“Hybrid” calibrations of a Dual Energy X-ray Scanner for material testing

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Abstract. Conventional x-ray tubes produce a fan-shaped x-ray beam covering a large spectrum of energies, which is why the fundamental law of x-ray attenuation is not readily applicable. As the mathematical formulation of the problem would be too cumbersome, calibrations using well-defined objects are carried out, which in turn allow the use of multi-energy x-rays for measurements. Occasionally, such calibrations may not lead to the desired results. This could be for instance due to an insensitivity of x-rays towards low atomic number elements. Here we present such a case on hand the example of raw natural fibre. The DEXA parameters correlated with the fibre parameter wool base, but show distinct correlation for geographical regions of the origin of the wool. A calibration that is valid independently of geographical origin can be achieved by including independently measured parameters of the calibration body. We demonstrate a successful calibration that uses dual energy x-ray scanning technology as well as a size parameter of the fibre in the regression equation.

1. Introduction
X-rays have been in use for about 100 years, with a multitude of applications. Traditional functions of x-rays focused on making interior aspects of objects visible; mainly for diagnostic reasons. Medical therapeutic uses followed, such as for cancer therapy [1]. Methods were developed to analyze material properties by using the fundamental law of attenuation and by the measurements of its coefficients [2]. Dual energy systems widened the potential use of x-rays, avoiding the need for precise knowledge of the object thickness. Applications of x-rays are still increasingly popular in industry, their uses being far from exploited [3, 4, 5]. This is partially caused by the increasing need for consistently high quality products in a strongly discerning market, and by the advances made in the x-ray scanning and detector technology; in particular with respect to stability and precision.

X-ray technology can be conveniently employed in public settings, as it is relatively safe to operate and, by using smart software, has a low operational impact. Therefore heavily labour based industries, such as the primary product sector, can profit from such equipment. Natural fibres are in decreasing demand, while on the other hand quality requirements are increasing with tight margins. In particular the wool industry has lost its market share to a competitive fibre and textile industry, which provides many advantages to the consumer. Traditional wool testing is highly labour intensive and hence costly, destructive, and based on sampling techniques, where less than 1% of a clip is tested and assumed to be representative for the entire clip. To remain economical, the natural fibre industry is therefore forced to develop novel, non-invasive methods that can measure the entire clip, and that significantly reduce the man-hours involved in such measurements.
2. Theoretical background

The calibrated scanner is an industry grade dual energy capable x-ray scanner clad in stainless steel, fully waterproof against hose-down, and designed to be installed in the food industry. The scanner is shown in Figure 1. The x-rays are created under 140 keV, where the mean energy of the created x-ray spectrum lies at about 80 keV. Raw 16 bit gray scale digital images are created internally for analysis. A conveyor belt transports the objects through the x-ray beam in the interior of the scanner.

![Figure 1. Calibrated DEXA scanner as used in food industry.](image)

The dual energy capability does result from the use of special detectors rather than two alternating x-ray sources. The two detector elements, shown in Figure 2, are placed directly in line behind each other, with a low energy filter element located in between them. This set-up has the advantage that no time or resolution lag exists between the two energy measurements, minimizing the error due to object variations and/or x-ray intensity fluctuations.

![Figure 2. Dual energy capable detector. LED – low energy detector, HED – high energy detector.](image)

The fundamental law of attenuation for a pencil shaped, monoenergetic beam, can be described for a binary mixture as

\[
I_L = I_{L0} \exp\left[-(\mu_{dL} m_x + \mu_{dL} m_y)\right] \\
I_H = I_{H0} \exp\left[-(\mu_{dH} m_x + \mu_{dH} m_y)\right]
\]

where \(I\) is the x-ray intensity measured at the detector, \(\mu\) is the mass attenuation coefficient [m/kg], \(m\) is the mass per unit area [kg/m\(^2\)]. The indices \(L\) and \(H\) stand for the low and high energy beam, respectively, the subscript 0 refers to the non-attenuated beam, and \(x\) and \(y\) indicate the materials of the given binary mixture. Under the assumption that the high energy mass attenuation coefficients for both components are the same, Equations 1a and b can be suitably converted to the mass partition expressed as the fractional composition according to:
\[
\omega = \frac{m_i}{m_i + m_y} \equiv \frac{\mu_H}{\mu_{sl} - \mu_{yl}} LR - \frac{\mu_{yl}}{\mu_{sl} - \mu_{yl}}.
\]

The entity LR is the so-called log-ratio and is calculated from the detector measurements of the high and low energy beams:

\[
LR = \frac{\ln \frac{I_0}{I_L}}{\ln \frac{I_0}{I_H}}.
\]

In Equation 2 the knowledge of the individual attenuation coefficients is not necessary, if they are assumed constant. Then the expressions before LR and the second term on the right hand side form the constants A and B, as in

\[
\omega = A \cdot LR + B.
\]

The constants will be determined through calibrations. Occasionally results improve if further factors are added, owing to beam hardening and scattering effects inside the object and scanner tunnel.

3. Natural fibre particulars and calibration

Equations 2 – 4 are valid for binary mixtures. Each component of the binary mixture may contain more than a single element, but is distinguishable from the other compound by a distinct effective atomic number (EAN). Methods for the calculation of the EAN are given in [6]. DEXA methods are therefore applicable to the calculation of the fat content in meat [7, 8], as the difference in EAN for lean meat and fat is large enough to be clearly distinguishable.

Natural fibres, such as wool, contain a whole range of components. Besides the wool these are grease, vegetable matter, and a sweaty secretion called suint. Moreover, the distinctiveness of wool can fade when the fibre is kept in its natural condition, i.e., as greasy wool from the animals back. That means that the wool can contain anything in addition to the wool components, with which the animal came in contact with. Therefore the assumption of the wool as binary mixture, i.e. wool and non-wool, is a very rough differentiation. In practical applications this distinction is made though, where the wool content is described in the term wool base (WB), which is the mass percentage of wool in greasy wool:

\[
WB = 100 - \text{nonwool}.
\]

The term “non-wool” does include water, and as wool is hygroscopic, the WB can change with changing environmental humidity. One wool parameter appears to have significant influence on the amount of non-wool, which is the fibre diameter. Statistically it will be called the mean fiber diameter, MFD. As shown in Figure 3, sheep breeds have distinct MFD, even though the sizes can be overlapping. For smaller MFD relatively more impurities can adhere to the fiber, because the ratio of circumference to diameter is larger than for thicker MFD. Presumably also more water can be taken up by the fibre. The fibre diameter became an important parameter for the calibration of the scanner.
It was known from earlier research that calibrations improve, when extra DEXA parameters were added to Equation 4 \[9\]. This is a consequence of the assumption of equal high energy mass attenuation coefficient made in Equation 2, the irregular shape of the scanned object, and scattering of x-rays. Usually these extra parameters contain the high and/or low energy detector measurement, the ratio to the undisturbed beam, or the logarithmic ratio. In this form, Equation 4 was extended to the following form:

$$\omega = A \cdot LR + B \cdot f(H, L) + C \cdot r(H, L) + D.$$  \[6\]

The functions \(f\) and \(r\) contain variables of the high and low energy detector measurements. Regression analysis using the scanned images of the wool samples were built on Equation 6 in the first tests. Earlier efforts to calibrate dual energy systems were based on Equation 6 or on a similar form of it, as it is not only applicable to DEXA systems \[10, 11, 12\].

However, purely DEXA parameter based regressions did not result in acceptable correlations for greasy wool independent of geographical origin. Inclusion of a non-DEXA based parameter, the MFD, improved the calibration considerably. That is:

$$\omega = A \cdot LR + B \cdot f(H, L) + C \cdot r(H, L) + D + MFD.$$ \[7\]

The MFD is too small to be resolved with the x-ray detector assembly used, which had a resolution of about 1 mm\(^2\). Therefore the MFD is a parameter which was independently measured by the commercial laboratory with traditional methods. Equation 7 was the second form of regression procedure used, which was called the “hybrid” regression.

4. Procedure

Wool bale core samples were thoroughly mixed according to laboratory testing guidelines. Samples were then divided, where one part of the sample was tested in laboratory while the other was stored. Then a selection of wool samples with a nominal WB between 40 and 80\% from different sheep races were chosen for DEXA scanning, so that a wide range of WB samples was available. The stored samples were assumed to have near identical WB values to the tested ones, which were completely used up in the testing process.

The samples were transported inside plastic bags, carefully sealed to avoid a change in water content of the wool. Weighing before and after transport excluded any noticeable water uptake or loss. During scanning the wool was kept inside the plastic bags as it was assumed that the thin plastic
material is negligible, of consistent quality, and was both included in the calibration and in later measurements.

The scanning speed was about 0.3 m/sec. The images were stored for analysis. Regression analysis was performed using Equations 6 and 7. Then the absolute difference between the laboratory measured WB and DEXA regression based WB was calculated as a function of the mean of the two values, according to a procedure pioneered by Bland and Altman [13]. In this way no bias was given for one method over another, assuming that both methods provided sources of errors.

5. Results

5.1. Calibrations using only DEXA parameters

The DEXA parameters of the scanned images were regressed over given laboratory values using Equation 6. The results are shown in Figure 4. However, the correlation as presented is not practical to have potential for industrial applications. It is evident that at least two major correlations exist, where the two correlations can be grouped into distinct geographic regions. A closer look at the data revealed that most of the samples of the offset correlation line originate from a specific location different from the other samples’ origin. Successful calibrations can be obtained for each region as long the origin of the sample is known, a known praxis for DEXA applications in the coal industry. Individual calibrations for the different sheep breeds also result in better correlations.

![Figure 4](image)

**Figure 4.** DEXA over laboratory regression results using exclusively DEXA parameters, see Equation 6. The error bars for the laboratory values represent the laboratory accredited limits, for DEXA they represent the measured precision.

The variance has been investigated for any existing bias, and can be seen in Figure 5. Although a very large spread of differences exists, the trend is increasing for increasing nominal WB. Generally, two error clouds seem to exist, one, at the high end WB values, has a slight positive bias, where the laboratory measured higher WB than the DEXA regression results. For nominal WB below 70%, this bias reversed to a significant negative bias, i.e., the DEXA result was higher than the laboratory WB. Further investigation of the origin of the bias, by plotting the WB differences over the MFD, showed a stronger bias at higher MFD (graph not shown).
5.2. Calibrations using DEXA and wool parameters
The same scans which have been used for the “DEXA only” calibrations were again regressed by adding the MFD to the otherwise identical regression equation. The influence was substantial, as can be seen in Figure 6, where the regression results are plotted. As in Figure 4, the laboratory values were plotted over the DEXA calibrated values. The $R^2$ value increased by about 80%, and although this is only an indication of the quality of a correlation, the visual inspection of the plot in Figure 6 is convincing of the improvement of the correlation. What was identified in Figure 4 as a second calibration line has completely disappeared. Further regressions were performed, where Merino and Crossbred wool was regressed individually, which revealed distinct correlations for the two wool groups, and provided best results overall. More information is provided in [12].

**Figure 5.** Absolute error between the laboratory and the DEXA calibrated WB value over the mean nominal WB (after Bland & Altman [13]).

**Figure 6.** DEXA over laboratory regression results including the MFD in the regression (Equation 7). The error bars are as in Figure 4.
In Figure 7 the absolute difference was again plotted over the mean of laboratory and DEXA determined WB. The improvement of the calibration is evident. No bias is shown when the error cloud is plotted over the MFD (graph not shown).

\[ y = 0.0399x - 2.5955 \]

Figure 7. Residual between laboratory and DEXA over the mean of laboratory and DEXA determined wool base value [13]. The bias is reduced to about a tenth of the former value, when the MFD was not included in the regression equation.

6. Conclusions
A DEXA scanner was calibrated with representative laboratory measured wool samples, so that the wool base can be determined using DEXA. Two methods were followed: A) the use of exclusively DEXA retrieved parameters from the images, B) a combined use of DEXA parameters and the independently measured MFD of the wool. While the first approach showed clear correlation between the wool base and the DEXA parameters, the correlation was not representative for wool breeds independent of its geographical origin and more than one correlation was visible in the correlation plot. As wool broker houses collect wool from different origins, calibrations reflecting the origin may not be practical in industrial settings. The second approach, where both DEXA and other wool parameters were used, showed good correlation for the entire wool clip independent of geographical origin. This second approach was termed a hybrid calibration, due to the different nature of the regression parameters. Although the approach may necessitate additional hardware for simultaneous scanning of the wool fibre and to determine the MFD value, DEXA provides a practical industrial solution for WB measurement. The method offers an opportunity to non-invasively determine the wool base, which traditionally is measured in a lengthy, labour-intensive and destructive sampling process.

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