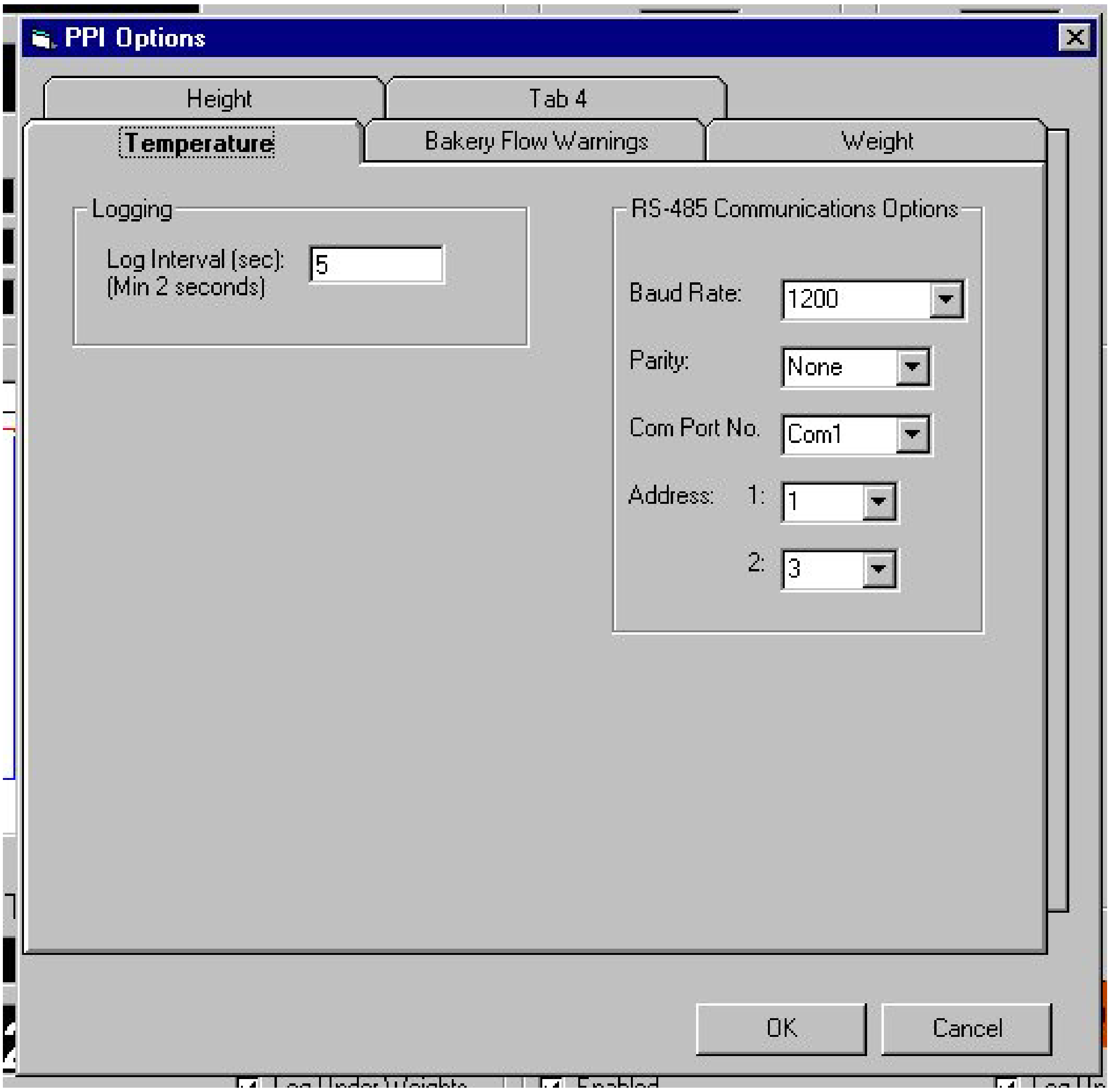

Figure C.32: Temperature

This tab allows the user to alter the interval at which temperatures are logged (in seconds). It also allows the communications options between the PC and the oven temperature controllers to be set.

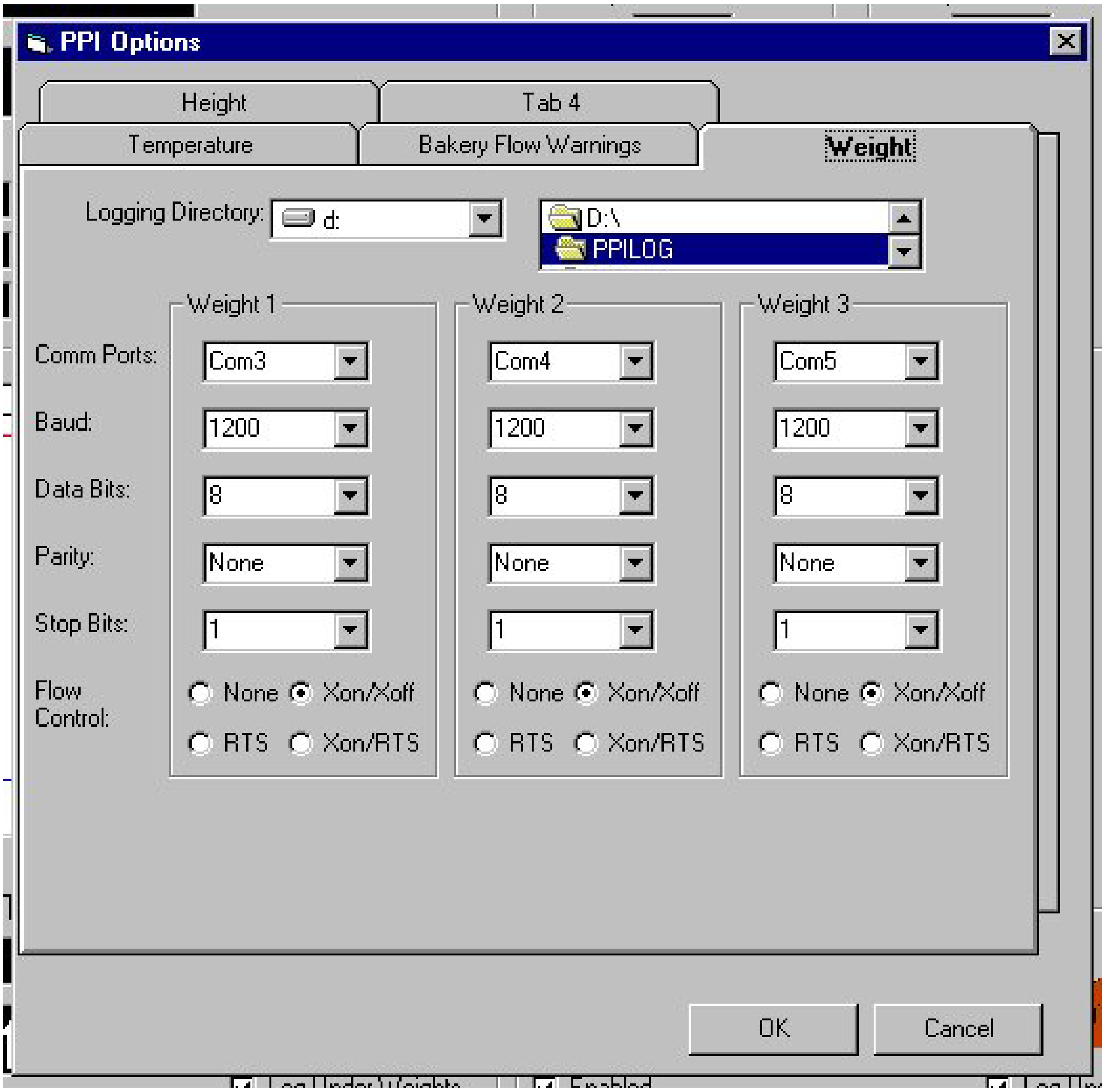

Figure C.33: Weight

In this tab, the user sets the logging directory for all files and also the communications options for the three checkweighers.