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Optimising the use of grain stirrers to enhance on-floor drying

by

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1. ABSTRACT

Grain stirring by vertical augers is a method of mixing grain in bulk stores. It is used to remove the gradients in moisture content (m.c.) that develop when drying a deep bed, and before or after drying. The stirring process adds an extra dimension to bulk drying because it can be used in various ways, *e.g.* speeding up the drying of the upper layers to reduce risk from fungi, reducing over-drying of the lower layers, and allowing higher temperature air to be used that can increase drying rate. The aim of this project was to examine how stirring influences drying, and how the potential advantages can be best exploited, with a particular focus on potential to save costs for users. A simulation model of bulk drying was used for the study, plus a new element to simulate the action of stirring on the grain bed. This model was validated successfully against a 25t wheat drying experiment at The Food and Environment Research Agency (Fera) in 2010, drying of two such bins in 2012, one stirred and one static, a published drying test for an 86t bin using higher air temperature, and data from a farm bulk store in 2012, one block of which was stirred, one static.

The simulation model generated performance data for drying wheat from m.c. values of 24 – 16% to a target of 14.5%, at bed depths of 4, 3 and 2m using 20 years of weather data from Lincs. Risk of fungal toxin was calculated, and only treatments giving 19 or 20 years without risk were counted as successful. A range of drying approaches was tested.

When using the drier with r.h. in the plenum regulated to 62%, stirring the bed continuously reduced the risk of fungal toxin Ochratoxin A (OA) substantially, compared with a static bed, and hence allowed grain at 2% higher m.c. or 1m higher depth to be dried. But drying with stirring took substantially longer and the fuel and electricity costs were higher. So, when using near ambient air temperature, stirring was only helpful if otherwise there was a risk of OA as judged by the HGCA Safe Storage Time Calculator.

Stirring allowed use of higher plenum air temperatures, within constraints of component design and safety. Use of higher air temperature when stirring, e.g. 30°C, reduced drying time substantially compared with using near ambient air temperature, Electricity cost was reduced because the fan and stirrers were used for a shorter time but fuel use was generally increased.

Guidelines set out which drying problems would, and would not, be addressed by stirring, and how to make best use of a stirring system.

2. SUMMARY

2.1. Introduction

Grain needs to be dried following harvest to avoid problems associated with fungi and mites during subsequent storage. In most seasons, on-floor drying, using ambient or heated air can be effective and economical but still requires considerable skill. In poor seasons, an on-floor system will incur considerable costs and may not achieve good enough results, however skilful the operator.

In a conventional on floor drier, the grain is static and drying proceeds from bottom to top. Grain at the top of the bed remains close to the initial moisture content (m.c.) until drying is nearly complete. In contrast, when vertical augers mix the grain bed during drying, layers of wetter grain are mixed into the mass, drying them more quickly and thus reducing the risk of spoilage by fungi. Other benefits of stirring in terms of quality and cost are available, in principle, whatever the season. For example, overdrying can be avoided so it may be possible to exploit different, and potentially more energy-efficient, drying strategies. If a greater depth of grain can be used, this would allow more grain to be dried with an existing drying floor.

This study examined stirring and how to integrate it with on-floor drying practice. The aim was to calculate drying performance with and without the use of stirring (likely success, drying time and cost) so as to help growers decide whether to invest in a stirring system and to show, with user guidelines, how to get the maximum benefits from a stirring system. This was tackled by developing and exploiting an integrated simulation model of stirring and drying, used with historical weather records, to run a wide range of drying scenarios.

2.2. Development of the new model

“Storedry” is a simulation of bulk drying which has been used for several HGCA projects. The new model of stirring was implemented as modifications to Storedry, and represented the essential features of the action of vertical augers on the grain bed.

The first stage of the new stirring model considers the action of a single auger, embedded in a grain mass but not moving laterally, which has been running for long enough to produce a stable flow pattern of grain. A circulation zone is formed in the grain by the action of the stirrer. Grain is lifted by the auger to form a cone at the bed surface. The moving mass of grain below the surface also formed a cone that extends from the bottom of the auger to meet the cone on the surface base to base (Figure 1). The assumption was made that the circulation of grain due to the action of the auger was enough to completely mix the grain in the circulating zone. This is justified by the slow lateral speed of augers that are lifting grain at quite high flow rates. The conical shape of the circulating zone implied that differing proportions of the drying model's grain layers were entrained (i.e. drawn into the circulating zone), small amounts at the point and larger amounts at the widest part of the cones. The m.c. and temperature in the circulating zone were calculated from the m.c. and temperature of the grain in each layer and the mass of grain entrained from each layer. Lateral distribution from the stationary auger was modelled by combining at each layer the appropriate proportion of grain in the mixed volume with that not entrained by the auger.

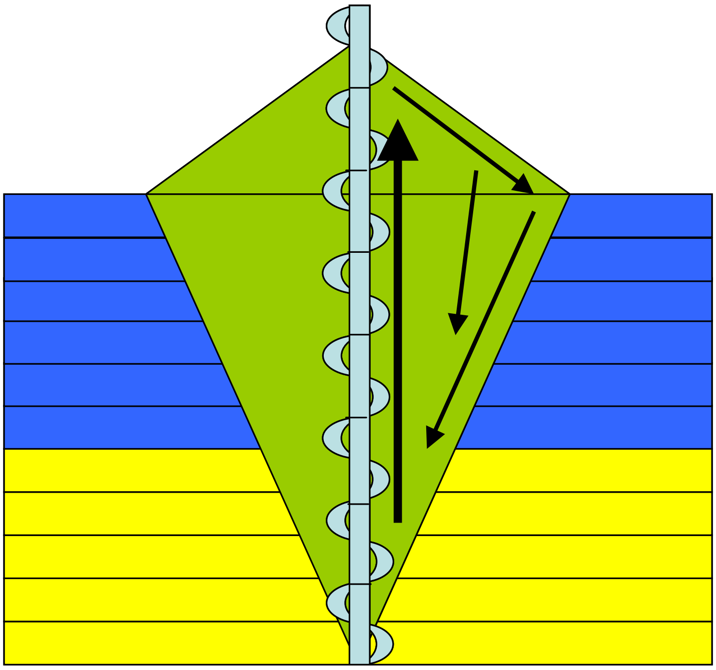

Figure 1. Circulation zone formed by auger (green), with arrows indicating grain flow direction and speed.

Movement of the augers around the grain store was modelled as follows. Storedry was modified to simulate drying in many "mini" grain beds in parallel, only one of which was stirred each hour. The model allowed for 20 such beds, enough to allow a realistic pattern of auger movement around the store to be defined. As the auger moved from one bed to the next, mixing of grain between the mini-bed just stirred and the next in the stirring sequence was modelled by a similar procedure as already described.

There is some evidence that stirring reduces air resistance, but only marginally unless the grain was compacted or deteriorated. Such a reduction would allow more airflow if the fan were capable of providing it. The stirring model was developed to allow a reduction in air resistance to occur.

In the new model, mixing and averaging was applied to physical parameters, *i.e.* moisture content and temperature, but was not appropriate to biological quality attributes, *i.e.* the progress towards the risk of Ochratoxin A (OA) and the loss of grain viability. So the new model takes a conservative approach by finding the layer in the bed before stirring in which biological attributes are worst and ascribing them to all the other layers in the bed after stirring.

The model allowed simulation of running the fan and heater for a time before starting stirring, and of stirring to even out the bed once drying was finished. An option to start with a non-uniform bed of grain was added, so that drying of grain in layers of different initial m.c. could be simulated.

Approximately 750 lines of code were needed to implement the changes described above.

2.3. Validation of the model

Validation was done in four stages. First, the model was run at ‘standard’ near-ambient drying conditions and the results with stirring were compared qualitatively with results when stirring was not used. This allowed the behaviour of the stirred bed drier to be checked to ensure it was reasonable. Second, the measured conditions in experiments carried out on 25t bins of wheat at the Food and Environment Research Agency (Fera) in 2010 and 2012 were used to run the model to predict conditions of temperature and moisture content in the bed during drying. These predictions were then compared with measurements. Third, an experiment reported in the literature in an 86t bin of wheat using a higher air temperature, 38^{o}C, was simulated and results compared with those reported. The fourth stage was to measure performance on a commercial site of stirred versus static drying and validate the model against these data.

The behaviour of the simulation model when run at ‘standard’ drying conditions was in line with expectations from principles already well understood, in that the entrainment of grain into the mixed zone reduced with increasing depth and the exhaust air relative humidity (r.h.) fell as stirred drying proceeded and so gave a reduced drying rate. Agreement with the within-bed data from the 25t wheat drying experiments at Fera was good in the important respects, particularly drying time, approach to and level of final m.c., effect of each mixing event on m.c. through the bed and rapid reduction of m.c. of surface layers to a lower value. Within the bed, the simulated drying rate of the middle layers was too fast, despite which, agreement was good in other respects. Simulation of the experiment reported in the literature in which an 86t bin of wheat was dried and stirred gave results which agreed very well with the measured overall performance. Wheat on the commercial site in 2012 needed little drying so the model was tested in low moisture removal conditions but results did not raise any doubts about its performance.

The overall conclusion from the validation work was that the model was sufficiently good over the range of m.c. encountered in the experiments and, because it was based on well-understood physics of drying, could be used with confidence over a wider range than found in validation experiments.

2.4. Simulations to explore the performance, effectiveness, energy saving and cost saving potential of stirring in normal on-floor drying

In this study, 21 sets of simulations of various drying systems were run to produce data on their likely performance under a wide range of conditions. By comparing performance in various ways, the benefits and drawbacks of one system versus another, or of one choice of operating condition versus another, was shown. First, static and stirred beds were compared under input conditions normal for a static bed drier. Then various approaches were used to find out how best to take advantage of the stirring system. Bed depths of 2-4m and initial m.c. values of 24-16% were used.

To enable a fair comparison, stirred drying was compared with best performance from static bed drying. This was found to be with the fan running continuously and a powerful heater set for 62% r.h. in the plenum. Under these conditions, stirring was very effective in reducing the progress towards risk of OA because, at higher values of initial m.c., stirring avoided the persistence of wetter grain at a condition that favoured fungal growth. Where a static bed approach resulted in risk of OA, stirring the same bed allowed drying without risk of OA from an initial m.c. of about 2% m.c. higher or for a grain bed depth 1m deeper than the limit for static bed drying. Over-drying of the bed as a whole was reduced by stirring. However, compared with static bed drying, stirring made the drying considerably less efficient and so increased drying time and cost of fuel and electricity. Drying is less efficient because air within the bed can only saturate as far as the surrounding grain moisture allows. The higher the m.c. of the grain the more saturated the surrounding air can become. Stirring the grain lowers the m.c. at the surface because drier grain is brought up from lower levels, and so the amount of water that is carried away per unit of air exiting the surface is also lowered.

In approaches where the r.h. in the plenum was regulated, drying performance was a compromise. Stirring reduced over-drying and the risk of OA but increased drying time and electricity and fuel costs. When the initial m.c., and hence the risk of OA, was not high, a useful approach was to stir to eliminate m.c. gradients only when the target average m.c. had been reached. This approach gave less over-drying than static bed drying and hence faster drying, lower fuel and electricity cost. Drying with stirring down to 18% m.c. and then stirring only once the average m.c. was reached gave a compromise between avoidance of OA risk and drying efficiency, and was effective for grain not over 20% initial m.c.

Using fewer augers, and hence stirring any location less often, reduced drying time and improved energy efficiency but the risk of OA increased at higher initial m.c.

Lower airflow increased drying efficiency but extended drying time, whilst higher airflow did the opposite.

Regulating plenum air temperature rather than r.h., and heating that air to 20°C or more, resulted in quicker drying, much reduced risk of OA and little over-drying. If using this approach, a plenum temperature of 30°C produced the best compromise between drying speed, energy use and tendency towards over-drying. Electrical energy use was greatly reduced at elevated air temperatures because of the shorter drying time, but fuel energy use was increased compared with static bed drying.

Drying rates achieved when drying with a static bed or continuous stirring and a regulated plenum r.h. were in line with the rate expected for a bulk drier of 0.5% m.c. per 24h. This rate could be increased substantially by using stirring together with plenum air temperature raised to 30°C and above.

2.5. Development of user guide-lines to show how to achieve the full range of benefits from stirring

The first area explored is whether a stirring system is likely to help solve various drying problems, *e.g.* high costs or slow drying rate, better than alternative investments. Addition of stirring to a standard drier may only be justifiable after the implementation of several other approaches to keeping the risk of OA low. These approaches include using a higher airflow (more fan capacity) and an increase in the heater power available.

Then, drying problems are considered from the viewpoint of whether a stirring system retro-fitted to the existing drier would be likely to be of benefit. In this scenario, the main problem that would be addressed is when grain is at risk of OA according to the HGCA Grain Safe Storage Time (s.s.t.) Calculator. If the s.s.t. is shorter than the time needed for the drying front to reach the surface, the surface grain would be at risk of OA. Stirring throughout drying would reduce the risk very substantially. However, the problem of high fuel and electricity costs would not be reduced by simply stirring an existing drier, because stirring reduced drying efficiency.

If, however, the drier is designed to use stirring with higher plenum air temperature, drying rate can be increased using this approach while OA risk and electricity cost can be reduced. The problem of high fuel cost will not be solved because even at higher plenum temperatures, stirring did not reduce fuel use.

If a stirring system is available, stirring the grain bed before drying can help the drying to be more uniform across the store. Thereafter, whether stirring will be helpful depends on the grower's priorities for drying. If operation at elevated plenum temperature is an option and if short drying time, low electricity cost or both are priorities, then the drier can be run with air temperature raised to at least 30^{o}C. This option will, however, increase fuel cost compared with static bed drying. If initial m.c. is above 18%, sampling should be done to check OA risk using the s.s.t. calculator and if there is a risk, stirring during drying will reduce it. If operation at higher temperatures is not possible, or if fuel costs are priority, then plenum air r.h. regulation to around 62% without stirring will give rapid drying. Fuel efficiency will be better than using higher temperature with stirring. Once the average m.c. of the grain bed has reached the target of 14.5% (for example), drying can be stopped and stirring used if it is necessary to even out gradients in the bed.

2.6. Conclusions

Work to validate the model showed that:-

1. The behaviour of the simulation model was in line with expectations in that, compared with a static bed, stirring reduced the m.c. of the grain near the surface, thus lowering the rate of spoilage and the risk of OA. But the reduced m.c. at the surface also lowered the exhaust air r.h. as drying proceeded, which resulted in a reduced drying rate of the stirred bed.
2. Considering the validation work overall, agreement of the model with the data from the 25t wheat drying experiment at Fera in 2010 was good in the important respects, particularly drying time, approach to and level of final m.c. Validation against data from a stirred and a static bin at Fera in 2012 showed that the model predicted the overall drying behaviour of both bins well and, although stirring in the model was less vigorous than in practice, the accumulated effect was sufficient to mix the bed to a similar degree. The drying fronts in the model were steeper than measured but this did not affect drying time, which was well predicted. Because the wheat on the commercial site in 2012 needed little drying, data could not be had for drying using significantly higher air temperature. Testing of the model in these low moisture removal conditions did not raise any doubts about its performance, and indeed together with the data from the bin experiments, allowed the relationship between m.c. and air r.h. to be confirmed. Simulation of a published experiment in which an 86t bin of wheat was stirred and dried with air at a higher temperature gave results which agreed very well with the measured overall performance. Because the drying time was well predicted, the fuel and electricity use were also, as they are the product of running time and heater and fan power. Overall, the model proved to be sufficiently good over the range of m.c., air temperature and stirring rate encountered in the experiments. Because it is based on well-understood physics of drying, the model, it was concluded, could be used with confidence over a wider range than found in validation experiments.

Extensive use of the simulation model showed that:-

3. For comparison with a stirred bed, the best performance from a static bed drier was to run the fan continuously and to use quite a powerful heater set to regulate plenum r.h. to 62%. Under this fan and heater use, stirring was very effective in reducing the progress towards risk of OA. Where a static bed approach resulted in risk of OA, stirring the same bed allowed drying without risk of OA from an initial m.c. of about 2% m.c. higher or for a grain bed depth 1m deeper than the limit for static bed drying.
4. Compared with static bed drying in identical conditions, stirring the grain bed continuously whilst drying made the drying less efficient and increased drying time and cost of fuel and electricity, but over-drying of the bed as a whole was reduced. Efficiency was reduced because the exhaust air was less saturated when stirring.
5. With 62% r.h. plenum air, performance of drying was improved compared with a static bed by stirring only when the target average m.c. had been reached, avoiding the need to continue drying the wetter part of the bed. This approach gave faster drying, lower fuel and electricity cost and less over-drying.
6. Using fewer augers, and hence stirring any location less often, reduced drying time and improved energy efficiency. But at higher initial m.c. the beneficial effect of stirring on risk of OA was reduced. Lower airflow when stirring extended drying time, reduced electricity cost but increased fuel cost and risk of OA. Higher airflow did the opposite.
7. Controlling plenum air temperature rather than r.h. and heating that air to 20^{o}C or more while stirring resulted in quicker drying and with much reduced risk of OA and little over-drying. If using this approach, a plenum temperature of 30^{o}C produced the best compromise between drying speed, energy use and tendency towards over-drying. Electrical energy use was greatly reduced at elevated air temperatures because of the shorter drying time, but fuel energy use was generally increased.
8. Drying rates achieved when drying with a static bed or continuous stirring were in line with the rate of 0.5 % m.c. per 24h, expected for a bulk drier. This rate was increased substantially by using stirring together with plenum air temperature raised to 30^{o}C and above.
9. User guidelines are presented, drawing on the simulation results in the report, that highlight which drying problems stirring is likely to help solve and which not, so as to guide investment decisions. Guidelines are also presented on how best to use a stirring system, if available, to meet the grower’s priorities for drying, whether drying speed, fuel or electricity costs.

3. TECHNICAL DETAIL

3.1. Introduction

Grain needs to be dried following harvest to avoid problems associated with fungi and mites. In most seasons, on-floor drying, using ambient or heated air can be effective and economical but still requires considerable skill. In poor seasons, an on-floor system will incur considerable costs and may not achieve good enough results, however skilful the operator.

In a conventional bulk drier, the grain is static and drying proceeds from bottom to top of the bed in response to airflow. However good the drying conditions, grain at the top remains close to the initial moisture content (m.c.) until drying is nearly complete. In normal practice for this “static bed” drier, air relative humidity (r.h.) in the plenum is normally regulated to bring the whole bed to a m.c. suitable for storage.

In drying with stirring, by contrast, the grain bed is mixed during drying using vertical augers. Layers of wetter and of drier grain from upper and lower parts of the bed are gradually mixed into the mass and approach a common m.c. By this means, the maximum m.c. of grain in the bed is reduced more quickly than in a static bed, thus reducing the risk of spoilage by fungi. In a difficult drying season when grain may arrive at the store wetter than usual and the weather may be less good for drying, for example when ambient temperature is low and r.h. is high, the capability to dry the wettest grain rapidly could make a crucial difference to the value of the grain. The importance of rapid drying in controlling risk of fungal toxins is emphasised in the HGCA Grain Storage Guide 3rd edition, 2011. Other benefits of stirring in terms of maintaining quality and reducing cost are available, in principle, whatever the season. For example, overdrying of the bottom of the bed can be avoided, or at least reduced, so it may be possible to exploit different, and potentially more energy-efficient, drying strategies. If stirring allows a greater depth of grain to be used without compromising grain quality, this would allow more grain to be dried with an existing drying floor.

These potential advantages of stirring are quite well known, but there are drawbacks too. Clearly, installing a stirring system on an existing drier to solve a drying problem requires a sizeable investment, for which the grower would wish to know the benefits. A major investment in a new store designed around stirring may need to be justified by savings in cost and/ or time. A small, single auger stirrer is low cost but how much difference might it make to drying performance?

This study aimed to examine stirring and how to integrate it with on-floor drying practice to find out how growers can get the maximum benefits from a stirring system, and establish guidelines for operation. This was achieved by developing, validating and exploiting a well-established simulation model of drying integrated with a new model of the stirring process. The integrated model was then run extensively to generate data on how drier performance would be likely to be influenced by initial m.c., bed depth, weather conditions, size of fan, conditions in the plenum and, of course, how the stirring system is used in relation to these factors. The work focused on how costs of fuel and electricity and drying time were affected by the factors just given. With this data and a better understanding of how stirring the bed affects drying, this work aims to help growers make the best decisions on whether to stir and how to stir.

It was convenient to structure this report using the milestones (MS), which are quoted in this report from the project documents for completeness. MS 1 describes the new model of stirring, MSs 2 and 5 present the validation, MSs 3 and 4 describe the simulation work done with the model and presents and analyses the resulting data, and MS6 develops guidelines to help in decisions on whether stirring is likely to be helpful and how best to use a stirring system.

3.2. Development of integrated model of drying and stirring

Milestone 1. "Revise the simple simulation of mixing developed in project HGCA 3133 and adapt it for a single, self-propelled stirring auger, variable auger depth, and rate of mixing."

The new, integrated model of stirring and drying was implemented as modifications to the simulation of bulk drying known as "Storedry", which has been used for several HGCA projects (Bruce *et al*. 2006, Nellist 1998A, 1998B) and was well established by extensive research at the former Silsoe Research Institute (*e.g*. Nellist, 1987, Nellist & Bartlett, 1988, Nellist & Brook, 1987). The model is written in FORTRAN computer language.

In the simulation of bulk drying, the grain bed is represented as a series of 100 layers, each thin enough for certain simplifications to be made in the calculations of exchange of heat and moisture. Air flows through each layer in turn. An inlet air condition is used for an hour, then the historical record is read and the ambient temperature and relative humidity weather conditions for the next hour are read and used. Depending on the particular control strategy being implemented, the ambient air conditions may be altered by heating. The grain bed is ventilated with the air representing the output from a fan, which will have an appropriate heating effect. The flow rate may be specified, or it may be calculated to reflect the performance of a particular model of fan operating against the resistance of the grain bed and duct system. Depending on the moisture and temperature conditions of the grain in each layer and of the air entering the layer, the air may heat or cool the grain and may dry or occasionally rewet it. If grain and air reach an equilibrium condition, no further exchange takes place. The conditions of the air and grain in each layer up through the bed are calculated each hour. Of the two methods for simulating the layer-by-layer exchange of heat and moisture in the grain, the "four equation" approach was used here, as opposed to the “equilibrium” approach used in HGCA project 2982 (Bruce *et al*., 2006) for example. This was because the four equation approach, though demanding significantly more computing time per drying run, was necessary when drying with the higher air temperatures that may best exploit the stirring system. Once the temperature and moisture conditions of each layer of the grain bed have been established for each time step, the effect on the grain quality in each layer is calculated. These include progress towards spoilage by fungal activity. Drying is halted when two grain moisture targets have been reached or a time limit of two months has expired. The targets are for the average m.c. of the whole bed and for the wettest m.c. in the bed to have fallen to or below specified values. At these times, various measures of performance and are calculated and output as required. The program has not been fully described but Sharp (1984) describes the theoretical basis and many of the features as they existed then.

Grain stirring was modelled in a simple way for HGCA project 2982, as appropriate to that project’s requirements. The focus in that work was on how to avoid the upper layers of the grain bed remaining at or around their initial moisture for most of the drying time, with the consequent risk of production of fungal toxins. Stirring could avoid this situation by reducing the m.c. of the upper layers more quickly and hence reduce the opportunity for fungal growth in these layers. The “stirring” in that model was done at particular times during the drying process and not throughout drying. At the specified times, *e.g*. once per 6h, the layers of grain were simply re-ordered in a random manner, thus effectively mixing the grain bed. In this simple model, the process took place in zero elapsed time. Each grain layer maintained its conditions of moisture content, temperature and progress towards spoilage, so any gradients developed by drying were destroyed. The differences in moisture and temperature between adjacent layers resulted in transfer of heat and moisture to and from the air in subsequent ventilation so that the sharp layer-to-layer differences were lost and the gradients in the bed were gradually re-established.

Though useful for the “quick look” at stirring required by HGCA project 2982, this model was not adequate for the present study with its focus on energy use and cost. The shortcomings of the previous model for this study are as follows.

- Instantaneously mixing of the whole bed is unrealistic and does not allow accounting for energy expended as the stirring system runs
- It was not possible to account for the impact of the number of stirring augers in a given area of drying bed on drying performance
- Lateral redistribution of grain arising from the vertical stirring augers was not modelled
- The changes in the bed arising from drying <u>during</u> stirring were not available
- The exhaust humidity was not well enough calculated. This was because the moisture content of surface layers, which determines the exhaust humidity, was determined by the layer that happened to end up on the surface after shuffling.

The action of stirrers moving through a grain bed is complex. The main action is the vertical lifting of grain near the auger and subsequent sinking further out from the auger, which is a complex pattern of particle flow that results in lateral as well as vertical flows. Add to this the effect of the movement of augers around the grain store, which leads to further lateral grain flow following the auger movement, and irregular stirring of any particular area of the store. Hence, the particle flow patterns are three-dimensional and time dependent.

As explained above, the drying model, "Storedry", represents the grain bed as a series of layers in the vertical direction, so it is a one-dimensional model. Hence, it would have been inappropriate to develop a model of stirring as a three-dimensional process, which it really is, because such a model could not be integrated into the drying framework. Instead, a one-dimensional stirring model was developed to integrate with the drying calculations, but which nonetheless represented the essential features of the action of vertical augers on the grain bed.

The first stage of the new stirring model considers the action of a single auger, embedded in a grain mass and running but not moving laterally, which has been running for long enough to produce a stable flow pattern of grain. Observation of this pattern in commercial devices and in an experiment reported below, shows that grain is lifted by the auger to form a cone at the bed surface, down the faces of which grain flows freely. (Once the auger has passed, the slope is static.) Grain is then drawn below the surface level as grain in the bed descends to replace that drawn upwards by the auger. Grain enters and leaves the vertical flow driven by the auger throughout its length but the main point of entry is at the bottom of the auger and most of the entrained grain exits at the top. Grain being removed by the auger from the point of entry results in a flow downwards from the footprint of the surface cone. The result is a circulation in the grain mass.

Although it is possible to calculate the shape of the descending mass within the grain bed, this is a very complex problem in particle flow. Flow is controlled by the properties of bulk materials, particularly by internal friction between the particles and the compressive stresses in the bulk grain resulting from its weight. The result is slip surfaces within the bulk between regions of flowing and of static particles. The material properties and the normal stresses determine the angle to the horizontal at which material will 'slip' against itself. (The angle in the bulk differs from the angle that the material forms when forming an unconstrained sloping face on which there is no normal stress.) So, based on the overall situation described, it was assumed that the moving mass of grain below the surface also formed a cone that extended from the bottom of the auger to meet the cone on the surface base to base. A partly dried bed is shown in Figure 1, with the yellow colour representing grain already dried and the blue colour yet to be dried.

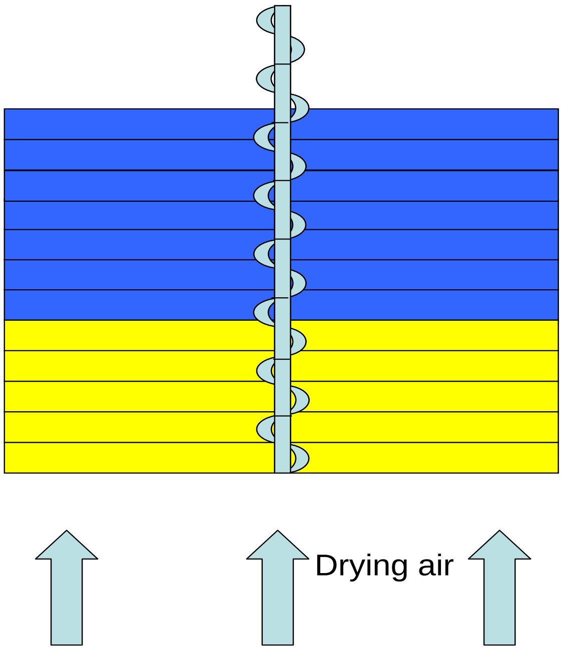

Figure 1. Schematic of a partly dried bed of grain showing airflow, stirring auger, grain already dried (yellow) and yet to be dried (blue).

In Figure 2, the circulation zone formed as a result of the action of a stationary auger is shown as green, with arrows indicating grain flow direction and speed. The rest of the bed is undisturbed except that the level beyond the cone has fallen, shown by the white 'layer' of displaced grain. Figure 3 shows the final state of the bed after lateral redistribution, the colours illustrating the differing proportions in each layer of mixed grain from the circulating zone and undisturbed grain.

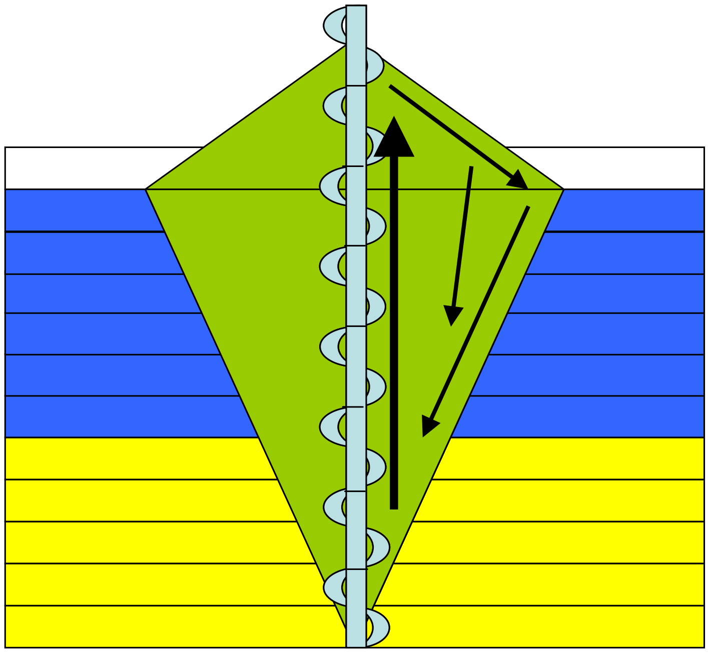

Figure 2. Circulation zone formed by auger (green), with arrows indicating grain flow direction and speed. The rest of the bed is undisturbed except that the level beyond the cone has fallen, shown by the white 'layer' of displaced grain.

The assumption was made that the circulation of grain due to the action of the auger was enough to completely mix the grain in the circulating zone, and thus to produce a volume of grain at a uniform moisture and temperature. This is justified by the slow lateral speed of augers that are lifting grain at quite high flow rates. The conical shape of the circulating zone implied that differing proportions of the drying model's grain layers were entrained. The m.c. and temperature in the circulating zone were calculated from the m.c. and temperature of the grain in each layer and the mass of grain entrained from each layer. Once this was known, the effect of lateral distribution from the stationary auger was modelled by combining at each layer the appropriate proportion of grain in the mixed volume with that not entrained by the auger as shown in Figure 3 which illustrates differing proportions in each layer of mixed grain from the circulating zone and undisturbed grain using colour. Dried grain is represented in yellow, grain at the original surface m.c. is represented in blue and grain at intermediate m.c.s in various shades of green.

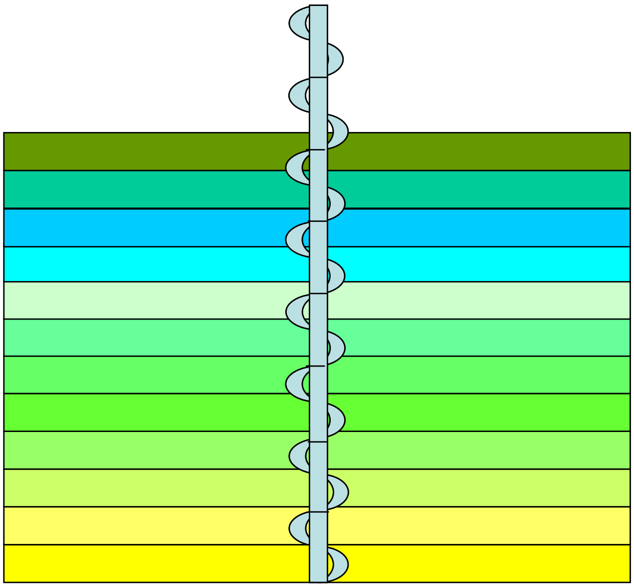

Figure 3. Bed after lateral redistribution in the simulation, the colours illustrating the differing proportions in each layer of mixed grain from the circulating zone and undisturbed grain.

Stirring systems move the augers within the store so as to mix the whole area of bed with only a small number of augers. The model is based on that fraction of the store effectively stirred by one auger. So if there are four augers the store area simulated is ¼ of the whole.

Movement of the augers around the grain store was modelled as follows. Storedry was modified to simulate drying in many grain beds in parallel, rather than just one. These 'mini-beds' had the same number of layers and were all ventilated in the same way, so moisture and temperature changes were calculated in each bed for each hourly timestep. However, only one of the beds was stirred each hour. Given the computing effort is much greater than for the single bed model, the number of beds in the sequence for stirring was limited to 20 for one stirring auger. This is enough to allow a realistic pattern of auger movement around the store to be defined. The sequence can overlap itself and does not have to include all beds an equal number of times so various patterns of movement can be specified. (An option was added to use a timestep of 0.25h if needed, so that the experimental data from the Food and Environment Research Agency (Fera) could be modelled as a four bed sequence stirred over a 1 hour period.)

Each mini-bed had a surface area that was as wide as the cone produced by a single auger, 1.0m based on experimental data from the project, and as long as the distance moved by the auger in the one hour timestep. So the number of beds in the sequence is found by dividing the area of the part of the store to be simulated by the area of each bed. As the auger moved from one bed to the next, mixing of grain between the mini-bed just stirred and the next in the stirring sequence was modelled by a similar procedure as already described: a proportion of the each layer from one of the mini-beds was mixed with the appropriate layer of the other to represent the grain mixing when the auger was operating at the edge of both mini-beds. However, side-to-side redistribution between beds along the current auger track and those in adjacent tracks was too complex to include.

The literature on stirring is not conclusive about the effect of stirring on air resistance of the bed. There is some evidence that stirring reduces resistance, but only marginally unless the grain was compacted or deteriorated (Anon., 1994). Such a reduction would allow more airflow if the fan were capable of providing it. The stirring model was developed to allow a reduction in air resistance to occur. The best way to do this would be for airflow resistance to be expressed as a function of bed porosity because, if stirring has any effect on the bed air resistance, it will be as a result of increased porosity. However, in Storedry, the resistance of the bed is calculated from grain depth and seed size and the porosity of the bed is not explicitly used. So the approach taken was to increase in airflow after a mini-bed was stirred by a user-determined multiplier. Settling of the grain bed after stirring would occur over time, which would gradually increase the porosity towards the original level, so the airflow was reduced at each time step after stirring again by a multiplier. This reduced the airflow towards its original value which, unless the bed was stirred again, would be reached in a user-set number of hours. The reduction in airflow as this settling occurred was continued even if stirring was off.

In the model of stirring developed for HGCA project 2982, grain quality attributes were calculated for each layer. These attributes, namely the progress towards the risk of Ochratoxin A (OA) and the loss of grain viability, followed that layer when it was re-shuffled. In the new model, the mixing and averaging of moisture content and of temperature did not allow the grain quality attributes of individual layers to be preserved through the stirring process. Whereas averaging was appropriate for physical parameters such as moisture content and temperature, it was not appropriate for grain quality parameters for the following argument. If a grain layer were very close to the spoiled condition, *i.e.* in which fungi would be about to produce OA, mixing and averaging that layer with another where the grain was still in prime condition would produce grain which was only half way to spoilage condition. This is not realistic because individual grains in the mixture would still harbour fungi at the critical level and would still be at high spoilage risk. So the new model takes a conservative approach by finding the layer in the bed before stirring in which biological attributes are worst and ascribing them to all the other layers in the bed after stirring.

The model had to be able to simulate drying with the auger not operating, or operating intermittently. A time-based arrangement allowed the auger to be run a specified times, *e.g*. turned on after 150h of drying. A control arrangement was also developed that modelled the commercial practice of running fan and heater for a time before starting stirring. Stirring was started only when a user-set temperature had been reached in the grain bed. At this time, a second fan could be started in parallel with the first, to provide increased airflow while stirring.

An option to start with a non-uniform bed of grain was added, such that the m.c. of all grain layers could be specified individually.

Approximately 750 lines of code were needed to implement the changes described above.

3.3. Validation

Milestone 2. "Plan and make measurements in the The Food and Environment Agency (Fera) grain store on stirring in bin, and on drying with and without stirring. Validate the stirring model using the data."

Milestone 5. "Plan and make measurements on a commercial floor store drier with a stirring system, and validate the model using the data"

Validation was done in four stages. First, the model was run at 'standard' near-ambient drying conditions and the results with stirring were compared qualitatively with results when stirring was not used. This allowed the behaviour of the stirred bed drier model to be checked to ensure it was reasonable. Second, two experiments were undertaken at Fera, where grain bins of about 30t capacity were available. In experiment A in 2010, the mixing pattern of a single, fixed auger was studied in a bin with two layers of different initial moisture content. The bin was then dried with stirring. In experiment B in 2012, two bins were dried, one with and one without stirring. Measured conditions for ingoing air and grain from each experiment were used as inputs to the model so that the predicted temperature and moisture content in the bed during drying could be compared with measurements. In the third stage of validation, an experiment reported in the literature on an 80t bin and using a higher air temperature, 38°C, was simulated and results compared with those reported. The fourth and final stage of validation was to measure drying performance with and without stirring in side-by-side bays in a commercial floor store and compare predictions made using the model with the data.

3.3.1. Stage 1 – behaviour of stirred bed drier

Drying with a static bed, *i.e.* not stirred, resulted in a drying zone developing such that grain nearest the air entry dried first, towards a moisture content at equilibrium with the incoming air, while further downstream the grain was continuing to dry, and near the air exhaust, grain was not changed from its initial condition. Although a target average m.c. may be reached, the lower part of the bed will in general be drier and the upper part wetter. (If grain were to be stored *in situ*, it might be necessary to continue drying to bring the upper part to a m.c. suitable for storage.)

Figure 4 shows the m.c. (always expressed on a wet weight basis in this report) versus drying time in such a drier, with a bed depth of 3m. The development of the drying zone is illustrated. At 100h for example, grain at 2.5m and deeper had already reached equilibrium of about 14.4%, grain at 1.5m and shallower was unchanged from initial m.c. and at 2.0m the m.c. was around 15%. At the end point when the average m.c. of 15% was achieved after 216h, a spread of m.c. remained in the bed, with the surface remaining near 19.5% and grain at 0.5m remaining at 15.8%.

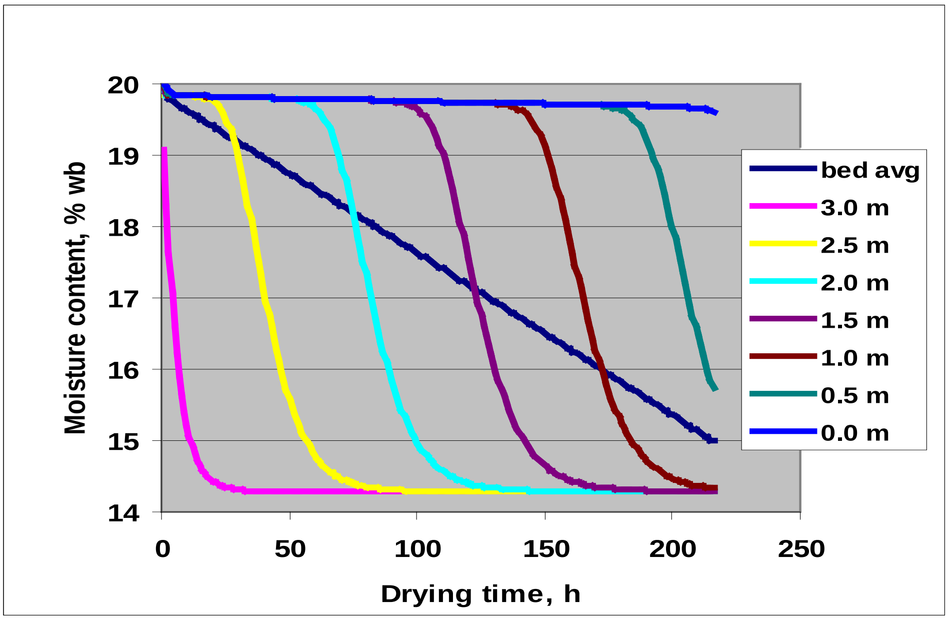

Figure 4. Moisture content at 7 depth locations and average moisture content versus time in a static bed 3m deep.

Figure 5 shows the effect of stirring the bed once for 4h at 100h. The differences in moisture were substantially removed by the stirring, shown by the fact that grain at 2.5 and 2.0m was made wetter while grain at 1.0m and shallower was immediately reduced in m.c. At 3.0m, grain was unaffected by stirring since a very small proportion of it was entrained in the mixed “cone”. Immediately after stirring ended, the drying zone began to re-establish itself as the deeper grain dried towards equilibrium. It is noted that the average bed m.c. was unaffected by stirring, as would be expected because no loss of moisture took place at that point in time. When the bed reached an average m.c. of 15% at 233h, moisture differences again existed although the wettest grain was less wet than in the static bed of Figure 4. It is also noted that drying to the same final average m.c. took longer in the bed stirred once. This is discussed later.

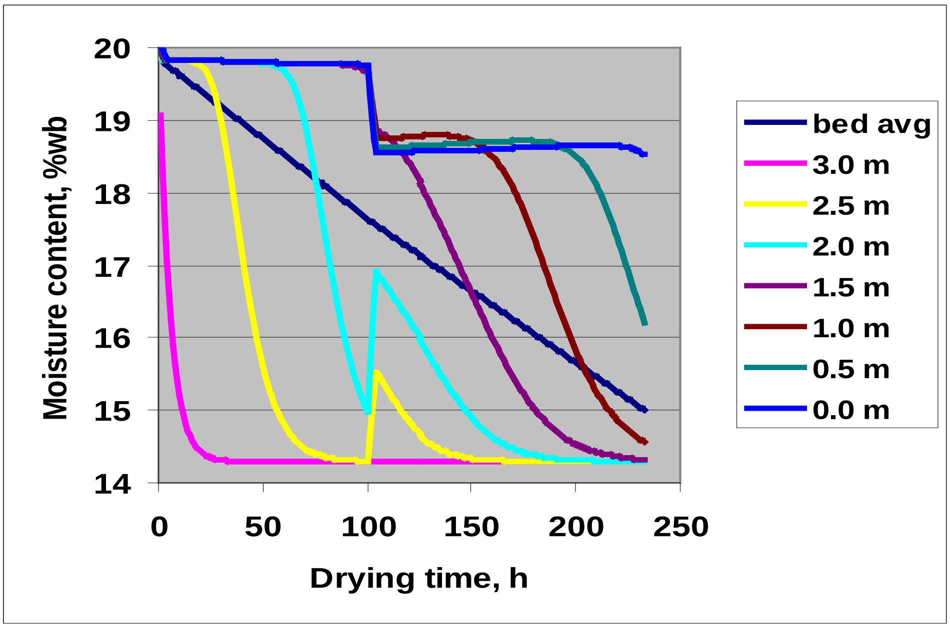

Figure 5. Moisture content at 7 depth locations and average moisture content versus time in a bed 3m deep stirred once at 100h.

In Figure 6, the stirring was continuous once initiated at 100h. Before this time, the behaviour was identical to that in Figures 4 and 5. Stirring results in the upper layers of the bed, down to 2.0m, have become indistinguishable from each other while the layer at 2.5m was similar but, being nearer the air inlet and being dried continuously by incoming air, followed a lower moisture trajectory than the rest of the bed. This appears reasonable given that the moisture content of the lower layers was being continuously reduced by drying but also being increased by mixing with wetter grain from above. In the lowest region of the bed, where the smallest proportion of grain was exchanged with the rest of the bed because of the conical shape of the mixing zone, the effect of the drying was most intense. At 3.0m, the grain was unaffected by stirring, for reasons previously explained. While drying was continued, the lower region of the bed would be expected always to be driest but if stirring were continued once drying was stopped, the grain would finally become uniform.

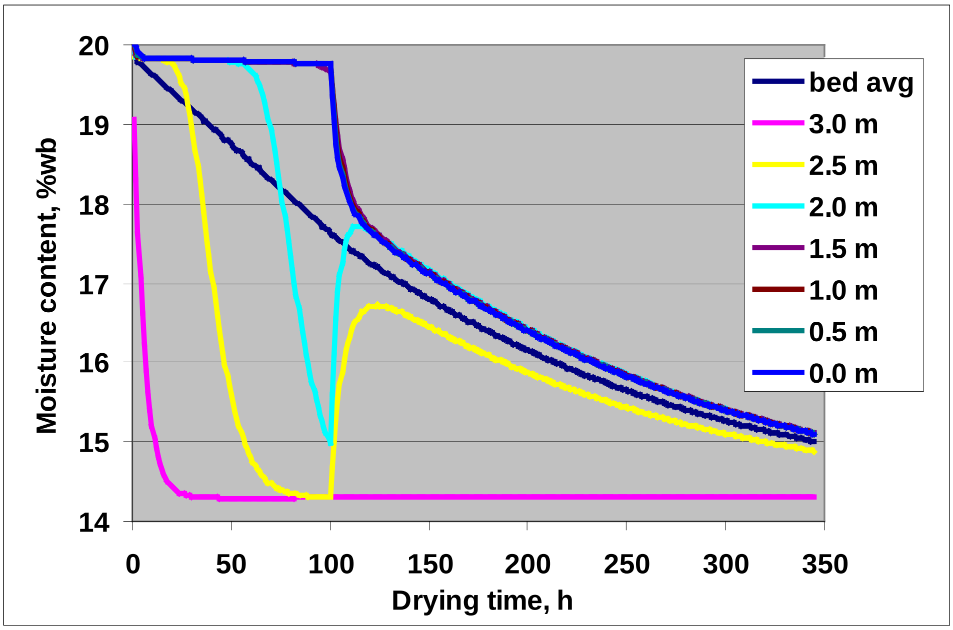

Figure 6. Moisture content at 7 depth locations and average moisture content versus time in a bed 3m deep stirred continuously from 100h.

In Figure 6, drying to the target average of 15% took almost 350h, compared with 233 h of Figure 5 when less stirring was used. The explanation for this is as follows. The air exhausting from the bed carries away the moisture so the more saturated it is, the more efficiently it is being used for drying. Given that the energy needed to pump each unit of air is the same, efficiency requires that exhaust saturation be as high as possible. (In practice exhaust air should be removed from the store to prevent any condensation or re-absorption.)

Figure 7 shows the exhaust air relative humidity (r.h.) versus drying time for the standard grain bed, static and stirred from 100h after the start of drying, and with drying continuing until a target average bed m.c. of 15% is reached. The static bed showed a steady exhaust r.h. until the leading edge of the drying zone reached the surface at about 210h, whereupon the r.h. began to fall towards that of the inlet air but for only a short time because drying to the required average m.c. was complete. Thus, for nearly all the drying time, the exhaust r.h. was consistently high, which means that the drying potential of the incoming air was well used. In the stirred bed, the r.h. started to fall earlier, as a result of the fall in m.c. of the well-mixed upper region of the bed, with which the exhaust air would be equilibrated. Early in the drying, there was no difference in the efficiency with which the drying potential of the air was used but once stirring started the stirred bed used the incoming air less efficiently. As a result of this, the average moisture content fell slower in the stirred bed and it took longer to reach the target under the conditions simulated. This principle would apply whatever air speed, temperature rise etc. were used, but the use of stirring might allow air and bed conditions to be used that would lead to problems in a static bed. Here, for example, the range of moisture content in the static bed once the average was achieved was too wide to be acceptable so further drying or perhaps mixing by outloading would be needed, thus increasing time and cost.

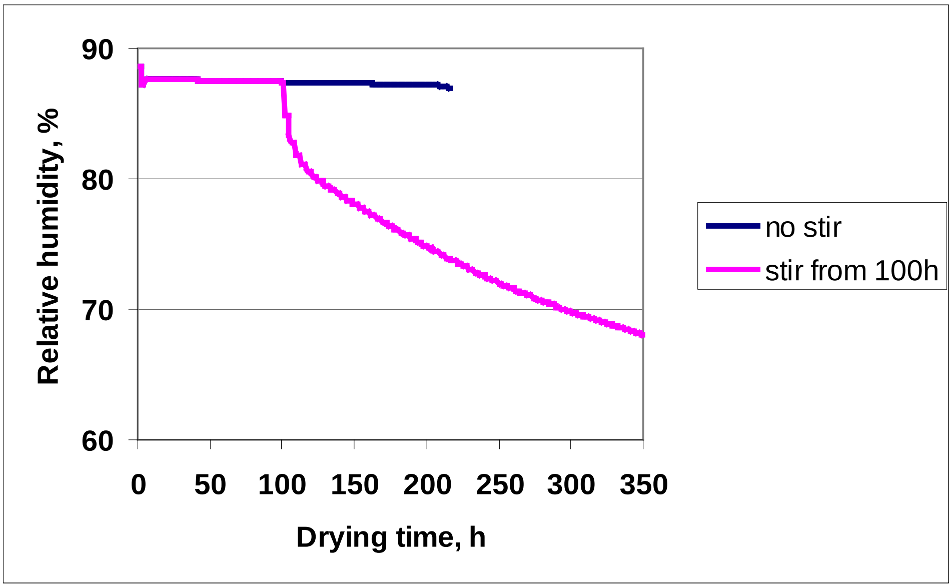

Figure 7. Exhaust air r.h. from static bed and from bed stirred from 100h, versus time.

3.3.2. Stage 2 – experiments in bin

Two experiments were undertaken in 30t grain bins in the Fera grain store. In experiment A in 2010, the mixing pattern of a single, fixed auger was studied in a bin with two layers of different initial moisture content. The bin was then dried with stirring. In experiment B in 2012, two bins were dried, one with and one without stirring.

Experiment A – Stirring action of a single Auger

The first part of the experiment carried out at Fera in 2010 was designed to give data on the stirring action of a single auger when stationary in a grain bed in which there were two zones with distinctly different moisture content, a dry zone surmounted by a wet zone.

Two batches of freshly harvested wheat were placed in Bin 3 in the Fera grain store, a square (3m by 3m) open top bin of 30 tonne capacity. The bin was fitted with a MR280 5.5kW fan from Air Control Industries Ltd, suitable for ambient air drying, connected to two parallel ducts running the length of the bin. The first batch was 10.2 tonnes and had a moisture content of 13.6%. The grain was levelled and then the second batch of 15 tonnes with a moisture content of 17.5% was placed on top (Figure 8).

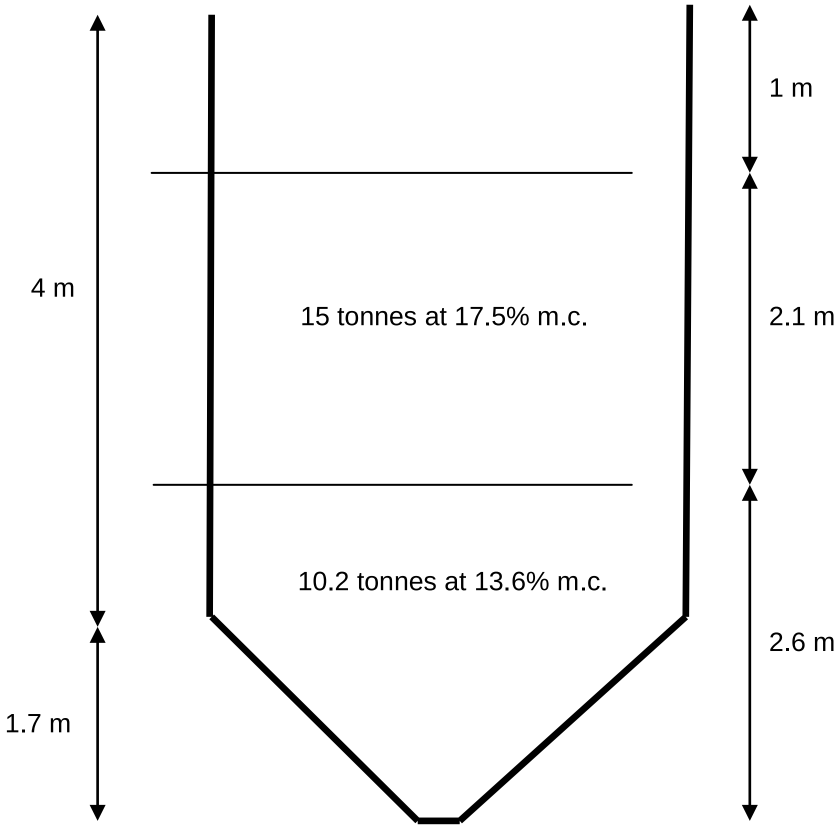

Figure 8. Bin 3 after loading and levelling.

A “Grain Butler” single auger machine, kindly loaned by BDC Systems Ltd and fitted with a 2.93 m auger, was fixed to a ladder (Figure 9) across the bin top so that it would be secure and not move when used. When the bin was filled initially with the two batches of grain the boundary between drier and wetter grain was not high enough for the auger to reach and so it was decided to dry the bin for a period to drive the dry-wet boundary sufficiently far up for the mixing test. After drying for 102h this had been achieved, according to temperature readings used to track the drying zone.

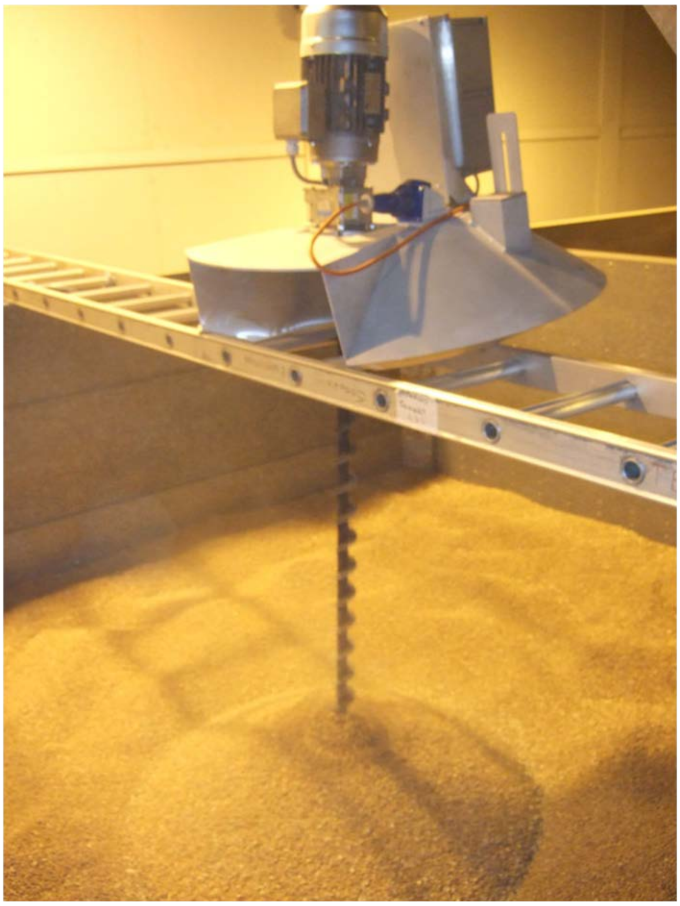

Figure 9. Single auger stirrer unit secured across the bin.

The dimensions were recorded of the grain cone that formed around the auger after it had been working for a long enough time (Figure 10). The diameter of the cone was found to be 1.0m so this value has been used in the model as the width of the zone stirred by the auger each hour.

Figure 10. Grain cone formed by running the auger

Because the mixed region below the grain bed surface was not directly observable, samples were taken by probe down into the grain bed within and without the surface cone. It was hoped that the moisture contents would show not only the location of the edge of the mixed zone below the surface but also confirm the mixing of the entrained grain from the two zones of differing moisture content.

Figure 11 shows oven m.c. values all taken at 0.2m from the auger axis, at 6 depths before mixing and at 4 depths after 20 minutes of mixing. It was expected that samples from outside the subsurface mixed zone would not change in m.c. while those within the zone would become drier as the dry grain from below was entrained and mixed. If the mixed zone were the shape of a cone of included angle 40^o from the tip of the auger, all of the four samples taken after mixing would, unfortunately, be in the mixed zone, so this hypothesis was not testable.

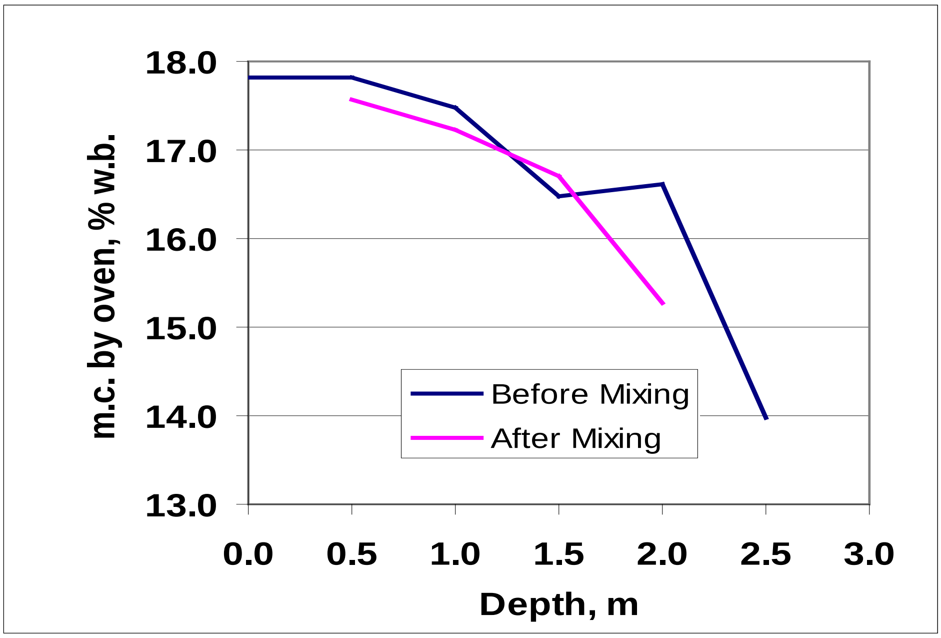

Figure 11. Effect of 20 min stirring on moisture content profile at 0.2m from auger axis.

Figure 11 shows that, before stirring, the m.c. at 2.5m was distinctly drier, because grain at that depth was initially dry, but in the upper zone of the bed moisture values were variable. At 2.0 and 1.5m, the grain was of intermediate m.c. suggesting that the drying front was not narrow and that it had reached both locations. The m.c. of the upper three samples, at 0, 0.5 and 1.0m was close to initial value for the wet grain.

The figure also shows that, after 20 min. stirring, 3 of the 4 samples were drier than those from the same depth before mixing, but only one, at the 2m depth, was significantly drier. A uniform m.c. through the samples would have shown complete mixing so the values observed do not confirm that mixing was complete. Once the auger had been run and the grain below had been disturbed, the measurements could not be repeated.

Moisture content values were also recorded from a probe pushed down into the grain bed, but these measurements did not establish any clearer a picture than the oven m.c. values so they are not presented here.

Experiment A - drying with stirring

The auger was then removed from the ladder so that it could move freely and the grain was dried with stirring. The auger stirring device was used intermittently to stir the bin rather than continuously because it was self-propelled and had to be supervised. The supplier recommended one hour of stirring per 24h so four periods of stirring each of 1h were carried out over 4 days while the bin was being dried. No heat was added to the air because the fan alone was known to heat the air by about 3^{o}C. Samples for oven moisture analysis were taken daily before and immediately after the period of stirring. The samples were taken at depth intervals of 0.5m, starting at the surface and sampling down to 2.5m, this last being in the zone of initially dry grain. The bed depth was effectively 3.6m so the lowest metre of grain was not sampled. The length of the auger was 2.93m.

The bed was dried for about 4d without stirring to move the dry-wet boundary up through the bed to a depth where the auger would mix dry and wet grain when operated. Temperature measurements were used to judge when this had been achieved. During two periods of 2d each, drying was stopped and only cooling with a low air flow took place. This was necessitated to avoid the drying front progressing too far when labour was not available for sampling. These two periods were cut out from the overall record to leave only the measurements obtained when a drying airflow was used. This was considered reasonable because cooling flows are small enough to achieve virtually no drying. However, the temperature and r.h. traces were affected so there were discontinuities in these traces which made their interpretation difficult.

The simulation was run using the measured air temperature, relative humidity and flow, and initial grain depths and initial moisture contents of the two grain batches. Each one hour period of stirring was modelled by 15 min stirring for each of four mini-beds, where a mini-bed represented one quarter of the bin. This was done four times to match the times when stirring was done during the experiment, at 102h, 122h, 158h and 181h.

Experiment A - results and discussion

Figure 12 shows the grain m.c. versus drying time for samples taken down through the bed at the centre of the bin to 2.5m depth. Figure 13 is the equivalent for samples taken from 0.5m from the side of the bin. Before drying started, the samples at 2.5m depth revealed the dry layer while grain at the other depths was initially wetter. As drying progressed to the first stirring time at 102h, grain at 2.5m (yellow trace), which was within a metre of the inlet duct, underwent some wetting and some drying but did not change substantially. At 2.0m depth, drying started after 1d and progressed. At 1.5m, drying started at 2d and, at 1.0m and less from the surface, there was no change in m.c. before stirring.

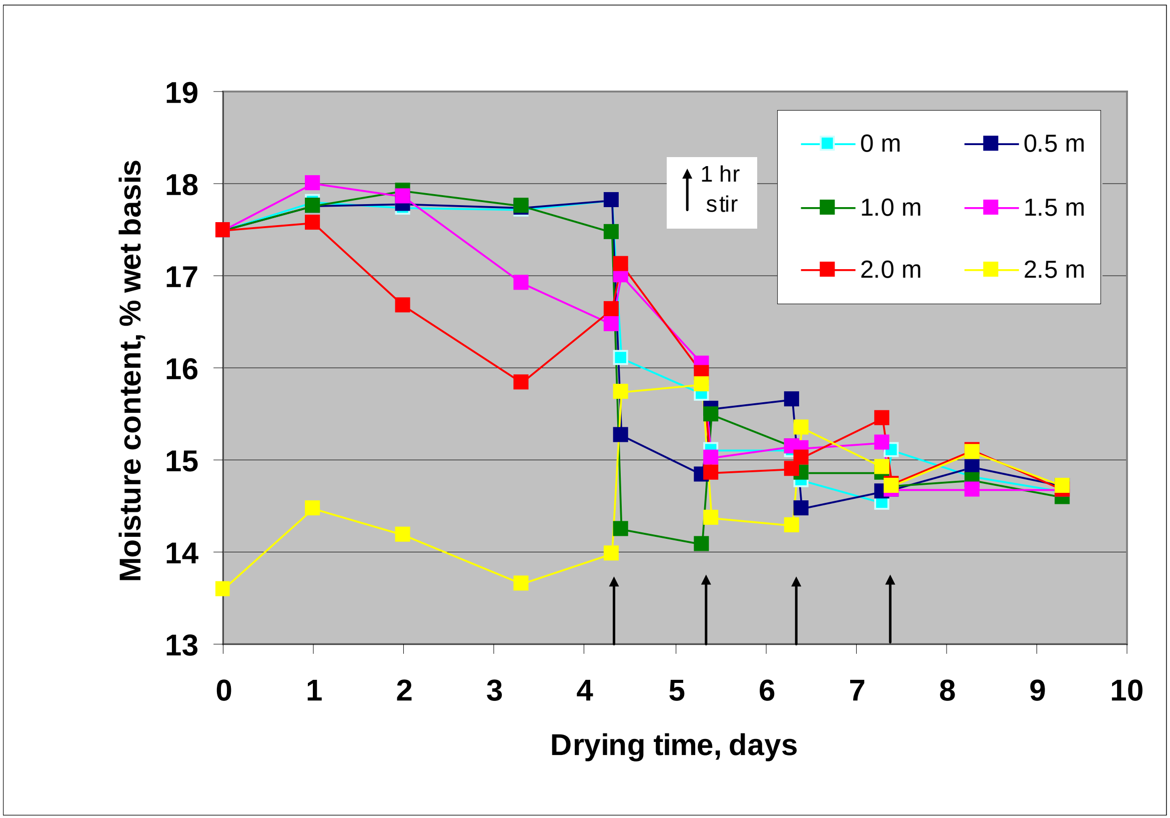

Figure 12. Moisture content versus time at 6 depths at centre of bin showing four times when bin was stirred.

Stirring, first at 102h and stirring on the subsequent three occasions, was highly effective in disrupting the layers of grain at the bin centre (Figure 12) judging by the m.c. samples from the six depths. It is particularly noteworthy that, after only 1h of stirring, the m.c. in the top 1m of the bed dropped immediately and none of the grain sampled remained at the initial m.c. It was evident that mixing was thorough enough for the surface grain to have been incorporated and not just moved to a lower depth. Had this initial m.c. been high enough for there to have been a risk of OA, which it was not in this experiment, such a fall in m.c. would have eliminated the risk almost immediately. Moisture traces from the bin centre showed that grain at 2.5m and at 0.5m must have been moved up because wetter grain reached 2.5m, which can only have come down from above, while drier grain arrived directly at 0.5m. On subsequent stirs, the situation was reversed but the changes got smaller as the mixing evened out the bed. At the side of the bin, Figure 13, the layer disruption was similar though not as complete, as shown by the observation that grain at 2.5m was not disturbed until the second stirring period and, from the second stir onwards, the m.c. at the 2.0m level remained wetter than the rest of the bed. This was probably because the physical size of the motor unit prevented the auger getting close to the side of the bin so there may have been little or no mixing at the depth of the tip of the auger close to the side face of the bin.

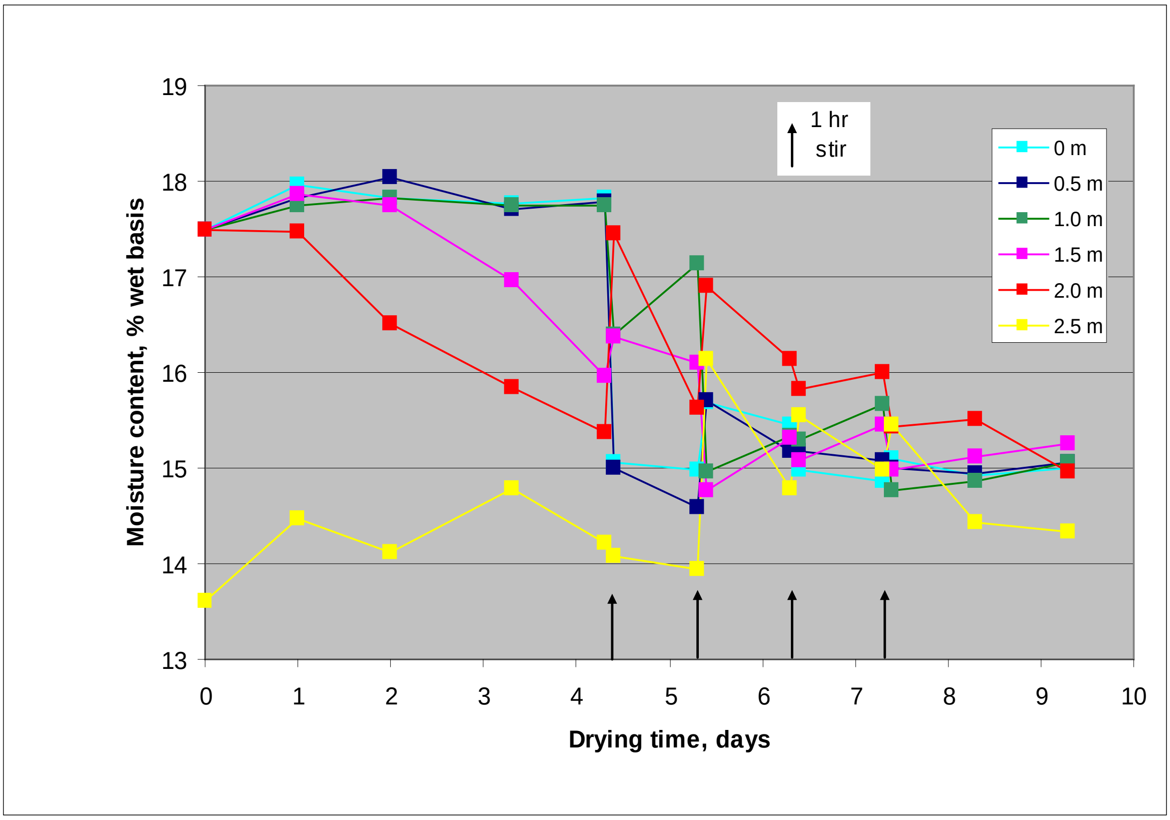

Figure 13. Moisture content versus time at 6 depths at edge of bin showing four times when bin was stirred

In Figure 14, grain moisture content at three depths, 0.5, 1.5 and 2.5m, averaged for the centre and side bin samples, are compared with values from simulation. Data values are shown as points, simulated traces as lines. Overall, agreement was acceptably good for the purpose of this investigation. The initial m.c. values were calculated from daily samples rather than being taken from the sampling on intake. Considering the three depths in detail allows some observations to be made. At 0.5m below the surface, both measured and simulated m.c.s were steady until disturbed by stirring. Thereafter both fell sharply and approached the final condition. Experimental points were a little lower than simulated values. At 1.5m the simulated m.c. fell after about 50h drying and was approaching equilibrium before stirring started. The measured m.c. started to fall later and fell more slowly and so a significant difference opened up. This was investigated further, below. Both were disturbed by stirring and after 2 stirring periods, both were approaching steady values. At 2.5m, measured and simulated values were steady until the first stirring, showing that the initial m.c. of this dry zone was close to the equilibrium value. However, the steady values differed, showing that the equilibrium m.c. in the model differed from that in experiment. The simulated m.c.

increased on each stirring occasion, just as did the measured m.c., but the simulated values remained below the measured. This was because continuing drying pulled the m.c. down towards a lower equilibrium value.

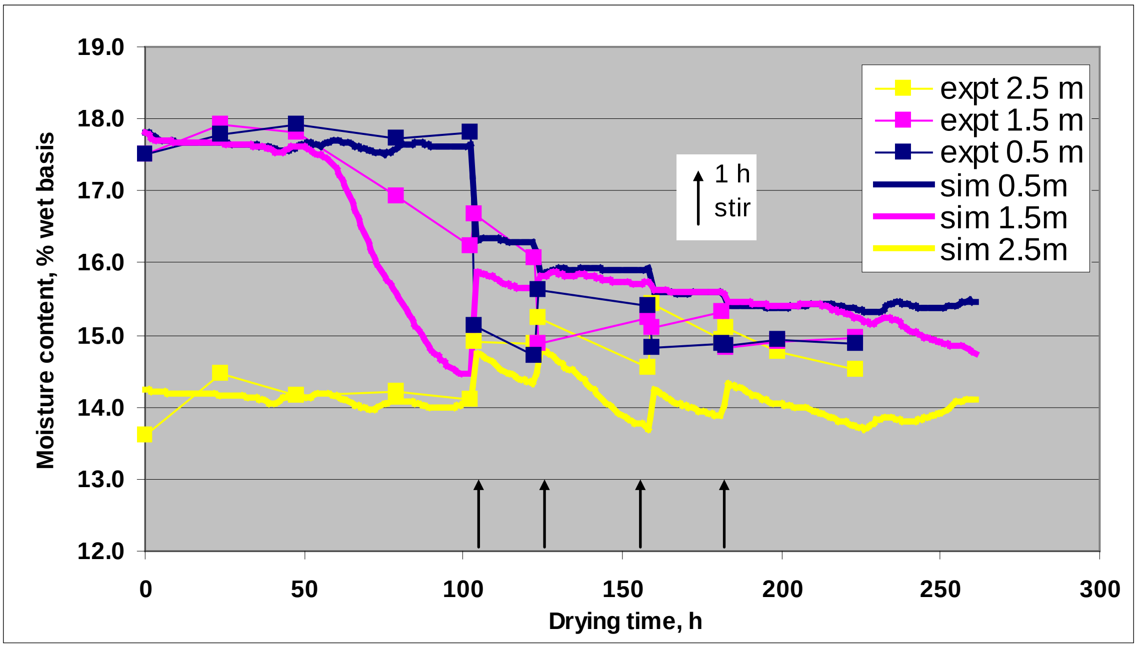

Figure 14. Progress of moisture content with time during drying, experiment versus simulation.

Three different equations describing the equilibrium relationship between air and grain were coded into the model (Sun and Woods, 1994, fitted to data below 20°C for soft wheat, Jonsson (personal communication), Equation 5 of Nellist and Dumont, 1979) and trialled to see whether agreement was improved but all actually resulted in worse agreement than the original isotherms fitted by Bruce to data on wheat (Appendix B of Bruce *et al*., 2006) because they gave lower equilibria. The model was also checked closely to ensure that it was running correctly. It was concluded that there was no programming error and that the most appropriate descriptors of grain properties had been used.

Temperature traces (Figure 15 at bin centre) were much more difficult to interpret than moisture traces because of (a) the stirring events themselves, (b) the diurnal fluctuation in temperature of drying air and (c) the jumps in the temperature record as a result of removal from the data records of the two periods of low-airflow cooling. Attempts at analysis did not give any clear results.

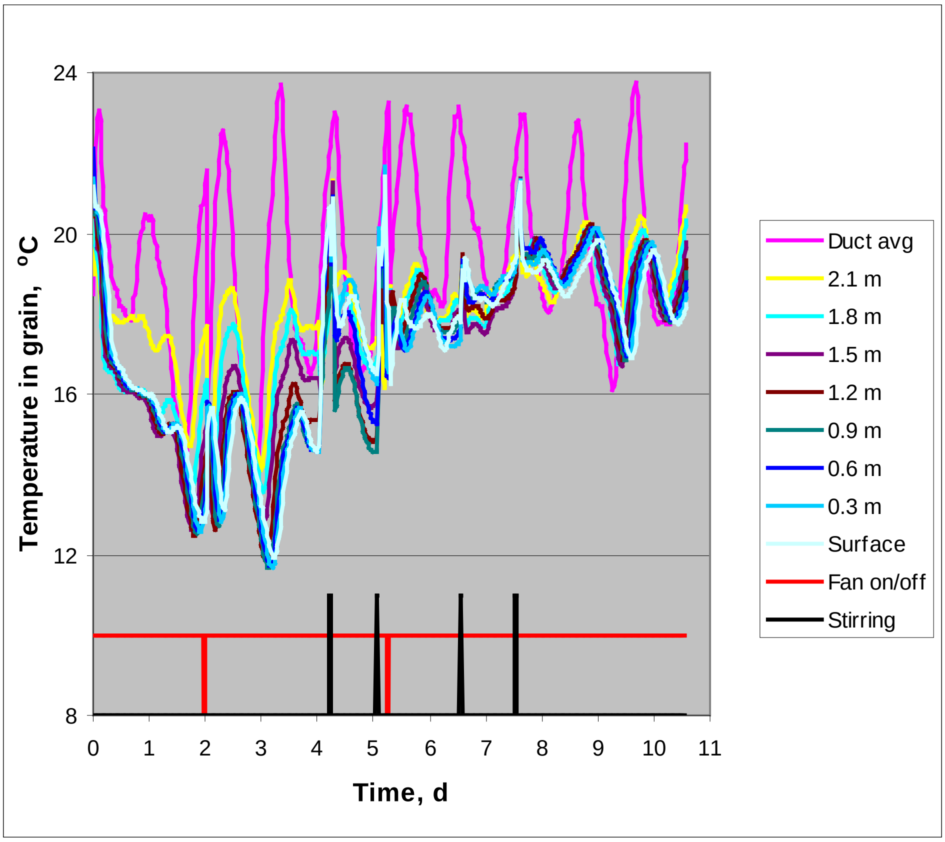

Figure 15. Temperatures at centre of bin versus time

The exhaust air r.h. was measured by a sensor at the bed surface. The trace was not straightforward to interpret for the reasons given above. The sensor had to be removed for the stirring and, once replaced, took longer than the temperature sensors did to settle. Between stirs 3 and 4, an error was made in that the r.h. sensor was not replaced on the surface but remained on the walkway of the bin. Figure 16 shows that up to the first stirring, the r.h. was around 86%, whereas simulated exhaust r.h. was 80%. This latter value is considered (P9 of McLean, 1989) to be in equilibrium with wheat at 17.6%, and the experimental grain was 17.8% so the experimental value was unexpectedly high. After the first stir, the measured r.h. fell to 76-74%, somewhat high considering the grain at the surface was around 15-16%. It was in good agreement with the simulation which gave a m.c. at the surface of 16.3% and an exhaust r.h. of 74.7% after the first stir. The next two periods were not steady, one because the sensor was not correctly in place. After the fourth stir, the measured r.h. settled to about 70%, again high for a final measured m.c. of 14.7%.

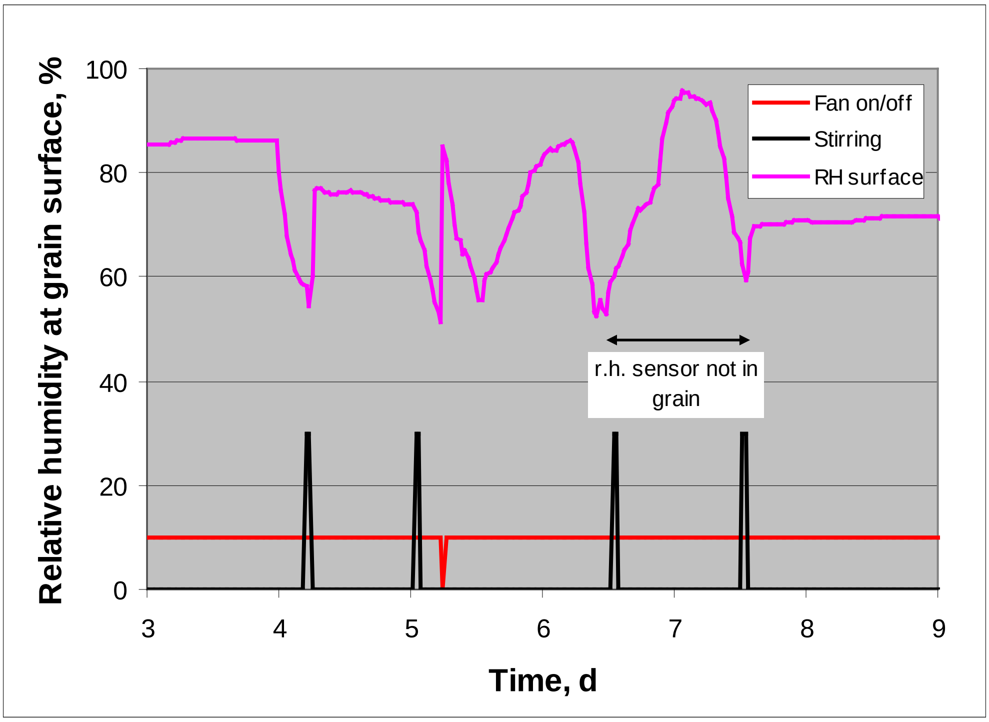

Figure 16. Effect of four stirring events on relative humidity at bed surface.

Overall, it was concluded from Experiment A that the simulation reproduced the experiment adequately well though with distinct areas of difference. The rapid fall in m.c. at the bed surface and approach to a common value for the whole bed was well modelled, though the tendency of the lowest layers to continue dry below the mixed average of the rest of the bed was stronger in the model than in the experimental data. It may be that the model of the stirring action incorporates a smaller proportion of grain from the lowest layers of the bed into the mixed zone than does a real-life stirring system.

Experiment B – drying in bin with and without stirring

Two bins were used, in one of which a single auger stirring device, used in Experiment A and previously described, was used to stir the grain in one of the bins. The other bin was not stirred. Bin 3, with the stirrer, was loaded with 25t of wheat via a conveyor, to a depth of 0.8m below the top edge. This wheat was freshly harvested and had a m.c. of about 20.5% wet basis. Five tonnes of this material was loaded into Bin 4, which was topped up with 20t wheat from a second load of freshly harvested wheat via the conveyor, to a depth of 0.8m below the top edge as before.

The second batch had a m.c. of about 16.5%. That the m.c. was much lower than the first load was unexpected, the supplier having been asked for two loads of similar m.c. It was decided that, given continuing warm weather and consequent drying of standing wheat in the area, the chance of obtaining a replacement load of higher m.c. wheat was low. So it was accepted that the unstirred bin would start with two levels of m.c. No heat was added to the air because the fan alone was known to heat the air by between 3 and 4^{o}C.

For each bin, two poles were inserted into the surface fitted with thermocouples attached at 0.3m intervals down to 2.4m depth. One pole was inserted at the centre of the bin and another 0.5 m from the side. Samples for oven moisture analysis were taken by sampling spear near the same central and side locations at depth intervals of 0.5m down to 2.5m. Initially, these samples were taken at least every other day, before and immediately after the period of stirring. The bed depth was effectively 3.6m so the lowest metre of grain was not sampled.

Initially, air speed was measured at 9 locations at the grain surface by a “Casella” rising disc anemometer at least every other day. After 9 days the air speed was also measured at 5 locations across the drying fan intake by vane anemometer. For the stirred bin, readings were taken before and after every stirring operation. The interval between grain sampling and flow readings was increased as drying neared completion. Sensors for relative humidity, dry bulb temperature and static pressure were installed in the air duct at the bottom of the bin to measure conditions of air entering the grain. At the surfaces of the bins, an r.h. sensor and thermocouple inserted just below the surface measured the air conditions exhausting from the bin. For the stirred bin, these sensors and the two poles were removed before stirring and re-inserted afterwards. Stirring was done for 45-60 min every 48h until drying had slowed down towards the end of the process. Stirring was not done for four days after starting the fan because, until that time, grain being dried was below the tip of the stirring auger, 2.93m below the grain surface. In each bin, the fan was run continuously until the wheat was close to equilibrium with the incoming air. After the fans were turned off, the grain was sampled for bulk density determination.

Experiment B - results

Air flow *vs* time in Bin 3.

The mean of flow measurements at the grain surface was 34.5 m^3/min, and as the bin was loaded with 25.0 t of wet grain, (calculated to be 19.88 t of dry matter), the specific airflow for Bin 3 was 0.0230 m^3/s/t wet matter. The readings made at the inlet to the fan gave an airflow 6% lower than the surface flow, which is a good agreement considering the low flow and limitations of the rising disc meter. For Bin 4, mean surface flow was 32.6 m^3/min. The bin held 25t of wet grain of two different batches, so that the specific airflow for Bin 4 was 0.0217 m^3/s/t wet matter. Bin 4 was calculated to be holding 20.69 t dry matter.

For the stirred bin, Bin 3, airflow fell by about 7% over the whole drying period. Looking at individual stirring events, on average over eight such events the flow after stirring was 14% lower than that before stirring, and the flow recovered to its pre-stirring level before the next stirring event. The bed was walked on for grain sampling. Stirring involved an operator walking on the grain surface to manoeuvre the single auger device so it was not possible to say what part of the flow decrease after stirring was due to the operator's weight compacting the grain and what part to any disturbance to grain packing when stirred. For the static bin, Bin 4, the flow fell by about 6% from its initial value during drying. This grain bed was also walked on for sampling and flow measurement. So the airflow in both bins reduced by a similar percentage over the drying period but stirring as done here led to an immediate reduction in airflow, followed by a slow recovery.

Grain depths in Bins 3 and 4 were reduced over the drying period by 0.46m and 0.27m, respectively. Bulk density after drying, of un-compacted samples, was 0.69 and 0.68 kg/hl at 15.5 and 14.7% wet basis m.c., respectively.

Ingoing temperature and r.h. *vs*. time.

Daily temperature fluctuations of about 5^{o}C were measured, and the mean daily temperature in the building housing the bins fell gradually during the period of drying from a peak of 19^{o}C at 4d from start of drying to 10^{o}C after 36d. Because of the temperature rise provided by the fan, the temperature of air entering the grain was about 3^{o}C higher. Relative humidity of the air entering the grain was close to 60% for the first 20d, increased to about 70% for 3 days, and then fell to about 60% again for the rest of the drying time. Daily fluctuation was between 10 and 20% points r.h.

Grain m.c. *vs.* time.

Unfortunately, because the initial m.c. of the grain was different between the two bins, the drying cannot simply be compared, but comparison is possible through use of simulation and this is described later. Figure 17 shows grain moisture data from the centre of Bin 3. The points are the measured values, and light lines are shown to help clarify, for two data points close together, which data point was the m.c. before stirring and which was following stirring. The stirring events are indicated by vertical lines below the m.c. traces. There was little effect on measured m.c. for the first 3d of ventilation time, in that the m.c. remained close to its initial value of 20.5% w.b. Some drying was being achieved but the grain being dried was below 2.5m, the maximum depth at which samples were taken. In Figure 17 there is a disturbance of the m.c.s at the first stirring event at 4d showing that by this time the dried zone had reached the level penetrated by the auger, some 3m down. For clarity Figure 18 shows only the m.c. traces at 2.0m depth and at the surface in the centre of Bin 3. Falls in m.c. caused by stirring are particularly clear at 7 and 9d, while at 5d stirring brought drier grain to 2m but wetter grain to the surface.

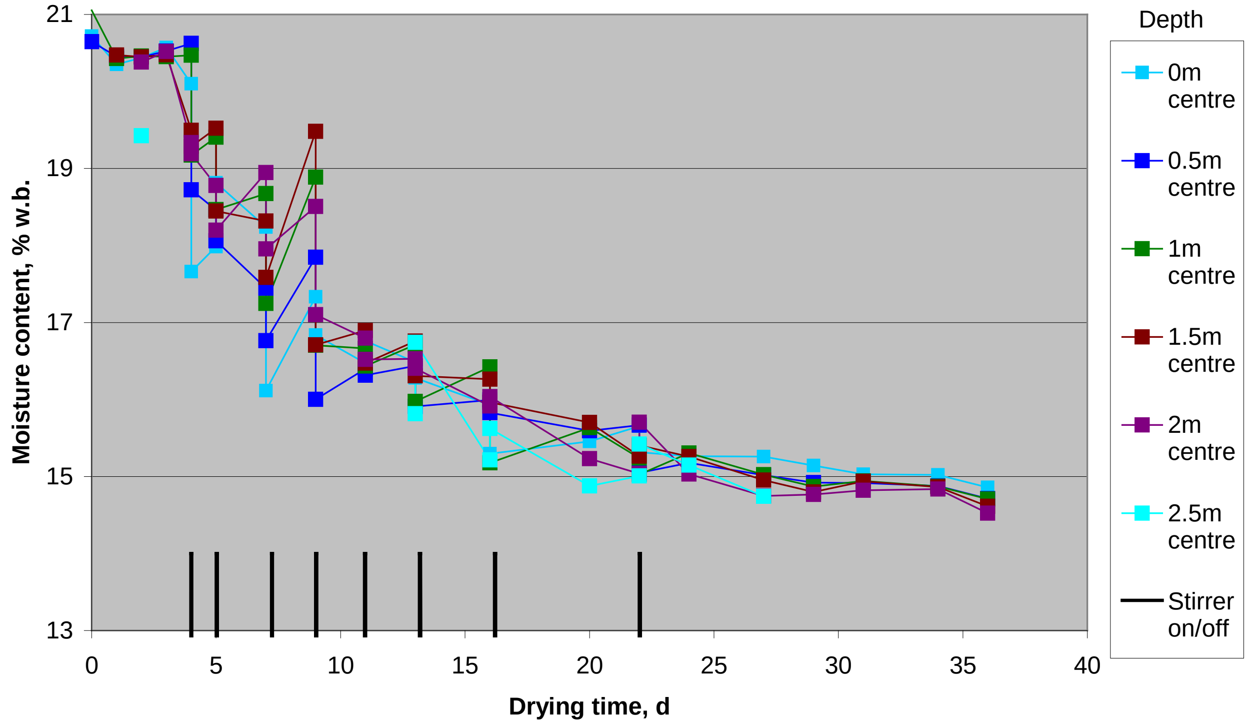

Figure 17. Moisture content versus drying time. Samples from centre of stirred bin, Bin 3, before and after stirring. Stirring events are shown by spikes on time axis. Points are joined by lines to show which sample was before and which after stirring.

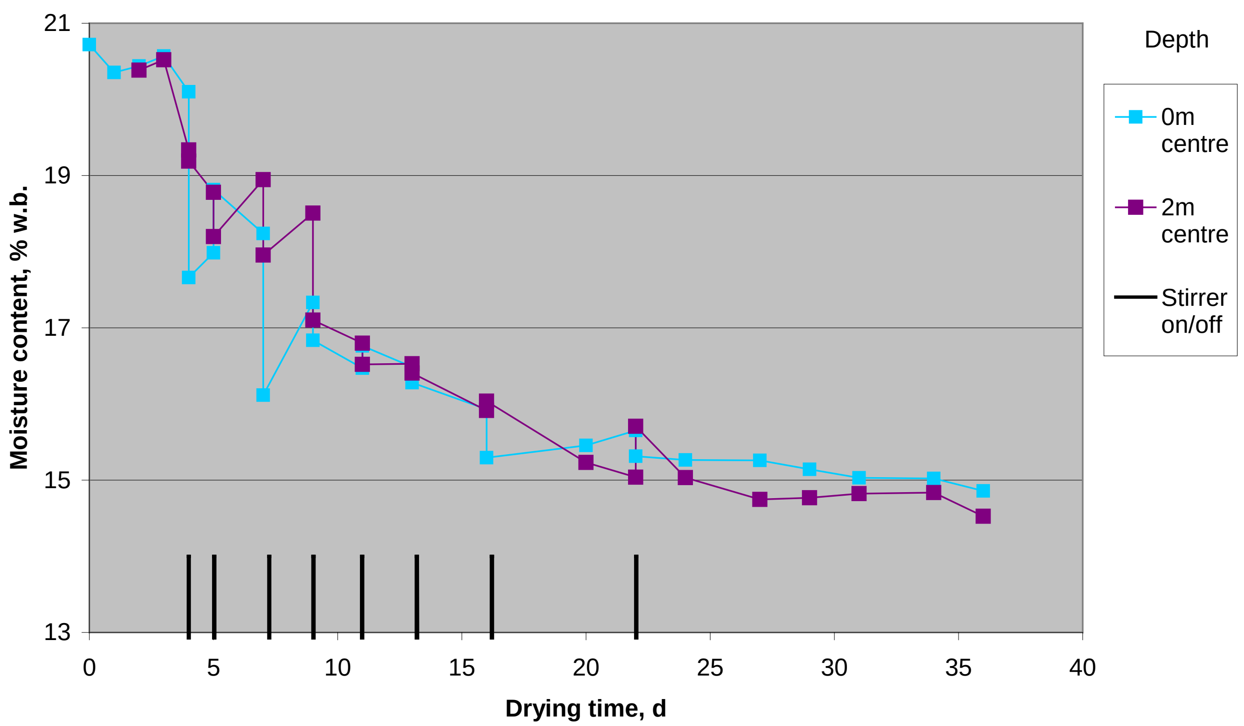

Figure 18. Moisture content versus drying time. Samples taken from centre of stirred bin, Bin 3, before and after stirring. For clarity, only data from 0 and 2m depth are shown.

Figure 19 shows grain moisture data from the side of Bin 3. Stirring at 4d did not bring up any dried grain, showing that drying was slower at the sides.

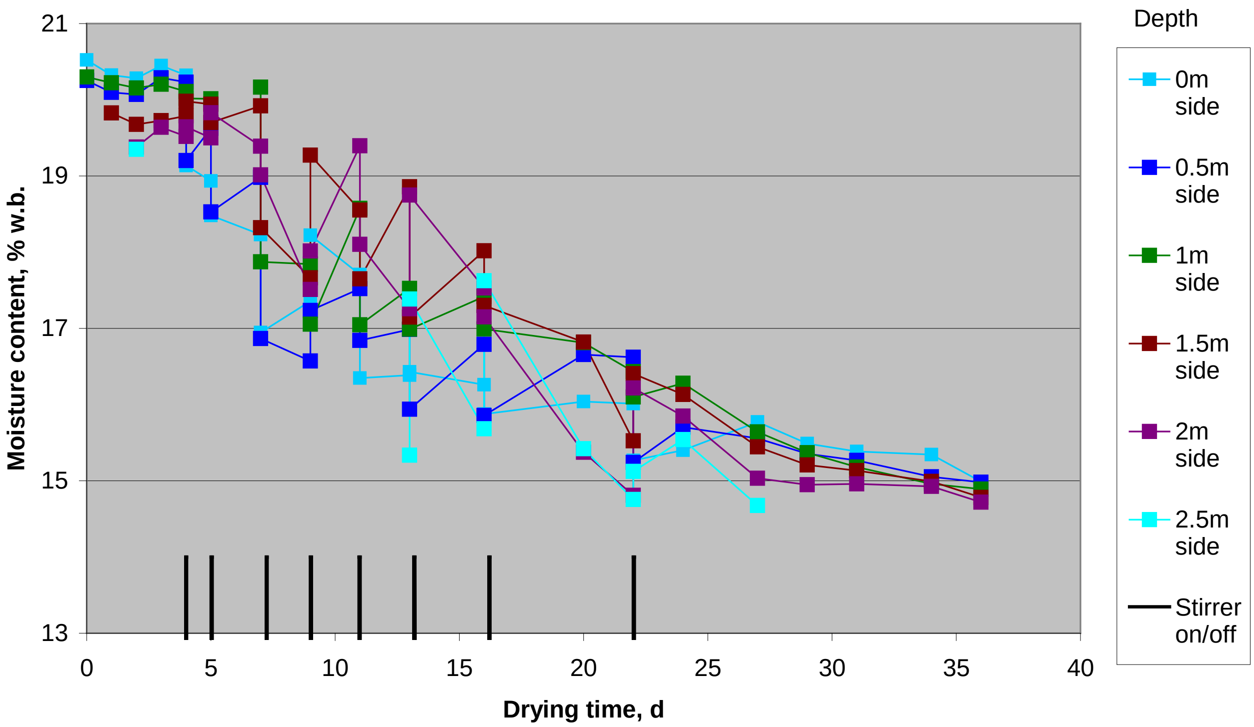

Figure 19. Moisture content versus drying time. Samples from side of stirred bin, Bin 3, before and after stirring.

Because stirring was mostly done once every 2d, allowing time between stirring events for moisture gradients to develop, the 'before' and 'after' measurements show quite large changes in m.c. at many sampling depths. The centre of Bin 3, Figure 17, dried rapidly between days 4 and 11, and stirring events at 5, 7 and 9d each produced much change in the m.c. at each sampled depth. Most of the depths sampled showed a reduction in m.c. at each stirring, as drier material from lower in the bed was brought up. After 11d, drying was slower and after 30d continuous ventilation the bed approached constant m.c.. At the side of the bin, Figure 19, the fall in moisture was more steady, stirring was effective and drying continued until the fan was turned off after 36d.

Figures 20 and 21 present the m.c. data vs. time for the centre and side sampling locations in the static bin, Bin 4.

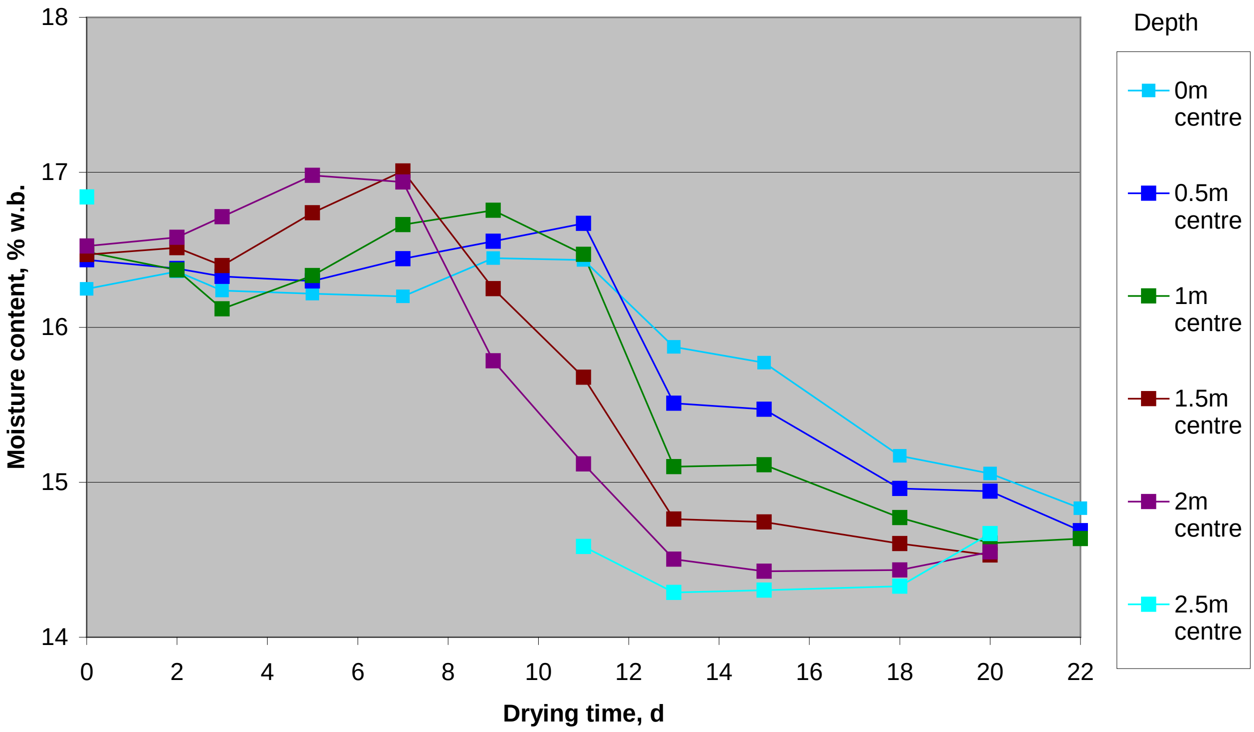

Figure 20. Moisture content versus drying time. Samples from centre of the static bin, Bin 4.

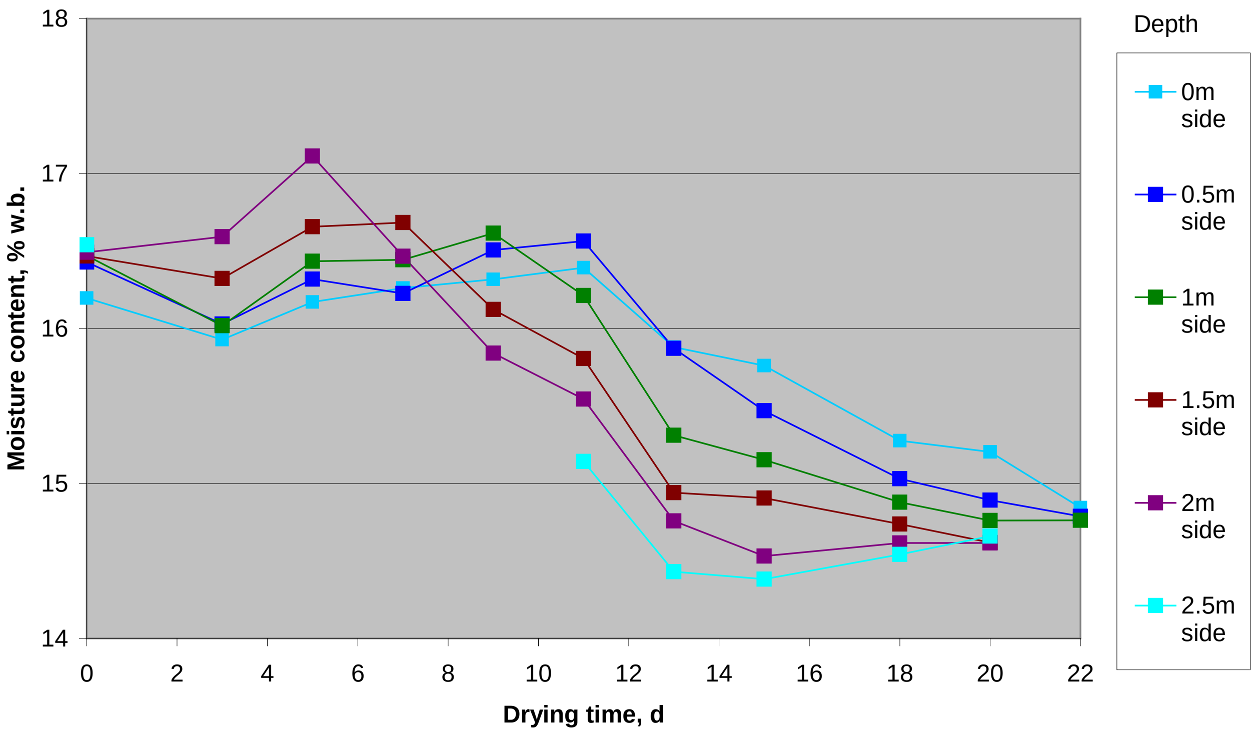

Figure 21. Moisture content versus drying time. Samples from side of the static bin, Bin 4.

The static bin reached a steady m.c. after about 22d of continuous ventilation. Initial m.c. data, at approximately 16.5%, show that the wheat in Bin 4 was drier than that in Bin 3, but the data do not show the wetter material, at about 20.5% m.c., present below the sampling depth. The wheat sampled over the first 6d of ventilation rose in m.c. This was because moisture was being evaporated from the wetter grain and the consequent high humidity of the air passing through the bed re-wetted that grain. After 9d, grain at 2m depth had started to dry and as the drying front moved up through the bed, samples at successively lower depths showed drying. By 20d, grain at 2.5m and 2.0m depths was rewetting, following the incoming r.h. and thereafter it was decided that the bed had reached steady conditions. At the side of the bin, the picture was very much the same, Figure 21.

Exhaust r.h. *vs.* time

The r.h. of air exhausting from Bin 3 is shown in Figure 22.

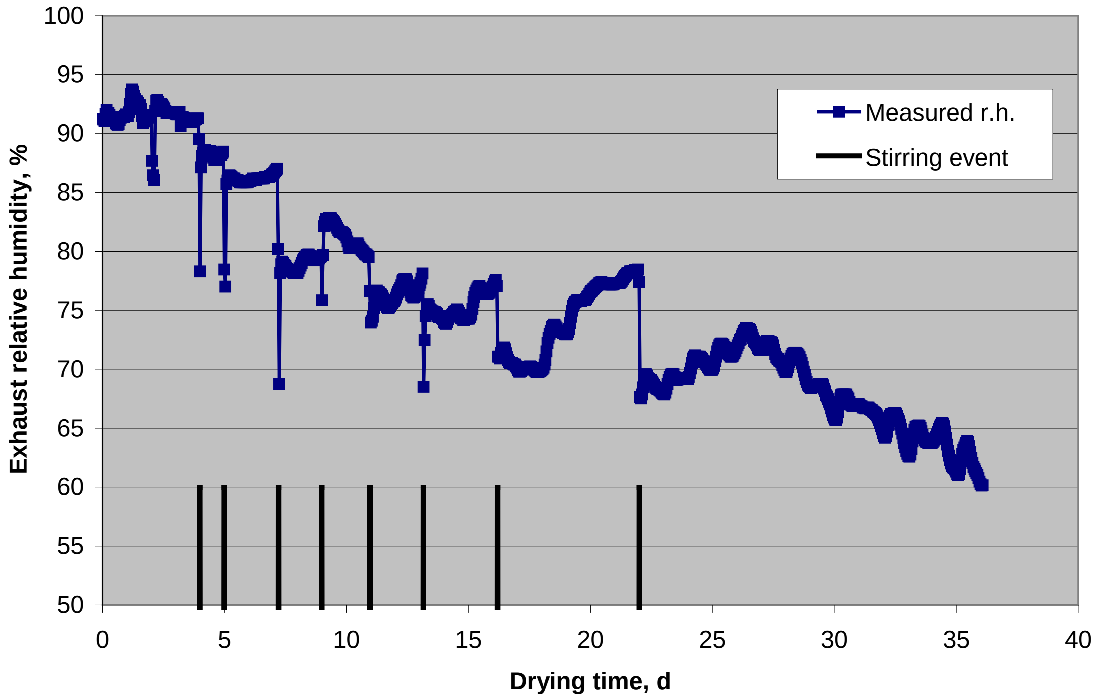

Figure 22. Relative humidity of air exhausting from the stirred bin, Bin 3, versus drying time.

At each stirring event, the r.h. fell because the sensor was removed from the surface of the bed to the walkway while the bed was stirred. From an initial level of 92% or so, the r.h. of the exhaust air fell steadily over the 36d of drying. At most stirring events the r.h. was lower following stirring because lower moisture grain was brought up to the surface by the auger. The exhaust trace from Bin 4, Figure 23, shows a much lower starting r.h. than for Bin 3, because of the lower m.c. in Bin 4, but which remained steady for some 7d and then rose for 4 days as a wetting front reached the surface. This was due to moisture evaporated from the layer of wet grain at the bottom of the bin leaving the surface. Thereafter, the exhaust r.h. fell steadily to that of the incoming air as the drying front reached the top of the bed.

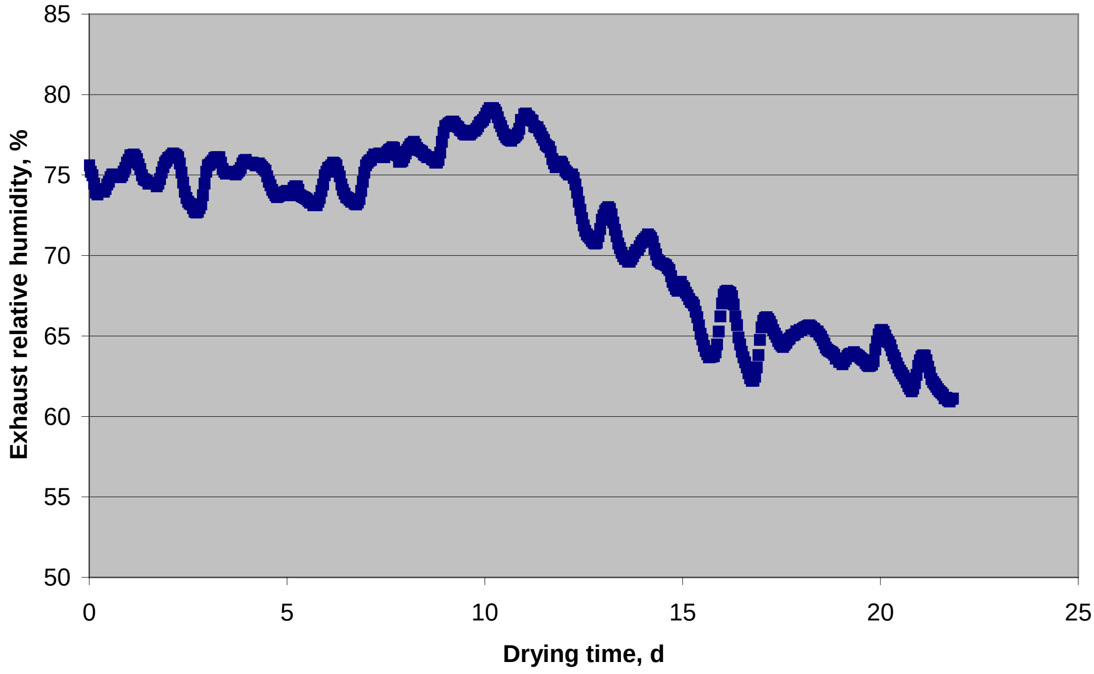

Figure 23. Relative humidity of air exhausting from the static bin, Bin 4, versus drying time.

Experiment B - simulation and discussion

The simulation was set up to match the initial state of the experimental grain beds. The measured conditions of ingoing air over the drying period (flow rate, temperature and relative humidity in the duct) were used in the drying simulation. Predictions by the simulation of grain conditions within the grain bed and of air conditions in the bed and exhausting from it were compared with measured values from the experiment. For the simulation of Bin 3, the stirring model was activated at the time when the grain had been stirred in the experiment, so that the events would line up on a time basis. Simulations of both bins were allowed to run to the end of the available data for the ingoing air rather than being stopped when the m.c. met that of the measured bed.

Stirred bin. Figure 24 shows for the centre of Bin 3 the measured m.c. data, as points joined by thin lines, and the m.c. from the simulation, as thick lines. The colours indicate depths.

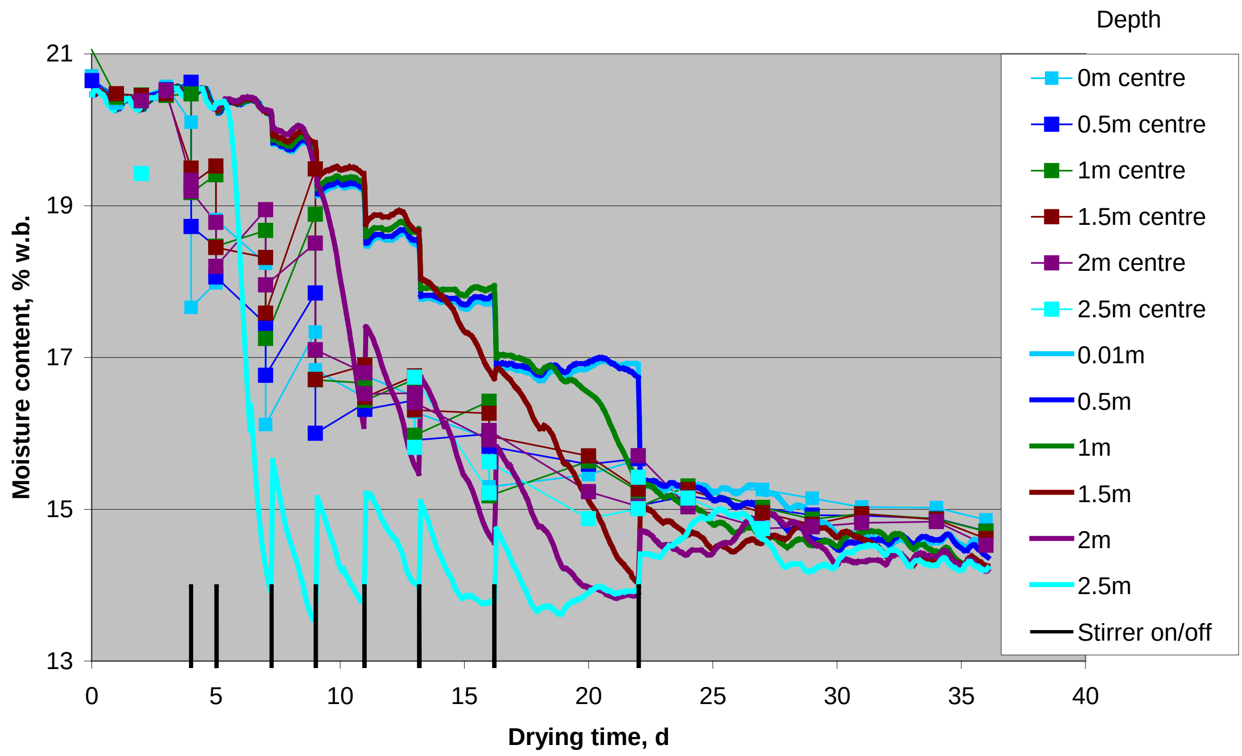

Figure 24. Progress of moisture content at centre of stirred bin, Bin 3. Experiment (points and thin lines) vs simulation (thick lines). Stirring events - spikes on time axis.

Though the picture is rather cluttered, it is clear that the simulated m.c. lines fall to a level close to the measurements by the end of the experimental data, but about 0.4% m.c. below the measured values. The time needed to dry the experimental bin was well matched by the simulation. At each stirring event, marked on the time axis by a black spike, between 7 and 22d, the simulated grain bed was disturbed with the result that wetter material at shallow depths became drier, by incorporation of grain from below, and deeper grain increased in m.c. as it was mixed with wetter material from above. This is easier to see in Figure 25 which shows only data points and simulated lines for 0 and 2m depth.

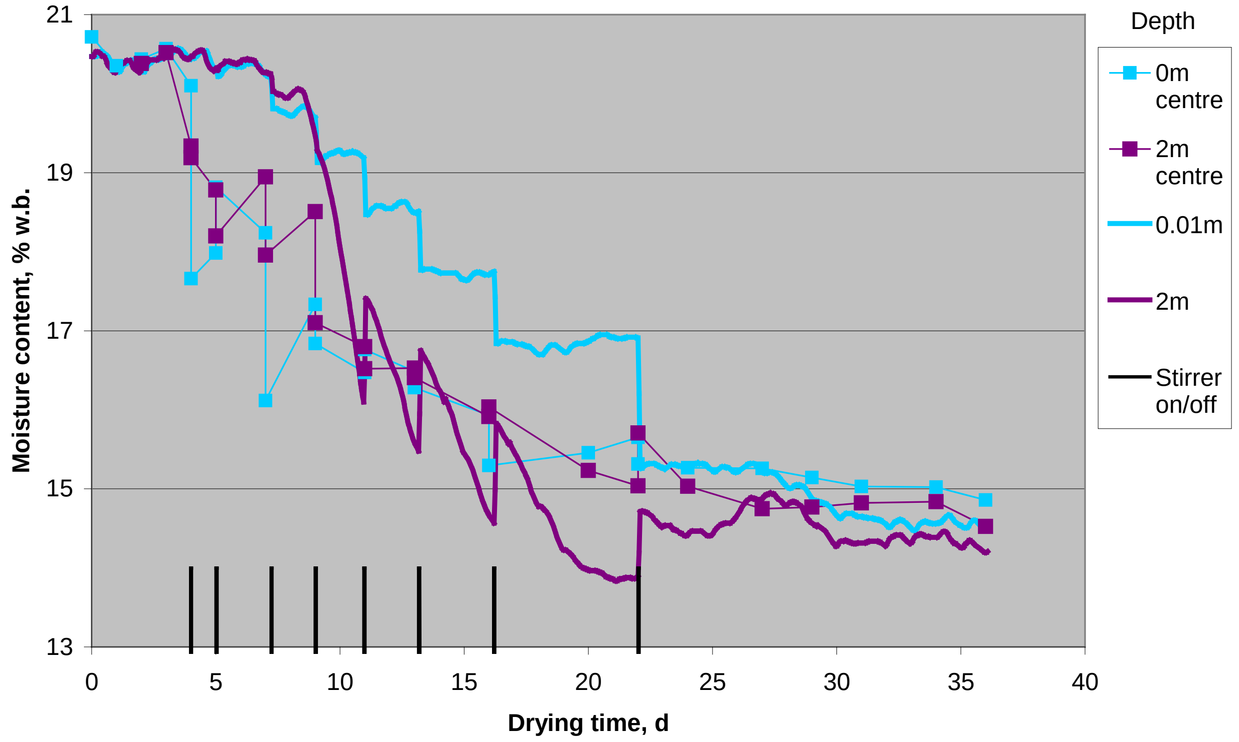

Figure 25. Progress of moisture content at 0 and 2m depth at centre of stirred bin, Bin 3. Experiment (points and thin lines) vs simulation (thick lines). Stirring events - spikes on time axis.

The simulated grain at 2.5m depth dried rapidly, followed by that at 2.0m and then 1.5m. This difference with depth did not develop in the experiment, in which the m.c. was more consistent between depths. In Figure 26, for the side of Bin 3, the experimental values are more spread out, and are more closely resembled by those from the simulation. (The simulation does not attempt to model differences in location across a bin.) In Figure 26, the strong drying tendency of the grain at 2.5m between stirring events is seen in the points and the lines.

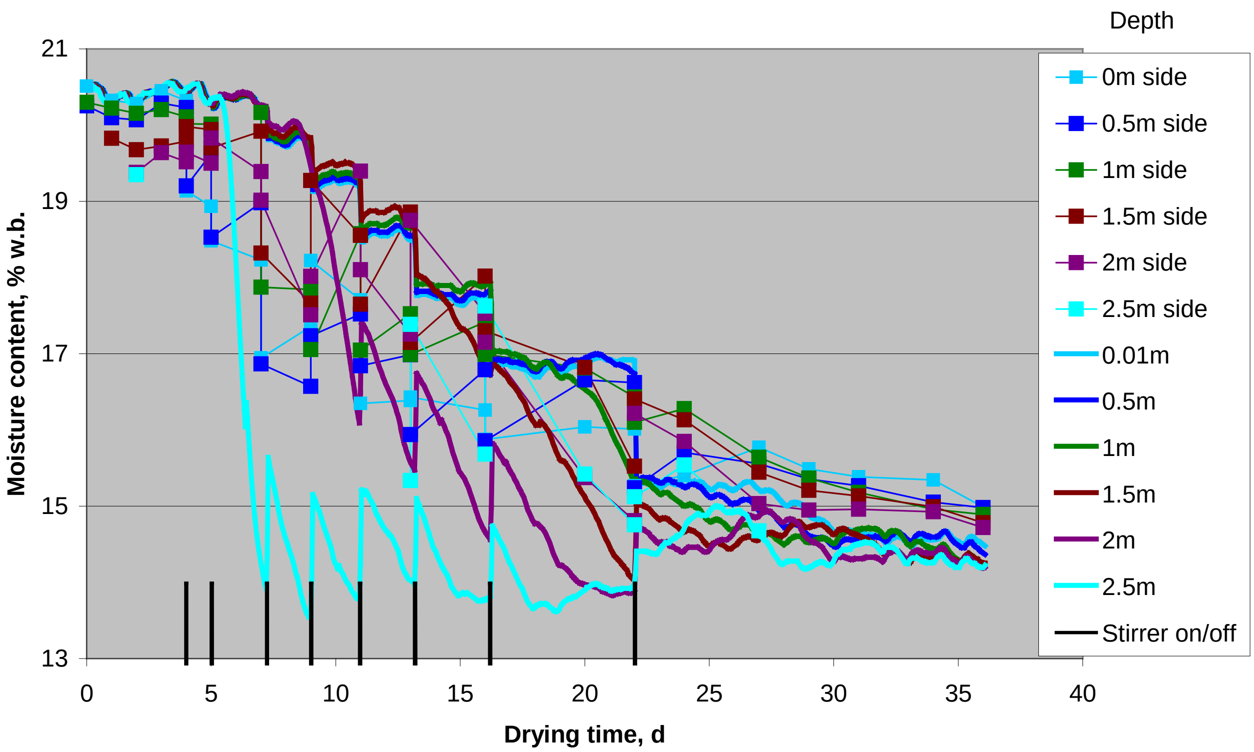

Figure 26. Progress of moisture content at side of stirred bin, Bin 3. Experiment (points and thin lines) vs simulation (thick lines). Stirring events - spikes on time axis.

Figure 27 shows simulated lines and experimental points only for 2m depth and the surface taken from the side, so as to present a simplified picture.

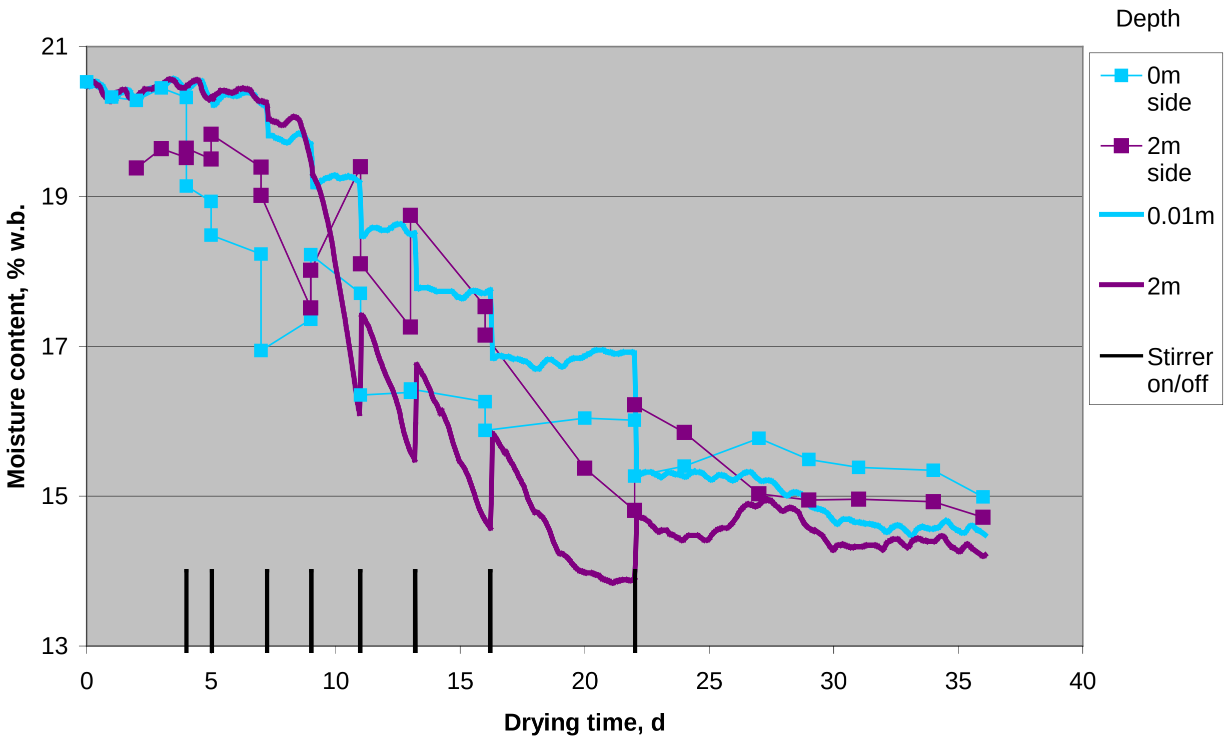

Figure 27. Progress of moisture content at 0 and 2m depth at side of stirred bin, Bin 3. Experiment (points and thin lines) vs simulation (thick lines). Stirring events - spikes on time axis.

In practice, stirring can invert the grain layers, *i.e.* draw up so much dry grain that the surface of the bed is drier than deeper down, a situation that developed in the experiment and is shown in Figure 27. In the model, the grain entrained into the conical volume stirred is completely mixed and then ‘proportioned’ back into the bed so no inversion can occur with this approach. But a succession of inversions in practice is likely to result in the more thorough mixing represented in the model, and hence the stirring action described in the model gave sufficiently good results.

Figure 28 shows for the centre of static Bin 4 the measured m.c. data, as points, and the m.c. from the simulation, as lines. The colours indicate depths.

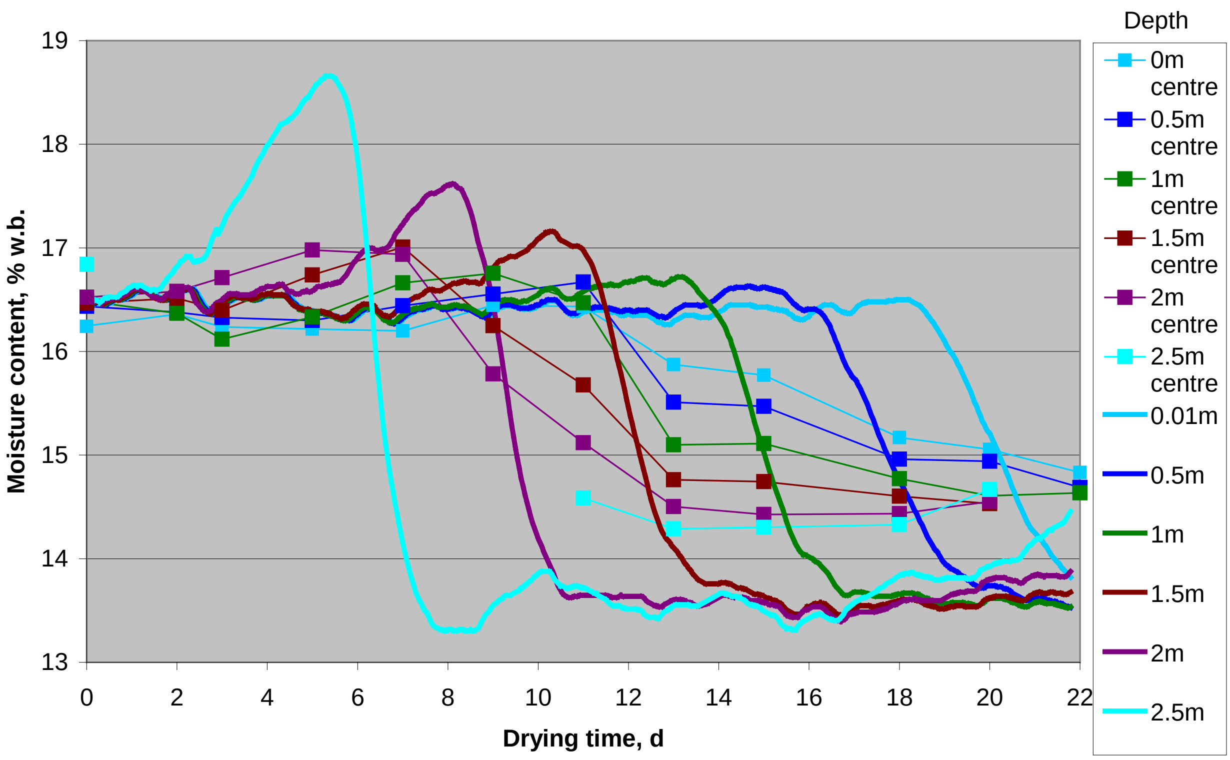

Figure 28. Progress of moisture content at centre of the static bin, Bin 4. Experiment (points and thin lines) vs simulation (thick lines).

The picture is less difficult to read than for the stirred bin because the measured data follow a simple pattern. Each of the simulated m.c. lines rose in turn as the wetting front was moved up, carrying moisture from the wetter grain in the bottom of the bin, then fell as the drying front developed and moved up and out of the surface. This behaviour matched the experimental data, though the peaks in m.c. are more pronounced. The fall is steeper and the final m.c. is below the measurements by the end of the experiment, by about 0.8% m.c. The time needed in simulation to dry the experimental bin below 15% agreed with the experiment. The picture is very much the same for the side of Bin B, Figure 29.

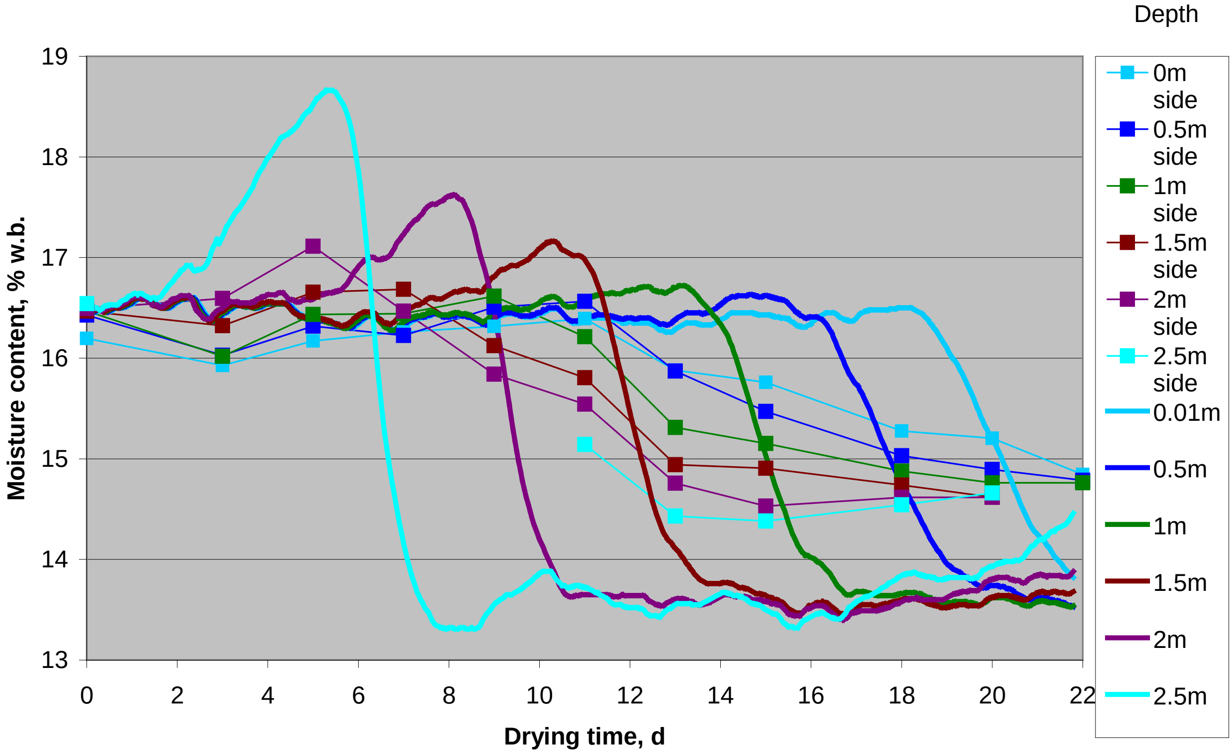

Figure 29. Progress of moisture content at side of the static bin, Bin 4. Experiment (points and thin lines) vs simulation (thick lines).

Overall, the spread of m.c. that developed in the simulation between about day 5 and day 21 was greater than that measured.because drying in the model took somewhat less time and depth than in practice, resulting in a steeper drying front. This steepness, which has been noted in previous work, would be important if the task were to predict m.c. at specific depths and times. But in terms of the bed as a whole, the simulation completed drying in a similar time and to a similar moisture level as was observed. The final m.c. was lower in the simulation, which is a consequence of the relationship used in the mathematical model at the core of the simulation to describe the equilibrium relationship between moist air and moist grain. Several relationships for this air-grain property are available from the literature and an alternative, and entirely suitable, relationship was tried in this case to find out if its use would improve the model's fit to the data. The result was a lower final m.c., *i.e.* worse agreement with the experiment. This suggested that the air-grain equilibrium equation used in the simulation was at least a satisfactory one.

Air temperatures measured in the grain bed for Bin 3 are shown in Figure 30, for a 5 day period from 12d. This shows the diurnal change in the temperature in the duct, followed by those in the grain bed.

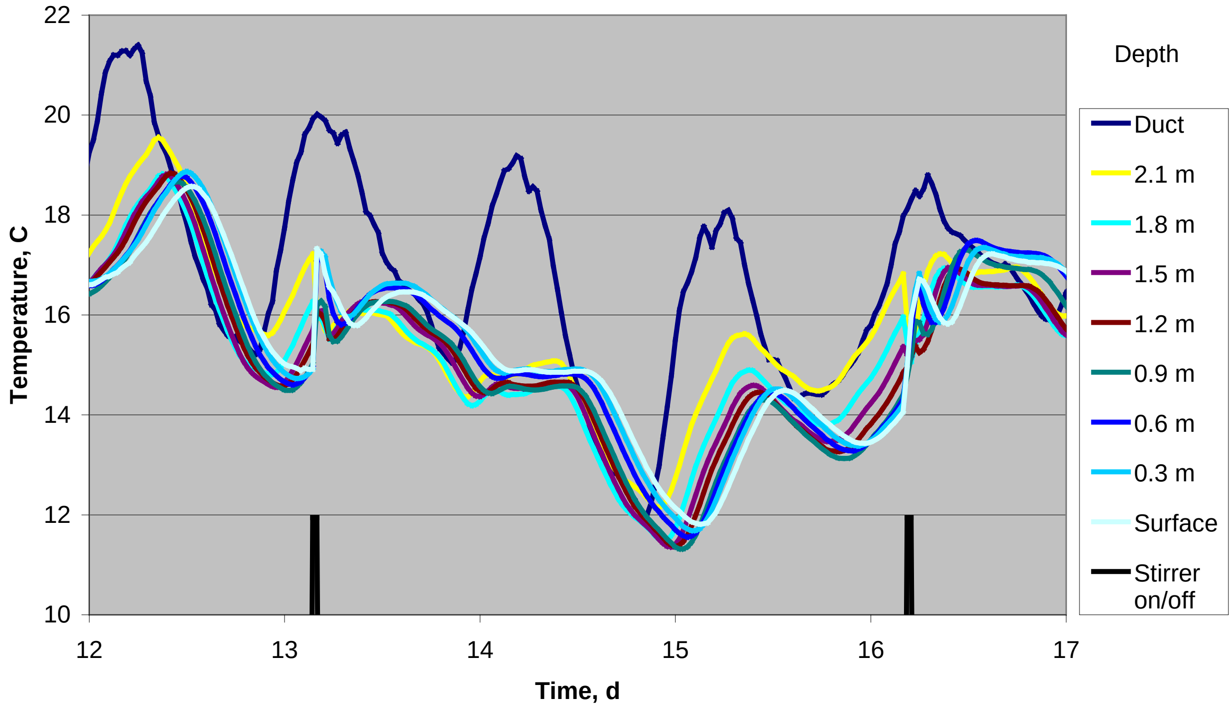

Figure 30. Measured temperatures at centre of stirred bin, Bin 3.

A lag can be seen between a change in the duct and the corresponding change in each level in the bed, as the temperature change propagated up through the grain. Stirring was done during days 13 and 16, most clearly shown in the disturbance of the temperature at the surface level. It is clear that the temperature in the bed very quickly recovered its characteristic pattern after stirring. The simulated temperatures for comparison are in Figure 31, and show a very similar pattern, the temperatures in the grain following the duct temperatures with a time lag. Stirring resulted in only a small and short-lived disturbance to this pattern. There is good agreement between the simulated and measured temperatures.

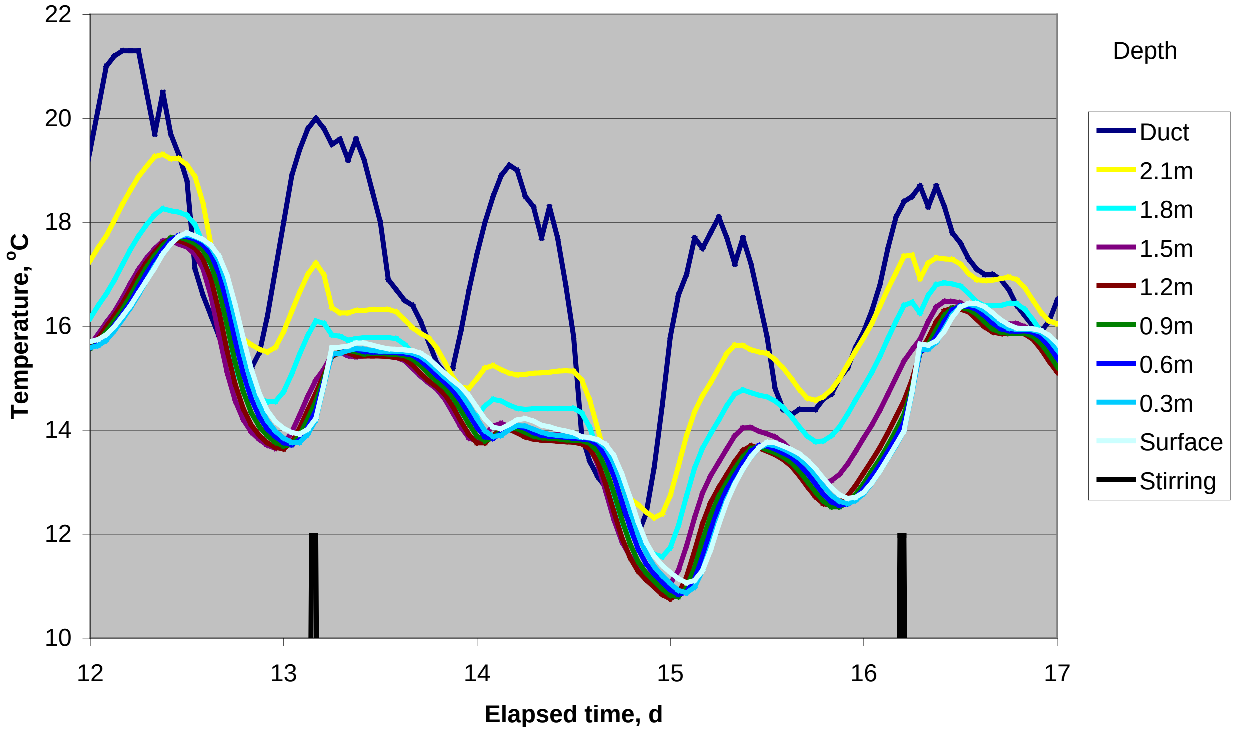

Figure 31. Simulated temperatures at centre of stirred bin, Bin 3.

Figure 32 shows the exhaust relative humidity, measured and simulated, for Bin 3. After 5d, the simulated r.h. followed the downward trend of the measured values. Disturbances to the simulated trace were less because the stirring, modelled as it was by mixing without inversion, did not result in such large changes to m.c. at the surface. The overall agreement was good.

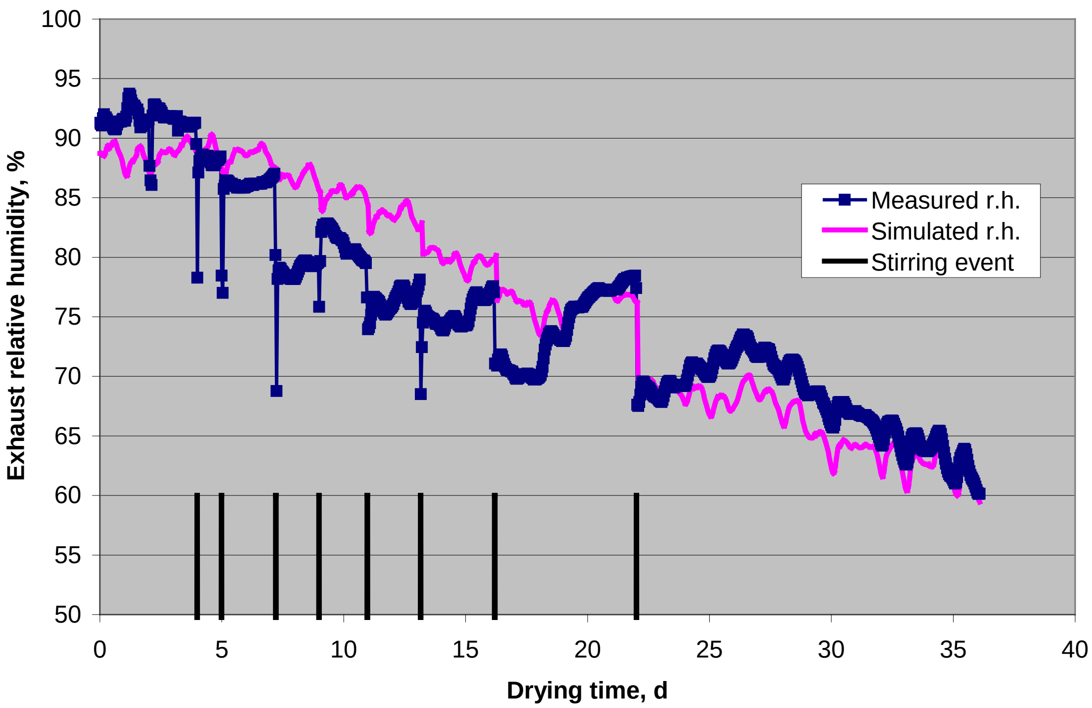

Figure 32. Relative humidity of exhaust air from stirred bin, Bin 3, versus time. Measured and simulated traces are shown.

For Bin 4, Figure 33 shows agreement was less good between simulated and measured r.h. versus drying time in that the measured r.h. showed a rise as the moisture lower in the bed was lost from the bed, but in the simulated bed this moisture was lost more gradually such that the r.h. stayed around the initial level for longer, before falling as the main drying front reached the surface. The overall result, in terms of moisture lost in the experimental time, was satisfactory. The difference may have resulted from the fact that the bottom of the bin, holding the 5t of wetter grain, is a tapering shape with two air ducts across it. Because of this shape, airflow in this zone is not the simple, one-dimensional upward flow that is modelled.

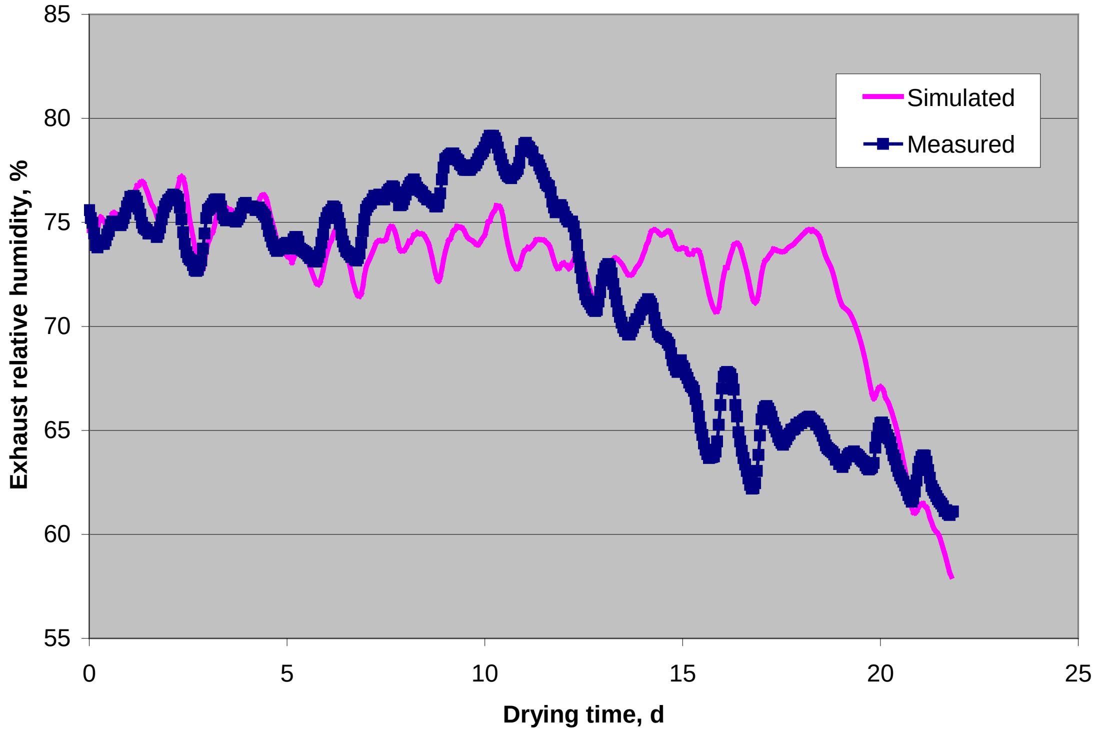

Figure 33. Relative humidity of exhaust air from the static bin, Bin 4, versus time. Measured and simulated traces are shown.

Because m.c. of grain in the two bins was not the same, direct comparison is not meaningful. So, to allow some comparison, the static bin was simulated with the initial m.c. of the stirred one, *i.e.* uniform m.c. of 20.5%. Small changes in other parameters, *e.g.* airflow and bulk density, were made to make the two bins' starting conditions very similar. Results are shown in Figure 34.

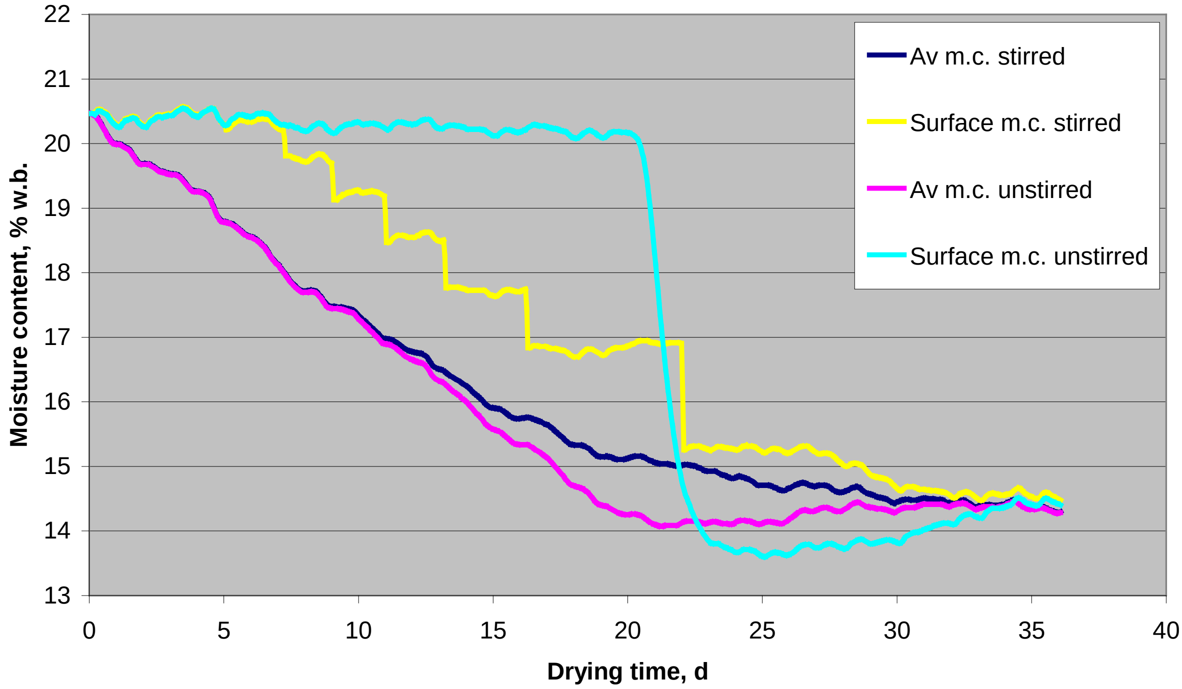

Figure 34. Simulated average and surface m.c. versus time, for the stirred bin and the static bin with same starting starting condition.

Drying was simulated until the weather data ran out, with the result that grain in the static bed rewetted in damper weather after 25d. The average m.c. of the stirred and static treatments followed the same path until 10d when the drying rate of the stirred treatment slowed. The result was that the static treatment reached 14.5% m.c. in 18.7d while the stirred treatment took 29.5d. The surface m.c. lines show that the m.c. of the static bed remained close to its initial value while the stirred surface started to dry after 5d. As previously noted, this was because air leaving the stirred bed was less humid and thus did less drying.

Reviewing this third stage of validation, it is clear that the simulation predicted sufficiently well the drying times and final moisture content of the grain in both stirred and static bins. Because the drying time was well predicted, the fuel and electricity use would also be, as they are the product of running time and heater and fan power. Prediction of moisture content within the bed during drying was good although the drying front was predicted to be steeper than measured, a difference reflected in the exhaust relative humidity. Despite this, the experiment confirmed the predicted difference in exhaust humidity over time between stirred and static beds. It is concluded that the measurements supported simulated drying, both with stirring and without, sufficiently well for the model to be used with confidence in the near-ambient conditions of the experiment.

3.3.3. Stage 3 - validation against published dataset for drying with elevated air temperature

Next, the validity of the model at an elevated air temperature was tested using published measurements on a circular bin of capacity about 100t fitted with a stirring system (McLean, 1993). Two sets of measurements are given but detailed study of the first set revealed an inconsistency in the data – insufficient energy use was recorded to raise the temperature of the reported airflow by the measured temperature rise. Given that the energy use or airflow was incorrect, the first data set was of little value, so only the second set was used. This was the more interesting case because it used a large temperature rise. Drying air was heated to about 38^{o}C which would result in serious overdrying near the air inlet of a static bed.

86t of wheat in a bed of 4.57m depth and at a uniform m.c. of 18.6% w.b. was stirred continuously and dried to an average m.c. of 14.4%, as measured by sampling when the bin was discharged. Air temperature was raised from ambient to a constant 38.1^{o}C by a propane heater. An airflow of 0.049 m^3/(s.t) was used, close to that recommended for near ambient drying. The average r.h. of the heated air was 22.7% but no diurnal variation is reported so the air condition had to be assumed to be constant for purposes of simulation. No measurements from within the bed were reported and so performance from the simulation was compared with reported overall performance measures, Table 1.

Table 1. Comparison of drier performance from McLean (1993) and simulation.

	Drying time to measured final m.c., h	Energy use (as propane), MJ	Energy use (as electricity for fan and stirrers), MJ	Moisture range, % points	Static pressure needed in plenum chamber, Pa
Experiment	73	19380	2900	5.8	1500
Model	77	18840	2960	7.7	1560

Agreement was very good on drying time to the reported final m.c., for the energy used for air heating (propane) and for the electrical energy used by the fan and stirring system. The range in m.c. from the simulation was wider but sampling on discharge, the method used in the experiment, would have resulted in some mixing so the extremes would not have been maintained, whereas the moisture values were well defined in the simulation. Pressure drop through the bed was very well predicted. These results show the model is able to predict drying with stirring at air temperatures raised considerably above ambient levels.

3.3.4. Stage 4 – Experiment on a commercial site

Method

To validate further the predictions of the simulation model, a set of data was obtained from a full-scale drier and stirrer system. Although the behaviour of such a drier could only be measured during commercial operations and, hence, under particular constraints, even a limited set of data was considered important to give added confidence to the model's predictions.

A suitable site was kindly identified by Harvest Installations Ltd for 2011. A data logging system developed for a previous project (Wontner-Smith *et al*., 2008) was installed at the site to record temperature, static pressure and air relative humidity. Unfortunately for the project, the weather before the wheat harvest in the area was dry and warm, with the result that wheat was brought into the bay at a m.c. of around 16.6% w.b., although it was initially reported as drier. The drier operator decided to use only one of the two fans and with no additional heating of the air. After installing equipment on site on 27 July, project staff at Fera kept in touch with the site management and visited the site four times to make measurements. Although all possible efforts were made, little useful data was obtained. Other sites were sought but there were no possibilities that would have provided a dataset good enough for validation of the model's predictions on wheat.

A second attempt to get a dataset from a full-scale facility was made the following harvest in 2012. David Bartlett of BioMeasurements Ltd identified a commercial on-floor drier in Hertfordshire, at which the farmer was willing to dry one half of the store with stirring and the other half without. This enabled a side-by-side comparison.

The method was as follows. The wheat had been loaded into the store, which measured 10.5m wide by 24.0m long, to a depth of 3.5m. The whole bulk was stirred for 24h before the start of drying to relieve any compaction due to pushing up of the wheat during loading and to mix the material vertically to reduce any moisture gradients. The bulk was notionally divided into two equal blocks each 10.5m by 12.0m. One block was stirred continuously during the drying process and the other was static. There were 4 stirring augers, two on each of two carriers on a single gantry. The effect of the gantry movement along the store and the movement of the carriers along the gantry was such that the horizontal speed of the auger across the grain surface was 0.29 m/min. A stirring cycle, *i.e.* for the gantry to travel once along the store and back, took 75 min.

During the drying treatment, the temperature and r.h. of the ambient air, the air in the main duct and the air leaving the top of the bulk were each recorded every 5 min by a self contained logger and sensor unit. In order to avoid the logger at the top of the bed being stirred into the bulk, it was attached to the centre of the stirring gantry so that it dragged along the grain surface. The logger in the static treatment was positioned at the centre surface of the bulk where it remained throughout.

Spot measurements of grain moisture profile were made at intervals during the drying process. These samples were taken at 0.5m vertical intervals at the centre of each of the treatment blocks using a plastic tube connected to a domestic vacuum cleaner. Three determinations of moisture content were made on whole grain at each sampling point using a “Protimeter” moisture meter. The meter was calibrated with reference to oven determinations made by Fera on samples of the grain taken from the bulk, one of which was dried in an oven to reduce its m.c. to around 10% w.b. On each visit to site to take moisture samples, spot measurements of air speed through the bulk were made with a “Casella” rising disc anemometer.

The drying plan had been to use additional heat to speed the process but, because the weather conditions were warm and dry, and the m.c. of the wheat was less than 17% w.b., the farmer decided to use ambient air with no additional heating. Part way through the drying process the weather became unfavourable so the process was stopped for nine days and was resumed when the weather improved.

Results

Measured air speed close to the grain surface was 3.70 m/min for static and 3.48 m/min for stirred treatments on 23/8/2012, two days after the start of drying. Airflow was measured in this way on three occasions, at 26h, 66h and 130h. It was stable until the last reading when it had risen by between 5% (static) and 15% (stirred). It is difficult to measure the airflow in a stirred bed accurately because of the unevenness of the surface created by the stirrer. The initial values were used for the simulation, in which the airflow is required to be constant.

Although the whole store had been stirred for 24h before the initial samples of grain were taken, moisture gradients were nonetheless present through the bed. This shows that further stirring would be needed if uniformity of m.c. were required. The points in **Figure 35** and **Figure 36** show m.c. at eight locations down through the bed, based on three determinations on each sample extracted.

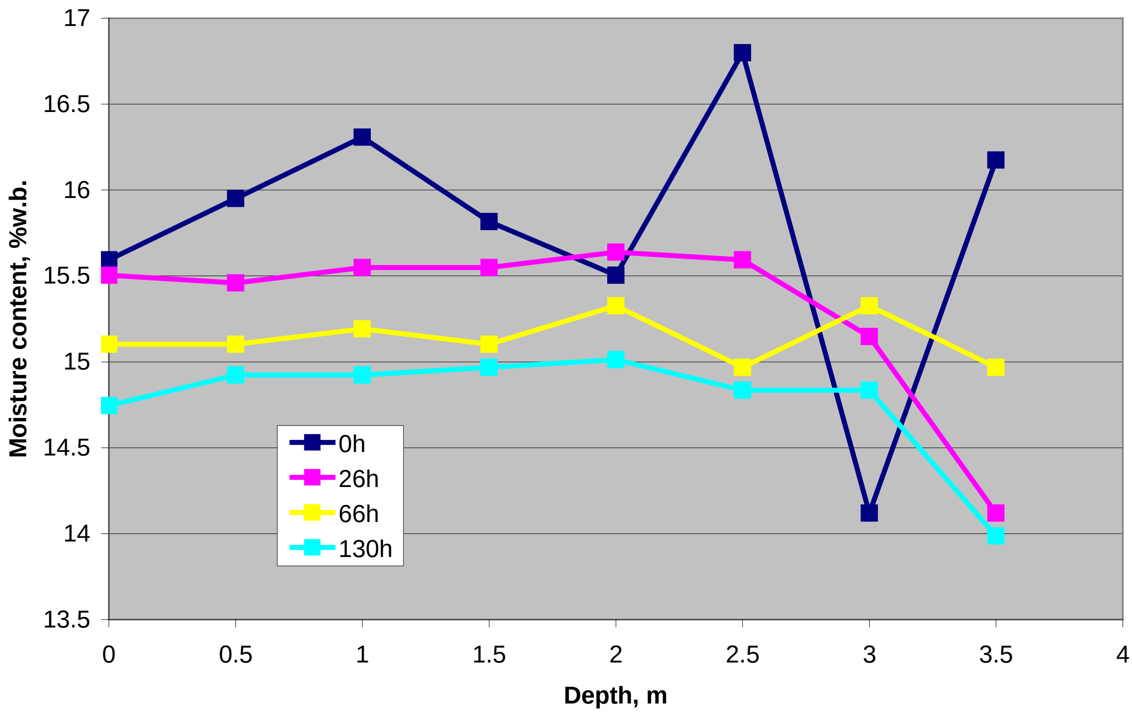

Figure 35. Stirred bed. Moisture content in farm store at 8 depths at each of 4 drying times.

For the stirred block of the store, Figure 35, the graph of m.c. versus depth after 26h of ventilation and stirring shows uniform m.c. above 2.5m, and lower m.c. below this level. The m.c. will have been reduced in this zone faster than the stirring was able to incorporate the dried grain. The initial m.c. differences with depth had been removed by this stage. After 66h of ventilation the bulk of the grain was a little drier but grain near the air inlet had re-wetted, and the operator decided to stop ventilation. After a break of nine days, ventilation was restarted during good weather and by 130 accumulated hours of ventilation, the bulk had been dried sufficiently to meet the store operator's requirement. Grain near the air inlet had dried more than had the bulk, for reasons given above.

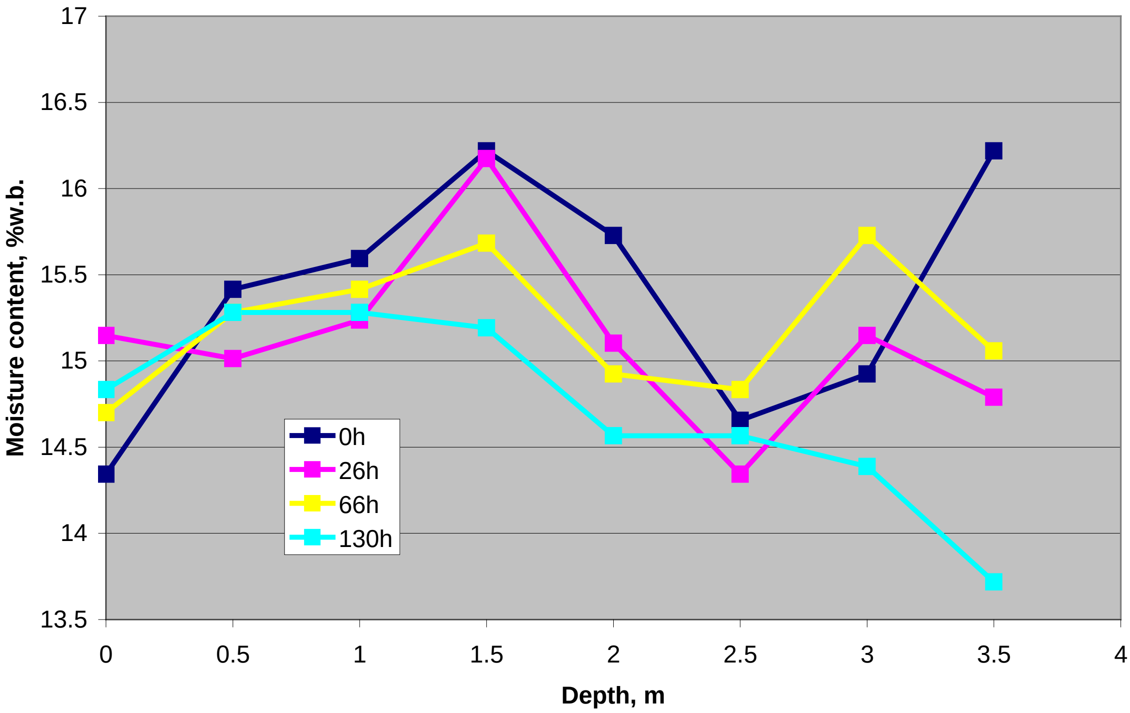

Figure 36. Static bed. Moisture content in farm store at 8 depths at each of 4 drying times.

For the static block of the store (Figure 36), the effect of ventilation was to move the initial moisture profile up through and then out of the bed, and gradually to reduce the m.c. of the wettest grain. By the end, 130h, the grain near the air inlet had reached much the same m.c. as in the stirred part of the store, and the profile up through the bed was also similar to that in the stirred treatment. Drying in both blocks was quite slow because heating was not used.

Measured exhaust conditions of temperature and relative humidity for the stirred and static blocks of the store are shown in Figure 37. The r.h. trace for the stirred block shows a daily fluctuation around a steady level of about 72%, a fluctuation probably due to the sensor being exposed to the airspace above the grain as it was pulled over the grain surface by the stirrer gantry. The temperature trace shows a smaller variation for the same reason. There was also a smaller variation in r.h., not clearly visible in the graph, due to the close approach of a stirring auger to the sensor. The exhaust r.h. for the static block started higher than in the stirred block, fell to a similar level after about 24h of ventilation, then rose slowly until about 100h, then fell to match the stirred bed condition.

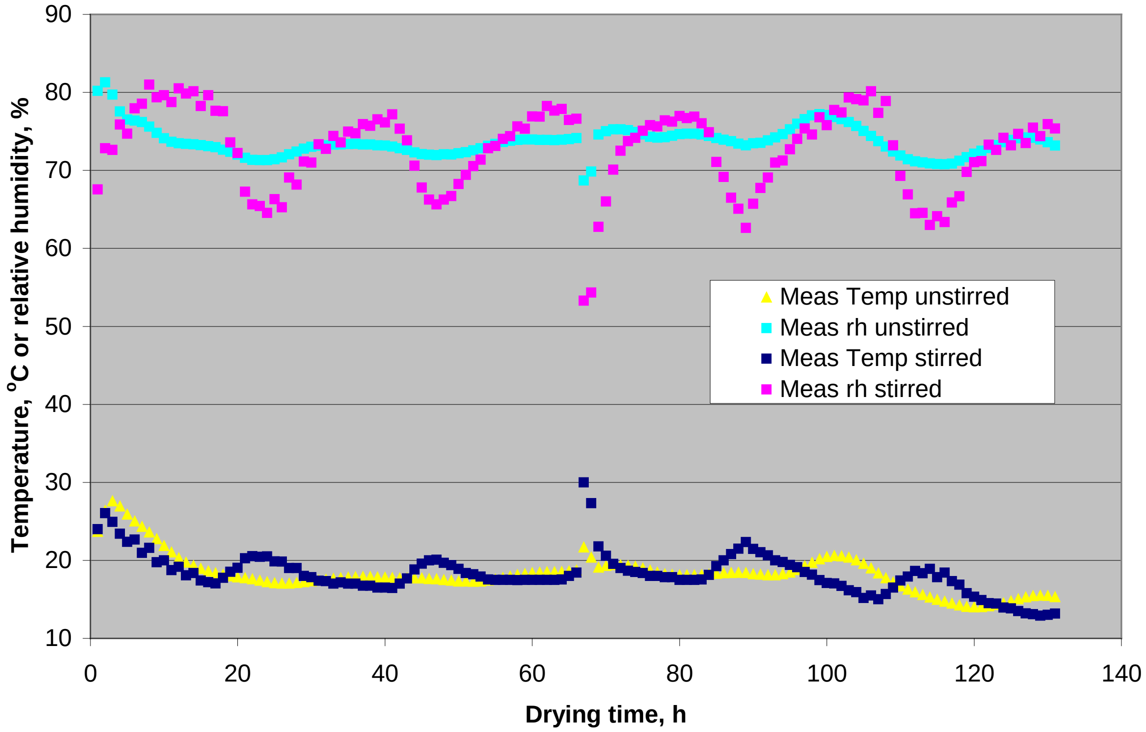

Figure 37. Measured exhaust conditions of temperature and relative humidity for the stirred and static blocks of the farm store.

Experiment on commercial site – Simulation and discussion

From the initial m.c. values in Figures 35 and 36 it was noted that the 24h period of stirring given to both blocks of the store before the fan was started had not homogenised the bed. Figure 35 shows that after 26h of further stirring (at double the rate as only half the area was being stirred) the bed was of uniform m.c. except at 3.5m where there was drying but would have been little grain entrainment by the auger.

The stirred treatment showed a lower exhaust dew point temperature than the static one for most of the ventilation time, and certainly during the first period when the bulk temperature was falling and most of the drying was taking place. The average exhaust dew point for the first 18h of ventilation was 17.7^{o}C for the static block of the store and 16.3^{o}C for the stirred block. The difference in dew point temperature is likely to have been the consequence of drier grain being raised to the surface by stirring. As a result, air leaving from where stirring was taking place would be less saturated than from locations that had not been stirred for some time. It would be good to check this observation with more data, given that the exhaust air sensor for the stirred block of the store could have been influenced by roof-space conditions.

Figure 38 shows the measured exhaust conditions for the stirred block, already shown in Figure 37, but together with the results from the simulation. There was good agreement except for the daily fluctuation, which was not present in the simulated values because effects of roof-space were not simulated in the model.

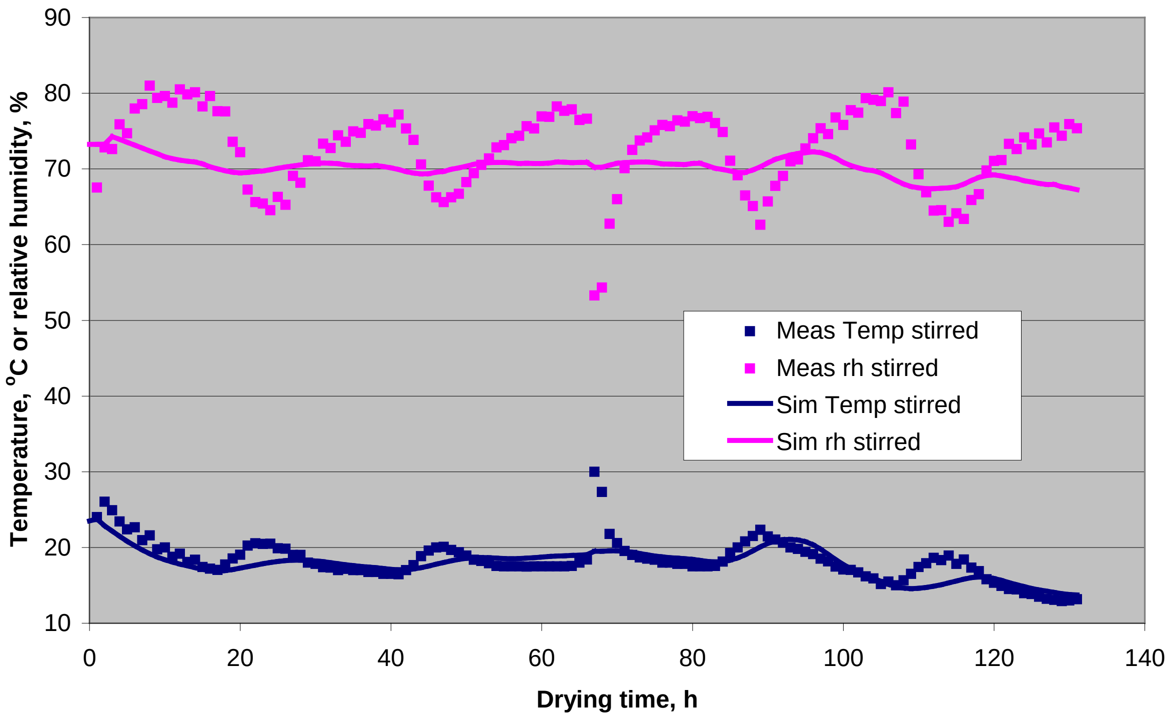

Figure 38. Measured and simulated exhaust conditions of temperature and relative humidity for the stirred block of the farm store.

For the static bed, Figure 39 shows both measured and simulated values.

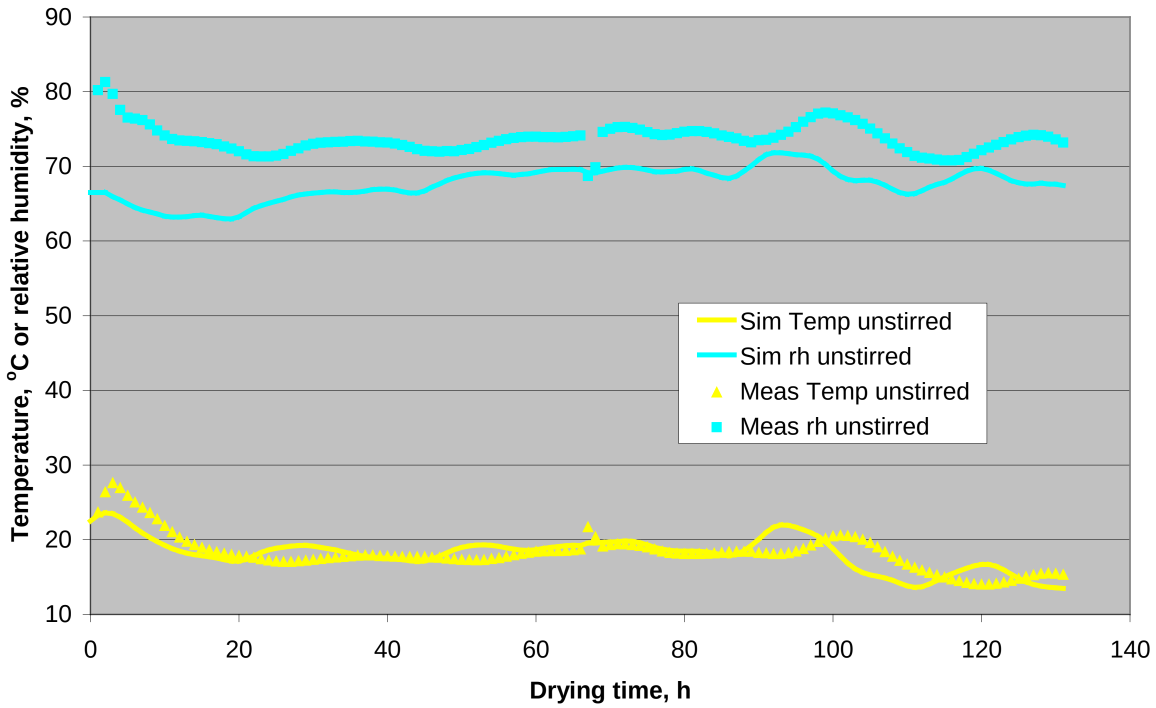

Figure 39. Measured and simulated exhaust conditions of temperature and relative humidity for the static block of the farm store.

Temperatures were in good agreement but over the whole experiment, and particularly at the start, the r.h. from the simulation was lower than that measured. The r.h. of the exhaust is determined by the m.c. of the grain in the few layers near the surface, before it exhausts, because air and grain will reach a moisture equilibrium. In the simulation, the grain m.c. profile through the bed, measured in the experiment before ventilation started, was used as a starting condition. As it happens, the m.c. of the sample from the surface differed between the two parts of the store – for the stirred and static blocks the surface layer m.c. was 15.6 and 14.3%, respectively, although the bed m.c. averages were much more similar for the two blocks, at 15.8 and 15.4%, stirred and static respectively. The lower surface layer m.c. for the static block gave rise to a significantly lower exhaust r.h. in the model. The difference between model and experiment reduced over the ventilation time, suggesting that the m.c. measured at the surface may not have applied throughout the top 0.25m of the bed, as had to be assumed.

The simulated m.c. at 3.45m depth, very near the bottom of the bed where air enters, is shown in Figure 40, together with the r.h. measured in the inlet air duct (and used directly in the simulation).

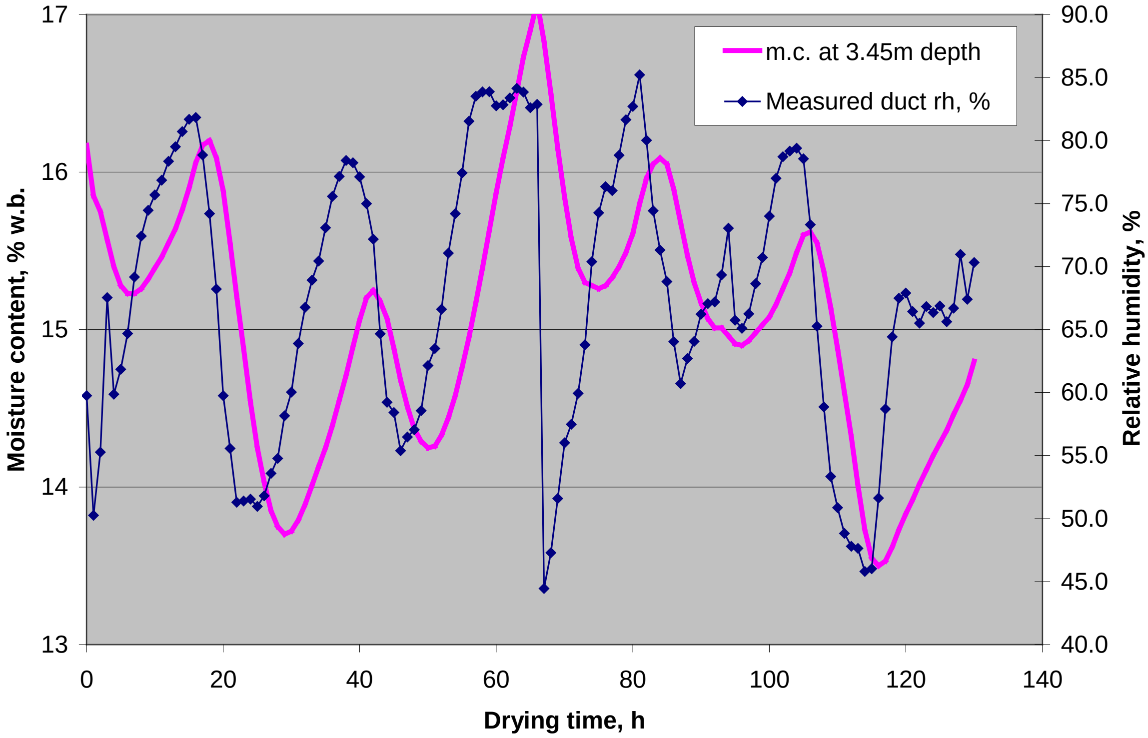

Figure 40. Relative humidity of air in the inlet duct and m.c. by simulation close to this depth.

The m.c. tends to follow the r.h. of the incoming air, as would be expected. There is a short lag because adsorption and desorption take time, as the grain moves towards equilibrium with the air condition to which it is exposed. Experimental m.c. data and simulated values for the stirred bed are shown in Figure 41. For clarity the simulated value at 3.5m depth, shown in Figure 40, is not shown in Figure 41.

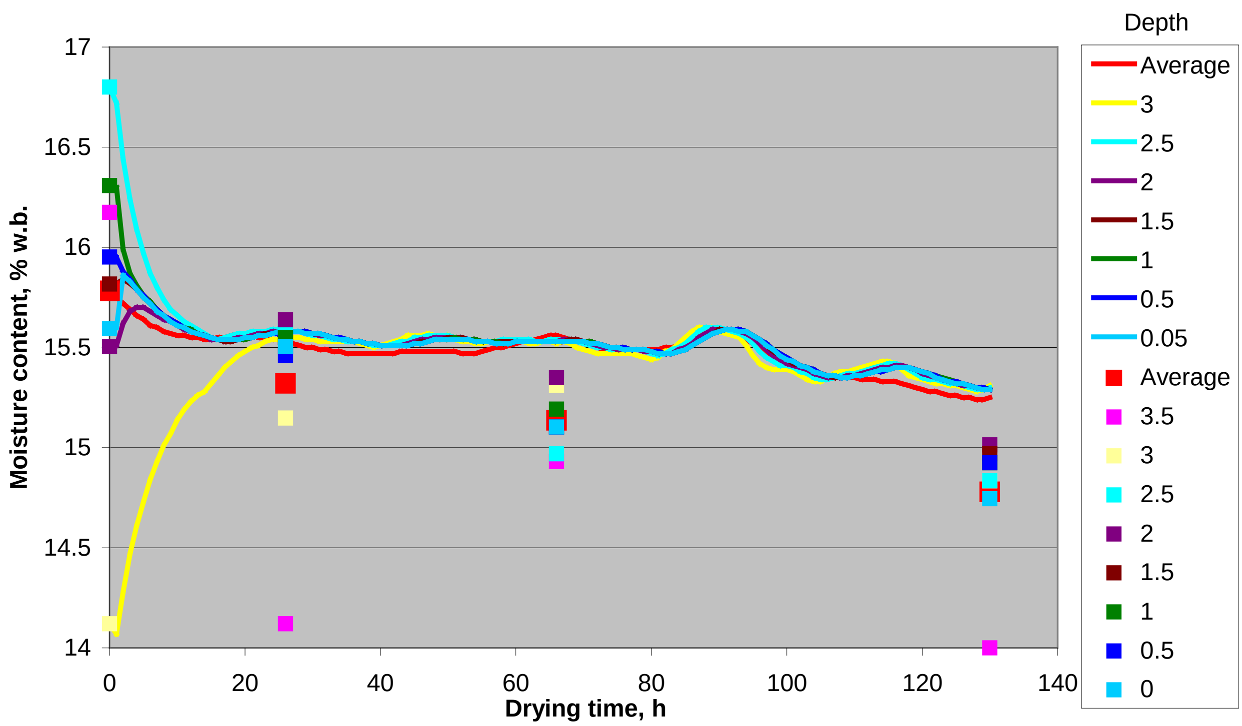

Figure 41. Experimental m.c. data (points) and simulated m.c. (lines) for the stirred block of the farm store.

The data show rapid drying over the first 26h, then slower to 66h and to the end of ventilation. Note that the break in ventilation at 66h cannot be seen in the elapsed ventilation time. Once drying was underway, the m.c. values were within a range of 0.5% points m.c. so overall there was good mixing although there was some inversion, *e.g*. at 3m depth the m.c. at 26h was less than at 66h.

Simulated values converged rapidly and stayed together, showing good mixing by the model. Drying was a little slower than measured after 26h and a difference of about 0.5% points m.c. remained at the end of ventilation. This difference was due to the equation used in the model for the moisture equilibrium between air and grain. An alternative, and equally valid, equation was used to simulate this experiment, and the result was closer agreement. But as mentioned in the analysis of Experiment B at Fera, this alternative equation gave significantly worse results in the simulation of that experiment. It was concluded that the moisture equilibrium relationship used in the simulation model was sufficiently good.

Even though the stirring in the farm trial was twice as intense as if the whole bed had been stirred, stirring in the model produced a more uniform bed than measured in the farm trial. Recalling that, in the Fera bin experiments, stirring in the model was less intense than in the experiment, these results taken together suggest that stirring implemented in the model was sufficient to be effective without being too intense.

Figure 40 also describes the static block of the store, in that the duct conditions were the same and the grain at 3.45m depth was not entrained by the stirring auger. The experimental data for the static side are shown in Figure 42.

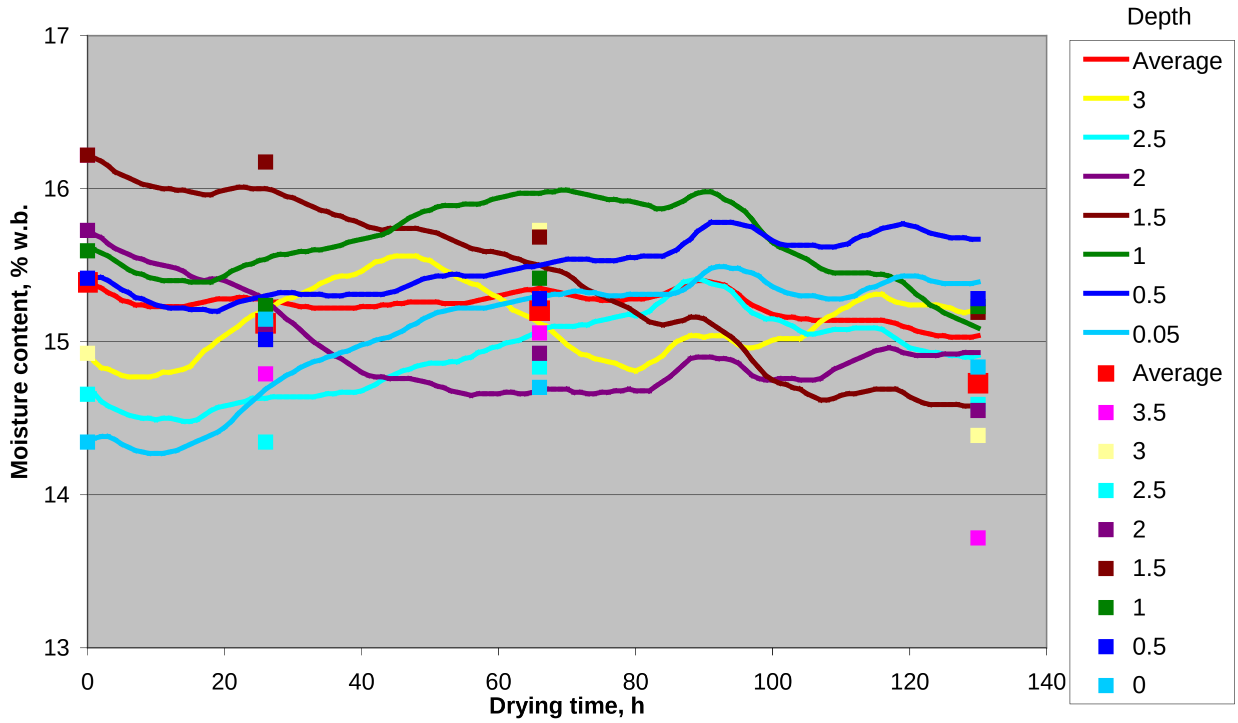

Figure 42. Experimental m.c. data (points) and simulated m.c. (lines) for the static block of the farm store.

Given that it was at a m.c. less than 16% m.c., the wheat started, and remained during the experiment, close to equilibrium m.c. with typical ambient conditions. Hence, changes in the r.h. of the incoming air lead to drying and rewetting fronts being pushed up through the bed by the air. These fronts caused the m.c. to move up and down, and are present in the simulated lines as well as the measured data. This situation can be contrasted with the experiment in the Fera bin where, once drying started in Bin B (Figure 28), the simulated lines all fell, in succession, until near the end. Only at that stage was the grain close to equilibrium with the incoming air, and absorption as well as desorption started to occur. Overall, the spread of the data points at each sampling time in the simulation agrees with the data. The final m.c. samples shows that the experimental grain dried about 0.4% points m.c. more than the simulation predicted, which was expected given the lower exhaust r.h. from the model than measured. The discrepancy is small and is, as previously discussed, much influenced by the model's air-grain equilibrium relationship.

As in comparison of the two bins in Experiment B at Fera, direct comparison between the two blocks of the store is not quite straightforward. Although the two blocks are very similar, the m.c. near the surface differed between the stirred block and the static, the static being wetter. The simulation for the static block was re-run, using the initial moisture profile through the bed from samples taken from the block to be stirred. The airflows were also equalised by a minor adjustment. The first period of ventilation showed only small differences so the results used to draw Figure 43 were from the second period.

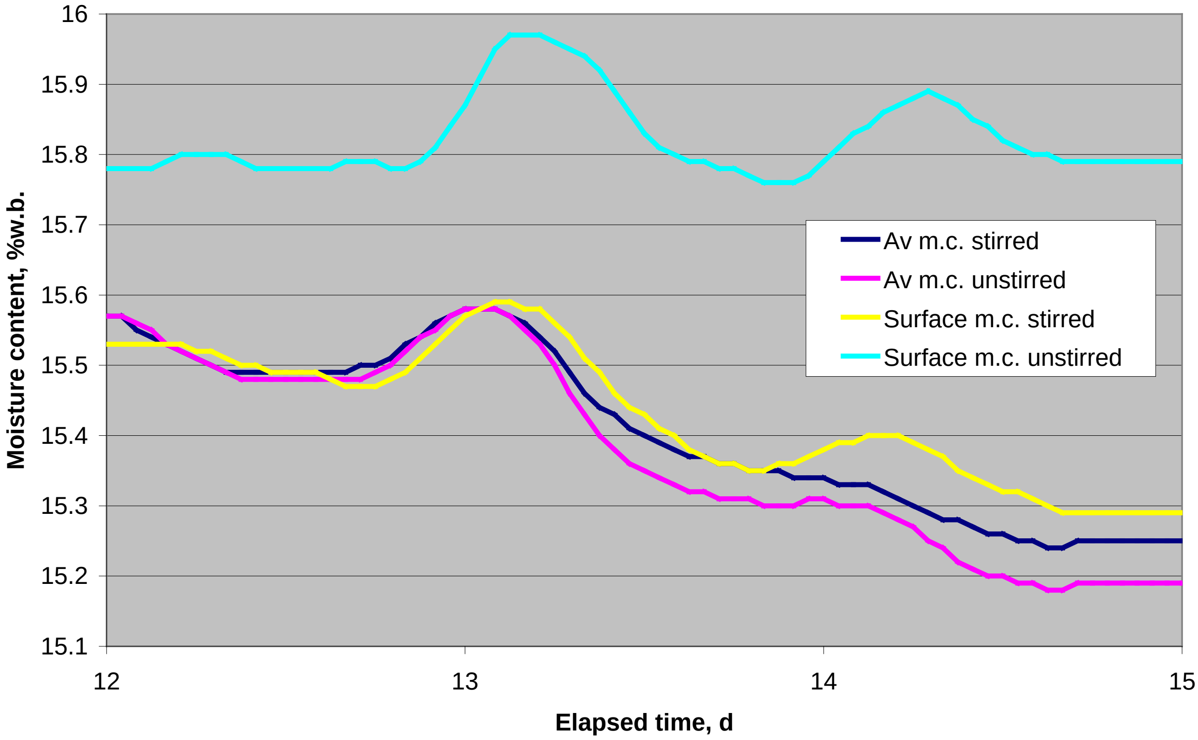

Figure 43. Progress of average bed and bed surface m.c. by simulation of stirred block of farm store, and of static block at same initial conditions.

The static block dried a little faster, shown by the average m.c. of the static block gradually falling below that of the stirred block. The reason for this is clear from the surface m.c. traces. That of the static block remained high during this second period whereas for the stirred block, the surface m.c. followed that of the bed as a whole. The air exhausting from the stirred surface would therefore have had a lower r.h. at much the same temperature and so the bed dried slower.

In conclusion, farm-scale testing of the model, albeit in conditions of low moisture removal, did not raise any doubts about its performance. Indeed, together with the data from the bin experiments, the farm-scale work allowed the relationship between m.c. and air r.h. to be confirmed. And although data for drying using significantly higher air temperature again was not obtained, this aspect had been covered by simulation of published data.

Considering the validation work overall, agreement of the model with the data from the 25t wheat drying experiment at Fera in 2010 was good in the important respects, particularly drying time, approach to and level of final m.c. Validation against data from a stirred and a static bin at Fera in 2012 showed that the model predicted the overall drying behaviour of both bins well and, although stirring in the model was less vigorous than in practice, the accumulated effect was sufficient to mix the bed to a similar degree. The drying fronts in the model were steeper than measured but this did not affect drying time, which was well predicted. Because the wheat on the test farm site in 2012 again needed little drying, data could not be had for drying using significantly higher air temperature. Testing of the model in these low moisture removal conditions did not raise any doubts about its performance, and indeed together with the data from the bin experiments, allowed the relationship between m.c. and air r.h. to be confirmed. Simulation of a published experiment in which an 86t bin of wheat was stirred and dried with air at a higher temperature gave results which agreed very well with the measured overall performance. Because the drying time was well predicted, the fuel and electricity use were also, as they are the product of running time and heater and fan power. Overall, the model proved to be sufficiently good over the range of m.c., air temperature and stirring rate encountered in the experiments. Because it is based on well-understood physics of drying, the model, it was concluded, could be used with confidence over a wider range than found in validation experiments.

3.4. Simulation runs and results

Milestone 3 and 4. "Run a range of simulations to explore the effectiveness and cost saving potential of stirring in normal on-floor drying. Simulate a wide range of options to study performance and hence potential for energy and capital cost saving:- single self-propelled auger to a multi-auger system, range of strategy (normal and significantly higher air temperature, increasing bed depth, temporary over-drying)"

3.4.1. Basis of this study

In this study, simulations of various drying systems were run to produce data on their likely performance under a wide range of conditions. By comparing performance in various ways, the benefits and drawbacks of one system versus another, or of one choice of operating condition versus another, can be shown.

A model such as Storedry cannot predict drying accurately in every aspect, but the performance predictions are likely to be substantially accurate because the model describes all the important physical and biological phenomena occurring during drying in quantitative ways that reflect the physical laws describing such phenomena. Changes in drier performance as a result of changes in the inputs to the model are likely to reflect how the real-life drying system would respond. Predictions from Storedry for very specific circumstances are compared with real-life data in this report to test the model, and these give confidence that the predictions are correct. The sound basis of the model, validated by these checks, allow it to be used over a wide range of circumstances in a way that would be impossible by physical experiment.

Given that the basis of this work is the comparison of one drying system with another to find out how performance can be improved, it is important to define the basis of this comparison. An improved system of drying would be one that would save cost (capital cost and/or recurring cost), save drying time, or produce improved grain quality, or some combination of these three. For two drying approaches to be comparable for cost, time and grain quality, in both approaches the grain bed would have to be dried to the required average m.c. for the batch, the wettest areas of the bed would not be excessively moist at the end point, and these targets would be reached with a high degree of certainty, irrespective of the weather conditions in a particular season.

In this work, each drying condition was simulated using 20 years of historical weather data so the success could be expressed as the number of years out of the 20 in which all the targets were reached. Success was, therefore, formally defined as meeting a target of 14.5% m.c. wet basis for the average of the whole bed and of 15.0% m.c. for the wettest part of the bed, without spoilage, within an elapsed time of 2 months, and in a sufficiently high proportion of the 20 years simulated. 19 or 20 out of 20 years was defined as “highly successful”, 15 to 18 out of 20 years as “moderately successful”.

Spoilage was assessed using a spoilage index as described in the report of HGCA project RD-2004-3133 (Bruce *et al*., 2006). It involves calculating how much of a ‘safe time before risk of fungal toxins’ has elapsed, a calculation which depends on the m.c. and temperature of each part of the grain bed. As was found in that report, if this index is not allowed to rise above 2.0, the grain is not at risk of the main fungal toxin of concern in the UK, Ochratoxin A.

The simulations reported here allow direct comparison of a stirring drier with a drier in which the bed is static. The main measures of performance were the drying time to the two m.c. targets described above, the energy used in the form of electricity (for the drying fan, the extraction fan(s) for the roof space and for the stirring system), fuel used for air heating, here assumed to be propane gas. The costs of each were calculated based on assumed prices per unit of energy of both electricity and gas and the net calorific value for propane (see Appendix A). Where the average m.c. was below the target figure, the cost of lost weight of grain for sale was added to give a total running cost. A value of grain at 14.5% was assumed (see Appendix A). Several measures of performance were calculated to make comparison easier, such as overall cost per tonne of dried grain and electricity cost per % moisture removed per dried tonne. Tables 10 to 30 (Appendix B) give starting conditions and drying performance under those conditions.

Given that a well designed and operated drier can work well without the bed being stirred, a decision to fit a grain stirring system to an existing drier or to specify a stirring system as part of a new drier, must take into account the likely costs and benefits. Part of the purpose of this project was to calculate any benefits of using stirring while drying so that such investment decisions could be better informed. Such an investment decision should also consider the benefits of alternative improvements to a drier that could be effective in improving performance, such as a replacement fan or heater, or improved controls. It was beyond the scope of this project to consider all the possible improvements, particularly because the calculations would differ between driers and between growers. For example, one drier may have too low an airflow to be sufficiently effective so a larger fan may be the most effective use of capital, while another may benefit most from a new relative humidity sensor to improve control of the air conditions in the plenum. Savings in drying time are also of differing value. In one case, a saving in drying time may be of low importance because the grower stores the grain *in situ* once it has been dried, whereas another grower may wish to dry several batches, in which case saving drying time may be crucial to his operations.

In this work, it was assumed that the static bed drier was designed such that, with a bed depth of 3m, the fan would deliver an airflow close to that recommended (Anon., 2011) of 180 $m^3/(h.t)$. When a deeper bed was used, the airflow would be reduced because of the additional resistance, and conversely it would be increased at bed depths less than 3m. This is how the airflow in a real-life drier changes, as the resistance of the grain bed interacts with the air delivery capability of the fan.

There are many approaches to controlling the fan and heater in a bulk drier. For example, r.h. control of fan only with no additional heat, through continuous use of the fan with a modest size of heater simply switched on, or auto control of heating aimed at regulating the r.h. in the plenum to a preset level. Advanced strategies involve sampling the grain and reducing in stages the setpoint for plenum r.h. as the m.c. in the bed falls. Each approach balances equipment (and hence capital cost), energy use and duration of drying, while trying to give even drying and avoid risk of spoilage.

In this work, for comparison with a stirred bed, a strategy for fan and heater control for static bed drying was needed that was as effective as possible without excessive capital cost. If a modest capital investment in a larger fan or a larger heater, for example, would make a standard static bed drier more effective, then this more effective drier should be the one to be compared with the stirred bed drier. This approach is justified on the basis that one or more such improvements would be cheaper than the option of installing a stirring system. A range of simulation runs was therefore done to determine an effective strategy for fan and heater control in the static bed drier.

When comparing the two drying systems, it was expected that both would be successful to a high degree in relatively easy drying scenarios, (successful being defined above as reaching the m.c. targets within constraints of drying time and spoilage risk in a high proportion of the 20 years simulated). Where both were successful, the benefits and disbenefits (including costs and others such as uneven drying) were tabulated and some detailed comparisons made at particular performance points.

But it was also apparent that in some scenarios, drying might be successful when grain stirring was used but not without it (or indeed the converse). The comparison then highlights the extended range of, for example, initial m.c. or bed depth over which the better system would allow drying to be carried out with confidence. The performance of the successful drying system is tabulated and commented on.

The simplest comparison of the two drying systems was where the only difference was the availability of the stirring system on otherwise identical driers. All the other parameters, in particular the fan characteristics, fan and heater control policy, bed depth and initial m.c., were the same for both. This would reflect the situation where a stirring system is ‘retro-fitted’ to an existing drier. The comparison then highlights whether and how a stirring system could be used to save marginal cost, to save drying time, to minimise risk of spoilage or a combination of all three, when compared with a static bed drier of the same, standard design.

A further comparison needed to be made, of a static bed drier with a drier designed from the outset to operate with a stirring system, rather than using standard design parameters, and thus exploiting to the best the potential of grain stirring. Again, comparison highlights whether and how a stirring drier run at its best operating conditions could be used to save marginal cost, to save drying time, to minimise risk of spoilage or a combination of all three, when compared with a static bed drier.

3.4.2. Simulations carried out

Table 3 gives details of the series of simulations carried out. Results are given in Tables 10 to 30 (Appendix B)

Table 3. Summary of simulation runs. Where there is more than one set of runs in an Approach, the factor that was changed is in bold type.

Approach	Results	Specification
Static bed	Table 10	Policy 18, 62% plenum air r.h. target, 15 Aug start, TC5 fan, static bed
Approach 0	Table 11	Policy 18, 62%, 15 Aug, TC5 fan, bed stirred throughout
Static bed	Table 12	Policy 18, 62%, 15 **Sep** start, TC5 fan, static bed
Approach 0	Table 13	Policy 18, 62%, 15 **Sep**, TC5 fan, bed stirred throughout
Approach 1	Table 14	Policy 18, 62%, 15 Aug, TC5 fan, bed only stirred once average mc target reached
Approach 2	Table 15	Policy 18, 62%, 15 Aug, TC5 fan, bed stirred until max mc <18% then not stirred then stirred once average mc target reached
Approach 3	Table 16	Policy 18, 62%, 15 Aug, TC5 fan, half the number of augers for given bed area, stirred throughout
Approach 4	Table 17	Policy 18, 62%, 15 Aug, **TC4 (smaller fan)**, bed stirred throughout
	Table 18	Policy 18, 62%, 15 Aug, **TC6 (larger fan)**, bed stirred throughout
Approach 5	Table 19	Policy 24, 15 Aug, TC5 fan, **20^{o}C** in plenum, stirred throughout + extraction fan
	Table 20	Policy 24, 15 Aug, TC5 fan, **30^{o}C** in plenum, stirred throughout + extraction fan
	Table 21	Policy 24, 15 Aug, TC5 fan, **40^{o}C** in plenum, stirred throughout + extraction fan
	Table 22	Policy 24, 15 Aug, TC5 fan, **50^{o}C** in plenum, stirred throughout + extraction fan
Approach 6	Table 23	Policy 24, 15 Aug, TC4 fan, **20^{o}C** in plenum, stirred throughout + extraction fan
	Table 24	Policy 24, 15 Aug, TC4 fan, **30^{o}C** in plenum, stirred throughout + extraction fan
	Table 25	Policy 24, 15 Aug, TC4 fan, **40^{o}C** in plenum, stirred throughout + extraction fan
	Table 26	Policy 24, 15 Aug, TC4 fan, **50^{o}C** in plenum, stirred throughout + extraction fan
Approach 7	Table 27	Policy 24, 15 Aug, **20^{o}C** in plenum, 1 TC3 fan & no stirring for 24h then 2 TC3 fans and stirred, 180m^2 bed + extraction fan
	Table 28	Policy 24, 15 Aug, **30^{o}C** in plenum, 1 TC3 fan & no stirring for 24h then 2 TC3 fans and stirred, 180m^2 bed + extraction fan
	Table 29	Policy 24, 15 Aug, **40^{o}C** in plenum, 1 TC3 fan & no stirring for 24h then 2 TC3 fans and stirred, 180m^2 bed + extraction fan
	Table 30	Policy 24, 15 Aug, **50^{o}C** in plenum, 1 TC3 fan & no stirring for 24h then 2 TC3 fans and stirred, 180m^2 bed + extraction fan

In each of the 21 sets of runs, all combinations of five values of initial m.c., (24, 22, 20, 18 and 16%) and three of grain bed depth (4, 3 and 2m) were simulated. Weather conditions were those from Waddington, Lincolnshire for the 20 years 1951-1970. Runs started on the 15th August each year except where a comparison with starting on 15th September was required. Other conditions are described in Table 3 and in Appendix A. In total, 6300 simulation runs were carried out.

Storedry produced 74 output values for each run, which were studied to find out whether or not the run was successful. Success was defined as meeting a target of 14.5% m.c. for the average of the whole bed and of 15.0% m.c. for the wettest part of the bed, without spoilage (spoilage index <2.0), within an elapsed time of 2 months, and in 19 or all 20 of the 20 years simulated. For successful runs, the average value of the most important measures of performance, averaged over the successful 19 or 20 years, were tabulated.

3.4.3. Results and discussion

1. Finding a good control policy for fan and heater as the basis of comparison of stirred and static bed driers

The performance of three such policies was investigated, all based on regulating the r.h. of the air in the plenum by adding heat with a propane burner. This heat was in addition to the small heating effect of the fan. This type of control, included in the approaches listed in the GSG 2nd edition (P10, Anon., 2003), was chosen here because it gave a good balance between effectiveness and cost. The three policies, using the numbering in Storedry, were:-

Policy 18, adding heat to reduce plenum r.h. to 62%, if achievable with the available heater power, or accepting a higher r.h. with the maximum heater power being used. During warm, dry weather, air at an r.h. of lower than 62% could occur.

Policy 19A. As above but making the r.h. setpoint dependent on the average m.c of the whole bed. The setpoint r.h. was stepped down from 100% r.h. (*i.e.* no heating permitted) at 20% m.c. or above, via 83% r.h. between 20 and 18% m.c. and 72% r.h. between 18 and 16% m.c., to 62% r.h. below 16% m.c.

Policy 19. As Policy 19A but the m.c. used was the spot value at a depth of 0.3m from the surface.

Other policies were simulated, such as drying with continuous use of fan only or with a small heater, or cutting off the fan at high atmospheric r.h., but these were found to give too few years of successful drying to be considered suitable.

To compare the performance of these control policies, drying was simulated using Policies 18, 19 and 19A with historical weather data for Waddington, Lincs. Drying was started rather later in the season, on 15th September, to ensure the conditions were sufficiently challenging. A bed depth of 3m, an airflow of 180 $m^3/(h.t)$ or 0.05 $m^3/(s.t)$, and initial m.c. values from 24 to 16% in 2% steps were used. Table 4 shows, for each of five values of initial m.c. and three of bed depth, the number of successful years out of the 20 simulated.

Table 4. Number of years out of 20 in which drying succeeded with each of three heater control policies.

Initial m.c., %	Bed depth, m	Policy 18	Policy 19	Policy 19A
	4	0	0	0
	3	0	0	0
24	2	0	0	0
	4	18	12	12
	3	18	6	7
22	2	18	2	4
	4	20	20	20
	3	20	20	20
20	2	20	18	19
	4	20	20	20
	3	20	20	20
18	2	20	20	20
	4	20	20	20
	3	20	20	20
16	2	20	20	20

None of the policies gave any successful years at 24% initial m.c. and all policies gave 20/20 years success at 18% initial m.c. and below, so the values at 22% initial m.c. were key. Here, Policy 18 led to drying success in 18 out of 20 years whereas the other control policies only gave 6 or 7 successful years. Policy 18 was therefore chosen as the best ‘standard’ control policy as the basis for comparing drying approaches in which stirring was used. However, to achieve the reduction in plenum air r.h. to 62% during most of the drying period, day and night, a larger heater may be needed than fitted to a ‘normal’ drier. As gas heaters are relatively low cost, this was considered a reasonable requirement.

Policy 18 was remarkably successful compared with other strategies. Given that it has a requirement of a temperature rise larger than the conventional guidelines (P10, Anon., 2003) it may be questioned by some. However the authors note that, in a lecture entitled “Practical – How to control energy costs” at UK Grain, East of England Showground, Peterborough, 2 Nov 2011, Mr Andrew Kneeshaw of FEC Services Ltd commented that traditional approaches to fan and heater control are efficient but slow and recommended an approach similar to Policy 18, calling it his ‘get on with it’ approach.

2. Comparison of stirred bed with static bed

A comparison was made between a static bed drier and a drier with a continuously stirred bed. Results for the static bed drier are presented in Table 10 and for the stirred drier in Table 11 (Appendix B). Drying was simulated using weather data from Waddington, Lincs, starting 15 August each year for 20 years. Other than the use throughout of stirring, both driers and conditions were identical. In particular, for both driers the heater was controlled using Policy 18 with a setpoint r.h. for plenum air of 62%.

First we compare drying success for combinations of initial m.c. and bed depth, based on achieving all drying targets in either 19 or 20 years out of 20. This shows where stirring made a crucial difference to drying success by avoiding risk of OA. The results are made easier to interpret because there was a sharp upper limit to allowable bed depth. Particular values in Tables 10 and 11 illustrate the success of static bed and stirred bed drying on spoilage index. At 24% initial m.c. and at 2m bed depth, both systems were successful. At this relatively shallow depth, a greater airflow per tonne of grain was delivered by the fan than the recommended flow. More moisture was removed from the bed per hour with the result that the static bed dried fast enough for the risk of spoilage to be avoided. At depths of 3 and 4m however, the grain near the surface of the static bed reached the ‘at risk’ condition before it had dried, so drying with a static bed failed in all 20 of the years simulated. Stirring allowed the 3m, 24% bed to dry successfully in all 20 years, but an increase in bed depth to 4m resulted in only 6 years success. Starting at 22% m.c., a 4m bed was successfully dried with stirring but in only 2 years could the static bed dry successfully. As a generalisation, for the stirred bed the maximum initial m.c. for drying to be successful was 2% (m.c.) higher than for static bed both at 4m and at 3m.

Table 5 shows the results when drying grain at relatively high initial m.c. in deep beds. For a static bed there was a sharp fall in success, from 19 to 2 years out of 20, between 3 and 4m bed depth at 22 % initial m.c. and between 2 and 3m at 24%. Similarly for a stirred bed at 24% initial m.c., only 6 years out of 20 were successful at 4m compared with 20 at 3m. The spoilage index values show are averages of all the 20 years simulated to give an overall view of the drying treatment, but each year was judged individually, success being when the index was less than 2.0.

Table 5. Effect of stirring on spoilage index and drying success. Spoilage index in bold shows where risk of OA was too great.

Continuous fan, plenum target r.h. = 62%	Spoilage index (and successful drying years out of 20)	
Initial grain m.c. and bed depth	Static bed	Stirred bed
22%, 3m	1.6 (19)	0.89 (20)
22%, 4m	**2.3** (2)	1.25 (20)
24%, 2m	1.7 (19)	0.94 (20)
24%, 3m	**2.7** (0)	1.5 (20)
24%, 4m	**3.7** (0)	**2.1** (6)

Now we compare results for stirring and static bed where both approaches resulted in successful drying. This comparison covers the range 24% initial m.c. at 2m bed depth, 22% at 2 and 3m, and 20, 18 and 16% at all three depths in Tables 10 and 11. In every case, stirred drying took longer to achieve both the drying targets, *i.e.* average bed m.c. <=14.5% and maximum bed m.c. <=15.0% and cost more per tonne of dried grain. However stirred drying gave significantly lower values of spoilage index and resulted in less over-drying.

Where either drying system failed at high initial m.c., it was owing to spoilage having occurred before moisture targets were met. The spoilage index had risen to be 2.0 or more, at which the grain would be considered to be at risk from fungal toxins. From this description one might expect a low spoilage index to be beneficial but this is not really the case, for the following reason. Although a spoilage index much lower than 2 would leave a margin of safety, the risk from fungal toxins is considered acceptably low provided the index is even marginally below 2. This is because the condition that spoilage index be <2 is a “pass or fail” one. So a drying treatment that results in a spoilage index well below 2 is no better in any practical, measurable way than one with a value close to 2.

In static bed drying, when the target average m.c. of <=14.5% was reached, there was always a very significant moisture gradient through the bed, such that the bottom of the bed was over-dried to below target m.c. and the surface region was under-dried and, hence, still at risk. Hence, the grain bed was not suitable for storage without further action. Drying was continued in all the simulations until the target of the wettest layer being <=15% m.c. was reached. Stirring made the bed more uniform so the wettest target was generally already achieved when the average m.c target was reached. But when drying with a static bed, drying had to be continued for some time after the average target was met to bring the wettest part of the bed, in the upper layers, below the maximum m.c. target. This extra drying, done with the same plenum r.h. target of 62% resulted in the lower part of the bed being over-dried. The costs of lost grain weight for sale, which were included in the total costs of drying, were substantial for static bed drying. (The extra energy costs to evaporate the addition water were also of course included, but in energy cost category.) The total cost of drying included the value of the dry matter lost owing to respiration and activity of fungi. The higher the initial m.c. of the grain, the higher was this dry matter loss, but it was never more than 2% of total cost and less than 1% where the initial m.c. was less than 20% w.b. As it was related to fungal activity, this element of cost responded to the various treatments much was did the spoilage index.

Even given this over-drying element, overall cost was lower for static bed drying than for stirred drying, and energy use was much lower. As the values of initial m.c. simulated were reduced, both stirred and static bed driers showed a fall in energy use per tonne dried but static bed drying was always lower in cost. Costs expressed as per % m.c. removed per dried tonne rose, especially between starting at 18% and starting at 16%. This results from the extra difficulty of evaporating water from drier grain as well as from the inefficiency with which the drying power of air is used in drying lower m.c. grain.

Table 6 shows the drying time and costs for a 3m bed dried from 22% initial m.c. For the static bed drier, this condition is at the limit for risk of fungal toxins, whereas for a stirred bed, the limiting depth at this initial m.c. was 4m. All three conditions are shown. For the 3m bed depth, drying with a stirred bed to the point where both drying targets were met (wettest m.c. <=15% and average m.c. <=14.5%) took 46% longer than with a static bed. Electricity use was 91% greater, fuel cost 58% was more but over-drying cost was 88% lower. At 4m for the stirred bed, the electricity cost was a little higher and the fuel cost was a little less than at 3m.

Table 6. Effect of stirring and bed depth on drying time and costs. Initial m.c. was 22%. Fan was run continuously with a plenum r.h. target of 62%. Limit = maximum depth at which spoilage index <2.0

	Static bed	Stirred bed	
Bed depth	3 m (limit)	3 m	4 m (limit)
Drying time, h	255	373	529
Electricity cost *	0.43	0.82	0.88
Fuel cost *	0.45	0.71	0.68
Over-drying cost *	0.16	0.02	0.02

* £/(dried tonne & % m.c. removed)

Understanding the reasons why the initial comparison fall in favour of static bed drying allows approaches to be developed later that better exploit the stirring.

The result that stirring extended the drying time and increased costs in a side-by-side comparison with static bed drying can best be explained by first considering the behaviour of the static bed. As drying proceeds in a static bed, the lower regions of the bed dry and approach an equilibrium m.c. determined mainly by the r.h. (but also by the temperature) of the incoming air. Meanwhile the upper layers will remain at or near their initial m.c. so this is the zone in which fungal growth rate is highest and hence where the risk of fungal toxins is highest. As the air moves up through the bed, it comes into contact with increasingly wet grain, and absorbs moisture from that grain. When it leaves the bed the air will be close to an equilibrium condition with the topmost grain layers and, hence, will have quite a high r.h. This situation persists until those upper layers finally dry below the wettest m.c. target and the process of drying is complete. When the m.c. of this zone finally falls, the rate of fungal activity is greatly slowed and then effectively stopped as the target m.c. is met. This is why static bed drying has been described as a ‘race to the top’ - the drying front must reach the top of the bed to stop the fungal activity before spoilage occurs. Provided the upper zone has not remained too moist for too long, there will be low risk of fungal toxins.

In a stirred-bed drier, the grain is moved vertically, and to a small degree spread sideways, which tends to eliminate the differences in m.c. that build up in a static bed. In most of the bed, including at the bed surface, the grain in a well-stirred bed will be close to the average m.c. So air leaving the surface will be close to equilibrium with grain at the average m.c. of the bed. Once drying has made some progress and the average m.c. has started to fall, the r.h. of the exhaust air will therefore be lower than if the bed had not been stirred. Less water will be carried away per unit of air used. Hence, as drying proceeds and the average m.c. falls, the efficiency of stirred-bed will fall compared with static bed drying.

It is clear that the wetter the upper layers of grain, the more water each unit of air will carry away. For this reason, a system in which grain at the surface is the last to dry will tend to make best use of each unit of air pushed through the bed by the fan. Hence for the same air flow and conditions entering the bed, a static bed will tend to dry more quickly, and hence use less energy from the fan and heaters, than a bed that is constantly stirred.

It has been noted that in static bed drying, the need to continue drying until the uppermost grain has reached the target means that the lower parts of the bed and, as a consequence, the bed as a whole become over-dried. For the final stage of static bed drying, an improved strategy would be to select a higher r.h. in the plenum than 62% so that the lower region of the bed would not continue to dry and might rewet to a limited degree. Meanwhile the air reaching the upper region would still be at a suitable r.h. to dry that grain. If this approach were successfully managed, the final average m.c. would be closer to the target of 14.5%. This would reduce the loss of saleable weight of grain, and hence reduce to some extent the costs due to over-drying. However, more management would be needed to monitor the process, and the overall drying time might be extended. This approach was not simulated for the present work.

The same comparison, of static with continuously stirred drying, was made starting on 15 September, Tables 12 and 13. The same trends were seen as for an August 15th start. Comparing results for August and September starts (Tables 10-13), drying always took longer in the colder and damper weather of September, but the limiting initial m.c. at which drying was successful did not change. Fuel and electrical costs were higher starting in September because of the longer drying time needed. For static bed drying, over-drying costs were lower in September because the ambient air was less likely than in August to be well below the target plenum r.h.

We now look at the effect of grain depth and of initial m.c. on drying performance, using Tables 10 and 11. The effects of altering grain bed depth on drying performance followed the same trends for static bed and for stirred driers, though the stirred drying in all instances took longer and cost more overall, as already noted. Reducing grain depth from 4m to 2m resulted in greatly reduced drying time. Of course the weight of grain dried on a given floor is also halved. As depth was reduced, the resistance of the bed to airflow was reduced so the fan delivered more air. The bed also contained less grain so the airflow per tonne of grain greatly increased. The fan and drying floor were sized to give approximately the recommended airflow of 0.05 $m^3/(s.t)$ at bed depth of 3m. So for a 3m depth of grain at initial m.c. of 20% over a 90 m^2 floor, the airflow was 0.056 $m^3/(s.t)$. The flow through a bed of 4m depth was reduced to 0.039 $m^3/(s.t)$ whereas using a bed depth of 2m increased the airflow to 0.090 $m^3/(s.t)$. This higher airflow increased the speed of the drying front passing through the shallower bed so drying was greatly speeded up. As a result of less fan energy being wasted to force air through the grain bed itself, reduction in bed depth from 4 to 3 to 2m resulted in a small reduction in electrical energy use per tonne and % removed. Fuel costs fell slightly as depth reduced. Overall energy costs did not change strongly in response to bed depth changes.

For initial m.c. also, the effects on both drying systems were the same. As initial m.c. reduced from 24% to 16%, drying time was greatly reduced. Although drying from 24% to the 15% wettest grain target required a reduction of 9% (m.c.) compared with a reduction of only 1% (m.c.) from 16% to 15%, the drying time was not reduced in proportion to the water loss because (a) it takes time to move moisture up through the bed before any overall reduction is achieved, and (b) drying from high m.c. is more efficient. It results in higher exhaust saturation so it makes better use of the air delivered by the fan.

The total energy to dry grain increased, of course, as the initial m.c. rose. In Table 10, the total energy for a 2m bed at 16% initial m.c. was 188 MJ/t, rising to 410 MJ/t at 24% initial m.c. But both fuel and electricity costs per % of moisture content removed per dried tonne, shortened to £/(%.t), were lower when drying high m.c. grain. In Table 10, as the initial m.c. changed from 16% to 24% at 2m depth, the total drying cost for the static bed drier fell from 2.4 to 0.95 £/(%.t).

Summarising the comparison of static bed and stirred bed drying with identical design, weather and plenum air heating control, based on Tables 10-13, a drier with continuous stirring was successful in conditions of high initial m.c. in which static bed drying failed because of excessive risk of fungal spoilage in the upper layers of the static bed. Generally, stirring allowed successful drying at an initial m.c. about 2% (m.c.) higher than for static bed, or for a grain bed depth 1m deeper than the limit for static bed drying. This was the case across the range of bed depth (4-2m) and whether starting drying in mid-August or mid-September. However, static bed drying with effective use of heat was successful at an initial m.c. of up to 20% at 4m bed depth, 22% at 3m and 24% at 2m. In conditions where both systems dried the bed successfully, stirring resulted in a longer drying time and in higher energy use and costs than drying with static bed, but with less over-drying of the bottom of the bed. This was the case across the whole range of initial m.c. of 24-16%, bed depth of 4-2m and starting time of mid-August or mid-September.

3. Alternative approaches to the use of stirring

Now we investigate what approaches could be employed to obtain the benefit of lower spoilage risk presented by stirring with the greater efficiency of exhaust air saturation in static bed drying. The case of continuously stirred bed will be referred to as “Approach 0”. Tables 10 to 30 are given in Appendix B.

Approach 1. Stir only when the target average m.c. has been reached.

By drying without stirring and allowing a damp zone to persist in the upper layers, the efficiency of air use could be maintained until the bed had reached the target average m.c. In general, at this stage of drying, the upper region of the bed would be above the target m.c. for the wettest layer and the lower region would be dried to below the average m.c target. If the bed were stirred at this stage, the wetter grain at the surface would be mixed with the drier grain from below and thus bring the whole bed to the same m.c., close to target. (Of course this mixing could in principle be done by other means than a grain stirring system, such as moving the grain to another floor by bucket loader, but such approaches are not considered as part of this work.)

Comparing Table 14, in which Approach 1 is implemented, with Table 10, the static bed case, we see that the time to reach the average m.c. of 14.5% was the same, and only two or three hours of stirring were needed to mix the wetter upper layers into the bed and reduce their m.c. to below the target of 15%. To meet this wettest m.c. target without stirring took an extra 33 h of drying (at the comparison point of 20% initial m.c. and 3m bed depth). Approach 1 reduced the drying time to below that for the static bed across the range of depth and initial m.c. but the upper depth limit for spoilage risk at 24% initial m.c. remained at 2m, whereas the continuously stirred bed had a limit of 3m. The fuel and electricity costs of Approach 1 were lower than with static bed drying because both the targets were met sooner and because the short stirring time reduced electricity use for the stirrer motors. Overall drying costs when stirring in this way were lower than for a static bed, partly because of this lower energy use but also because there was less over-drying. Risk of spoilage was a little lower than with static bed drying because the m.c. of the upper layers, where conditions are most favourable for fungi, was reduced so quickly once stirring started.

The disadvantages of this approach are

1. The maximum m.c. and depth limits are lower than when stirring continuously. This approach is static bed drying until the average m.c. target is reached, so conditions may favour fungi in the upper layers during drying. Hence drying was not successful at 4m at 22% initial m.c. and at 3m at 24% initial m.c., whereas it was with continuous stirring.
2. In practice, the bed may have settled and become more compacted during drying to the average m.c. target, and it might not be possible for the electric drive motors to start the augers if they had been embedded in the grain bed.

Approach 2. Stir from the start of drying until the maximum m.c. in the bed reaches 18%, then stop stirring and start again only once the target average m.c. has been reached.

This approach sought to control spoilage risks better than Approach 1, by stirring until the m.c. of the wettest grain had dropped below the threshold of 18%. At this m.c. the risk of OA is eliminated

(Grain Storage Guide, 3rd edition, Anon., 2011, based on results of Northolt and Bullerman, 1982). Thereafter, the approach was the same as Approach 1.

Comparing Approach 2 with Approach 1 (Table 15 with Table 14), the drying times with Approach 2 were longer, overall costs were higher, particularly at higher values of initial m.c., because more stirring time was required until the 18% m.c. threshold was reached. However, risk of spoilage was indeed lower over the range, and as a result drying was successful at up to the same m.c. and depth limits as with continuous stirring, *i.e.* 24% initial m.c. at 3m depth and 22% m.c. at 4m, in each case 2% points m.c. higher than with Approach 1 at the same bed depth.

Compared with continuous stirring (Table 11) Approach 2 saved considerable time and the spoilage index was only a little higher. If initial conditions were close to the worst case, the higher risk might be unacceptable, but otherwise Approach 2 could save time and cost compared with continuous stirring.

Comparing Approach 2 with the static bed drier, (Table 15 with Table 10), the drying times were slower for Approach 2 at high initial m.c. but faster below 20%. This is because the stirring made drying less efficient initially but once the target average m.c. was met, stirring was very effective in completing the drying by bringing the wettest grain below its target of 15%. Overall cost was higher at high initial m.c. but lower below 20%. The over-drying component of cost was small with Approach 2, as it was with Approach 1.

Approach 3. Use fewer stirring augers

Clearly, if fewer stirring augers are used and if they are evenly active around the store, the time between passes at any location in the store will increase. Electricity costs for running the augers would also be reduced. Compared with stirring continuously with the normal number of augers per unit area (Approach 0, Table 11), there were only marginal differences when drying while stirring with half the number of augers per unit area (Table 16). Drying time was reduced by a small margin and drying was less expensive by a small margin and the spoilage index was a little higher. The explanation is that, as the number of augers per unit area is reduced, stirring at any location is less frequent and more of the grain bed is undisturbed for longer. The bed effectively becomes more like a static bed, so it is not surprising that the results show these trends. In this approach stirring the bed to mix it, once the target average m.c. is achieved, would take longer so some time advantage would be lost.

Approach 4. Use a lower or higher airflow.

Drying was simulated with a smaller fan (Table 17) and with a larger fan (Table 18), in both cases stirring continuously throughout drying, to compare with the results using a ‘standard’ Pellcroft

Typhoon TC5 fan used in Approach 0 (Table 11). The area of grain bed simulated was 90 m^2 and the fans used were the Typhoon TC4 and TC6 models for lower and higher airflows respectively. At 20% initial m.c. and 3m bed depth, the airflows generated by the three fans were 0.047, 0.056 and 0.060 m^3/(s.wet tonne).

Using a larger fan reduced drying time. For example at 20% initial m.c. and 3m bed depth, drying time was reduced from 314h to 296h, a saving of 18h. At this performance point, over-drying costs were marginally higher when drying with the larger fan, while total costs were slightly lower. With a smaller fan, drying time was increased compared with the standard fan, *e.g.* at 20% initial m.c. and 3m bed depth, drying time was increased from 314h to 381h, an extra 67h. Fuel cost was increased, electricity cost was decreased but the overall result was that cost was decreased by 5p/(%.t). The main effect of fan size was on the drying time, and the energy cost was not greatly affected by changing the fan one ‘size’ up or down.

Approach 5. Use a higher drying air temperature at normal airflow.

As background to this approach, it is noted that drying may be done in two essentially different ways. The first is drying with the aim of bringing the grain into balance with the relative humidity of the air. The second is drying with air that is heated and has a very low relative humidity, and where drying is stopped well before grain reaches equilibrium. The first is the basis of a conventional static bed drier while the second is what happens in a conventional heated-air drier in which grain is constantly moving and drying air temperatures of about 40^{o}C upwards are used.

Stirring the grain bed, because it moves the grain, allows the use of more intense drying treatments that would over-dry the lower part of a static bed, and might cause the upper part of a static bed to be so warm and damp that fungi would grow very rapidly. So instead of regulating the plenum r.h. to achieve gradual, fairly slow drying, the temperature of the plenum air could be raised while stirring to give faster drying. To explore this approach, plenum air temperatures of 20, 30, 40 and 50^{o}C were used in simulations of continuously stirred beds. Results are given in Tables 19-22. In conventional static bed drying, a temperature rise of no more than 5-10^{o}C would be the maximum possible to limit over-drying and to avoid excessively warm and damp surface conditions. While a plenum temperature of 20^{o}C may be within the normal range, depending on the weather, maintaining this during the night would require more heat than usual, and above 20^{o}C plenum temperature a larger heater power than available in a standard bulk store would certainly be needed. The heat power requirements are discussed below.

There are practical matters to be taken into account if considering drying with significantly higher temperatures. Items such as fan motors and bearings, and sensors and cables, fittings etc. would be subjected to those higher temperatures. Clearly, they must be able to function safely and reliably. There are other hazards such as risk of fire, and locations where access for the operator is not possible because the surfaces or air are too hot.

When using a plenum temperature setpoint of 20^{o}C, Approach 5 succeeded in drying with very low risk of fungal spoilage up to a bed depth of 3m at initial m.c. of 24%, the same limit as Approach 0. At 30^{o}C plenum temperature and above, grain at 4m depth could be dried successfully, so use of Approach 5 extended the range of conditions in which drying was successful.

Table 7 shows the effect on drying times and energy costs when drying from 22% initial m.c. with a bed depth of 3m. Drying time fell dramatically as drying air temperature rose, and at 30^{o}C and above, the stirred bed dried faster than the static bed. This rapid fall in drying times as drying temperature rose was seen across the whole range of initial m.c. and depth (Tables 19-22). At 20% initial m.c. and 3m bed depth, drying time was reduced from 314h where 62% plenum r.h. was maintained in Approach 0 to 278h at 20^{o}C plenum temperature, to 80h, 53h and 42h at plenum temperatures of 30, 40 and 50^{o}C respectively.

Table 7. Effect of plenum air condition on performance for initial m.c. of 22% and bed depth 3m. Fan was run continuously.

	Static bed	Stirred bed		
Plenum air target	62% r.h.	20^{o}C	30^{o}C	40^{o}C
Drying time, h	255	323	104	68
Electricity cost *	0.43	0.74	0.22	0.14
Fuel cost *	0.45	0.75	0.78	0.82
Over-drying cost *	0.16	0.01	0.12	0.24

* £/(dried tonne & % m.c. removed)

At higher drying air temperatures, the average m.c. fell below the target 14.5% before the maximum m.c. target of 15% was met. This was because drying was so intense in the lower layers of the bed that even constant stirring could not prevent significant over-drying of that grain. This is seen in the 'over-drying cost' line of Table 7. It must be noted that at 50^{o}C there is the possibility of heat damage to the grain exposed directly to the full temperature.

The case of 22% initial m.c. and 3m depth in Table 7 shows how electricity cost was reduced as plenum air temperature rose from 20 to 40^{o}C whereas fuel cost increased a little. At the lower m.c. of 20% and 3m, comparison of Tables 11 and 20 shows that the electricity cost of continuous stirring (Approach 0), £0.93 per dried tonne and % m.c. removed, was substantially reduced to £0.23 /(t.%) by increasing the drying air temperature to 30^{o}C. This was because the fan and stirrers were in operation for a much shorter time. The total energy used for drying was reduced from 469 to 364 MJ/tonne dried by moving from 20 to 30^{o}C plenum temperature, so drying at 30^{o}C was more efficient. But the fuel cost of Approach 0 did not change much as the temperature was increased to 30^{o}C, £0.88 to £0.81/(t.%). Much the same fuel was used but just over a shorter time. The reduced total energy use was largely due to reduced electricity use. As the drying air temperature was raised to 40 and then to 50^{o}C (Tables 22 and 23), over-drying increased and the total energy also increased. Fuel used /(t.%) was not much changed by the over-drying. This meant a greater % m.c. was removed unnecessarily so fuel cost rose, up to £6.16 /dried t at 50^{o}C for 20% initial m.c. and 3m bed depth. Overall, the advantages of increased temperature were most apparent at 30^{o}C plenum temperature. At higher values, drying speed was further increased but over-drying was excessive when using the simple policy here of drying until both targets were met. More management of the drying process would be needed to avoid over-drying, commented on further below.

Comparing drying with stirring at elevated temperature, Approach 5, with ‘normal’ static bed drying at constant 62% plenum r.h., the temperature used by the stirred drier had to be 30^{o}C or above to improve on the drying time of the static bed at 20%, 3m. At 30^{o}C, the total cost was also lower by a small margin. Overall costs were greater at higher or lower drying air temperature than 30^{o}C (albeit explored here in rather large, 10^{o}C steps). Heat losses would certainly increase fuel costs as temperature was increased so it appears that 30^{o}C may be somewhere near the optimum plenum air temperature.

In normal near-ambient drying, there would be little heat wasted to the environment because the temperature would only be raised by a few degrees. But where temperatures of 40 or even 50^{o}C are generated, heat would be lost before the air contacted the grain bed, from the hot upper and side surfaces of the main duct, in heating the structure itself and to the ground. The simulation model did not include any of these heat loss routes so the simulated energy use values will be less than in reality, by an amount that depends on the drier design. Each drier will be different so a generalised answer cannot be given. The higher the plenum air temperature the more important would energy saving measures be to maximise the benefits of using an increased temperature. Heat loss could be reduced by insulating the sides and top of the plenum and under the plenum and lateral ducts. This would be easier and cheaper if done during construction than afterwards. Insulating the plenum is likely to be cost effective. If there no grain on the other side of an un-insulated plenum, there will be more heat loss from the exposed plenum wall than if grain is present. Of course, grain there will be warmed and may need cooling later for safe storage.

The over-drying occurred because the lower part of the bed was being dried intensely and the stirring system was not able to incorporate that grain into the bulk sufficiently quickly so the difference was not removed by stirring. By the time the target maximum m.c. of 15% was reached, some of the bed was well below the required average m.c. of 14.5%. Clearly, this situation could be avoided, and the over-drying cost reduced and perhaps avoided, if the drying were made less intense as the targets were approached. There would be various ways to do this, including turning off the heaters and continuing to blow while stirring to mix the grain, or reducing the temperature rise well before the target and continuing to dry but less intensely, or turning off both heaters and fan and simply mixing the grain to eliminate the differences in the bed. In addition, it is clear that the grain when dried at elevated temperature would need to be cooled to reach a temperature suitable for sale, or prior to further cooling for safe storage. Cooling of warm grain will tend to evaporate further moisture, so drying could be terminated at a higher m.c. to allow for this final drying. However, the amount of drying would be small if grain were cooled rapidly with the drying fan and the stirring system running. Slower cooling with no stirring would give more loss of moisture, but some moisture and temperature gradients would develop in the grain bed as it cooled so final stirring to even out such differences would be advisable.

As noted above, higher heater power would be required for some of the approaches described here, assuming the same airflow from the fan. Where a target temperature of say 30^{o}C is used, there will be times of peak heat demand when raising the air temperature to the target demands the greatest power. This will occur when the air is coldest. In the simulation, the power needed to be able to achieve the target temperature during the drying weather conditions was found and used in the simulation runs. It may be that the available heater is powerful but not powerful enough always to reach the target temperature. What effect would this have on performance? An example case of the effect on drying time of using less power than this maximum was explored. Results are shown in Table 8 for 30^{o}C target plenum temperature drying a bed of 3m depth and 90m^2 area from 20% initial m.c. with a 15th August start for each of the 20 years historical data for Lincs.

Table 8. Effect of heater power on drying time when stirring

Heater power, kW	Average plenum temp, ^{o}C	Drying time to both targets, h
300	29.9	80.4
275	29.7	81.2
250	29.2	83.2
225	28.5	87.1
200	27.6	92.8

Results show that having less heater power available extended the drying time, which would in turn increase the electrical energy used for running the fan and stirrers. More detailed investigation was beyond the scope of this project.

Approach 6. Use a higher drying air temperature at reduced airflow.

The use of higher drying air temperatures with normal airflow was highly effective in reducing drying times, and hence electricity costs, but not in reducing fuel costs. If lower airflow were used, lower heater power would be needed to achieve the set temperature and it was possible that drying would still be accelerated sufficiently to present a good compromise between cost and performance. Results in Tables 23-26 were generated using a smaller fan, the Pellcroft Typhoon TC4 model, but otherwise with the same conditions as for Approach 5.

When using a plenum temperature setpoint of 20°C, Approach 6 succeeded in drying with very low risk of fungal spoilage up to a bed depth of 3m at initial m.c. of 24%. At 30°C and above, 4m depth could be dried successfully. Drying took longer but was still fast enough even at 24% initial m.c. to avoid risk of fungal toxin formation. The limit was the same as in Approaches 0 and 5, so using a smaller fan did not in this case reduce the upper limit of initial m.c.

Using 20°C (Table 23), the drying time of 325h at initial m.c. 20% and 3m bed depth was longer than the 314h needed for Approach 0 (the control stirred treatment with plenum air setpoint of 62% r.h., Table 11.) But as temperature was raised to 30, 40 and 50°C, the drying time dropped to 96h, 63h and 49h respectively (Tables 24-26). These drying times were longer than with Approach 5 using normal airflow but still represent a huge saving compared with Approach 0. As with the normal airflow of Approach 5, fuel cost £/(t.%) with Approach 6 hardly changed with plenum temperature over the temperature range but electricity cost fell as drying times reduced. The minimum overall cost was £1.14 /(t.%) at 30°C plenum temperature, of which £0.82 was fuel and £0.20 was electricity (Table 24).

Compared with the original fan (Table 20), the smaller fan (Table 24) gave a lower electricity cost and a fuel cost nearly the same. For example at 30°C plenum temperature, 20% initial m.c. and 3m bed depth, fuel cost was £0.81/(t.%) with the normal airflow versus 0.82 with smaller fan, where electricity costs were £0.23/(t.%) and 0.20, respectively. Over-drying was reduced because drying was slower while rate of incorporation of over-dried grain by the stirring rate was the same. Hence, the lower fan size was in this case effective and cheaper to run. It is generally the case that drying with a lower airflow is more efficient in terms of fan energy. Air resistance of the grain bed is non-linear with air velocity so, at lower airflow, less energy is used to force air through the resistance imposed by the bed. But the result of lower airflow is slower drying because the speed of the drying zone up through the bed is linked to air speed.

Comparing overall drying costs at normal airflow and reduced airflow with the static bed drying, we see they were similar at £1.18, 1.14 and 1.20 per dried tonne per % m.c. removed, respectively, at 20% initial m.c. and 3m depth. But the electricity and fuel elements of the overall cost were quite different. Using Approach 6 with 30°C plenum air setpoint, 20% initial m.c. and 3m bed depth, £0.82 was fuel and £0.20 was electricity, whereas for static bed drying at the same conditions, fuel costs were £0.51 and electricity costs £0.49 per dried tonne per % m.c. removed. This means that the best approach will depend on the relative cost of fuel and electricity for a grower; the more expensive the electricity relative to fuel, the more energy cost would be saved by using an approach of stirring with elevated air temperature.

Approach 7. Use a higher drying air temperature with low airflow for the first 24h then with higher flow.

This approach was similar to that recommended by some of the equipment suppliers, in that the grain bed was at first ventilated with a lower airflow at the elevated temperature but without stirring. In this case, a fixed period of 24h ventilation without stirring was used. Thereafter, a higher airflow was used until the target m.c. values were reached, by running a second identical fan in parallel with the first and maintaining the temperature of the increased airflow using higher burner power. In this set of runs, a bed area of 180m^2 was used with one and then with two Pellcroft Typhoon TC3 fans, which produced airflows of 0.023 and 0.039 m^3/(s.tonne at 20% initial m.c.), respectively in a bed of 3m depth. For comparison, the airflow for Approaches 0 and 5 was 0.056 m^3/(s.t), and for Approach 6 was 0.047 m^3/(s.t).

When using 20°C air, this approach resulted in low risk of fungal spoilage at 4m bed depth and 22% (Table 27), but at 24% initial m.c., the depth had to be reduced to 2m to keep the risk low enough. By raising the plenum temperature to 30°C (Table 28), the bed depth could be raised to 3m without compromising grain safety. At 24%, a depth of 4m was not suitable, even at 40 or 50°C (Tables 29 and 30). Hence, Approach 7 reduced the upper limit of initial m.c. that could be dried without risk compared with Approaches 5 and 6.

As in Approaches 5 and 6, the drying times fell rapidly as the plenum temperature setpoint was raised from 20 to 50°C. Also, the lowest cost per % removed and per tonne dried was at 30°C, above which, over-drying costs increased more than electricity costs reduced.

With the different fans used and the airflows they produced, Approach 7 was slower (130h at 20% initial m.c. and 3m depth with plenum temperature of 30°C) than Approach 5 (80h) or Approach 6 (96h). The overall cost of drying, £1.16/(t.%), was between those of Approaches 5 and 6. But the electricity cost was significantly lower at £0.14 per % removed per tonne dried, compared with £0.23 and £0.20 per % removed per tonne dried for Approaches 5 and 6, respectively at this comparison point. The over-drying cost for Approach 7 was higher and this brought up its total cost. The reason why the low airflow treatment gave over-drying was that the store area was doubled from 90 to 180m^2 to bring the specific airflow down to the required low figure, and so the interval between stirrings at each location was also doubled. Incorporation of over-dried grain at the bottom of the bed was, therefore, less effective.

4. Drying rates

The drying rate considered achievable in normal conditions by near ambient driers has been 0.5 % m.c. per 24h (P55 of McLean, 1989). The drying rate achieved in the simulation runs was calculated, using the final average m.c. and the time to achieve both the average and wettest m.c. targets. The drying rate was most strongly influenced by bed depth because this determined how much air was delivered from the fan, and this airflow in turn determined the drying rate. There was also an influence of initial m.c. - the higher the value, the higher the overall drying rate. Drying rates were calculated for each of the three depths but averaged over all the initial m.c. values at which drying was successful. Results are given in Table 9.

Table 9. Drying rate, % m.c. per 24h, for each set of runs and bed depth.

Approach and table of results	Static 10	Ap.0 11	Static 12	Ap.0 13	Ap.1 14	Ap.2 15	Ap.3 16	Ap.4 17	Ap.4 18	Ap.5 19
Bed depth, m										
4	0.4	0.3	0.3	0.2	0.4	0.4	0.3	0.2	0.3	0.3
3	0.6	0.4	0.5	0.3	0.6	0.6	0.4	0.3	0.4	0.5
2	1.0	0.7	0.9	0.6	1.0	0.9	0.7	0.5	0.7	0.8

Table 9. continued

Approach and table of results	Ap.5 20	Ap.5 21	Ap.5 22	Ap.6 23	Ap.6 24	Ap.6 25	Ap.6 26	Ap.7 27	Ap.7 28	Ap.7 29	Ap7 30
Bed depth, m											
4	1.2	2.0	2.8	0.3	1.0	1.7	2.4	0.2	0.8	1.3	1.4
3	1.7	2.9	4.1	0.4	1.5	2.4	3.4	0.3	1.1	1.7	1.9
2	2.8	4.7	6.6	0.6	2.3	3.9	5.5	0.5	1.7	2.6	2.7

The ‘standard’ static bed treatment, Table 10, achieved the 0.5 %/24h at a bed depth between 3 and 4m, whereas the stirred version, Table 11, needed a bed depth less than 3m to do so. A rate of up to 4.1% m.c. per 24h was achieved at 3m depth by raising the drying air temperature to 50^{o}C using stirring with Approach 5.

3.5. Development of user guidelines

Milestone vi. “From the results, develop user guide-lines to show how to achieve the full range of benefits from stirring”

Results presented in this report show how stirring influences the performance of a bulk drying system. There are also aspects of stirring that impact on the whole operation of drying that could make a contribution to a grower’s operations. These are discussed to allow a potential user to make good investment decisions.

The success of the drying process will be judged against a number of measures. Depending on the grower’s business model, these measures and others will have differing weighting. Measures will include the absence in the grain of fungal toxins produced by storage fungi (which means OA in the UK), suitability for the market of the moisture content of the dried grain (average value, and range within the store, particularly the wettest), marginal costs of the drying operation (costs of electricity and fuel and labour), drying time (or more precisely the time until the store is available for another batch of grain to be accepted), and the opportunity cost of the investment in the drying equipment.

Freedom from toxins is likely to be the highest priority because the grain is not likely to be acceptable to the market if OA is detectable. Stirring has been shown in this report to reduce the spoilage index, which is linked to the risk of OA. But because the energy costs and drying time using a standard bulk drier are increased by stirring, the use of stirring with a standard drier may only be justifiable after the implementation of several other approaches to keeping the risk of OA low. These approaches include using a higher airflow (more fan capacity), appropriate use of supplementary air heating, possibly requiring increasing the heater power available, improved instrumentation to measure the plenum air condition and to control the fan and heater operation, increased area of standard drying floor or use of a solid floor with temporary air ducts and fans, drying grain in two stages to extend the safe storage time. It is outside the scope of this report to go into details of these options, but one or more of the options may prove better investments than a stirring system.

3.5.1. User guidelines

It was not part of this project to investigate the more practical aspects of the use of stirring, so the following is based on the authors' understanding of stirring good practice.

To use stirring to best advantage, a decision is needed about whether stirring is required, and if so, when to start and stop. It is assumed that the user is familiar with the HGCA's Safe Storage Time Calculator software package for cereals. This calculates the time, at a particular grain temperature and moisture content, until there is an unacceptable risk of the fungal toxin OA being present in the grain. (It also calculates the risks from insects, mites and loss of viability, but those do not concern us here.) The safe storage time (s.s.t.) changes as the temperature and moisture change. To use this calculator during drying, and hence to see if the grain in the drier is at risk, the user needs to have an estimate of the drying time in a static bed until the surface m.c. falls. This happens when the drying front has moved up through the bed and the grain near the surface starts to dry. If there is no other way to estimate this time, it could be calculated on the basis that a well-designed drier loaded and used as recommended by the suppliers, would be expected to remove 0.5% points of moisture per 24h of operation. So by this estimate, drying from say 19.5% to 14.5% would take 10d or 240h. For most of this time the surface would remain at the initial m.c.. So if the s.s.t. for grain at 19.5% and at a temperature measured in the store is longer than 240h, the drying front should reach the surface and dry the last grain without risk of OA. If the s.s.t. were shorter than 240h, the surface grain would be at risk of OA, and stirring would reduce this risk. Stirring throughout drying would reduce the risk very substantially. But as shown in this report, stirring in this way extends the drying time and costs more in electricity and fuel. So guidance is given as to when to start and stop the stirring to avoid the risk of OA.

Explanatory notes for the following points are given below.

A. Retro-fit of stirring system to existing bulk drier

If you have the following problems, the use of a grain stirring system as an add-on to your current drying system may help.

A1. Grain at the m.c. and temperature in your store is at risk of OA according to the HGCA Grain Safe Storage Time Calculator software package.

A2. Grain is compacted in the store, either from loading itself or a delay after loading during which moist grain has become compacted.

A3. There are differences in m.c. of several % m.c. between grain at various levels in the store, *e.g*. because wet grain has been loaded at the bottom, and drier grain loaded on top.

A4. Grain from various sources needs to be made into a uniform blend.

A5. Grain in part of the store has self-heated because of dampness.

A6. There are regions in the bed where airflow is low because of compaction or presence of fines under a loading spout.

A7. The bed is stratified in m.c. between top and bottom. The grain near the air inlet may be dried to below the target m.c. Although the bed as a whole has reached the target m.c., the grain near the top of the bed may be too damp for safe storage.

If you have the following problems, a retro-fit grain stirring system will not help.

A8. Too much fuel is consumed for heating the drying air.

A9. The electricity used by the fan is too high.

A10. Drying is slow in a normal drying season.

A11. Drying is slow because the weather is poor for drying this season.

A12. Grain is significantly wetter in one location in the store so drying is slow there.

B. Drying system designed around stirring, with capability to use higher drying air temperature

If you have the following problems, a grain stirring system designed to use stirring with higher air temperature may help.

(In addition to items 1-7 for retro-fit stirring system)

B1 Faster drying is needed so that the grain can be outloaded quickly.

B2. More certainty is required that drying can be achieved year on year, irrespective of the weather and with low risk of fungal toxins.
B3. The electricity used by the fan is too high.
B4. More drying capacity is needed from the existing store footprint.
B5. The fan is too small for the current drying requirement.

If you have the following problems, a grain stirring system designed to use stirring with higher air temperature will not help.
B6. Too much fuel is consumed heating the drying air.

Explanatory notes

A1. Stirring the grain bed means that all of the grain dries as soon as the fan and air condition allows it. Grain near the bed surface, which in a static bed would stay undried until the process was nearly completed, dries with the bulk. As the risk of fungal toxins reduces with m.c., the risk starts to fall as soon as drying has started in a stirred bed. Even if drying takes longer overall, the risk of OA is still very much reduced. By contrast, in a static bed the risk for the upper region is not reduced as the bed dries because that region does not dry till last, and so drying must be completed sooner than if the bed is stirred. If the m.c. at loading is such that the expected drying time is longer than the safe storage time, drying with a static bed is a high risk option. Stirring continuously will reduce the risk but cost more and take longer. Because the toxin is not produced by the fungi at below 18% m.c., a compromise is to stir the bed until the grain is below 18% m.c. and then complete drying to the target average m.c. without stirring. Stirring without further drying will ensure the bed is sufficiently uniform.
A2. Of course compaction of the grain when loading should be avoided if possible. However, to get the required bed depth, grain pushers are often used which (anecdotally) tend to compact the grain. Stirring will reduce compaction, *i.e.* loosen the grain. Though the evidence is weak for the effect of this on drying, stirring a compacted bed may allow a higher airflow to be delivered by the fan. The grain will be loosened and become less dense. Less dense grain will permit more air to be delivered from a given fan. But the bed will also become deeper when it is loosened. A deeper bed will offer more resistance to the fan. Under these two opposing influences, the airflow delivered by the fan may not change significantly. The result will also depend on the type of fan and where on its pressure versus flow curve the fan is operating.
A3. In any part of the store, any differences between bottom, middle and top of the bed will be reduced by stirring before drying. Starting with a uniformly moist grain through the depth of the bed will make drying easier because wetter zones will have dried by contact with drier parts simply as a result of being mixed by the stirring system.
A4. Stirring will tend to blend the grain in a vertical sense, so the grain to be blended must be spread in layers. Stirring is most effective at incorporating grain into the bulk from the upper half of

the bed, and least effective at incorporating grain from the bottom of the bed. If it is vital that a particular batch of grain be well mixed into the blend, avoid placing that material into the store first, *i.e*. at the bottom of the bed.

A5. The removal of the heat requires at least a cooling airflow to be delivered through the bed once the grain has been loosened. The temperature of the grain should be monitored to check that it is falling quickly enough.

A6. While it would be better to avoid such issues than have to solve them, a stirrer would be effective at dispersing material from one location. The stirrer augers would need to be run through that region intensively to achieve results right down to the bottom of the bed.

A7. See A4. It will take a stirrer system longer to incorporate over-dried grain because it is at the bottom, than to mix in under-dried grain which will be at the top.

A8. In a bulk drier operated with near-ambient air conditions, not only will stirring not save fuel, it will use more. However fast or slowly grain is dried, the same mass of water must be evaporated. So if the efficiency of drying is the same, the total amount of heat energy, and hence fuel, needed to dry the batch will not change. A static bed drier is efficient because air leaves the grain bed after contact with wettest grain near the surface, and hence the air is well saturated. This remains so until near the end of static bed drying when the surface starts to dry, at which stage efficiency of drying falls too. In a stirred bed the surface dries as the bulk dries, which is why the risk of fungal toxins is controlled. However, the air leaving a stirred bed is not as well saturated so the efficiency of drying is lower than for a static bed. This explains why a stirred bed drier using air at close to ambient conditions will take more time to achieve the target m.c. and because the heater is running for longer, stirring will use more fuel to dry over a given range of m.c.

A9. As explained in A8, drying takes longer so the fan as well as the stirring system, is run for longer. Electricity use is therefore <u>higher</u> than with a static bed drier under the same, near-ambient air conditions.

A10. As explained in A8 and A9, stirring the bed during drying makes the operation less efficient, and hence take longer. So a drier which is too slow will be made worse by stirring the grain. The problem may be that the fan is delivering insufficient air through the bed, in which case replacing the fan with one of higher capacity against the resistance of the system would be more appropriate than installing a stirrer system.

A11. Stirring would not speed up drying in a poor season, when drying would be slowed because of cold or wet weather and perhaps because of higher initial m.c. However the use of stirring, although it will not speed up drying, will reduce the risk of fungal toxins (see A1).

A12. Only a small amount of lateral movement, as opposed to vertical movement, is achieved by auger stirring, so stirring will not be effective at redistributing across the store any wetter, or drier, grain loaded into a particular region of the store.

B1. When air at higher temperature meets damp grain, drying is faster and the m.c. that the grain will arrive at is lower. In a static bed, this would result in severe over-drying of the lower part of the bed and condensation and rapid spoilage in the upper part. Stirring the bed allows the drying to take place throughout the bulk at more or less the same rate. As the temperature of the air is raised, the drying rate that can be achieved increases. At an air temperature of 30^{o}C or over, drying is faster than would be possible in a static bed. See also A1 because faster drying gives reduced risk of fungal toxins.

B2. B1 explains why higher air temperatures when stirring can increase the drying rate throughout the bulk. As the temperature of the air is raised by heating it, the relative humidity of the air is greatly reduced. Hence the influence of the ambient humidity on drying rate diminishes. Hence, provided the drying system has been designed for this, the use of higher drying air temperature can allow drying to be successful irrespective of the weather.

B3. As the drying time is shorter when higher air temperature and stirring are used, the fan and stirrers are running for less time and so use less electricity. However, air for cooling will need to be supplied and the drying fan may need to be used for this if no cooling fan is fitted.

B4. By installing a stirred drier using higher temperature drying air, the drying capacity per m^2 will be increased, all else being equal.

B5. Stirring may help but a better option would be to replace the fan with one capable of delivering the correct airflow.

B6. The explanation of A8 applies here. Even if the air temperature used for drying in a stirred bed is higher, the level of saturation of the air leaving the surface of the stirred bed decreases as grain of a higher m.c. at the surface is mixed with dried grain from lower in the bed. This means that the efficiency of drying will be lower than for a static bed. Because the exhaust air is warm, each unit of air leaving the bed carries away a considerable mass of water, much more per unit of air than for the cool exhaust of a normal bulk drier. But the energy used to heat the drying air to the higher temperature is also more. Overall, the energy per unit of water evaporated from the grain remains higher than for a static bed, so more fuel is used in a given drying task.

3.5.2. Assuming a stirring system is available, how should it best be used?

1. If, because of problems A2 to A6 inclusive or other issues, stirring before drying is called for, sufficient stirring time and passes through the grain should be allowed to achieve the amount of mixing required. Stirring at the start of drying for up to 24h will have little effect on the drying time, so the mixing achieved in that time can be considered as taking place pre-drying. Exactly how long stirring needs to be done depends on the design of the stirring system, in particular auger diameter, whether solid flight or coil flight, auger pitch, rotational speed, number of augers operating, forward speed and route around the store. Details differ between stirring systems so no general rule can apply, but to mix the grain adequately, one supplier suggests six passes over the store of a four auger system are needed before the bed can be considered well mixed. Experience in this project suggests 24h stirring was not sufficient, but that another 24h (with the stirrer working only half the normal area) resulted in a well mixed bed. Grain sampling is advisable to ensure grain

is sufficiently well mixed to address the particular problem, especially if a requirement is that grain from the bottom of the bed be mixed into the bulk.

2. Thereafter, advice depends on whether the drier can be operated at higher temperature and what priority is given by the grower to the drying rate, fuel use and electricity use, because there are trade-offs to be decided.

3. If operation at elevated plenum temperature is an option and if short drying time, low electricity cost or both are priorities, then the drier can be run with air temperature raised to at least 30^{o}C. This option will increase fuel cost compared with static bed drying, particularly if the main air duct has not been insulated. Heat loss from an uninsulated duct is likely to be significant, and hence expensive. The higher the air temperature, the greater the heat loss will be. Any grain next to the duct will be warmed. When using higher air temperature for drying, higher rate of water loss from the bed will be achieved, which will lead to high humidity in the headspace above the grain bed. Unless this moist air is removed sufficiently fast, there may be condensation of vapour onto the structure which can drip onto the grain and cause locally severe re-wetting problems. Fans to clear the headspace may be essential.

4. If operation at higher temperatures is not possible, or if fuel costs are priority, then plenum air r.h. regulation to around 62% without stirring will give rapid drying (but see 5 below). Fuel efficiency will be better than in option 3. Once the average m.c. of the grain bed has reached the target of 14.5% (for example), drying can be stopped and stirring started. As the grain is stirred, differences in m.c. will be gradually removed and the upper layers not yet dried to the target will be mixed in, but the average m.c. should not change. Without stirring, drying would need to continue to bring the surface layers within the specification, which would add energy costs and possibly over-dry the bed as a whole.

5. If the initial m.c. of the grain is above 20%, and particularly if it is much higher than this, drying with a static bed, *i.e.* option 4, may take long enough that the grain is at risk of OA. In this circumstance, the Safe Storage Time Calculator for sampled grain conditions will show that the risk is too high, based on the grower’s expected or estimated drying time for the upper layers of the bed. Drying can be started without stirring, and once the m.c. of the bulk has fallen by at least 1% m.c., stirring will rapidly reduce the m.c. of the wettest grain, near the surface. After a long enough period of stirring to mix the bed, the grain should be sampled to find the highest m.c. and the temperature of the grain should be measured. The safe storage time of this grain should again be estimated using the s.s.t. calculator. If the s.s.t. is greater than the expected remaining drying time, stirring can be stopped and the static bed can be dried to the required average m.c. If drying is

slowed by poor weather, the check of m.c and s.s.t should be repeated. After drying, stirring will even out differences in the bed if this is needed.

3.6. Conclusions

Work to validate the model showed that:-

1. The behaviour of the simulation model was in line with expectations in that, compared with a static bed, stirring reduced the m.c. of the grain near the surface, thus lowering the rate of spoilage and the risk of OA. But the reduced m.c. at the surface also lowered the exhaust air r.h. as drying proceeded, which resulted in a reduced drying rate of the stirred bed.
2. Considering the validation work overall, agreement of the model with the data from the 25t wheat drying experiment at Fera in 2010 was good in the important respects, particularly drying time, approach to and level of final m.c. Validation against data from a stirred and a static bin at Fera in 2012 showed that the model predicted the overall drying behaviour of both bins well and, although stirring in the model was less vigorous than in practice, the accumulated effect was sufficient to mix the bed to a similar degree. The drying fronts in the model were steeper than measured but this did not affect drying time, which was well predicted. Because the wheat on the test farm site in 2012 needed little drying, data could not be had for drying using significantly higher air temperature. Testing of the model in these low moisture removal conditions did not raise any doubts about its performance, and indeed together with the data from the bin experiments, allowed the relationship between m.c. and air r.h. to be confirmed. Simulation of a published experiment in which an 86t bin of wheat was stirred and dried with air at a higher temperature gave results which agreed very well with the measured overall performance. Because the drying time was well predicted, the fuel and electricity use were also, as they are the product of running time and heater and fan power. Overall, the model proved to be sufficiently good over the range of m.c., air temperature and stirring rate encountered in the experiments. Because it is based on well-understood physics of drying, the model, it was concluded, could be used with confidence over a wider range than found in validation experiments.

Extensive use of the simulation model showed that:-

3. For comparison with a stirred bed, the best performance from a static bed drier was to run the fan continuously and to use quite a powerful heater set to regulate plenum r.h. to 62%.
4. Under this fan and heater use, stirring was very effective in reducing the progress towards risk of OA. This was because, at higher values of initial m.c., stirring avoided the persistence of wetter grain at a condition that favoured fungal growth. Where a static bed approach resulted in risk of OA, stirring the same bed allowed drying without risk of OA

from an initial m.c. of about 2% m.c. higher or for a grain bed depth 1m deeper than the limit for static bed drying.

5. Compared with static bed drying in identical conditions, stirring the grain bed continuously whilst drying made the drying less efficient and increased drying time and cost of fuel and electricity, but over-drying of the bed as a whole was reduced. Efficiency was reduced because the exhaust air was less saturated when stirring.
6. With 62% r.h. plenum air, performance of drying was improved compared with a static bed by stirring only when the target average m.c. had been reached. Using stirring in this way avoided the need to continue drying the static bed until the wetter, upper part of the bed had dried, thus overdrying the bed as a whole. This approach gave faster drying, lower fuel and electricity cost and less over-drying. Stirring while drying down to 18% m.c. and then only stirring again once the average m.c. was reached gave a compromise between avoidance of OA risk and drying efficiency, and was effective for grain not over 20% initial m.c.
7. Using fewer augers, and hence stirring any location less often, reduced drying time and improved energy efficiency. But at higher initial m.c., the beneficial effect of stirring on risk of OA was reduced.
8. Lower airflow when stirring extended drying time, reduced electricity cost but increased fuel cost and risk of OA. Higher airflow did the opposite. Total energy use was little affected.
9. Controlling plenum air temperature rather than r.h. and heating that air to 20^{o}C or more while stirring resulted in quicker drying and with much reduced risk of OA and little over-drying. If using this approach, a plenum temperature of 30^{o}C produced the best compromise between drying speed, energy use and tendency towards over-drying. Electrical energy use was greatly reduced at elevated air temperatures because of the shorter drying time, but fuel energy use was generally increased.
10. Drying rates achieved when drying with a static bed or continuous stirring were in line with the rate of 0.5 % m.c. per 24h, expected for a bulk drier using near-ambient air conditions. This rate was increased substantially by using stirring together with plenum air temperature raised to 30^{o}C and above.
11. User guidelines are presented, drawing on the simulation results in the report, that highlight which drying problems stirring is likely to help solve and which not, so as to guide investment decisions. Guidelines are also presented on how best to use a stirring system, if available, to meet the grower's priorities for drying, whether drying speed, fuel or electricity costs.

3.7. Acknowledgements

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APPENDIX A. PARAMETERS FOR DRIER, CROP, WEATHER AND ENERGY FOR SIMULATION RUNS

These are the conditions unless otherwise stated in the particular case.

Drier

Bed area ventilated by fan, m^2	90
Number of fans	1
Fan	Pellcroft Typhoon TC5, centrifugal
Airflow at 3m bed depth	approx. 0.05 m^3/(s.t at initial m.c.)
Bed depth, m	4, 3, 2

Crop	Wheat
Moisture content, % wet basis	
Initial	24, 22, 20, 18, 16
Vertical profile	uniform
Target	
Average	14.5
Wettest	15.0
Temperature, ^oC	20
Density, kg dry matter/m^3	672
Value, £/tonne at 14.5% w.b.	160

Weather

Historical records on hourly basis for Waddington, Lincs from 1951-1970

Starting date for drying 15 August each year

Energy

Electricity is 'Economy 7' rate, off-peak is from 12 midnight to 7a.m.

On-peak electricity price, p/kWh	15
Off-peak electricity price, p/kWh	5
Propane gas (liquid) price, p/l	40
Calorific value of liquid propane gas, MJ/l	26.8

Stirring system

Grain stirred every, h	6
Clearance between auger tip and floor, m	0.05
Power used by augers + gantry motors, kW	4.6
Power used by extraction fans, kW	1.2

(only used for runs at elevated plenum temperature)

APPENDIX B. TABLES 10 TO 30

Table 10. Static bed, 62% plenum air r.h. target, 15 Aug start, TC5 fan, Policy 18

Initial m.c., % w.b.	Bed depth, m	Successful years of 20	Time when average mc target met (watm), h	Time when both targets met (wbtm), h	Fan time wbtm, h	Heater time wbtm, h	Stirrer time wbtm, h	Av mc wbtm, %wb	Max spoilage index wbtm	Overdrying wbtm, kg/dried t	Total energy wbtm, MJ/dried t	Fuel cost wbtm, £/dried t	Overdrying cost wbtm, £/dried t	Total cost incl dm loss & overdrying wbtm, £/dried t	Fuel cost wbtm, £/(dried t % removed)	Elec cost wbtm, £/(dried t % removed)	Total cost incl dm loss & overdrying wbtm, £/(dried t % removed)
24	4	0	n/a														
	3	0	n/a														
	2	19	166	189	189	156	0	13.8	1.65	8.1	410	4.43	1.30	9.69	0.44	0.37	0.95
22	4	2	n/a														
	3	19	223	255	255	210	0	13.9	1.56	7.5	347	3.61	1.20	8.47	0.45	0.43	1.04
	2	20	140	165	165	135	0	13.8	0.98	7.8	353	3.80	1.25	8.42	0.47	0.40	1.03
20	4	20	262	307	307	249	0	13.8	1.13	8.0	289	2.90	1.29	7.45	0.47	0.52	1.21
	3	20	185	220	220	180	0	13.8	0.79	7.8	298	3.09	1.26	7.42	0.51	0.49	1.20
	2	20	118	143	143	118	0	13.9	0.47	7.2	306	3.30	1.15	7.29	0.55	0.46	1.20
18	4	20	210	262	262	212	0	13.8	0.44	7.8	247	2.48	1.25	6.45	0.60	0.65	1.55
	3	20	149	187	187	153	0	13.8	0.30	7.6	249	2.57	1.22	6.36	0.63	0.62	1.54
	2	20	96	122	122	101	0	14.0	0.18	6.3	260	2.81	1.01	6.21	0.71	0.59	1.54
16	4	20	145	210	210	170	0	13.9	0.13	7.1	196	1.96	1.14	5.25	0.96	1.04	2.52
	3	20	106	147	147	120	0	13.9	0.09	6.5	194	2.00	1.04	5.04	1.01	0.99	2.48
	2	20	66	91	91	74	0	14.0	0.05	5.3	188	2.01	0.84	4.64	1.06	0.92	2.40

Note:

Average target for the bed as a whole was 14.5% m.c.

wbtm = when both targets met, 14.5% average and 15.0% wettest part

Table 11. Bed stirred throughout, 62%, 15 Aug, TC5 fan, Policy 18

Initial m.c., % w.b.	Bed depth, m	Successful years of 20	Time when average mc target met (watm), h	Time when both targets met (wbtm), h	Fan time wbtm, h	Heater time wbtm, h	Stirrer time wbtm, h	Av mc wbtm, %wb	Max spoilage index wbtm	Overdrying wbtm, kg/dried t	Total energy wbtm, MJ/dried t	Fuel cost wbtm, £/dried t	Overdrying cost wbtm, £/dried t	Total cost incl dm loss & overdrying wbtm, £/dried t	Fuel cost wbtm, £/(dried t % removed)	Elec cost wbtm, £/(dried t % removed)	Total cost incl dm loss & overdrying wbtm, £/(dried t % removed)
24	4	6	n/a														
	3	20	427	427	427	356	427	14.5	1.49	0.14	624	6.16	0.02	13.5	0.65	0.75	1.42
	2	20	265	265	265	220	265	14.5	0.94	0.13	609	6.26	0.02	12.8	0.66	0.67	1.35
22	4	20	529	529	529	435	529	14.5	1.25	0.05	539	5.12	0.01	11.9	0.68	0.88	1.58
	3	20	373	373	373	310	373	14.5	0.89	0.12	541	5.33	0.02	11.6	0.71	0.82	1.55
	2	20	232	232	232	194	232	14.5	0.55	0.17	533	5.49	0.03	11.1	0.73	0.74	1.48
20	4	20	443	443	443	367	443	14.5	0.66	0.10	452	4.31	0.02	9.86	0.78	0.99	1.79
	3	20	314	314	314	260	314	14.5	0.46	0.08	448	4.40	0.01	9.60	0.80	0.93	1.74
	2	20	190	190	190	158	190	14.5	0.28	0.19	431	4.41	0.03	8.97	0.80	0.82	1.63
18	4	20	355	355	355	293	355	14.5	0.29	0.11	360	3.42	0.02	7.82	0.98	1.24	2.23
	3	20	241	241	241	200	241	14.5	0.20	0.13	345	3.39	0.02	7.36	0.97	1.12	2.10
	2	20	148	148	148	123	148	14.5	0.12	0.16	332	3.40	0.03	6.91	0.97	0.99	1.97
16	4	20	202	202	202	166	202	14.5	0.09	0.08	202	1.91	0.01	4.39	1.27	1.64	2.91
	3	20	142	142	142	118	142	14.5	0.07	0.11	201	1.97	0.02	4.28	1.30	1.52	2.84
	2	20	92	92	92	77	92	14.5	0.04	0.17	207	2.12	0.03	4.29	1.40	1.42	2.83

Note:

Average target for the bed as a whole was 14.5% m.c.

wbtm = when both targets met, 14.5% average and 15.0% wettest part

Table 12. Static bed, 62%, 15 Sep, TC5 fan, Policy 18

Initial m.c., % w.b.	Bed depth, m	Successful years of 20	Time when average mc target met (watm), h	Time when both targets met (wbtm), h	Fan time wbtm, h	Heater time wbtm, h	Stirrer time wbtm, h	Av mc wbtm, %wb	Max spoilage index wbtm	Overdrying wbtm, kg/dried t	Total energy wbtm, MJ/dried t	Fuel cost wbtm, £/dried t	Overdrying cost wbtm, £/dried t	Total cost incl dm loss & overdrying wbtm, £/dried t	Fuel cost wbtm, £/(dried t % removed)	Elec cost wbtm, £/(dried t % removed)	Total cost incl dm loss & overdrying wbtm, £/(dried t % removed)
24	4	0	n/a														
	3	0	n/a														
	2	20	179	200	200	175	0	14.0	1.52	5.5	458	5.05	0.88	10.1	0.51	0.40	1.01
22	4	11	n/a														
	3	20	238	269	269	233	0	14.0	1.45	6.1	382	4.05	0.98	8.87	0.51	0.46	1.11
	2	20	153	176	176	153	0	14.1	0.87	4.4	397	4.37	0.71	8.62	0.56	0.44	1.10
20	4	20	280	325	325	279	0	14.0	1.00	6.2	319	3.26	0.99	7.67	0.54	0.56	1.27
	3	20	201	233	233	203	0	14.1	0.69	5.0	330	3.50	0.81	7.54	0.59	0.54	1.27
	2	20	130	152	152	132	0	14.1	0.42	4.5	342	3.76	0.72	7.49	0.64	0.51	1.27
18	4	20	231	277	277	240	0	14.0	0.39	5.8	273	2.80	0.93	6.60	0.71	0.71	1.65
	3	20	165	199	199	173	0	14.1	0.26	4.9	279	2.94	0.78	6.44	0.75	0.69	1.65
	2	20	107	130	130	113	0	14.2	0.16	3.9	293	3.24	0.62	6.39	0.85	0.66	1.67
16	4	20	167	221	221	191	0	14.1	0.11	4.6	216	2.22	0.74	5.21	1.18	1.20	2.76
	3	20	119	154	154	133	0	14.2	0.08	3.9	213	2.25	0.63	4.96	1.23	1.14	2.71
	2	20	77	96	96	84	0	14.2	0.05	3.2	218	2.41	0.51	4.78	1.37	1.06	2.70

Note:

Average target for the bed as a whole was 14.5% m.c.

wbtm = when both targets met, 14.5% average and 15.0% wettest part

Table 13. Bed stirred throughout, 62%, 15 Sep, TC5 fan, Policy 18

Initial m.c., % w.b.	Bed depth, m	Successful years of 20	Time when average mc target met (watm), h	Time when both targets met (wbtm), h	Fan time wbtm, h	Heater time wbtm, h	Stirrer time wbtm, h	Av mc wbtm, %wb	Max spoilage index wbtm	Overdrying wbtm, kg/dried t	Total energy wbtm, MJ/dried t	Fuel cost wbtm, £/dried t	Overdrying cost wbtm, £/dried t	Total cost incl dm loss & overdrying wbtm, £/dried t	Fuel cost wbtm, £/(dried t % removed)	Elec cost wbtm, £/(dried t % removed)	Total cost incl dm loss & overdrying wbtm, £/(dried t % removed)
24	4	13	n/a														
	3	20	521	521	521	459	521	14.5	1.39	0.11	793	7.99	0.02	16.9	0.84	0.91	1.78
	2	20	297	297	297	262	297	14.5	0.88	0.17	722	7.59	0.03	14.9	0.80	0.75	1.57
22	4	20	666	666	666	589	666	14.5	1.16	0.09	719	7.05	0.01	15.5	0.94	1.10	2.06
	3	20	433	433	433	381	433	14.5	0.82	0.09	651	6.54	0.01	13.8	0.87	0.95	1.84
	2	20	257	257	257	228	257	14.5	0.52	0.19	623	6.56	0.03	12.8	0.87	0.82	1.70
20	4	20	558	558	558	491	558	14.5	0.61	0.05	592	5.77	0.01	12.7	1.05	1.25	2.31
	3	20	376	376	376	331	376	14.5	0.43	0.12	564	5.67	0.02	11.9	1.03	1.12	2.16
	2	20	221	221	221	195	221	14.5	0.27	0.20	528	5.55	0.03	10.8	1.01	0.95	1.97
18	4	20	413	413	413	363	413	14.5	0.28	0.06	434	4.22	0.01	9.33	1.20	1.45	2.66
	3	20	277	277	277	243	277	14.5	0.19	0.13	414	4.17	0.02	8.71	1.19	1.28	2.48
	2	20	179	179	179	156	179	14.5	0.12	0.11	420	4.38	0.02	8.63	1.25	1.20	2.46
16	4	20	239	239	239	208	239	14.5	0.09	0.11	248	2.40	0.02	5.34	1.59	1.93	3.54
	3	20	173	173	173	150	173	14.5	0.06	0.07	254	2.53	0.01	5.36	1.68	1.87	3.56
	2	20	112	112	112	99	112	14.5	0.04	0.16	266	2.78	0.03	5.43	1.84	1.73	3.59

Note:

Average target for the bed as a whole was 14.5% m.c.

wbtm = when both targets met, 14.5% average and 15.0% wettest part

Table 14. Bed only stirred once average mc target reached, 62%, 15 Aug, TC5 fan, Policy 18

Initial m.c., % w.b.	Bed depth, m	Successful years of 20	Time when average mc target met (watm), h	Time when both targets met (wbtm), h	Fan time wbtm, h	Heater time wbtm, h	Stirrer time wbtm, h	Av mc wbtm, %wb	Max spoilage index wbtm	Overdrying wbtm, kg/dried t	Total energy wbtm, MJ/dried t	Fuel cost wbtm, £/dried t	Overdrying cost wbtm, £/dried t	Total cost incl dm loss & overdrying wbtm, £/dried t	Fuel cost wbtm, £/(dried t % removed)	Elec cost wbtm, £/(dried t % removed)	Total cost incl dm loss & overdrying wbtm, £/(dried t % removed)
24	4	0	n/a														
	3	0	n/a														
	2	19	166	168	168	139	2	14.4	1.59	1.05	362	3.91	0.17	7.71	0.41	0.35	0.80
22	4	5	n/a														
	3	19	223	225	225	185	2	14.4	1.48	0.63	305	3.16	0.10	6.59	0.42	0.41	0.87
	2	20	140	142	142	118	2	14.4	0.94	0.86	306	3.31	0.14	6.39	0.44	0.37	0.84
20	4	20	262	265	265	214	2	14.5	1.03	0.47	248	2.49	0.08	5.42	0.45	0.49	0.98
	3	20	185	187	187	153	2	14.4	0.73	0.66	249	2.57	0.11	5.31	0.46	0.46	0.96
	2	20	118	120	120	100	2	14.4	0.44	0.85	258	2.78	0.14	5.33	0.50	0.42	0.96
18	4	20	210	212	212	173	3	14.5	0.39	0.55	199	2.00	0.09	4.29	0.56	0.61	1.21
	3	20	149	152	152	124	3	14.4	0.27	0.68	201	2.07	0.11	4.27	0.58	0.58	1.20
	2	20	96	98	98	81	2	14.4	0.16	0.61	206	2.21	0.10	4.23	0.62	0.54	1.19
16	4	20	145	148	148	121	3	14.5	0.10	0.35	137	1.38	0.06	2.94	0.90	0.98	1.92
	3	20	106	107	107	89	2	14.5	0.07	0.46	143	1.48	0.07	2.99	0.96	0.94	1.95
	2	20	66	68	68	56	1	14.5	0.04	0.55	143	1.54	0.09	2.94	1.00	0.85	1.90

Note:

Average target for the bed as a whole was 14.5% m.c.

wbtm = when both targets met, 14.5% average and 15.0% wettest part

Table 15. Bed stirred until max mc <18% then not stirred then stirred once average mc target reached, 62%, 15 Aug, TC5 fan, Policy 18

Initial m.c., % w.b.	Bed depth, m	Successful years of 20	Time when average mc target met (watm), h	Time when both targets met (wbtm), h	Fan time wbtm, h	Heater time wbtm, h	Stirrer time wbtm, h	Av mc wbtm, %wb	Max spoilage index wbtm	Overdrying wbtm, kg/dried t	Total energy wbtm, MJ/dried t	Fuel cost wbtm, £/dried t	Overdrying cost wbtm, £/dried t	Total cost incl dm loss & overdrying wbtm, £/dried t	Fuel cost wbtm, £/(dried t % removed)	Elec cost wbtm, £/(dried t % removed)	Total cost incl dm loss & overdrying wbtm, £/(dried t % removed)
24	4	1	n/a														
	3	20	340	342	342	282	213	14.4	1.55	0.62	483	4.84	0.10	10.5	0.51	0.56	1.10
	2	20	214	216	216	179	137	14.4	0.97	0.89	485	5.08	0.14	10.2	0.53	0.51	1.07
22	4	20	404	407	407	332	218	14.5	1.34	0.55	400	3.90	0.09	8.83	0.52	0.62	1.17
	3	20	286	288	288	236	157	14.4	0.94	0.70	399	4.00	0.11	8.63	0.53	0.58	1.14
	2	20	179	181	181	150	102	14.4	0.59	0.99	401	4.20	0.16	8.42	0.55	0.53	1.11
20	4	20	316	320	320	260	131	14.5	0.74	0.41	309	3.02	0.07	6.72	0.55	0.64	1.21
	3	20	223	225	225	186	96	14.4	0.52	0.60	311	3.15	0.10	6.63	0.57	0.60	1.19
	2	20	141	143	143	119	63	14.4	0.32	0.88	313	3.31	0.14	6.53	0.59	0.55	1.17
18	4	20	214	218	218	177	5	14.5	0.37	0.52	204	2.05	0.08	4.39	0.58	0.63	1.24
	3	20	151	153	153	125	3	14.4	0.26	0.64	203	2.09	0.10	4.30	0.59	0.59	1.21
	2	20	97	99	99	82	2	14.4	0.16	0.64	208	2.24	0.10	4.28	0.63	0.54	1.21
16	4	20	145	148	148	121	2	14.5	0.10	0.39	137	1.37	0.06	2.94	0.90	0.98	1.92
	3	20	106	107	107	89	2	14.5	0.07	0.46	143	1.48	0.07	2.99	0.96	0.94	1.95
	2	20	66	68	68	56	1	14.5	0.04	0.57	143	1.54	0.09	2.94	0.99	0.85	1.90

Note:

Average target for the bed as a whole was 14.5% m.c.

wbtm = when both targets met, 14.5% average and 15.0% wettest part

Table 16. Bed stirred throughout, half the number of augers for given bed area, 62%, 15 Aug, TC5 fan, Policy 18

Initial m.c., % w.b.	Bed depth, m	Successful years of 20	Time when average mc target met (watm), h	Time when both targets met (wbtm), h	Fan time wbtm, h	Heater time wbtm, h	Stirrer time wbtm, h	Av mc wbtm, %wb	Max spoilage index wbtm	Overdrying wbtm, kg/dried t	Total energy wbtm, MJ/dried t	Fuel cost wbtm, £/dried t	Overdrying cost wbtm, £/dried t	Total cost incl dm loss & overdrying wbtm, £/dried t	Fuel cost wbtm, £/(dried t % removed)	Elec cost wbtm, £/(dried t % removed)	Total cost incl dm loss & overdrying wbtm, £/(dried t % removed)
24	4	2	n/a														
	3	20	416	416	416	346	416	14.5	1.54	0.16	607	5.99	0.03	13.2	0.63	0.72	1.39
	2	20	255	255	255	213	255	14.5	0.98	0.24	591	6.09	0.04	12.4	0.64	0.64	1.30
22	4	20	516	516	516	425	516	14.5	1.29	0.09	525	4.99	0.01	11.6	0.66	0.85	1.54
	3	20	364	364	364	303	364	14.5	0.92	0.19	529	5.21	0.03	11.4	0.69	0.80	1.51
	2	20	219	220	220	183	220	14.5	0.58	0.29	504	5.19	0.05	10.6	0.69	0.70	1.40
20	4	20	438	438	438	363	438	14.5	0.67	0.13	446	4.26	0.02	9.75	0.77	0.98	1.77
	3	20	303	303	303	250	303	14.5	0.47	0.12	431	4.22	0.02	9.25	0.77	0.90	1.68
	2	20	182	182	182	152	182	14.5	0.29	0.17	412	4.22	0.03	8.60	0.77	0.78	1.56
18	4	20	345	345	345	284	345	14.5	0.30	0.13	348	3.31	0.02	7.58	0.94	1.21	2.16
	3	20	232	233	233	193	233	14.5	0.20	0.20	333	3.27	0.03	7.10	0.93	1.08	2.02
	2	20	142	142	142	119	142	14.5	0.13	0.26	320	3.28	0.04	6.69	0.93	0.95	1.90
16	4	20	194	194	194	159	194	14.5	0.09	0.10	193	1.82	0.02	4.21	1.21	1.57	2.79
	3	20	138	138	138	115	138	14.5	0.07	0.12	195	1.92	0.02	4.17	1.27	1.48	2.76
	2	20	87	87	87	72	87	14.5	0.04	0.11	195	1.99	0.02	4.03	1.32	1.34	2.67

Note:

Average target for the bed as a whole was 14.5% m.c.

wbtm = when both targets met, 14.5% average and 15.0% wettest part

Table 17. Bed stirred throughout, 62%, 15 Aug, TC4 fan, Policy 18

Initial m.c., % w.b.	Bed depth, m	Successful years of 20	Time when average mc target met (watm), h	Time when both targets met (wbtm), h	Fan time wbtm, h	Heater time wbtm, h	Stirrer time wbtm, h	Av mc wbtm, %wb	Max spoilage index wbtm	Overdrying wbtm, kg/dried t	Total energy wbtm, MJ/dried t	Fuel cost wbtm, £/dried t	Overdrying cost wbtm, £/dried t	Total cost incl dm loss & overdrying wbtm, £/dried t	Fuel cost wbtm, £/(dried t % removed)	Elec cost wbtm, £/(dried t % removed)	Total cost incl dm loss & overdrying wbtm, £/(dried t % removed)
24	4	0	n/a														
	3	18	526	526	526	445	526	14.5	1.75	0.11	624	6.55	0.02	13.1	0.69	0.65	1.37
	2	20	329	329	329	279	329	14.5	1.14	0.19	623	6.83	0.03	12.6	0.72	0.58	1.32
22	4	20	653	653	653	548	653	14.5	1.49	0.05	557	5.68	0.01	11.8	0.76	0.79	1.57
	3	20	448	448	448	383	448	14.5	1.07	0.07	539	5.69	0.01	11.1	0.76	0.70	1.48
	2	20	285	285	285	242	285	14.5	0.67	0.09	536	5.88	0.01	10.8	0.78	0.63	1.43
20	4	20	541	541	541	455	541	14.5	0.79	0.07	459	4.68	0.01	9.64	0.85	0.88	1.75
	3	20	381	381	381	325	381	14.5	0.56	0.10	454	4.79	0.02	9.32	0.87	0.81	1.69
	2	20	239	239	239	204	239	14.5	0.35	0.11	451	4.96	0.02	8.99	0.90	0.72	1.63
18	4	20	423	423	423	356	423	14.5	0.35	0.10	357	3.64	0.02	7.46	1.04	1.08	2.13
	3	20	297	297	297	252	297	14.5	0.25	0.10	348	3.65	0.02	7.14	1.04	0.99	2.04
	2	20	180	180	180	152	180	14.5	0.15	0.14	333	3.63	0.02	6.65	1.03	0.85	1.89
16	4	20	247	247	247	208	247	14.5	0.12	0.08	207	2.11	0.01	4.32	1.40	1.46	2.87
	3	20	173	173	173	145	173	14.5	0.08	0.10	199	2.08	0.02	4.09	1.38	1.32	2.71
	2	20	114	114	114	97	114	14.5	0.05	0.19	211	2.31	0.03	4.20	1.52	1.23	2.77

Note:

Average target for the bed as a whole was 14.5% m.c.

wbtm = when both targets met, 14.5% average and 15.0% wettest part

Table 18. Bed stirred throughout, 62%, 15 Aug, TC6 fan, Policy 18

Initial m.c., % w.b.	Bed depth, m	Successful years of 20	Time when average mc target met (watm), h	Time when both targets met (wbtm), h	Fan time wbtm, h	Heater time wbtm, h	Stirrer time wbtm, h	Av mc wbtm, %wb	Max spoilage index wbtm	Overdrying wbtm, kg/dried t	Total energy wbtm, MJ/dried t	Fuel cost wbtm, £/dried t	Overdrying cost wbtm, £/dried t	Total cost incl dm loss & overdrying wbtm, £/dried t	Fuel cost wbtm, £/(dried t % removed)	Elec cost wbtm, £/(dried t % removed)	Total cost incl dm loss & overdrying wbtm, £/(dried t % removed)
24	4	10	n/a														
	3	20	403	403	403	339	403	14.5	1.41	0.13	622	6.22	0.02	13.3	0.65	0.72	1.40
	2	20	240	240	240	200	240	14.5	0.85	0.17	615	6.44	0.03	12.7	0.68	0.64	1.34
22	4	20	517	517	517	426	517	14.5	1.23	0.07	538	5.13	0.01	11.8	0.68	0.87	1.57
	3	20	357	357	357	300	357	14.5	0.84	0.13	545	5.45	0.02	11.6	0.73	0.80	1.55
	2	20	204	204	204	170	204	14.5	0.50	0.26	516	5.39	0.04	10.7	0.72	0.69	1.42
20	4	20	439	439	439	364	439	14.5	0.64	0.15	457	4.38	0.02	9.95	0.79	0.99	1.81
	3	20	296	296	296	247	296	14.5	0.43	0.12	444	4.41	0.02	9.44	0.80	0.90	1.71
	2	20	171	171	171	141	171	14.5	0.25	0.16	423	4.40	0.03	8.75	0.80	0.78	1.59
18	4	20	349	349	349	288	349	14.5	0.29	0.09	360	3.44	0.01	7.81	0.98	1.24	2.23
	3	20	229	229	229	192	229	14.5	0.19	0.10	344	3.43	0.02	7.27	0.98	1.09	2.07
	2	20	134	134	134	112	134	14.5	0.11	0.20	333	3.48	0.03	6.84	0.99	0.95	1.95
16	4	20	198	198	198	163	198	14.5	0.09	0.10	201	1.91	0.02	4.37	1.26	1.62	2.90
	3	20	136	136	136	115	136	14.5	0.06	0.13	203	2.02	0.02	4.30	1.34	1.50	2.85
	2	20	82	82	82	68	82	14.5	0.04	0.13	200	2.08	0.02	4.12	1.37	1.34	2.73

Note:

Average target for the bed as a whole was 14.5% m.c.

wbtm = when both targets met, 14.5% average and 15.0% wettest part

Table 19. Bed stirred throughout, 15 Aug, TC5 fan, 20^{o}C in plenum, + extraction fan, Policy 24

Initial m.c., % w.b.	Bed depth, m	Successful years of 20	Time when average mc target met (watm), h	Time when both targets met (wbtm), h	Fan time wbtm, h	Heater time wbtm, h	Stirrer time wbtm, h	Av mc wbtm, %wb	Max spoilage index wbtm	Overdrying wbtm, kg/dried t	Total energy wbtm, MJ/dried t	Fuel cost wbtm, £/dried t	Overdrying cost wbtm, £/dried t	Total cost incl dm loss & overdrying wbtm, £/dried t	Fuel cost wbtm, £/(dried t % removed)	Elec cost wbtm, £/(dried t % removed)	Total cost incl dm loss & overdrying wbtm, £/(dried t % removed)
24	4	15	n/a														
	3	18	345	345	345	301	345	14.5	1.33	0.17	608	6.41	0.03	12.6	0.67	0.63	1.33
	2	20	235	235	235	206	235	14.5	0.90	0.20	651	7.09	0.03	13.2	0.75	0.62	1.38
22	4	20	439	439	439	378	439	14.5	1.18	0.11	528	5.34	0.02	11.2	0.71	0.76	1.49
	3	20	323	323	323	274	323	14.5	0.85	0.18	542	5.61	0.03	11.3	0.75	0.74	1.50
	2	20	191	191	191	166	191	14.5	0.53	0.29	525	5.71	0.05	10.6	0.76	0.63	1.41
20	4	20	369	369	369	314	369	14.5	0.62	0.09	434	4.36	0.01	9.18	0.79	0.86	1.67
	3	20	278	278	278	239	278	14.5	0.45	0.13	469	4.87	0.02	9.68	0.88	0.86	1.76
	2	20	155	155	155	135	155	14.5	0.27	0.34	420	4.55	0.05	8.46	0.82	0.69	1.53
18	4	20	291	291	291	249	291	14.5	0.28	0.12	342	3.44	0.02	7.19	0.98	1.06	2.05
	3	20	189	189	189	163	189	14.5	0.19	0.12	318	3.32	0.02	6.54	0.94	0.91	1.86
	2	20	119	120	120	105	120	14.5	0.12	0.29	320	3.46	0.05	6.45	0.98	0.83	1.83
16	4	20	152	152	152	132	152	14.5	0.09	0.12	180	1.82	0.02	3.76	1.20	1.27	2.49
	3	20	114	114	114	97	114	14.5	0.07	0.14	184	1.89	0.02	3.82	1.25	1.26	2.53
	2	20	82	82	82	70	82	14.5	0.05	0.22	208	2.21	0.04	4.23	1.45	1.31	2.78

Note:

Average target for the bed as a whole was 14.5% m.c.

wbtm = when both targets met, 14.5% average and 15.0% wettest part

Table 20. Bed stirred throughout, 15 Aug, TC5 fan, 30^{o}C in plenum, + extraction fan, Policy 24

Initial m.c., % w.b.	Bed depth, m	Successful years of 20	Time when average mc target met (watm), h	Time when both targets met (wbtm), h	Fan time wbtm, h	Heater time wbtm, h	Stirrer time wbtm, h	Av mc wbtm, %wb	Max spoilage index wbtm	Overdrying wbtm, kg/dried t	Total energy wbtm, MJ/dried t	Fuel cost wbtm, £/dried t	Overdrying cost wbtm, £/dried t	Total cost incl dm loss & overdrying wbtm, £/dried t	Fuel cost wbtm, £/(dried t % removed)	Elec cost wbtm, £/(dried t % removed)	Total cost incl dm loss & overdrying wbtm, £/(dried t % removed)
24	4	20	174	180	180	180	180	14.2	1.37	3.6	569	7.45	0.58	10.6	0.76	0.24	1.08
	3	20	121	128	128	128	128	14.1	0.99	5.1	580	7.67	0.81	10.9	0.77	0.22	1.09
	2	20	75	81	81	81	81	13.9	0.64	7.2	593	7.95	1.15	11.2	0.79	0.20	1.11
22	4	20	141	147	147	147	147	14.2	0.80	3.5	461	6.04	0.55	8.60	0.77	0.24	1.10
	3	20	98	104	104	104	104	14.1	0.58	5.2	471	6.23	0.84	8.93	0.78	0.22	1.12
	2	20	61	66	66	66	66	13.9	0.37	7.5	482	6.46	1.19	9.35	0.79	0.20	1.15
20	4	20	107	113	113	113	113	14.2	0.39	3.7	357	4.68	0.59	6.75	0.80	0.25	1.16
	3	20	74	80	80	80	80	14.1	0.28	5.1	364	4.82	0.81	7.02	0.81	0.23	1.18
	2	20	46	51	51	51	51	13.8	0.18	7.7	376	5.05	1.23	7.56	0.82	0.21	1.23
18	4	20	71	78	78	78	78	14.2	0.15	3.5	245	3.21	0.56	4.77	0.85	0.26	1.26
	3	20	49	56	56	56	56	14.0	0.11	5.5	256	3.40	0.88	5.20	0.86	0.23	1.31
	2	20	31	37	37	37	37	13.9	0.07	7.3	271	3.64	1.16	5.66	0.88	0.21	1.37
16	4	20	35	41	41	41	41	14.2	0.04	3.7	129	1.70	0.58	2.79	0.94	0.28	1.54
	3	20	24	31	31	31	31	14.1	0.03	5.2	141	1.88	0.84	3.20	0.97	0.25	1.64
	2	20	16	21	21	21	21	13.9	0.02	6.8	146	1.95	1.08	3.53	0.94	0.24	1.70

Note:

Average target for the bed as a whole was 14.5% m.c.

wbtm = when both targets met, 14.5% average and 15.0% wettest part

Table 21. Bed stirred throughout, 15 Aug, TC5 fan, 40°C in plenum, + extraction fan, Policy 24

Initial m.c., % w.b.	Bed depth, m	Successful years of 20	Time when average mc target met (watm), h	Time when both targets met (wbtm), h	Fan time wbtm, h	Heater time wbtm, h	Stirrer time wbtm, h	Av mc wbtm, %wb	Max spoilage index wbtm	Overdrying wbtm, kg/dried t	Total energy wbtm, MJ/dried t	Fuel cost wbtm, £/dried t	Overdrying cost wbtm, £/dried t	Total cost incl dm loss & overdrying wbtm, £/dried t	Fuel cost wbtm, £/(dried t % removed)	Elec cost wbtm, £/(dried t % removed)	Total cost incl dm loss & overdrying wbtm, £/(dried t % removed)
24	4	20	106	115	115	115	115	13.6	1.33	10.0	601	8.31	1.59	11.6	0.80	0.15	1.12
	3	20	74	82	82	82	82	13.4	0.97	12.7	623	8.66	2.04	12.2	0.82	0.13	1.16
	2	20	46	53	53	53	53	13.0	0.64	17.2	650	9.11	2.75	13.3	0.83	0.12	1.21
22	4	20	85	94	94	94	94	13.7	0.79	9.9	489	6.76	1.59	9.67	0.81	0.15	1.16
	3	20	59	68	68	68	68	13.4	0.58	13.1	507	7.05	2.09	10.4	0.82	0.14	1.20
	2	20	37	44	44	44	44	13.0	0.39	17.0	528	7.40	2.72	11.3	0.83	0.12	1.26
20	4	20	64	73	73	73	73	13.6	0.41	10.2	381	5.27	1.63	7.88	0.83	0.15	1.24
	3	20	44	53	53	53	53	13.4	0.30	13.0	399	5.56	2.08	8.55	0.84	0.13	1.29
	2	20	28	35	35	35	35	13.1	0.20	16.8	427	5.99	2.69	9.50	0.86	0.11	1.37
18	4	20	43	52	52	52	52	13.6	0.17	10.2	273	3.78	1.63	6.08	0.86	0.15	1.39
	3	20	30	39	39	39	39	13.4	0.12	12.9	289	4.03	2.06	6.72	0.88	0.14	1.46
	2	20	19	26	26	26	26	13.1	0.08	16.7	307	4.31	2.67	7.62	0.87	0.13	1.55
16	4	20	21	31	31	31	31	13.7	0.05	9.8	161	2.23	1.57	4.16	0.96	0.15	1.78
	3	20	15	23	23	23	23	13.5	0.04	12.1	170	2.37	1.93	4.70	0.94	0.16	1.85
	2	20	10	16	16	16	16	13.2	0.02	15.0	189	2.65	2.40	5.39	0.96	0.12	1.94

Note:

Average target for the bed as a whole was 14.5% m.c.

wbtm = when both targets met, 14.5% average and 15.0% wettest part

Table 22. Bed stirred throughout, 15 Aug, TC5 fan, 50°C in plenum, + extraction fan, Policy 24

Initial m.c., % w.b.	Bed depth, m	Successful years of 20	Time when average mc target met (watm), h	Time when both targets met (wbtm), h	Fan time wbtm, h	Heater time wbtm, h	Stirrer time wbtm, h	Av mc wbtm, %wb	Max spoilage index wbtm	Overdrying wbtm, kg/dried t	Total energy wbtm, MJ/dried t	Fuel cost wbtm, £/dried t	Overdrying cost wbtm, £/dried t	Total cost incl dm loss & overdrying wbtm, £/dried t	Fuel cost wbtm, £/(dried t % removed)	Elec cost wbtm, £/(dried t % removed)	Total cost incl dm loss & overdrying wbtm, £/(dried t % removed)
24	4	20	76	87	87	87	87	13.2	1.44	15.8	635	8.98	2.52	12.8	0.83	0.10	1.18
	3	20	54	63	63	63	63	12.8	1.04	20.2	665	9.44	3.23	13.9	0.84	0.10	1.24
	2	20	34	41	41	41	41	12.3	0.69	25.6	697	9.95	4.10	15.1	0.85	0.09	1.30
22	4	20	61	72	72	72	72	13.1	0.87	15.9	521	7.36	2.55	11.0	0.83	0.11	1.24
	3	20	43	52	52	52	52	12.8	0.65	20.2	549	7.79	3.24	12.0	0.84	0.10	1.30
	2	20	27	34	34	34	34	12.3	0.43	25.6	588	8.40	4.09	13.3	0.87	0.08	1.38
20	4	20	46	57	57	57	57	13.1	0.46	16.2	417	5.90	2.60	9.25	0.86	0.10	1.34
	3	20	32	42	42	42	42	12.8	0.35	20.1	434	6.16	3.21	10.1	0.85	0.10	1.40
	2	20	20	27	27	27	27	12.3	0.23	25.5	466	6.65	4.08	11.4	0.87	0.09	1.49
18	4	20	31	42	42	42	42	13.1	0.20	15.9	301	4.25	2.54	7.33	0.88	0.11	1.51
	3	20	22	31	31	31	31	12.8	0.15	19.7	327	4.64	3.15	8.28	0.89	0.09	1.60
	2	20	14	21	21	21	21	12.3	0.10	25.2	349	4.97	4.03	9.52	0.88	0.09	1.68
16	4	20	16	26	26	26	26	13.2	0.06	15.4	190	2.68	2.46	5.48	0.95	0.12	1.95
	3	20	11	20	20	20	20	12.9	0.05	18.3	203	2.89	2.93	6.15	0.94	0.11	2.00
	2	20	7	14	14	14	14	12.6	0.03	22.3	232	3.32	3.57	7.17	0.97	0.08	2.10

Note:

Average target for the bed as a whole was 14.5% m.c.

wbtm = when both targets met, 14.5% average and 15.0% wettest part

Table 23. Bed stirred throughout, 15 Aug, TC4 fan, 20^{o}C in plenum, + extraction fan, Policy 24

Initial m.c., % w.b.	Bed depth, m	Successful years of 20	Time when average mc target met (watm), h	Time when both targets met (wbtm), h	Fan time wbtm, h	Heater time wbtm, h	Stirrer time wbtm, h	Av mc wbtm, %wb	Max spoilage index wbtm	Overdrying wbtm, kg/dried t	Total energy wbtm, MJ/dried t	Fuel cost wbtm, £/dried t	Overdrying cost wbtm, £/dried t	Total cost incl dm loss & overdrying wbtm, £/dried t	Fuel cost wbtm, £/(dried t % removed)	Elec cost wbtm, £/(dried t % removed)	Total cost incl dm loss & overdrying wbtm, £/(dried t % removed)
24	4	3	n/a														
	3	18	411	411	411	370	411	14.5	1.60	0.12	607	6.77	0.02	12.2	0.71	0.54	1.28
	2	20	300	300	300	263	300	14.5	1.11	0.17	666	7.55	0.03	13.1	0.79	0.56	1.38
22	4	18	479	479	479	434	479	14.5	1.30	0.08	514	5.62	0.01	10.4	0.75	0.61	1.39
	3	20	379	379	379	331	379	14.5	1.01	0.11	529	5.80	0.02	10.7	0.77	0.63	1.42
	2	20	265	265	265	233	265	14.5	0.66	0.17	589	6.70	0.03	11.5	0.89	0.63	1.53
20	4	20	442	442	442	389	442	14.5	0.73	0.11	441	4.71	0.02	9.00	0.85	0.76	1.63
	3	20	325	325	325	284	325	14.5	0.53	0.13	449	4.91	0.02	9.01	0.89	0.73	1.64
	2	20	192	192	192	170	192	14.5	0.33	0.17	431	4.93	0.03	8.37	0.89	0.61	1.52
18	4	20	347	347	347	303	347	14.5	0.33	0.07	340	3.60	0.01	6.93	1.03	0.94	1.98
	3	20	262	262	262	230	262	14.5	0.25	0.10	362	3.97	0.02	7.22	1.13	0.92	2.06
	2	20	144	144	144	127	144	14.5	0.15	0.20	320	3.64	0.03	6.21	1.04	0.72	1.76
16	4	20	196	196	196	172	196	14.5	0.12	0.09	192	2.05	0.01	3.90	1.36	1.22	2.59
	3	20	133	133	133	118	133	14.5	0.08	0.12	184	2.01	0.02	3.66	1.33	1.08	2.43
	2	20	98	98	98	85	98	14.5	0.06	0.15	205	2.29	0.02	4.02	1.51	1.12	2.65

Note:

Average target for the bed as a whole was 14.5% m.c.

wbtm = when both targets met, 14.5% average and 15.0% wettest part

Table 24. Bed stirred throughout, 15 Aug, TC4 fan, 30°C in plenum, + extraction fan, Policy 24

Initial m.c., % w.b.	Bed depth, m	Successful years of 20	Time when average mc target met (watm), h	Time when both targets met (wbtm), h	Fan time wbtm, h	Heater time wbtm, h	Stirrer time wbtm, h	Av mc wbtm, %wb	Max spoilage index wbtm	Overdrying wbtm, kg/dried t	Total energy wbtm, MJ/dried t	Fuel cost wbtm, £/dried t	Overdrying cost wbtm, £/dried t	Total cost incl dm loss & overdrying wbtm, £/dried t	Fuel cost wbtm, £/(dried t % removed)	Elec cost wbtm, £/(dried t % removed)	Total cost incl dm loss & overdrying wbtm, £/(dried t % removed)
24	4	19	203	210	210	210	210	14.2	1.58	3.2	568	7.58	0.51	10.4	0.78	0.21	1.06
	3	20	146	152	152	152	152	14.1	1.17	4.5	575	7.74	0.72	10.5	0.78	0.19	1.07
	2	20	91	96	96	96	96	13.9	0.76	6.6	587	7.99	1.06	10.9	0.79	0.17	1.08
22	4	20	168	174	174	174	174	14.3	0.94	2.9	458	6.10	0.47	8.36	0.79	0.21	1.08
	3	20	117	124	124	124	124	14.1	0.68	4.5	468	6.30	0.72	8.66	0.80	0.20	1.10
	2	20	72	78	78	78	78	13.9	0.44	6.6	481	6.55	1.06	9.06	0.81	0.17	1.12
20	4	20	128	134	134	134	134	14.3	0.46	2.9	353	4.70	0.46	6.48	0.82	0.22	1.13
	3	20	89	96	96	96	96	14.1	0.34	4.3	358	4.82	0.69	6.72	0.82	0.20	1.14
	2	20	54	61	61	61	61	13.9	0.22	7.0	376	5.13	1.12	7.32	0.84	0.17	1.20
18	4	20	86	92	92	92	92	14.3	0.18	2.8	242	3.22	0.45	4.54	0.86	0.23	1.21
	3	20	59	66	66	66	66	14.1	0.13	4.8	250	3.37	0.76	4.95	0.86	0.21	1.27
	2	20	37	43	43	43	43	13.9	0.09	6.9	262	3.58	1.10	5.43	0.88	0.18	1.33
16	4	20	41	47	47	47	47	14.2	0.05	3.1	125	1.67	0.50	2.61	0.94	0.25	1.48
	3	20	29	36	36	36	36	14.1	0.04	4.5	137	1.86	0.73	2.99	0.98	0.22	1.58
	2	20	18	24	24	24	24	14.0	0.02	6.3	144	1.96	1.01	3.38	0.96	0.21	1.66

Note:

Average target for the bed as a whole was 14.5% m.c.

wbtm = when both targets met, 14.5% average and 15.0% wettest part

Table 25. Bed stirred throughout, 15 Aug, TC4 fan, 40°C in plenum, + extraction fan, Policy 24

Initial m.c., % w.b.	Bed depth, m	Successful years of 20	Time when average mc target met (watm), h	Time when both targets met (wbtm), h	Fan time wbtm, h	Heater time wbtm, h	Stirrer time wbtm, h	Av mc wbtm, %wb	Max spoilage index wbtm	Overdrying wbtm, kg/dried t	Total energy wbtm, MJ/dried t	Fuel cost wbtm, £/dried t	Overdrying cost wbtm, £/dried t	Total cost incl dm loss & overdrying wbtm, £/dried t	Fuel cost wbtm, £/(dried t % removed)	Elec cost wbtm, £/(dried t % removed)	Total cost incl dm loss & overdrying wbtm, £/(dried t % removed)
24	4	20	125	136	136	136	136	13.7	1.58	9.0	596	8.31	1.43	11.3	0.81	0.13	1.10
	3	20	89	98	98	98	98	13.5	1.14	11.5	611	8.57	1.84	11.8	0.82	0.12	1.13
	2	20	55	63	63	63	63	13.2	0.76	15.5	639	9.04	2.48	12.7	0.84	0.10	1.18
22	4	20	101	111	111	111	111	13.7	0.93	8.9	485	6.77	1.42	9.37	0.82	0.13	1.13
	3	20	71	80	80	80	80	13.5	0.69	11.6	502	7.05	1.86	9.98	0.83	0.12	1.17
	2	20	44	52	52	52	52	13.2	0.46	15.7	525	7.43	2.52	10.9	0.84	0.10	1.24
20	4	20	76	87	87	87	87	13.7	0.48	9.0	377	5.26	1.44	7.55	0.84	0.13	1.20
	3	20	53	63	63	63	63	13.5	0.35	11.7	392	5.50	1.87	8.17	0.85	0.12	1.26
	2	20	34	41	41	41	41	13.2	0.24	15.3	410	5.80	2.44	8.97	0.85	0.10	1.32
18	4	20	51	61	61	61	61	13.7	0.20	9.1	268	3.75	1.45	5.78	0.88	0.13	1.35
	3	20	36	45	45	45	45	13.5	0.15	11.6	278	3.91	1.86	6.34	0.87	0.12	1.41
	2	20	22	30	30	30	30	13.2	0.10	15.4	305	4.32	2.46	7.27	0.90	0.10	1.51
16	4	20	25	36	36	36	36	13.7	0.06	8.9	157	2.19	1.42	3.92	0.97	0.14	1.74
	3	20	18	27	27	27	27	13.6	0.04	11.0	166	2.34	1.77	4.43	0.96	0.13	1.81
	2	20	11	18	18	18	18	13.3	0.03	13.9	180	2.55	2.23	5.08	0.95	0.11	1.89

Note:

Average target for the bed as a whole was 14.5% m.c.

wbtm = when both targets met, 14.5% average and 15.0% wettest part

Table 26. Bed stirred throughout, 15 Aug, TC4 fan, 50°C in plenum, + extraction fan, Policy 24

Initial m.c., % w.b.	Bed depth, m	Successful years of 20	Time when average mc target met (watm), h	Time when both targets met (wbtm), h	Fan time wbtm, h	Heater time wbtm, h	Stirrer time wbtm, h	Av mc wbtm, %wb	Max spoilage index wbtm	Overdrying wbtm, kg/dried t	Total energy wbtm, MJ/dried t	Fuel cost wbtm, £/dried t	Overdrying cost wbtm, £/dried t	Total cost incl dm loss & overdrying wbtm, £/dried t	Fuel cost wbtm, £/(dried t % removed)	Elec cost wbtm, £/(dried t % removed)	Total cost incl dm loss & overdrying wbtm, £/(dried t % removed)
24	4	20	91	102	102	102	102	13.3	1.71	14.6	628	8.94	2.34	12.5	0.83	0.09	1.16
	3	20	64	74	74	74	74	13.0	1.23	18.0	648	9.26	2.89	13.3	0.84	0.09	1.20
	2	20	41	48	48	48	48	12.5	0.82	23.4	681	9.78	3.75	14.5	0.85	0.08	1.26
22	4	20	73	84	84	84	84	13.3	1.02	14.5	516	7.34	2.31	10.6	0.84	0.09	1.21
	3	20	51	61	61	61	61	13.0	0.76	18.1	538	7.69	2.90	11.4	0.85	0.08	1.26
	2	20	33	40	40	40	40	12.5	0.51	23.3	566	8.13	3.72	12.6	0.86	0.07	1.33
20	4	20	55	67	67	67	67	13.3	0.54	14.4	403	5.73	2.31	8.72	0.85	0.09	1.30
	3	20	39	49	49	49	49	12.9	0.40	18.1	423	6.04	2.90	9.60	0.86	0.09	1.36
	2	20	25	32	32	32	32	12.5	0.27	23.5	461	6.62	3.76	10.9	0.88	0.07	1.46
18	4	20	37	49	49	49	49	13.2	0.23	14.7	295	4.20	2.36	7.04	0.88	0.10	1.48
	3	20	26	36	36	36	36	13.0	0.18	18.1	317	4.54	2.90	7.87	0.90	0.08	1.56
	2	20	17	24	24	24	24	12.5	0.12	22.9	339	4.86	3.67	8.98	0.89	0.08	1.64
16	4	20	19	30	30	30	30	13.3	0.07	14.2	185	2.64	2.27	5.18	0.97	0.10	1.91
	3	20	14	23	23	23	23	13.0	0.06	17.0	197	2.82	2.72	5.83	0.95	0.10	1.97
	2	20	8	16	16	16	16	12.7	0.04	21.6	224	3.21	3.46	6.92	0.96	0.08	2.07

Note:

Average target for the bed as a whole was 14.5% m.c.

wbtm = when both targets met, 14.5% average and 15.0% wettest part

Table 27. 1 TC3 fan & no stirring for 24h then 2 TC3 fans and stirred, 15 Aug, 20^{o}C in plenum, 180m^2 bed + extraction fan, Policy 24

Initial m.c., % w.b.	Bed depth, m	Successful years of 20	Time when average mc target met (watm), h	Time when both targets met (wbtm), h	Fan time wbtm, h	Heater time wbtm, h	Stirrer time wbtm, h	Av mc wbtm, %wb	Max spoilage index wbtm	Overdrying wbtm, kg/dried t	Total energy wbtm, MJ/dried t	Fuel cost wbtm, £/dried t	Overdrying cost wbtm, £/dried t	Total cost incl dm loss & overdrying wbtm, £/dried t	Fuel cost wbtm, £/(dried t % removed)	Elec cost wbtm, £/(dried t % removed)	Total cost incl dm loss & overdrying wbtm, £/(dried t % removed)
24	4	0	n/a														
	3	5	n/a														
	2	18	316	317	317	286	293	14.5	1.40	0.44	573	7.06	0.07	10.7	0.74	0.35	1.13
22	4	17	580	580	580	528	556	14.5	1.67	0.08	494	5.87	0.01	9.50	0.78	0.45	1.27
	3	18	428	428	428	387	404	14.5	1.24	0.22	492	5.92	0.03	9.34	0.79	0.43	1.24
	2	20	309	310	310	272	286	14.5	0.91	0.39	527	6.42	0.06	9.85	0.85	0.43	1.31
20	4	20	504	504	504	451	480	14.5	0.93	0.13	405	4.75	0.02	7.78	0.86	0.53	1.41
	3	20	385	385	385	339	361	14.5	0.70	0.10	415	4.92	0.02	7.87	0.89	0.52	1.43
	2	20	266	267	267	236	243	14.5	0.48	0.42	452	5.52	0.07	8.39	1.00	0.50	1.52
18	4	20	407	407	407	357	383	14.5	0.42	0.08	311	3.61	0.01	5.97	1.03	0.66	1.70
	3	20	309	309	309	271	285	14.5	0.32	0.11	327	3.88	0.02	6.16	1.10	0.64	1.76
	2	20	180	181	181	160	157	14.5	0.20	0.38	303	3.72	0.06	5.58	1.05	0.51	1.58
16	4	20	269	269	269	237	245	14.5	0.16	0.07	200	2.32	0.01	3.83	1.54	0.99	2.54
	3	20	161	162	162	144	138	14.5	0.10	0.18	167	2.00	0.03	3.14	1.32	0.73	2.08
	2	20	113	114	114	101	90	14.5	0.07	0.41	177	2.16	0.07	3.28	1.42	0.69	2.15

Note:

Average target for the bed as a whole was 14.5% m.c.

wbtm = when both targets met, 14.5% average and 15.0% wettest part

Table 28. 1 TC3 fan & no stirring for 24h then 2 TC3 fans and stirred, 15 Aug, 30°C in plenum, 180m² bed + extraction fan, Policy 24

Initial m.c., % w.b.	Bed depth, m	Successful years of 20	Time when average mc target met (watm), h	Time when both targets met (wbtm), h	Fan time wbtm, h	Heater time wbtm, h	Stirrer time wbtm, h	Av mc wbtm, %wb	Max spoilage index wbtm	Overdrying wbtm, kg/dried t	Total energy wbtm, MJ/dried t	Fuel cost wbtm, £/dried t	Overdrying cost wbtm, £/dried t	Total cost incl dm loss & overdrying wbtm, £/dried t	Fuel cost wbtm, £/(dried t % removed)	Elec cost wbtm, £/(dried t % removed)	Total cost incl dm loss & overdrying wbtm, £/(dried t % removed)
24	4	3	n/a														
	3	19	179	193	193	193	169	13.9	1.64	7.0	571	7.91	1.11	10.7	0.78	0.14	1.06
	2	20	117	129	129	129	105	13.7	1.15	9.3	586	8.20	1.48	11.1	0.80	0.12	1.08
22	4	20	207	222	222	222	198	14.1	1.32	5.2	459	6.30	0.84	8.56	0.79	0.16	1.08
	3	20	149	163	163	163	139	13.9	0.99	6.6	465	6.44	1.06	8.78	0.80	0.14	1.09
	2	20	97	109	109	109	85	13.8	0.70	8.7	477	6.67	1.38	9.16	0.81	0.12	1.11
20	4	20	161	175	175	175	151	14.1	0.66	5.2	354	4.86	0.83	6.71	0.82	0.16	1.13
	3	20	116	130	130	130	106	13.9	0.50	6.8	364	5.04	1.08	7.05	0.83	0.14	1.16
	2	20	75	88	88	88	64	13.7	0.36	8.9	375	5.25	1.43	7.48	0.84	0.12	1.19
18	4	20	111	126	126	126	102	14.0	0.27	5.3	249	3.43	0.85	4.95	0.87	0.16	1.25
	3	20	81	95	95	95	71	13.9	0.20	6.8	256	3.55	1.09	5.25	0.87	0.15	1.29
	2	20	54	67	67	67	43	13.6	0.15	10.0	272	3.81	1.59	5.96	0.88	0.12	1.37
16	4	20	58	73	73	73	49	14.0	0.07	5.6	136	1.89	0.90	3.12	0.95	0.17	1.58
	3	20	44	58	58	58	34	13.9	0.06	6.6	143	1.99	1.06	3.35	0.96	0.14	1.62
	2	20	32	44	44	44	20	13.6	0.05	10.0	160	2.26	1.61	4.16	0.96	0.12	1.77

Note:

Average target for the bed as a whole was 14.5% m.c.

wbtm = when both targets met, 14.5% average and 15.0% wettest part

Table 29. 1 TC3 fan & no stirring for 24h then 2 TC3 fans and stirred, 15 Aug, 40^{o}C in plenum, , 180m^2 bed + extraction fan, Policy 24

Initial m.c., % w.b.	Bed depth, m	Successful years of 20	Time when average mc target met (watm), h	Time when both targets met (wbtm), h	Fan time wbtm, h	Heater time wbtm, h	Stirrer time wbtm, h	Av mc wbtm, %wb	Max spoilage index wbtm	Overdrying wbtm, kg/dried t	Total energy wbtm, MJ/dried t	Fuel cost wbtm, £/dried t	Overdrying cost wbtm, £/dried t	Total cost incl dm loss & overdrying wbtm, £/dried t	Fuel cost wbtm, £/(dried t % removed)	Elec cost wbtm, £/(dried t % removed)	Total cost incl dm loss & overdrying wbtm, £/(dried t % removed)
24	4	1	n/a														
	3	19	117	134	134	134	110	13.1	1.68	16.6	629	8.98	2.66	12.8	0.82	0.08	1.18
	2	20	80	94	94	94	70	12.6	1.19	22.3	654	9.39	3.57	14.0	0.82	0.08	1.23
22	4	20	130	150	150	150	126	13.3	1.37	13.7	499	7.09	2.19	10.3	0.82	0.09	1.18
	3	20	96	114	114	114	90	13.1	1.03	16.6	516	7.37	2.65	10.9	0.83	0.08	1.22
	2	20	66	80	80	80	56	12.6	0.75	21.7	545	7.83	3.47	12.1	0.84	0.07	1.29
20	4	20	101	121	121	121	97	13.3	0.71	13.7	393	5.59	2.19	8.48	0.84	0.09	1.27
	3	20	75	93	93	93	69	13.1	0.55	16.7	408	5.83	2.68	9.17	0.84	0.09	1.32
	2	20	53	67	67	67	43	12.6	0.40	22.1	437	6.29	3.54	10.4	0.85	0.07	1.41
18	4	20	71	91	91	91	67	13.3	0.30	13.7	286	4.07	2.20	6.74	0.87	0.10	1.44
	3	20	54	72	72	72	48	13.1	0.24	16.9	302	4.32	2.70	7.47	0.87	0.09	1.51
	2	20	40	53	53	53	29	12.6	0.18	21.8	330	4.75	3.49	8.63	0.89	0.07	1.61
16	4	20	41	60	60	60	36	13.3	0.10	13.6	179	2.56	2.17	4.99	0.96	0.09	1.87
	3	20	33	49	49	49	25	13.1	0.08	16.2	190	2.73	2.59	5.58	0.95	0.09	1.93
	2	20	25	39	39	39	15	12.7	0.06	20.8	219	3.16	3.33	6.72	0.97	0.07	2.05

Note:

Average target for the bed as a whole was 14.5% m.c.

wbtm = when both targets met, 14.5% average and 15.0% wettest part

Table 30. 1 TC3 fan & no stirring for 24h then 2 TC3 fans and stirred, 15 Aug, 50^{o}C in plenum, 180m^{2} bed + extraction fan, Policy 24

Initial m.c., % w.b.	Bed depth, m	Successful years of 20	Time when average mc target met (watm), h	Time when both targets met (wbtm), h	Fan time wbtm, h	Heater time wbtm, h	Stirrer time wbtm, h	Av mc wbtm, %wb	Max spoilage index wbtm	Overdrying wbtm, kg/dried t	Total energy wbtm, MJ/dried t	Fuel cost wbtm, £/dried t	Overdrying cost wbtm, £/dried t	Total cost incl dm loss & overdrying wbtm, £/dried t	Fuel cost wbtm, £/(dried t % removed)	Elec cost wbtm, £/(dried t % removed)	Total cost incl dm loss & overdrying wbtm, £/(dried t % removed)
24	4	0	n/a														
	3	18	108	125	125	125	101	12.8	1.70	19.3	642	9.20	3.09	13.4	0.83	0.08	1.20
	2	20	76	90	90	90	66	12.4	1.21	24.7	669	9.62	3.95	14.6	0.83	0.07	1.26
22	4	20	115	135	135	135	111	13.0	1.44	17.1	518	7.42	2.74	11.1	0.83	0.08	1.23
	3	20	89	106	106	106	82	12.9	1.06	19.1	529	7.60	3.05	11.5	0.83	0.08	1.26
	2	20	64	77	77	77	53	12.4	0.76	24.4	556	8.00	3.90	12.7	0.84	0.07	1.32
20	4	20	90	110	110	110	86	13.1	0.75	16.9	411	5.88	2.70	9.21	0.85	0.08	1.33
	3	20	70	88	88	88	64	12.8	0.57	19.6	425	6.10	3.13	9.84	0.85	0.08	1.37
	2	20	51	66	66	66	42	12.4	0.41	24.5	452	6.52	3.92	11.0	0.86	0.07	1.45
18	4	20	65	85	85	85	61	13.0	0.33	17.0	305	4.37	2.73	7.52	0.88	0.08	1.52
	3	20	51	69	69	69	45	12.8	0.25	19.8	318	4.57	3.17	8.17	0.88	0.08	1.57
	2	20	39	52	52	52	28	12.5	0.18	23.5	337	4.86	3.76	9.01	0.88	0.07	1.63
16	4	20	39	58	58	58	34	13.1	0.10	15.9	191	2.74	2.55	5.53	0.96	0.08	1.93
	3	20	32	49	49	49	25	12.9	0.08	18.7	202	2.91	2.99	6.16	0.94	0.08	1.99
	2	20	25	39	39	39	15	12.6	0.06	22.1	228	3.30	3.54	7.06	0.97	0.07	2.08

Note:

Average target for the bed as a whole was 14.5% m.c.

wbtm = when both targets met, 14.5% average and 15.0% wettest part