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Virtual dissection of pig carcasses

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ABSTRACT

This paper proposes the use of computed tomography (CT) as a reference method for estimating the lean meat percentage (LMP) of pig carcasses. The current reference is manual dissection which has a limited accuracy due to variability between butchers. A contextual Bayesian classification scheme is applied to classify volume elements of full body CT-scans of pig carcasses into three tissue types. A linear model describes the relation between voxels and the full weight of the half carcass, which can be determined more accurately than that of the lean meat content. Two hundred and ninety-nine half pig carcasses were weighed and CT-scanned. The explained variance of the model was $R^2 = 0.9994$ with a root-mean-squared error of prediction of 83.6 g. Applying this method as a reference will ensure a more robust calibration of sensors for measuring the LMP, which is less prone to variation induced by manual intervention.

1. Introduction

Throughout the European Union (EU) the lean meat percentage (LMP) is used for classifying pig carcasses and is defined as the ratio of weighed lean meat versus the weight of the pig carcass. Measuring the LMP is typically done using ultrasound or optical sensors which are calibrated towards a common manual dissection method of half pig carcasses, cf. Commission of the European Communities (EC) (1994) and Walstra and Merkus (1996). The accuracy and precision of these calibrations are limited by that of the dissection method. Only highly trained butchers are involved in such a dissection. Even so there is still a significant difference between butchers as reported by Nissen et al., 2006. The maximum difference in estimated LMP between 8 butchers is found to be 1.96 LMP units and the jointing of the carcasses is found to be a critical point in the EU dissection method. Furthermore variation between countries were also found. Olsen et al. (2007) report that in general variations between butchers is more important than variations between copies of the same type of instrument, when calibrating instruments to manual dissection.

X-ray computed tomography (CT), cf. Cho, Jones, and Singh (1993), is a non-invasive technique that measures the radio-density of a material, i.e. the relative attenuation of X-rays through the material and is measured in the Hounsfield scale. The scale is calibrated such that air is at −1000 Hounsfield Units (HU) and water at 0 HU, making HU-values comparable across scanners and settings. Fat tissue is usually around −60 HU, meat tissue around +60 HU and bone tissue above ∼150 HU. The CT-volume consists of discrete volume elements (voxels) and are not necessarily isotropic. Voxels might also consist of more than one class of tissue. The latter is denoted partial volume effects (PVE) and results in overlapping probability density functions (pdf) of the different tissues. Fig. 1 shows a typical histogram in the fat/meat range for a CT-scanned pig carcass. The left peak represents fat and the right peak represents meat. Bone is above the range shown.

The fixed Hounsfield scale of CT is a major reason for using CT instead of magnetic resonance imaging (MRI) because it is comparable across scanners. Applying different settings, or protocols, in a specific CT-scanner has been shown by Christensen, Vester-Christensen, Borggaard, and Olsen (2008) to give quite robust results w.r.t. LMP. Based on 23 pig carcasses and using 7 different protocols they find a maximum difference of 0.27 LMP units and a maximum difference in the estimated carcass weight of 0.22 kg.

Typically a simple threshold in the CT histogram is used to distinguish fat, meat and bone tissue, but this will often result in errors caused by noise in the reconstruction, artifacts and PVE.

Several attempts have been made on calibration of CT-scans of pigs carcasses to predict the lean meat content of manual dissections. Glasbey and Robinson (2002) derive and compare estimators of tissue volumes in CT images taking mixed pixels, or PVE, of fat and meat into account. A moment-based estimator performs best in both a simulation study and in a particular application where tissue composition of sheep is estimated. The improvement in

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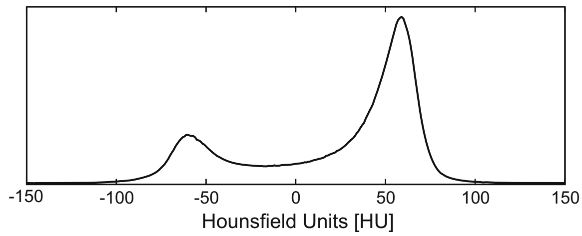

Fig. 1. Histogram of a CT-volume of a pig carcass. The ordinate is scaled to show the distribution of fat (left) and meat voxels (right).

precision is reported to be minor compared to Cavalieri sampling, cf. Roberts et al. (1993).

Dobrowolski, Branscheid, Romvàri, Horn, and Allen (2004) and Romvàri et al. (2006) use thresholds in the histogram of CT and Collewet et al. (2005) of MRI scans to segment meat voxels. In these studies partial least-squares regression (PLSR) of histogram values is applied to model the dissected lean meat content. Table 1 summarizes their results along with those ofJohansen, Egelandsdal, Røe, Kvaal, and Aastveit (2007). R^2 is the explained variance and RMSEP/C are the root-mean-squared errors of prediction/calibration. Johansen et al. (2007) apply thresholds to the histogram of 15 anatomically chosen slices of 120 CT-scanned carcasses of lamb to segment fat and meat tissue. A multidimensional PLS model is applied on the histogram values of fat and meat to predict the corresponding weights in a manual dissection. The RMSEP of the meat content is reported to be 772 g before and 561 g after bias correction, with an $R^2 = 0.96$. Common for the above mentioned methods is that they only take into account the histogram value of the voxel to be classified and not any of the neighboring voxels.

Lyckegaard, Larsen, Christensen, Vester-Christensen, and Olsen (2006) apply a multivariate Bayesian 2D contextual classification scheme to each slice as described by Larsen (2000). Certain combinations of neighboring voxels are taken into account modeled in a Bayesian scheme with priors obtained from thresholds in the histogram. Linear regression is used to estimate the parameters of a model mapping the volume of fat, meat and bone to the total weight of the carcass, with an $R^2 = 0.991$ and a RMSEP = 584 g.

This paper presents an experiment consisting of 299 pig carcasses, which are weighed and CT-scanned. Applying methods from image processing along with a contextual classification scheme the CT-volume is classified into several types of tissue. A linear model determines the mapping from voxels to the full weight of the half carcass, which is then used for estimating the CT-based LMP.

2. Materials and methods

2.1. Data

Two hundred and ninety-nine carcasses representing the Danish pig population with respect to weight (warm slaughter weight) and fatness (fat depth between the 2nd and 3rd hindmost thoratic vertebra) were selected. Half of which were gilts and the rest castrates. The pigs were slaughtered at a commercial Danish abattoir and cooled. The day after slaughtering the left side of the carcasses were prepared for dissection. The preparation was done according to Walstra and Merkus (1996), but the head except the cheek and toes were cut off before scanning. All half carcasses were weighed on a DIGI DS160 industrial scale with an accuracy of 20 g. Subsequently they were scanned with a GE HiSpeed CT/i single-slice scanner. In the following the term carcass weight denotes the weight of the scanned left side of the carcass. The scanning protocol parameters were: 140 kV voltage, $0.9 \times 0.9 \times 10$ mm voxel size, 0.7 mm spot size and 10 mm between slice centers, yielding 299 CT-volumes of pig carcasses with corresponding weight. Fig. 2 shows a left side of a carcass prepared and ready for scanning.

2.2. Full dissection

Of the 299 carcasses scanned, a subsample of 29 carcasses with 13 gilts and 16 castrates were selected. The subsample was selected representing the distribution of weight and fatness. After scanning a full dissection was made on the same carcass to calculate the lean meat content. The LMP is defined as the ratio of the meat and the total weight of the carcass exclusive head and toes. Full dissection is not standardized yet. In this trial the meat fraction consists of all muscles including tendons, fascia and periosts. Periosts appear by, e.g. extraction of ribs, femur bone in ham and front part. Tendons from certain muscles stretch around the bones as e.g. *Bicepc brachii* and other muscles in the front part and ham. These tendons are not left entirely on the muscles, but are cut off where they touch the bone. The fat fraction consists of subcutaneous and inter-muscular fat including skin and glands, veins and loose membrane tissue. Loose membrane tissue is defined as all membrane tissue which can be lifted between two fingers and can be cut without damaging the underlying muscle. The bone fraction consists of all bones including cartilage. No bones are scraped to remove periosts or remains of tendon.

2.3. Tissue classification

For identifying meat voxels, the tissue from CT is traditionally classified by applying thresholds in the histogram. This method

Fig. 2. Left side of a carcass prepared and ready for scanning.

Table 1
Previous work. Papers (Collewet et al., 2005; Dobrowolski et al., 2004; Johansen et al., 2007 & Romvàri et al., 2006) apply PLS-methods on histograms for meat pixels, modeling the lean meat weight obtained from dissection. Lyckegaard et al. (2006) apply a contextual Bayesian classifier and linear regression for predicting the full weight of half carcasses. R^2 is the explained variance, RMSEP/C are the rms errors of prediction/calibration, with the corresponding bias reported in some cases.

Paper	Dobrowolski et al. (2004)	Collewet et al. (2005)	Romvàri et al. (2006)	Johansen et al. (2007)	Lyckegaard et al. (2006)
Modality	CT (full, 150 sl.)	MRI (full)	CT (full)	CT (15 anat. sl.)	CT (full)
Vox/spac. [mm]	–/–	[0.77,1.02,8]/10	$[\sim 1, \sim 1, 10]/10$	[0.78,0.78,3]/var.	[1,1,10]/10
Comment	1/2 pig carc.	1/2 pig carc.	1/2 pig carc.	Lamb carc.	1/2 pig carc.
Amount	60	120	60	120	57
R^2	0.990	–	0.992	0.961	0.991
RMSEP/C [g]	270/–	465/400	–/232	772/–	584/554
Bias [g]	16	–	–	530	–

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introduces errors due to PVE as mentioned earlier. In the current work a multivariate Bayesian 2D contextual classification scheme is applied to each slice, cf. Larsen (2000). Background voxels are removed and tissue voxels are classified into three classes; fat, meat and bone. The classifier takes certain configurations of neighboring voxels into account as well as the prior probability as described in Lyckegaard et al. (2006). All fat, meat and bone tissue irrespective of their anatomical position are regarded as belonging to the same corresponding class. As a postprocessing step the bones are morphologically closed such that marrow will be part of the bone class. In CT skin voxels are more similar to meat. When comparing the LMP obtained by CT to that obtained by manual dissection the skin is segmented separately and considered as fat such that the LMP can be computed according to Commission of the European Communities (EC) (1994). Segmentation of the skin is done using mathematical morphology, cf. Gonzalez and Woods (2002).

2.4. Density estimation

Estimating the weight of a carcass requires an approximation of the densities ρ of the tissue types in every voxel. The carcass weight is modeled as a linear combination of the weights of the tissue classes. Labeling of a particular voxel is done by choosing the class with *maximum-a-posteriori* (MAP) probability, see Larsen (2000). The MAP model applied for a single carcass with three tissue classes is

$$w_i = \rho_f n_f v + \rho_m n_m v + \rho_b n_b v + \epsilon_i, \quad (1)$$

where v is the voxel volume, n_f, n_m and n_b are the number of voxels classified as fat, meat and bone, respectively. w_i is the measured ith carcass weight and $\epsilon_i \in N(0, \sigma_i)$. Including all carcasses and using linear regression the density approximations can be obtained.

Due to PVE a single voxel might consist of more than one type of tissue. However, in the model in Eq. (1) each voxel is labeled as either fat, meat or bone. Including PVE in the model can be done using the value of the posterior probability of each class. Thus all voxels have a weighted contribution from all classes.

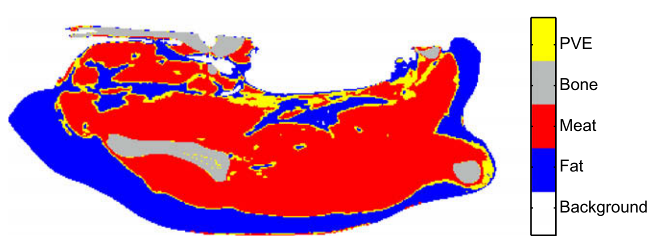

Fig. 3. Partial volume effects shown in a CT-slice from the shoulder part of half a pig carcass. Yellow denotes voxels with a probability above 0.5 and below 1.0 of belonging to the meat class. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 3 illustrates the issues with PVE. The figure depicts a slice in the shoulder part of the carcass where voxels with a posterior probability above 0.5 and below 1 of belonging to the meat class are yellow, indicating that they contain something else than meat. These are primarily located where the meat interfaces with fat. Integrating PVE in the carcass weight model yields

$$w_i = \rho_f \sum_{i=1}^{n} p(c_f|x_i)\, v + \rho_m \sum_{i=1}^{n} p(c_m|x_i)\, v + \rho_b \sum_{i=1}^{n} p(c_b|x_i)\, v + \epsilon_i, \quad (2)$$

where n is the total number of voxels. $p(c_f|x_i), p(c_m|x_i)$ and $p(c_b|x_i)$ are the posterior probabilities of voxel x_i belonging to the fat, meat or bone class respectively, and $\epsilon_i \in N(0, \sigma_i)$. Both the MAP and the PVE model are applied with and without an additional constant term c, for comparison.

To avoid the effect of outliers the linear regression problem is solved using an iteratively re-weighted least-squares algorithm presented in Holland and Welsch (1977). Leave-one-out cross-validation is performed and the root-mean-squared error of the residuals of prediction (RMSEP) is reported as well as the bias and explained variance (R^2).

3. Results and discussion

3.1. Comparison with manual dissection

Fig. 4 shows the range of LMP for both CT (left) and manual dissection (right) and is approximately [55, 75] units. The half carcass weight range is seen in Fig. 6 to be approximately [31, 49] kg. Data used in both dissection methods cover the variation in LMP of the Danish pig population. Table 2 and Fig. 5 compare the estimated tissue content from the manually dissected carcasses with the corresponding estimate from the CT dissection. On average CT scanning identifies 1227 g more meat, 968 g less fat and 225 g less bone in a carcass than manual dissection. It is expected that tissues like tendons, fascia, periosts and cartilage, which consist of protein, will be considered as meat in a CT scan. From the description of the three main groups of tissue, meat, fat and bone obtained with manual dissection, it is seen that only a part of all protein-containing tissues is defined as meat. It seems reasonable that the limitations of manual separation together with the definition of meat cause the main contribution to the differences between LMP determined with CT and manual dissection. Furthermore Table 2 indicates a larger standard deviation when compared to the mean value of the residuals of the bone class than for the meat and fat classes.

3.2. Modeling total weight

Applying both models described in Section 2.4 reveal similar results. Fig. 6 shows a plot of the correlation between estimated carcass weight and measured carcass weight using the MAP model, cf.

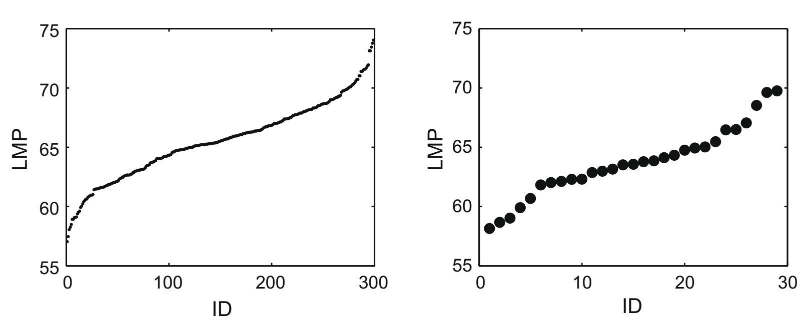

Fig. 4. The resulting LMP estimated by CT, 299 carcasses (left), and by manual dissection, 29 carcasses (right), sorted by LMP.

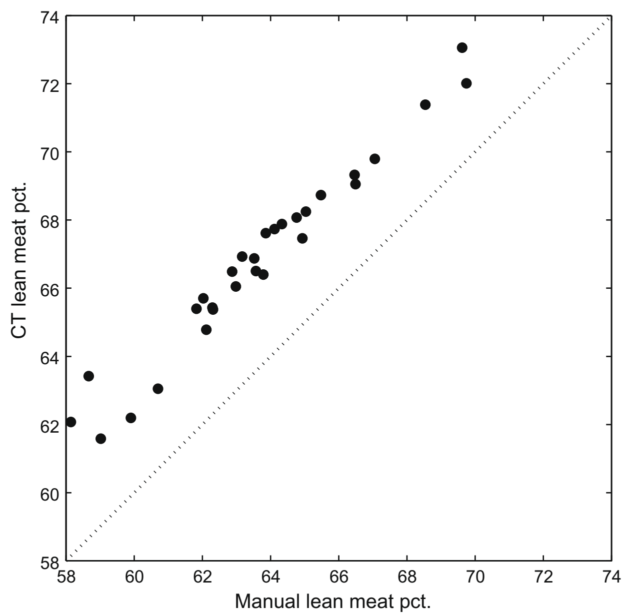

Fig. 5. LMP estimated by manual dissection versus CT estimated LMP using the MAP model.

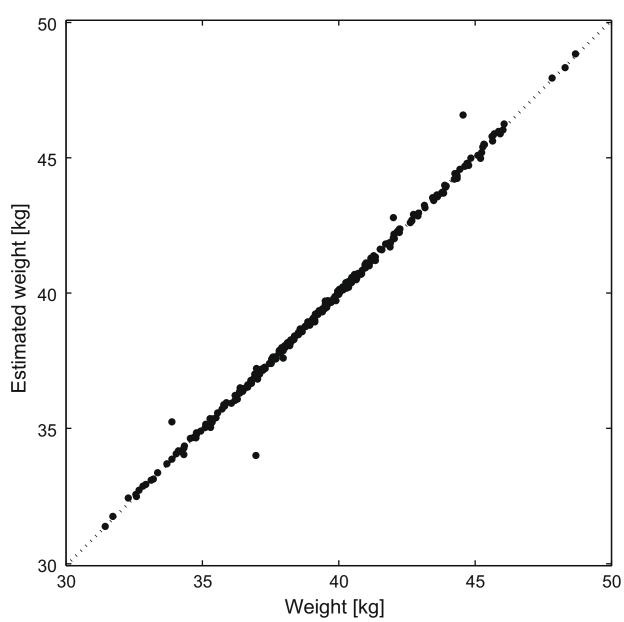

Fig. 6. Estimated weight using the MAP model versus measured weight.

Table 2
Mean and standard deviations of the residuals obtained by comparing CT dissection with manual dissection.

Tissue Type	Fat	Meat	Bone
Res. mean ± std [%]	2.49 ± 0.55	−3.07 ± 0.57	0.58 ± 0.33
Res. mean ± std [g]	968 ± 181	−1227 ± 210	227 ± 130

Eq. (1). The estimated parameters and correlation results for the MAP model and the PVE model, with and without constant terms c, are reported in Table 3. In all regressions the robust algorithm detects 5 outliers, which are identified as errors in the data acquisition. These are subsequently removed in the calculation of the parameters and the correlation results as well.

Table 3
Predictive performance of the two models, with and without a constant term c, using leave-one-out cross-validation.

Model	R^2	RMSEP [g]	Bias [g]
MAP	0.9994	83.6	2.6
PVE	0.9994	79.0	2.3
MAP + c	0.9994	79.1	1.8
PVE + c	0.9994	75.5	1.7

Table 3 shows that the four models perform equally well with large correlations to the measured weight. Applying a one way analysis of variance (ANOVA) on the weight estimates from all models reveals no significant difference between them. Including a constant term would make the definition of the LMP ambiguous, since it does not belong to a specific tissue class. Subsequently the simple MAP model without a constant term is preferable. Modeling PVE has no effect on the quality of the predicted weight. In a randomly chosen carcass only 1.6% of all the voxels classified as meat have a fat probability above 0.1. Thus the influence of PVE is very limited with regards to the total weight. Table 4 and Fig. 7 show that the values of the parameters of fat and meat are not significantly different when comparing the PVE and MAP models contrary to the bone parameter. A voxel containing both bone and soft tissue will tend to be classified by the MAP model as bone. A voxel in the PVE model contributes to all tissue types. This results in more bone voxels using MAP than using PVE.

All in all the results obtained are very encouraging when compared to Table 1. The simple MAP based model has an explained variance of $R^2 = 0.9994$, a bias of 2.6 g and RMSEP = 83.6 g estimated using leave-one-out cross-validation.

For all models the three tissue types are assumed to have the same properties regardless of their anatomical position. Thus the parameters ρ_f, ρ_m, and ρ_b can be viewed as the average density of all fat, meat and bone in the half carcass. Previous work (Romvàri et al. (2006)) reports the importance of modeling different tissue properties, and they do this by manually separating the CT-volume into three carcass parts. This is prone to operator dependent errors. In this study, it is argued that using average tissue properties yields a more robust estimate of the carcass weight due to operator independency. It should be noted though, that the parameters might not have a strict physical interpretation as densities of the specific tissue classes.

Even though there is a clear definition of which of the three tissue fractions the tendons and glands etc. belong to, the specific butcher makes the final decision. Nissen et al. (2006) report considerable variation between butchers and separation of muscles and especially small muscles are very dependent on the butcher. The contribution from the butchers affects mainly the precision of dissection and less the average result. Two main sources of error are present when calibrating online instruments to LMP. One is the error or variation, which expresses the imperfect relation between the reference LMP and the online measurements, including the accuracy of the online measurements, and the other one is the accuracy of the dependent variable, i.e. the reference LMP.

LMP based on CT is a very promising candidate for an instrumental reference for pig carcass classification. Previous investigations have shown very high repeatability. However, before CT LMP can be used as a global reference, it has to be documented that the results can be reproduced independently of CT instruments, time and pig population. The method described in this paper is based on a specific scanning protocol and reconstruction algorithm. Although the method seems robust to these factors a thorough documentation will be necessary. Especially the choice of slice thickness, resolution and reconstruction algorithm has to be general and available on all types and makes of CT scanners. A

Table 4
The resulting parameters for the MAP and PVE models excluding and including a constant term *c*. Ninety-five percentage confidence intervals are shown in brackets.

Model	ρ_f [CI]	ρ_m [CI]	ρ_b [CI]	c [CI]
MAP	0.997 [0.992 1.003]	1.117 [1.111 1.124]	1.433 [1.368 1.497]	
PVE	0.994 [0.988 0.999]	1.114 [1.107 1.120]	1.516 [1.448 1.583]	
MAP + c	0.991 [0.985 0.997]	1.111 [1.104 1.118]	1.368 [1.298 1.438]	0.367 [0.230 0.505]
PVE + c	0.988 [0.982 0.994]	1.109 [1.102 1.116]	1.448 [1.372 1.524]	0.319 [0.185 0.454]

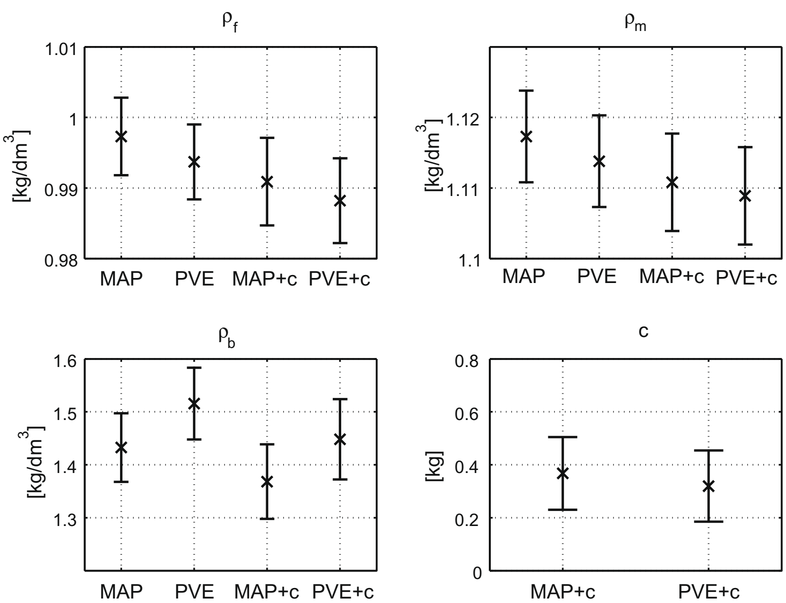

Fig. 7. Estimated parameters and their corresponding 95% confidence intervals for the two models, with and without a constant term *c*.

possible tool to ensure the reproducibility over time, including a possible bias correction, could be calibration using phantoms that mimic different types of carcasses with known values of LMP. How such phantoms should be designed is an area of future research.

Replacing the manually determined LMP with CT-based LMP will improve the calibration problem significantly, even though the lack of a perfect relationship is an important issue. Disregarding the fixed costs related to the purchase of a CT-scanner and installing it in a trailer, the lower costs using CT is a considerable advantage compared to manual dissection. If only the maintenance of the scanner is taken into account alongside the salary of the operators, a CT-based LMP costs less than half that of a manual dissection.

4. Conclusions

Previous work shows CT-based methods as robust compared to manual dissection, and as such constitute a suitable reference. This work presents a robust and accurate calibration reference, where variation due to manual intervention is minimized. Given a model of the carcass weight, the LMP can be estimated based on the classification of the volume elements (voxels) in the CT-volume. Using this more accurate method as a reference will make the calibration procedures of other LMP sensors much more standardized and accurate.

Contextual models based on segmentation of the carcass into three classes is validated on a large data set of 299 half pig carcasses. Incorporating the influence of partial volume effects is found not to be significantly better than a maximum-a-posteriori model. All models correlate very well with the full weight of the half carcasses, with the simple maximum-a-posteriori based model being the model of choice. The model has an explained variance of $R^2 = 0.9994$, a bias of 2.6 g and a root-mean-squared error of prediction of RMSEP = 83.6 g. These results are very encouraging compared to previous work, for which reason the method is suggested as a new reference for calibration of sensors used for pig carcass grading.

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