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QUALITY AND PRODUCTIVITY IMPROVEMENTS IN FOOD PROCESSING USING AUTOMATED CONTROL

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Abstract
This paper presents a novel approach for automated control of food production in order to improve quality of the product and the productivity of the process. The research work investigates quality improvement in the production and processing of french-fries (chips). The aim of the work is to design an automated control system for an industrial dryer that is utilised to remove moisture from the product prior to the frying process. An investigation is conducted to determine the relationships between the variable settings of a two-stage conveyor dryer with four independently controlled zones using a specially constructed 1:10 scale model of a single dryer zone. The relationship between the control settings and the final condition of the product is investigated using fractional and full factorial experiments and the associated analysis of variance calculations. Orthogonal array experiments are found to be suitable for system calibration and commissioning in order to minimise factory down-time. An automated control system has been designed which utilised the stack humidity and product bed-depth as the measured variables, and the residence time and extraction air flow as the control variables. The project is scheduled for implementation in a real industrial 20 tonnes-per-hour production facility in December 2005; estimated savings brought about by the system are in the region of £1 million/annum.

1. INTRODUCTION
Control systems in food processing facilities often take the form of simple first or second order reactive control systems designed to maintain the current processing conditions. They are often reliant on operator intervention to periodically adjust the system gain or sensitivity as the characteristics of the natural raw material drift in or out of specification. Since food processing technology is often concerned with relatively high volumes and usually subject to cleaning in place (CIP), the automation systems are often designed for robustness and simplicity, over precision and dexterity of control. This approach has served the industry well in previous years, but as rising energy and labour costs combine with tighter profit margins, the systems controlling food processing facilities must become ever more precise to maximise yields. Whilst becoming increasingly autonomous to reduce the need for manual intervention by the dwindling staff of machine operators.

Thermal drying processes are some of the most energy hungry operations in modern food processing plants, and since most food stuffs are water based the drying process represents a very direct method of controlling the yield of product from the raw material [1]. Typical relative energy consumptions of the thermal processes from a french-fry plant are shown in Figure 1.

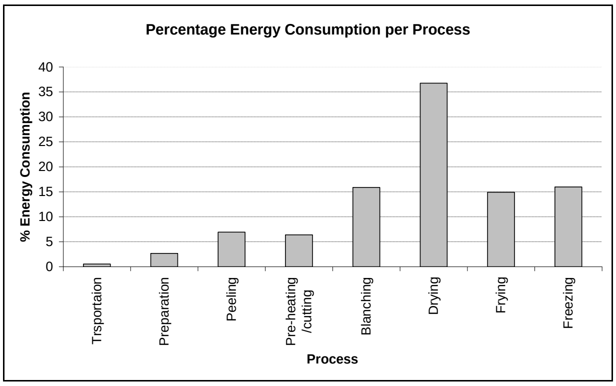

Figure 1: Relative energy consumption of different processes in chips manufacturing

The primary aims of food processing are to produce the required volume of product at the right price, so that it can be competitively marketed. Cheap products must be produced at very high yields, and premium products must be produced to very high quality and often a tight specification. Small changes to the properties of the processed product can have a dramatic effect on its value, so accurate control of the process is very important to the commercial success of the product and the manufacturer.

2. CONVEYOR DRYERS
Several types of dryers exist on various scales in industry. Conveyor or "apron" dryers are particularly common in vegetable processing applications because of their gentle treatment of the feed and continuous high throughput capabilities.

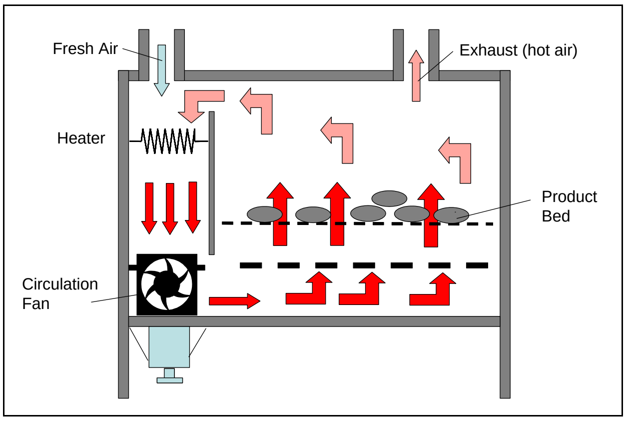

Figure 2: A The basic idea of a conveyor dryer

Conveyor dryers are self-contained units and provide a gentle method of drying [2]. Figure 2 presents the main concept of a conveyor dryer. The feed is transferred into a perforated belt forming a "bed" of product, and carried through a succession of compartments or "zones" within the dryer. The carrier is drawn into the heating compartment through an inlet duct. The heated air is then blown through the drying chamber by a second fan in a forced draft manner. Airflow can be either across the belt – cross flow, or more commonly up or down through the belt – through the bed flow. Apron-type seals are used between the moving belt and the dryer housing to prevent the carrier 'short circuiting' the feed. A proportion of the warm moist air is removed through an exhaust outlet on the pressure side of the fan. Both inlet and outlet are typically damped to allow the proportion of recirculated air to be regulated.

3. CURRENT CONTROL STRATEGY

The current control strategy is to perform tests of solids content on samples taken periodically from the line after packaging. A standard test measuring weight loss after mastication and dehydration is performed and the results recorded in the control room log, along with intake data. A supplementary 'dry loss' test measuring the weight loss through the dryer is conducted, which involves measuring the weight of a sample of french-fries before and after the dryer; the resulting weight loss is recorded as the mass of water removed. Problems with this test include the surface area variation if longer or shorter fries are chosen in the sample. Typical solids fluctuation over a 24-hour period is shown in Figure 3; the intake solids data is advanced by two hours so that the solids measurement at intake coincides on the x-axis with the solids measurement of the sample taken post fryer. It can be seen that any correlation between the two is fleeting and unstable, so the french-fries are fluctuating between being under dried and over dried.

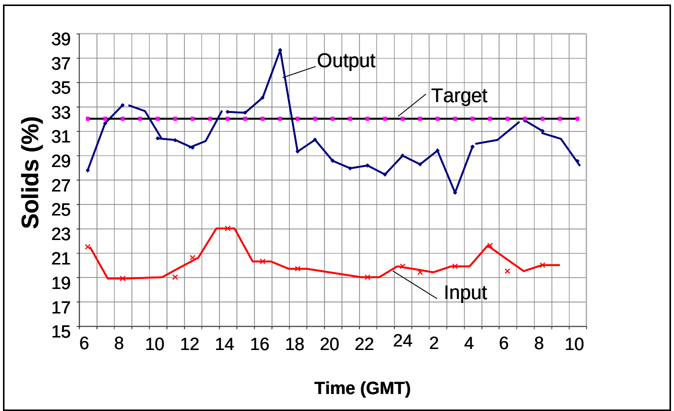

Figure 3: Dryer solids output variation in the industrial process.

Recent developments have been toward long residence time and high operating humidity sometimes approaching 100%. These approaches are geared toward processing for product texture and specification, rather than moisture content. This has the benefit of allowing blanching and texture changes to occur within the dryer and also avoids the temperature gradient through the dryer, making temperature dependant processes such as batter application more stable [3].

The content of this project is for application on a high volume line without processes such as batter application, so more traditional drying techniques will be utilised, such as intermediate temperature/humidity control, and short residence times increasing the volume throughput of the dryer.

4. EXPERIMENTAL METHOD

Several manual controls are incorporated into the design of the aforementioned conveyor dryer, and its operation can be controlled in a number of ways:

- Louvre dampers can restrict extraction airflow.
- Conveyor speed can be ramped up/down to change the residence time and bed depth of product in the dryer.
- The steam supply to the heating banks can be throttled on/off to change the degree of heating.

The air circulation fan speed can be ramped up/down, to vary the circulating airflow.
Another common feature of conveyor dryer installations is the addition of variable speed drives (VSD's) to the extraction fans.
In effect these controls provide 5 controllable factors that affect the operation of the dryer:

1. Product bed depth
2. Circulating airflow
3. Circulating air temperature
4. Product residence time
5. Proportion of extracted air

4.1 Test methodology

In order to completely test the effects and interactions of 5 variables at 2 arbitrary chosen values, it would be necessary to perform $2^5 = 32$ test runs. If repeat runs are to be made, as would usually be the case, then the number of test runs would be fairly large. The number of required test runs can be significantly reduced if fractional factorial experimentation is performed. This involves testing a proportion of the possible combinations of variables, and using the variance of the gathered data to predict the results of test runs that are not physically undertaken. A mathematical grid or Orthogonal Array (OA) is used to determine which test runs need to be carried out, the analysis of variance (ANOVA) process, also called Taguchi's method is used to determine the contribution of each variable to the overall affect on the output variable, and to highlight any interactions between variables [4]. Taguchi's method can be implemented whereby a fraction of these possible combinations could be tested and the variance of the results analysed (ANOVA) to indicate the effect of changing each factor on: the output result and the effect on the output result of the remaining factors [5].

Orthogonal arrays and the ANOVA process are used to determine the best control variable for the system. That is, the variable that had most predictable effect on the output result of the system, in this case the dryness of the product.

4.2 The Test rig

A test rig, shown in Figure 4, is constructed for the purposes of experimentation; the rig is a 1:10 scale replica of a single zone of the dryer. Airflow and heating capabilities are also scaled to 1:10. Volumetric dimensions are kept accurate, and a section of the conveyor belt from the real dryer is used to support the product bed, thus providing the same airflows through the rig. An 'iris' type damper and VSD fans are used to regulate circulation and extraction. Electric heaters controlled with pulse width modulation (PWM) are used to supply varying degrees of heating to the rig.

The sensory array is shown below, and comprised of temperature and humidity probes located above and below the product bed, in the extraction ducting, and outside the rig. The test data is fed into a laptop computer through an Analogue to Digital (ATD) card, and recorded using DASYLab™ data acquisition software. Figure 5 presents a photo of the constructed test rig.

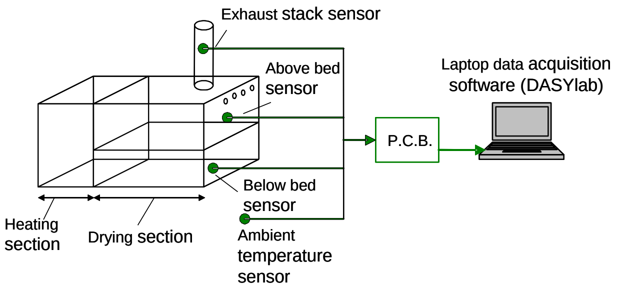

Figure 4: The excremental set-up including the sensors and data acquisition system.

Figure5: A photo of the test rig.

4.3 Experimental Parameters

Two experiments are conducted; the first to determine the best way to control the air extraction, and the second to investigate the effect of the 5 control variables.

Estima type potatoes are obtained for the experiments; the batch is purchased from a local retailer, and care is taken to ensure that the potatoes are all from the same batch. Each test sample is cut with a 10mm x 10mm square chip cutter, and blanched in hot water for 7 minutes prior to processing. Samples are weighed before and after drying to determine the dry loss through processing.

Each variable is assigned to sensible levels for testing purposes, with consideration given to the feasible real world range of that particular variable.

Fan speeds could be varied between maximum rpm and zero if frequency inverters are used, so five levels ranging between maximum rpm and stopped are chosen.

The bed depth parameter is known to vary by around 50% in normal processing, so the volume of test product is varied by 50% to simulate this.

The dampers may be set by hand to any position between fully open and closed, so five levels ranging between maximum damping and no damping are chosen.

The heating bank is known to vary between 40 to 60ºC, so levels of 40 ºC and 60ºC are chosen. Residence time is known to vary between 12 and 13 minutes during normal production, since the model is based around one of the four zones, levels of 3 minutes and 3 minutes: 30 seconds are chosen for investigation.

5. RESULTS AND DISCUSSION

Figures 6 and 7 shows that airflow control is closer to being directly proportional to fan speed, than damper position. This infers that VSD fans have an operational advantage over fixed speed damped fans, since a system with a directly proportional change in airflow would be the simplest to automate. Furthermore, the advantages of VSD's over fixed speed damped drives can be widely read to include lower energy consumption, and maintenance costs, culminating in a lower whole-life cost for the unit.

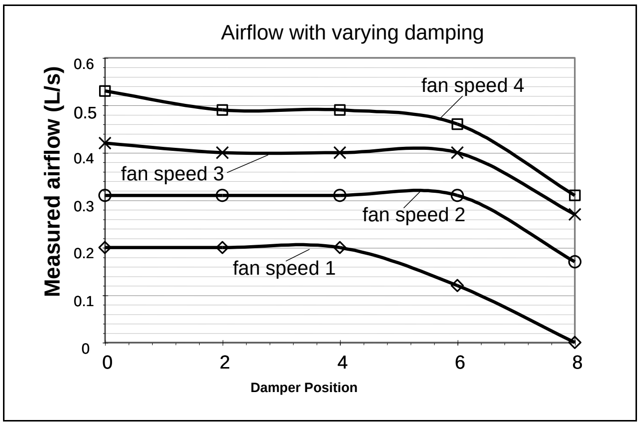

Figure 6: The relationship between airflow and damper position.

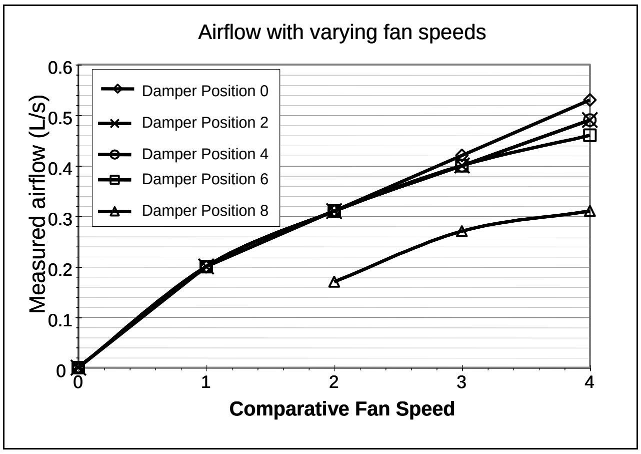

Figure 7: The relationship between airflow and fan speed.

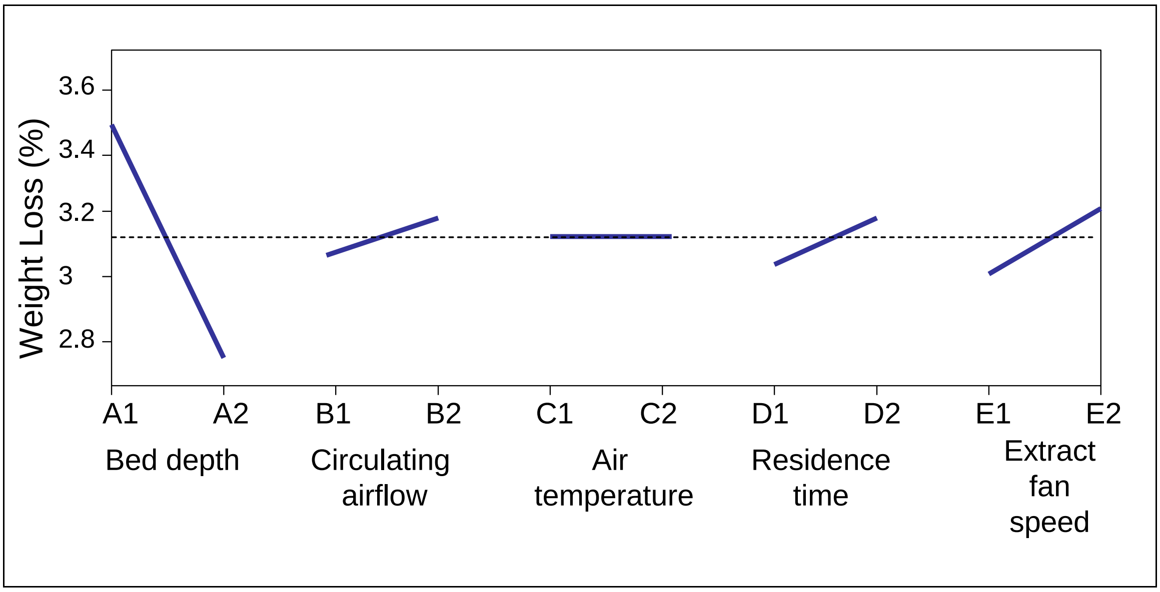

Figure 8: ANOVA Trend of control parameters against weight loess

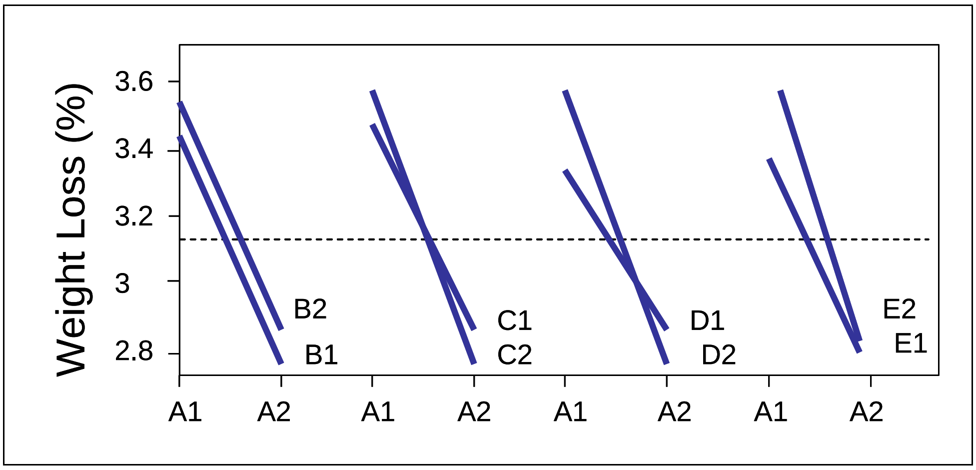

Figure 9: Presents the interaction for bed depth with other factors.

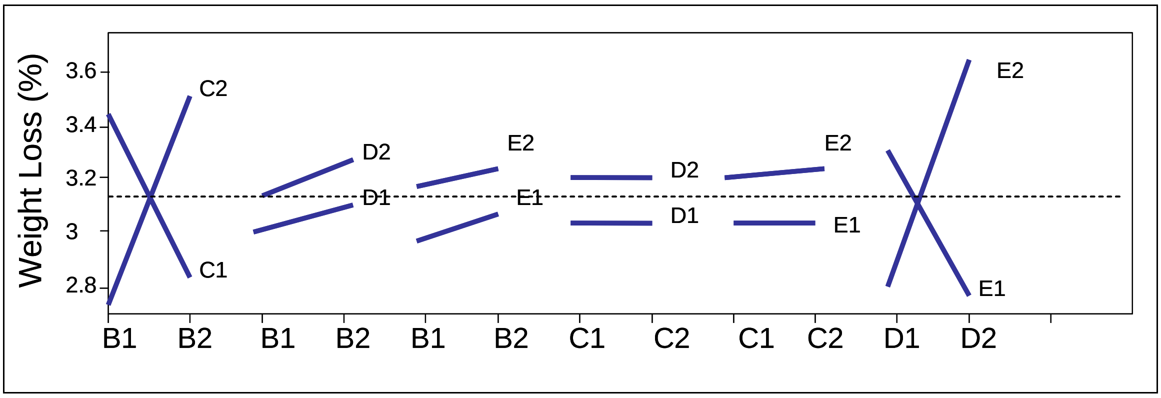

Figure 10: presents the interaction between circulating flow, air temperature, time and extract fan speed.

A= Bed depth, B = Circulating airflow, C = Air temperature, D = Residence time & E = Extract fan speed.

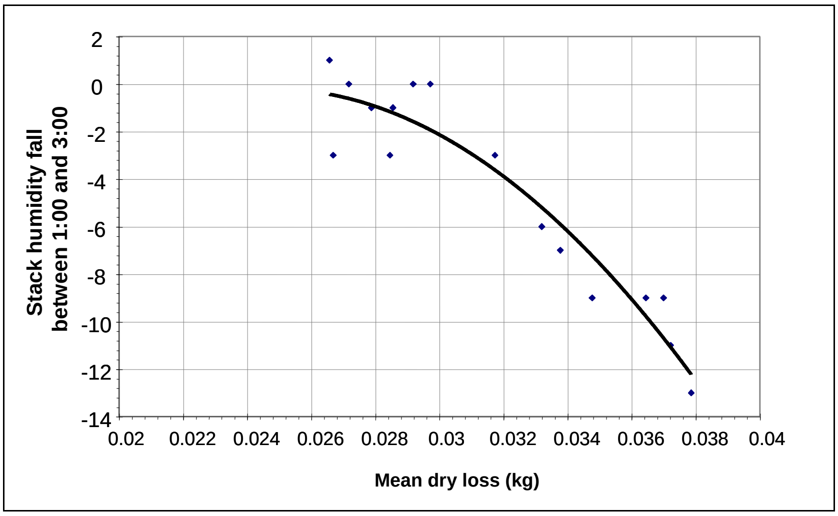

Figure 11: The relationship between humidity and mean dry loss.

Figure 8 presents the effect of each variable on the dry loss achieved, as determined by performing the ANOVA process on the full factorial dataset using ANOVA-TM software. The mean effect of each parameter is shown. It can be seen that bed depth has the greatest effect on solids output, and temperature the least effect. Extraction fan speed is second most effective, followed by residence time and circulating air speed.
Figures 9 and 10 show the possible interactions from all five variables investigated. Interactions are indicated by crossing lines and independent factors by parallel lines. Interactions between temperature and bed depth, and temperature and circulating airflow are visible. Interactions between residence time and bed depth, and residence time and extracted proportion of air can also be seen. In summary, each factor can be seen to interact with at least one other factor.
Figure 11 presents the relationship between the fall in humidity measured in the exhaust stack and the weight loss through the experiment. This is the most important relationship uncovered during this investigation, since it represents a possible measurement variable for an automated control system. Similar graphs of weight loss against the humidity measured below the bed and above the bed showed some correlation but much less accuracy.
Fractional factorial analysis yielded almost identical results to the full factorial analysis.

6. DISCUSSION

Temperature appears to have little effect within the range of 40ºC to 60ºC and only serves to interact with the bed depth and circulating flow factors. If temperature were kept constant in the dryer, then these interactions could be ignored. The circulating flow has a mild effect, and only interacts with the temperature factor, already deemed to be static. A high circulating flow is known to favour the drying process, so if this factor were also fixed then the remaining factors would be bed depth, residence time, and proportion of extracted air.
Bed depth would be the most effective parameter to control, followed by the proportion of extracted air. Since bed depth is inextricably linked to residence time, and the pair show interaction in any case, it would seem sensible to control – and consider – both factors as one.
The fall in stack humidity through the drying process appears to be closely related to the amount of moisture removed from, or ‘dry loss’ of, the product. The increased drying efficiency is probably due to the increased humidity gradient between the product and the carrier. Since, as known experimentally, overly rapid drying is not of benefit to the process, it would seem sensible to closely control the rate of extraction to ‘fine tune’ the drying process.
The use of fractional factorial experiments to find response curves for the control system is recommended. As the number experiments increases by a power equal to the number of levels, response curve fitting could greatly reduce commissioning time.

7. THE PROPOSED CONTROL STRATEGY

Since the bed depth/residence time parameter has a large effect on solids output, and the proportion of extracted air controlled by the extractor fan has a milder effect, it would be possible to build a dual control system using the residence time/bed depth parameter as a course control, and the extractor fans as a fine control. Dual systems of this kind are useful if the range of variability is large, but the output must be controlled to fine accuracy.
The proposed system, shown in Figure 12, would use temperature probes below the product bed to modulate the steam valve to the heating bank via a PLC proportional loop or look-up table. Humidity sensors in the exhaust ducts from each zone would measure the fall in carrier humidity through the dryer, and a bed depth gauge would measure the depth of the formed bed. A suitable bed depth measurement device would be a simple “arm and wheel” connected to a potentiometer, much akin to the mechanical operation of a ball float valve.
Utilising the proposed sensors a suitable control algorithm is illustrated in Figure 12, the corresponding block diagram is shown in Figure 13. The system works on a two-simultaneous-loop basis; that is, it is designed to use the conveyor belt speed as a course control of output moisture content, and the extraction fan speed as a fine control. If the fine control is operating near the upper limit of its range, it activates the course control to bring the fine control nearer the lower half of its range. This keeps the fine control mid range, ensuring system agility, and also places emphasis on energy efficiency, by acting to minimise the amount of extracted warm air.

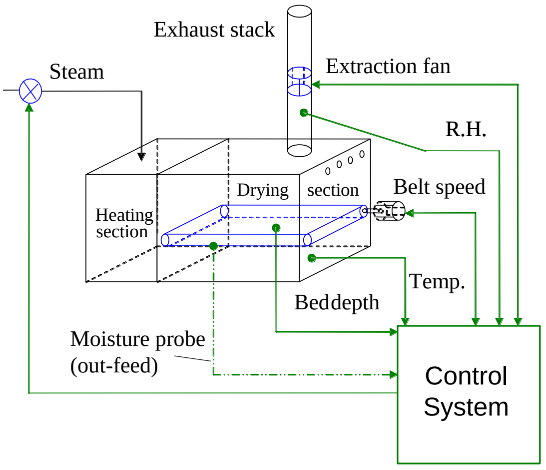

Figure 12: A schematic diagram of the proposed control system.

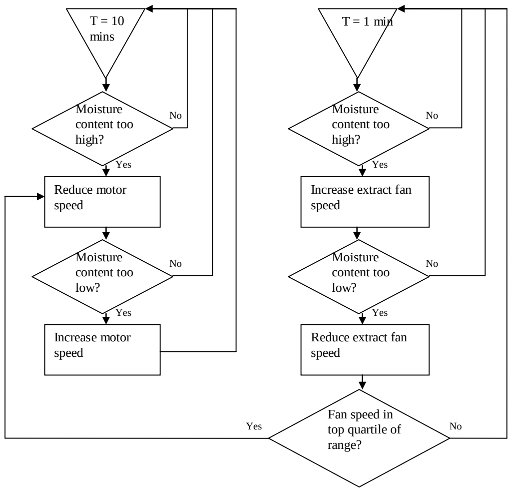

Figure 13: The proposed control algorithm

The proposed control system will utilise the capabilities of fuzzy logic control algorithms. The advantage of Fuzzy logic that it strikes a good balance between significance and precision, by defining the boundaries of control ranges as variable, or 'fuzzy', depending on other conditions. Fuzzy logic seeks to map input variables to output variables without the need for direct proportional control. Using the Fuzzy Logic Toolbox platform of the MATLAB software package, a Fuzzy Interference System (FIS) is constructed to process inputs of: Stack humidity; Extract fan speed; Below bed temperature; and Conveyor speed. The output variable is the moisture content of product. The relevance of each input to the product moisture content is expressed using "membership functions", which represent the varying strength of the effect of an input on the output, with varying values of that input. Usually three functions are given to each input, to describe its effect at low, medium, and high values. The choice of functions that make up the membership function is based on a combination of experience and the known theoretical response to an input.
By assigning a few simple Boolean logic functions to the inputs and outputs, a response surface can be generated that represents the output as a function of the two control inputs, that is the extract fan speed and the conveyor speed.
Response curves could be obtained for the heating bank, extract fan speed, and residence time/bed depth modulation. These relationships can be ascertained with the use of a model, but would then have to be replicated with the real dryer to find the performance curves.

8. OTHER QUALITY ISSUES

Low fat products can be produced by 'case hardening' the fries with a quick burst of intense drying, forming a more oil resistant layer around the soft centre of the french-fry. The test rig could be used to investigate the performance of a conveyor dryer and its ability to 'case harden' french-fries.
The amount of surface water entering the dryer is largely dependant on the surface area of product, so larger line rates drag more surface water into the dryer and increase energy consumption by a greater than proportional amount. The effect of modulating the amount of mechanical dewatering to reduce dryer loading and increase plant efficiency could be investigated. After further discussion with process supervisors at the dryer installation it has come to light that the residence time parameter is believed to have more effect than the bed depth parameter, although the pair are of course interrelated. This discrepancy could stem from the experiment set-up because the bed depth (or product volume) is varied by 50%, whereas the residence time is varied by 17%. However, the author believes the relationship to be more complex than the rule of thumb that the process supervisors follow. The exact response curve could be ascertained to better understand the interplay of these factors.

9. FINAL CONCLUSION

This paper has presented an investigation into automated control production and processing of french-fries (chips) in order to improve quality of the product and the productivity of the process. The aim of the work is to design an automated control system for an industrial dryer that is utilised to remove moisture from the product prior to the frying process. An experimental work has been conducted to determine the relationships between the variable settings and the output quality. The relationship between the control settings and the final condition of the product is investigated using fractional factorial experiments and the associated analysis of variance calculations using Taguchi's method. An automated control system has been proposed that utilises the results found in this investigation. The project is scheduled for implementation in a real industrial 20 production facility with estimated in the region of £1 million/annum.

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