final report

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Bone Belt DEXA OCM Mass Balance Yield System – Stage 1

Final Report – Public Version

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Abstract

Waste stream monitoring at processing facilities provides a significant opportunity for yield recovery and increased boning room efficiency. This project explored the use of dual-energy x-ray absorptiometry (DEXA) technology for this application. After a number of methods were trialled, the system was able to be accurately calibrated by using carefully prepared, homogenised mixtures of beef fat and lean meat which were chemically tested for lean content. A solution was then presented to the customer which would be able to identify the presence of saleable primals as well as large pieces of lean meat attached to bone. After passing factory acceptance testing, the machine was sent to site where a larger sample set of bone belt could be scanned under different scenarios. This allowed a clearer picture of the machine's strengths and limitations to be obtained and algorithms to be further developed and refined.

Executive Summary

Waste stream monitoring is an application which presents a significant value proposition to the industry through yield recovery and potentially increased efficiency. Dual-energy x-ray absorptiometry (DEXA) is a technology widely used for composition analysis by observing the attenuation of x-rays at two different energy levels.

An existing single-energy x-ray inspection machine was upgraded to dual-energy by installing a sandwich-style dual-energy detector. The initial approach to the application was to quantify the amount of bone, fat and lean for the entire x-ray image, to quantify the amount of each tissue passing down the belt.

Another approach was then implemented which is currently used in the medical industry for human composition analysis. A number of scans were then taken of bone belt material. While the concept was implemented successfully, a number of issues presented with the accuracy obtained. A key issue is the presence of tissues such as bone marrow, tendons, ligaments and cartilage.

Factory acceptance testing was performed on the machine with a set of different bones obtained from a bone belt. These were scanned twice – raw and then with bits of meat placed over them to simulate recoverable lean meat. The results of these trials were then presented to the customer, with the machine’s strengths and limitations discussed. Acknowledging the limitation of being confined to areas of the image where no bone is present, they still felt that the machine presented value to the company by being able to identify large saleable primals. The identification of large pieces of red meat still attached to bone where possible would serve as a bonus. It was also suggested than a second sensing technology may augment well with the DEXA data to improve performance.

The machine was then sent to the customer’s site. It was installed close to the bone belt to enable easy access to product. A large number of scans were then conducted to further evaluate the system’s ability to identify lean meat. The data collected also provided an opportunity to refine the vision processing algorithms.

The trials were successful and further reinforced the system’s capability in identifying small chunks of lean meat on bone belt material if the amount of overlap is minimised. Thus, identification of primals would be possible along with significant chunks of recoverable lean on bone under some circumstances.

Moving forward, a mechanical intervention on the bone belt would be required upstream of the DEXA machine to control product presentation.

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1 Background

This project of developing and installing a DEXA Bone Belt monitoring system will enable processors to monitor their waste stream material. This will allow an opportunity to recover yield and measure boning room performance to improve efficiency over time.

Scott Automation and Robotics will base this project on an existing single energy x-ray carton inspection machine, to be supplied by Teys. The equipment will be refurbished and fitted with a dual energy x-ray (DEXA) detector. The overall system will be updated to calculate values, either volumetric or weight basis, for material passing through on the bone conveyor belt and flag material to be diverted from the bone belt for further trimming. The machine will then be re-installed in a Teys facility.

2 Project Objectives

At the conclusion of this project, Scott will have:

- Developed and demonstrated a system (within the Scott Melbourne factory) that utilises DEXA to measure the meat, fat and bone content of product passing along the bone belt, to identify product containing significant portions of lean which are to be flagged for removal from the bone belt for further trimming.

At the conclusion of this project it is expected that the machine will then be temporarily installed in a Teys facility, on the floor such that bone belt material can be manually fed into the machine for evaluation.

3 System Design and Manufacture

An existing x-ray inspection machine was provided by Teys for the project. This was a single-energy x-ray inspection machine (see Figure 1). This machine was to be upgraded to a Dual-Energy X-ray Absorptiometry (DEXA) machine and modified for the purpose of waste stream assessment. The benefit in utilising DEXA over single energy x-ray is that it offers the potential to differentiate between types of materials as well as measure them. In the case of this application, it is the characterisation of bone, fat and lean which is of interest.

DEXA scanning can be achieved a number of different ways. One way is to have two separate x-ray systems one after the other, operating at two different energies. The alternative is to use a detector which has been designed to detect two different energy levels. This is done by essentially 'sandwiching' a low energy detector on top of a high energy one. After initial evaluations, it was decided to retrofit the XR-3000 inspection machine with a Sens-tech DEXA detector.

Figure 1 - XR-3000 X-ray Inspection Machine - the platform for the beef bone belt DEXA system

4 Material decomposition and measurement

The key enabler to this project is accurate measurement of bone, soft tissue, fat and lean using DEXA hardware. A significant amount of work was invested in developing a methodology for achieving this and assessing the requirements of the hardware used.

DEXA can be used to differentiate materials in a sample based on differences in how they attenuate x-rays. There are two major processes involved in attenuating the x-rays - the photoelectric effect (PE) and the Compton effect (CE). These 2 processes behave differently. PE depends upon chemical composition and falls rapidly as x-ray energy increases. CE depends only upon density and is relatively constant with energy. The difference in their energy dependence allows the relative amounts of PE and CE for a given mixture to be calculated by measuring attenuation at two energies. The attenuation of any pure substance is also a sum of PE and CE components.

At a fundamental physics level, DEXA is able to differentiate only between two materials at a time. Two measurements can only calculate two simultaneous unknowns. There are methods for overcoming this in a practical sense however. Firstly, the issue can be broken down such that, for any given pixel:

- if bone exists, identify the amount of bone and 'soft tissue'; or
- if no bone exists, directly identify the amount of fat and lean.

From here, a number of methods are available to estimate the soft tissue composition. By reducing the problem into two-compartment models, DEXA is able to be utilised to generate measurements.

The hardware utilised has a significant effect on the ability of DEXA to be able to differentiate between materials. Ideally, the x-ray sources would be monochromatic – emitting only the energy levels of interest. However, this technology isn't yet commercially feasible. Industrial x-ray tubes emit a spectrum across a range of energies. Figure 2 illustrates the difference between the two. This creates an overlap in the illumination of the two energy levels which must be overcome.

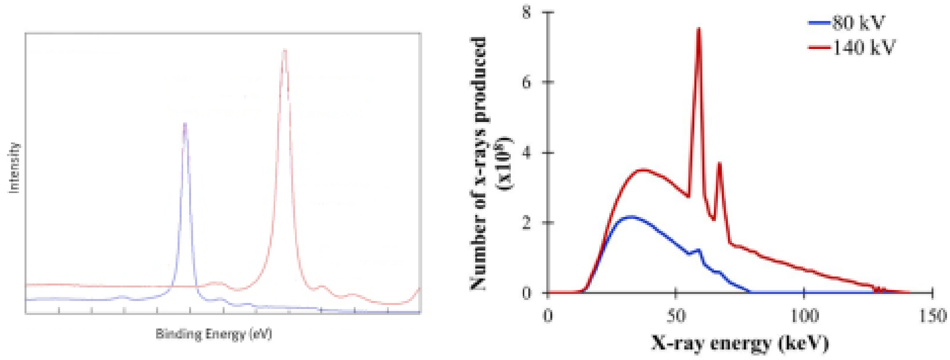

Figure 2 - monochromatic spectrum (left) vs polychromatic spectrum (right) (source: http://www.frontiersin.org/Journal/Abstract.aspx?s=322&name=experimental_pharmacology_and_drug_discovery&ART_DOI=10.3389/fphar.2015.00256)

One measure used to determine the amount of each material in a given part of an x-ray image is the R-value. The use of R-values assumes that there is a constant ratio (R) between the high and low energy signals for a given material regardless of thickness. A look-up table is essentially a map of how the low energy and high energy signals behave for a given material at different thicknesses.

Look-up tables (LUTs) are generated by acquiring data to model the response of the low energy and high energy detectors at a range of mixture compositions and thicknesses. As with any model, the more data points used, and the more accurate the input data, the better the model.

The development of a calibration methodology to accurately measure beef characteristics using DEXA is therefore a complex task, but one which has far-reaching positive implications throughout all DEXA projects once achieved.

In order to perform the calibration, a number of materials and construction methodologies were trialled as reference objects. Eventually a methodology was found which was able to produce good results.

Upon completion of this work, the system was calibrated to give measurements of bone, soft tissue, fat and lean. While it is known that a DEXA system cannot be calibrated for bone, fat and lean measurement simultaneously, a number of trials were conducted to attempt to model the relationship of the lean and fat signals in the presence of bone. It was hoped that a measurement of lean could then be estimated, with a certain level of accuracy, in the presence of bone.

5 Bone belt application development

It was initially hoped that a means would be found to measure or estimate the amount of bone, fat and lean for all the material passing through the system. As aforementioned however, a DEXA system cannot be calibrated to accurately quantify fat and lean in the presence of bone. A number of analyses were performed using test data to determine if lean and fat content could at least be *estimated* when bone was present. This was not found to be mathematically possible from the data that was obtained. The upshot of this is that, for the pixels in the DEXA image where bone is present, the amount of fat and lean can't also be calculated or estimated accurately.

6 Factory Acceptance Testing

Various bones were removed from the bone belt at a processor facility. They were first scanned by the system which flagged any excess lean meat. A piece of thin and thick steak comprising of lean and fat was then placed on the sample and rescanned. The system was set up to highlight areas where lean content was above a certain threshold and an alarm was also sounded.

The samples obtained from the bone belt included: a femur; a scapula; a hip; a point-end brisket; and a section of vertebrae.

The samples were first scanned 'raw' to show what the system would identify as lean meat. A small piece of 'thin' and 'thick' meat was then placed over the bone to simulate meat that should be flagged for further recovery.

6.1 Sample 1 – Femur

Figure 3 shows the femur sample. It can be seen that there is a fair bit of lean around the femur, particularly around the condyles. However there is also a fair bit of connective tissue around this area as well.

Figure 3 - Sample 1 - Femur

A scan was first performed of the raw product. The result of this is shown in Figure 4. It can be seen that the scan identifies the areas of lean but also detects this connective tissue as lean as well. This can particularly be seen around the epicondyles, condyles and at the joint between the femur and the small section of tibia still attached (right-hand side of x-ray image in Figure 4, circled in blue).

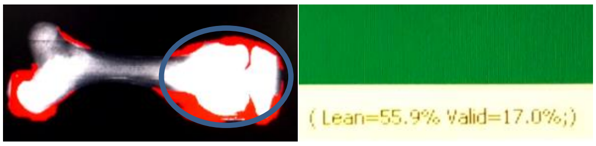

Figure 4 - Scan 1a – Femur

A thick and a thin steak were then placed on the sample (orange and green rectangles in Figure 5, respectively). Each steak had a strip of fat with them.

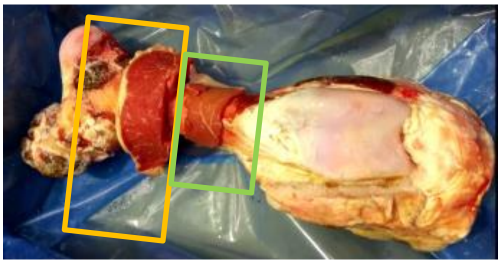

Figure 5 - Sample 1b - Femur with additional meat

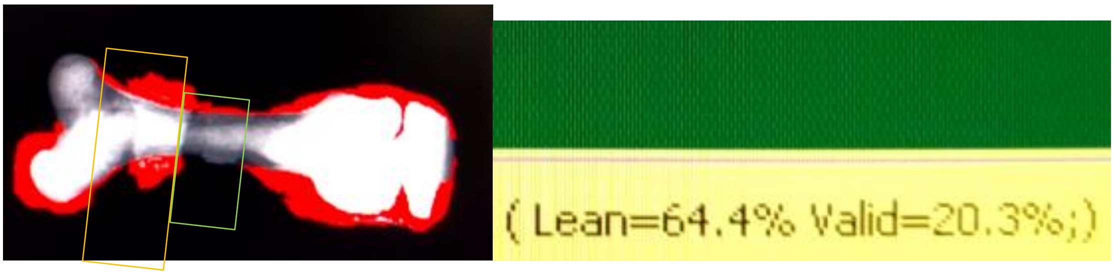

Figure 6 - Scan 1b - Femur with additional meat

6.2 Sample 2 – Scapula

It can be seen that there is very little lean meat on this sample in the non-bone regions (Figure 7). The scan still identified 10.9% valid pixels however (Figure 8). For this scan it can be seen that the system did detect a few sizeable chunks of lean meat.

Figure 8 - Sample 2 – Scapula

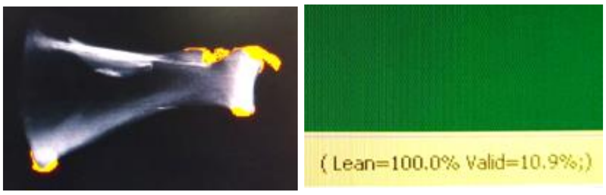

Figure 7 - Scan 2a - Scapula

Figure 9 - Close-up of areas of detected lean for scapula

The scapula was then scanned with a thick and thin piece of steak placed on it (orange and green rectangles in Figure 10, respectively). Chunks of lean in this situation would be difficult to identify.

Figure 10 – Sample 2b - Scapula with additional meat

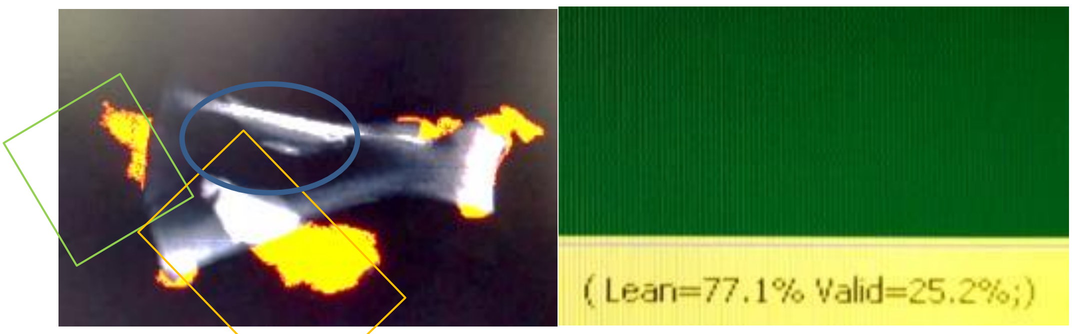

Figure 11 - Scan 2b – Scapula with additional meat

6.3 Sample 3 – Hip

The hip sample is shown in Figure 12. It can be seen that there was a fair amount of lean meat on this sample which was detected at the edges of the x-ray image (Figure 13).

Figure 12 - Sample 3 – Hip

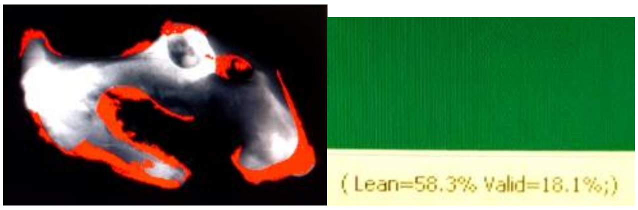

Figure 13 - Scan 3a – Hip

The hip was then scanned with a piece of thin and thick steak placed on top (green and orange boxes, respectively, in Figure 14 and Figure 15).

Figure 14 - Sample 3b - Hip with additional meat

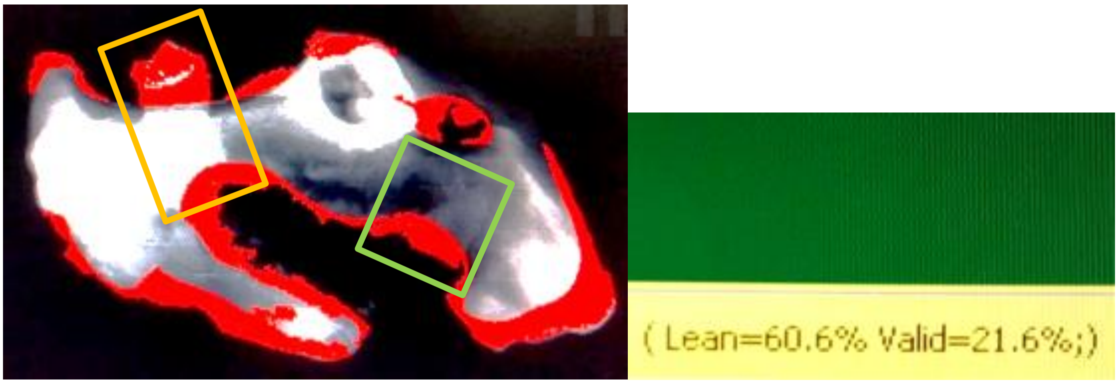

Figure 15 - Scan 3b - Hip with additional meat

6.4 Sample 4 – Point-end Brisket

The sample of brisket (Figure 16) had a significant amount of red meat, particularly between the lower ribs. The x-ray image (Figure 17) detected all of this meat quite successfully where no bone is present. Where there is bone present however (e.g. the ribs), it is very difficult to discern any 'chunks' of soft tissue, let alone lean meat.

Figure 16 - Sample 4 – Brisket

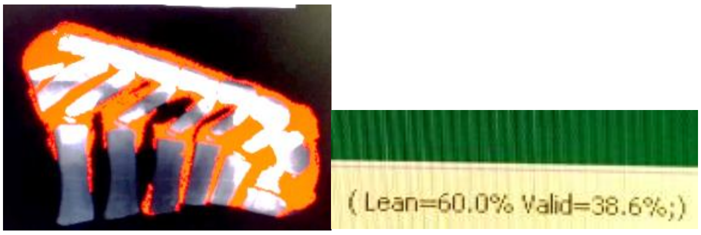

Figure 17 - Scan 2a - Brisket

The brisket was again scanned with a thin and thick steak placed on top of it (green and orange box, respectively, in Figure 18 and Figure 19).

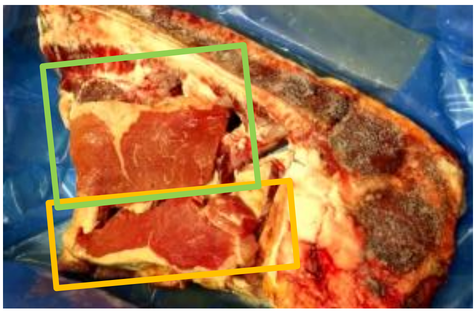

Figure 18 - Sample 4b - Brisket with additional meat

Figure 19 - Scan 4b - Brisket with additional meat

6.5 Sample 5 – Vertebrae

The final sample was a piece of vertebrae (Figure 20). This sample had a significant amount of meat on it.

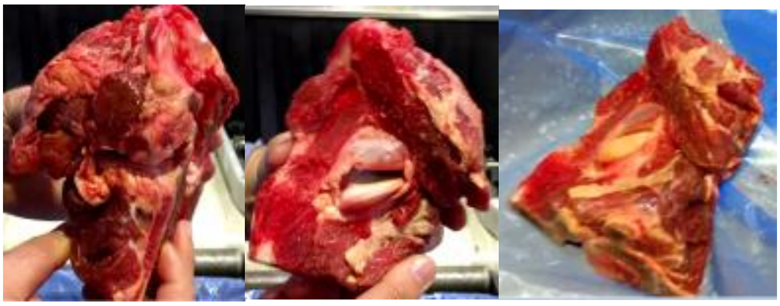

Figure 20 - Sample 5 - Vertebrae

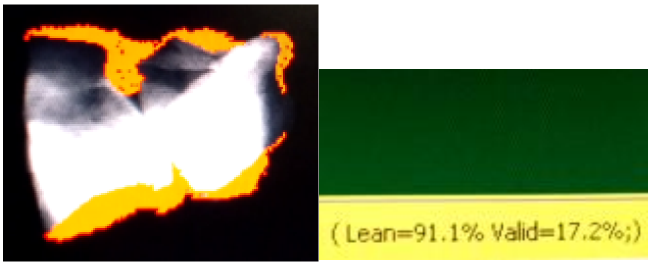

Figure 21 - Scan 5a – Vertebrae

As this sample already had a significant amount of lean meat, it was re-scanned in a different orientation (Figure 22). It can be seen that the result obtained was very similar (19.9% valid area, 91.1% lean) which demonstrates a level of repeatability from the system (Figure 23).

Figure 22 - Sample 5b - Vertebrae in different orientation

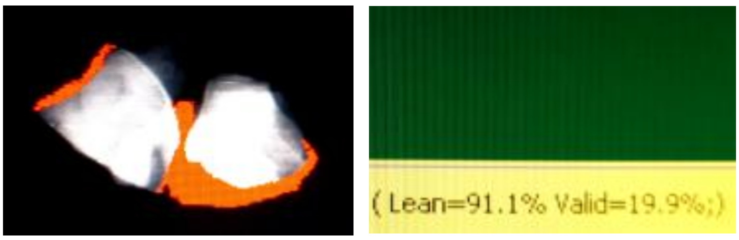

Figure 23 - Scan 5b - Vertebrae in different orientation

6.6 Conclusions

DEXA technology is not able to quantify the amount of fat and lean in a given pixel if there is also bone present. An attempt to create a robust model to estimate this behaviour was also unsuccessful. A method was then examined whereby an estimate of lean content for the ‘soft tissue’ identified was made using surrounding non-bone-containing pixels. Such an approach has been utilised in the medical industry. For this application however, the accuracy of this approach was compromised by the fact that bone marrow is currently detected as soft tissue, as well as fat and lean.

6.7 Client Review

Following the completion of FAT, a review meeting was held with the client to discuss the results achieved. The successes as well as the limitations of the machine’s performance were outlined. It was deemed that a system capable of identifying primals which should not be on the waste belt in and of itself would still be a valuable piece of equipment to the processor’s facilities. An ability to attempt to identify and redirect product possessing large chunks of recoverable lean meat would be seen as a secondary advantage, acknowledging the limitation of assessing this when bone is present. In order to maximise the performance of the machine, the waste stream material would have to be mechanically singulated to minimise the amount of overlap between product.

A site trial of the machine was then organised to assess the machine’s ability to perform these tasks and to capture enough data to enable algorithms to be developed.

7 Site Trials

7.1 Introduction

The Bone Belt DEXA machine was transported to a processor. The system was set up near the bone belt to enable easy access to a large variety of test samples (Figure 24). A number of scans were performed to assess the system's performance in identifying saleable material amongst bone belt material. A number of trials were designed in order to assess the system's performance in a number of key areas. Performing these trials would enable a clearer picture of the system's performance to be presented and would enable the development of optimised algorithms.

Figure 24 - Bone Belt DEXA machine installed at the customer's site

7.2 Methodology

In order to test the validity of the system as a whole, a range of differenct scenarios were tested at site. This was to put the system under the stress of a working environment. The scenarios and samples used are shown in the tables below.

Table 1 - Overview of Trialling Scenarios

Scenario number	Brief Description
1	Scans with bone only, to calibrate algorithm to eliminate false positives.
2	Scans with bone and fat to determine the effect of fat in the detection of lean meat. Particularly with bone marrow and cartilage.
3	Scans of the ideal single layered bone, meat and fat to determine detection reliability.
4	Scans where meat is concealed under bone
5	Scans where the meat is on top of bone
6	Scans with bone that contains meat which we would want to be recovered

Table 2 - Overview of Trialling Samples

Sample Number	Description
1	Lean steak. It should be easily detectable.
2	Lean steak, but smaller than sample 1.
3	Fatty piece of steak.
4	Rib blade with little meat attached.
5	Cube roll plate which is smaller than sample 4 and has minimal lean meat on it.
6	Sub Scapular which is very lean but has an interesting colour.
7	Dirty Neck Bone.
8	Dirty Naval-end Brisket.
9	Dirty Scapular.
10	Dirty Point-end Brisket.
11	Dirty Chuck.

7.3 Results

For scenarios 1 and 2, the data set is made up of 49 scans of which contain multiple bones in order to get a good range of data to ensure the algorithm isn't too sensitive to pick up meat on these bones. There are 14 different samples used to populate scenarios 3, 4 and 5, each of which is scanned with various levels of spread of waste material. A total of 66 scans were taken to get a reasonable idea of how the system will perform with a significant variety of meat. The dirty bone data, scenario 6, is made up of five samples because these were difficult to acquire on site. These five samples were scanned with different levels of spread and were also scanned once they had been trimmed correctly to prove the detection occurred due to the non-trimmed meat left on the bone. A total of 30 scans were taken for this scenario.

8 Conclusions

Waste stream monitoring is an application which presents a significant value proposition to the industry. Dual-energy x-ray absorptiometry (DEXA) is a technology widely used for composition analysis by observing the attenuation of x-rays at two different energy levels. DEXA technology is currently used in the red meat industry for the purpose of quantifying bone, fat and lean composition. This project aimed to investigate the ability to apply DEXA technology for the purposes of waste stream monitoring. Doing this would allow yield to be recovered and provide a metric for boning room performance to help drive increases in efficiency.

An existing single-energy x-ray inspection machine was upgraded dual-energy by replacing the original detector with a sandwich-style DEXA detector. Such a detector works by essentially having two detectors on top of each other – a low energy and a high energy – to get the two different responses. The software was modified heavily to communicate with the detector and take advantage of its finer data resolution.

The system was then calibrated to measure quantities of bone, soft tissue, fat and lean. This involves scanning either the materials themselves, or a proxy materials which demonstrates similar x-ray attenuation properties, at multiple thicknesses and combinations. This allows a multi-dimensional map to be created to translate the system's response to the amount of a given material. After trialling a number of concepts, a successful calibration was able to be obtained by using a number of carefully prepared samples of fat and lean beef at multiple compositions and multiple thicknesses. These samples were chemically tested for their composition.

The initial approach involved examining each pixel in the DEXA image to identify the amount of bone, fat and lean present. This would allow the system to identify saleable primals which shouldn't be on the waste belt. It would also enable the system to identify waste material with significant amounts of lean meat attached to be redirected off the line for further trimming, further improving yield. A cumulative measure of bone, fat and lean over the course of each shift may also provide an indication of boning room efficiency.

There are two major processes involved in attenuating x-rays – the Compton effect and the photoelectric effect. For bone, fat and lean, the relative contribution of each of these effects can thus be used to determine how much of a material is present in a given pixel. As there are only two knowns in this equation however, only two materials can be solved for at a time. That is, if there is only fat and lean present in a given pixel, the amounts of fat and lean can be determined.

Bone belt material was acquired and a number of scans were taken to test this algorithm. The first issue that presented was the fact that there are other forms of soft tissue present in a carcase other than fat, lean and bone.

Factory acceptance testing was then performed with the machine whereby a number of bone belt samples were scanned through the machine. These samples were also scanned with bits of meat placed over the top of them to simulate recoverable chunks of lean. The performance of the system from these trials was then presented to the client, with the machine's strengths and limitations discussed. The processor informed that, even if the machine is not able to accurately measure the waste belt material, they would still find significant value in a machine that could detect saleable primals. Identifying significant chunks of recoverable meat on bones where possible would be seen as a bonus.

A site trial of the machine was then organised whereby the machine would be set up adjacent to the bone belt line and a large number of scans taken. This would help gather data for further refinement of algorithms and provide more information about the system's performance under different scenarios.

During the site trials a number of scenarios were tested. Firstly, genuine waste material was scanned in order to calibrate the system to minimise the false positive rate of detection. A number of different meat samples were then obtained, varying in size, shape, composition and colour. These samples were scanned amongst bone belt material in different presentations. This included the samples being completely separated from the bone material and with varying levels of overlap. A number of 'dirty bones' were also scanned – bone belt material with recoverable lean meat still attached to it.

The results of the site trials were positive in demonstrating the ability of the system to identify small chunks of meat when there is little or no overlap with bone. In the case of large primals then, a significant amount of overlap can be tolerated. The system is thus capable of operating as a monitor for waste belt material as long as the product flow is controlled to present a single layer of material through the system to minimise overlap. This could be achieved through mechanical interventions.

9 Moving Forward

The system has been shown to be capable of identifying small chunks of lean meat on bone belt material if the amount of overlap is minimised. Thus, identification of primals would be possible along with significant chunks of recoverable lean on bone under some circumstances.

In moving forward, a mechanical intervention would have be designed and implemented to control the presentation of the waste material such that a single-layer was presented through the system, with minimal overlap. This would be key to the machine's success.

The machine would have to be modified to enable adequate x-ray shielding. Currently, lead-lined curtains are used at the infeed and outfeed of the machine. Such an arrangement wouldn't be appropriate for continuously conveyed waste material. The machine will therefore need to be modified to replace the curtains with an appropriate labyrinth.

The software on the x-ray machine would have to be updated to process continuous product flow rather than discrete scans. The vision processing algorithms would have to be integrated with the x-ray data capture as well.

Following these tasks, the system would be ready for installation and commissioning on-site. This would involve tuning the system's performance as per the client's preference for sensitivity. If required by the processor, integration with their existing control systems framework and/or some form of reporting could also be implemented.