ACCOUNTING OF EXTRACTED HARVESTING RESIDUES USING FORWARDER BOOM SCALES

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Abstract. The objective of this study is to evaluate the feasibility of using forwarder-based weighing systems for measurement of extracted biomass to improve the accuracy of the accounting and to ensure faster production data flow. The study aims at comprehensive assessment of biomass measurement using a forwarder boom scale system, to compare it with traditional volume measurements and to develop a model for converting of a stacked biomass into chipped volume units (loose m³). The proposed method is intended to improve accuracy of the measurement of forest harvesting residues, small-diameter unbranched wood, and other types of forest biomass. During forwarding biomass was weighed using the Intermercato XW 50 PS grapple scales with a measurement accuracy of ± 2% and the integrated weighing system of John Deere forwarders. Both weighing systems were installed on the forwarder's boom, between the rotator and the grapple. Despite both weighing systems provided sufficient measurement accuracy (with an average uncertainty of no more than 5%), the study results point out benefits of manufacturers – integrated weighing solutions, which offer better integration with forwarder production data flow. The use of the forwarders manufacturers' integrated weighing systems also reduces the workload associated with initial data processing. The research also pointed out the need to evaluate available or to develop new IT solutions for transferring weighing data from the forwarder to a data storage system to automate the data exchange process.

Keywords: wood biomass, forwarder, scales.

Introduction

The use of biomass in energy production is a crucial element in the sustainable energy supply and decarbonization strategy, promoting an increased share of renewable energy sources in overall energy consumption. Latvia's National Energy and Climate Plan for 2030 emphasizes the role of biomass resources, including wood, straw, and reeds, in heat and electricity production, as well as the development of biofuels and biogas in the transport sector. The plan envisions investments in improving energy efficiency in heating, modernizing district heating systems, and utilizing local energy resources to reduce dependence on fossil fuels. Furthermore, the use of biomass supports sustainable management of natural capital, fostering the development of the forestry and agricultural sectors while integrating circular economy principles. These measures collectively strengthen national energy independence, reduce greenhouse gas emissions, and facilitate the transition to a climate-neutral economy.

The use of biomass for energy production is becoming increasingly important as a sustainable alternative to fossil fuels. However, the low density, seasonal availability, and high logistics cost [1] of biomass present significant challenges for its efficient utilization. As noted by Nunes [2], one of the most critical aspects is the structuring and optimization of the supply chain, which includes resource collection, transportation, storage and processing. Recent advancements in remote sensing technologies [3] have also enabled more accurate and large-scale assessments of biomass availability, supporting improved planning and decision-making in wood biomass supply chains. However, there is a lack of research to accurately estimate the volume of wood biomass supplied; a similar problem, including regarding assortments, is pointed out in another article [4].

For the theoretical calculation of biomass volume, it is possible to adapt the equations developed by J. Liepiņš [5]. These equations are designed for CO_2 calculations, but despite this, they can theoretically be used for volume estimation before logging. The use of biomass for energy production involves sequential steps. Initially, biomass preparation is carried out using a harvester [6]. During logging operations, when using forest machines equipped with standard mechanisms for assortment production, roundwood logs are produced, but the additional extraction of biofuel feedstocks is not accounted for (as its registration is not technically feasible). The only possibility for accounting exists if the equipment is used exclusively for biofuel feedstock production, utilizing harvester heads designed for this purpose. Such data recording is also implemented in assortments – biofuel, ensuring accounting in the harvester's computer system [7]. After biomass preparation it is left for storage at the felling site for 2-6 months, ensuring rapid drying of the material [8], [9]. After the material is stored at the felling site, it is transported and unloaded at a roadside storage site. During the transportation process, the volume of biofuel feedstock is visually assessed, allowing an estimation of the delivered amount. This accounting system is feasible if the forest machine operator has several years of experience and well established feedback system. After transportation, the material is unloaded at the roadside storage site, where it is stored for another 3-6 months. In Latvia, the precise assessment of biofuel feedstock volume is conducted based on measurements taken at the roadside storage site [10]. Despite the existence of a detailed measurement methodology, there is a possibility that the measured volume may be underestimated or, conversely, overestimated. This can occur when converting from one volume unit (stacked cubic meters) to another unit characterizing biomass (loose cubic meters). Using a conversion coefficient, this value ranges from 0.2 to 0.7. For biofuel (wood chips) conversions a coefficient of 0.38 is often used [9].

Materials and methods

During the biofuel feedstock transportation process, the Intermercato XW 50 PS weighing system and the John Deere integrated boom scale weighing system were used. To account the delivered volume, storage site measurements were performed by determining the length, the average height and width of the roadside storages [10].

In the biofuel transportation process the Intermercato XW 50 PS grapple scales (Fig. 1.) were installed on the forwarder's manipulator system, positioning the scales between the rotator and the grapple grip. The weighing system was set to an automatic operating mode. To evaluate the recorded number of biofuel feedstock loads, the operator was required to make additional annotations regarding the delivered material. Using the weighing system, the biofuel feedstock transportation process separately accounted for material loading (at the felling site) and unloading (at the roadside storage site). The records were entered via a handheld computer display by selecting the appropriate button. For research purposes the weighing system was activated with a global positioning signal, allowing more accurate calculations of the spatial distribution of the delivered volume during subsequent data processing, as well as for calculating the total traveled distance (equation 1). In total, using the Intermercato measurement system, the material was transported from 25 felling sites. The transportation process consumed 724.8 forwarder operating hours, collecting data on 10,154 tons of the delivered biofuel feedstocks from regenerative felling sites.

$$L = \operatorname{acos}\left(\sin\left(Lat * \frac{\pi}{180}\right) * \sin\left(Lat * \frac{\pi}{180}\right) + \cos\left(Lat * \frac{\pi}{180}\right) * \cos\left(Lat * \frac{\pi}{180}\right) * \cos\left(Lon * \frac{\pi}{180} - Lon * \frac{\pi}{180}\right)\right) * 6371000 \tag{1}$$

where L – distance traveled, m;
Lat – latitude, m;
Lon – longitude.

The John Deere weighing system is developed by the machine manufacturer and integrated into the forwarder's computer system. Trials with the John Deere weighing system (Fig. 1.) were conducted between 07.10.2022 and 02.04.2024.

Fig. 1. **Weighing systems used in the study:** 1 – Intermercato scale; 2 – JohnDeere scale

Within the study logging residues were transported to 98 roadside storage sites, including data collection on biofuel feedstocks transportation from 28 sites in 2024. After the material was transported to a roadside storage site, additional measurements were performed manually to measure the delivered volume, allowing the collected data to be used for development of the equation for prediction of the delivered biomass. Such an equation is necessary because settlements for the delivered volume are based on volume units (loose cubic meters, LV). After the initial data quality check data from 92 storage sites were used for further data processing.

Results and discussion

For further use of weighing systems in production conditions the quality of data collection and the additional time investment in data processing are crucial. When using the Intermercato XP 50 PS weighing system in automatic weighing mode, all measurements are recorded, including operations not directly related to the main work (such as moving fuel tanks, support chains, etc.). To utilize the data from the weighing system, post-processing is required to filter out data unrelated to direct work or manual recording of the loaded material is required, which increases additional working time. In certain cases, the Intermercato XW 50 PS weighing system cannot identify the exact weighing location. This occurs when the distance between the roadside storage site and the felling site is less than 10 meters. Additionally, issues arise when the material is transported from different forest compartments to the same storage site. To identify the origin of the transported material, an additional marking (by selecting the appropriate setting) is required in the weighing system to specify the material's location (felling site, storage site, or road reinforcement).

When comparing the weighing results using the Intermercato weighing system, a significant difference ($p = 0.00$) was found between the weights recorded at the felling site and the upper storage site (AGK) during the biofuel feedstock loading process. This process includes picking up separately placed large fractions, resulting in an overall 2.7-fold difference between loading and unloading. This discrepancy is related to the fact that during the loading process the same bundle can be recorded multiple times during picking several packets of residues during loading. The average loaded bundle weight at the felling site was 201 ± 154 kg, while at AGK it was 414 ± 256 kg. The large dispersion in the arithmetic mean value in both cases indicates that, most likely, the automatic mode records the same bundle multiple times (during interception, relocation and supplementation). To improve the accuracy, weighing should be performed manually, recording only the lifted or placed bundles. By pressing the weighing control pedal, the operator activates the weighing system, which records the obtained measurement. In some trial sites the opposite situation was observed – the volume loaded at the felling site was smaller than the volume unloaded at AGK. This can be explained by the fact that the weighing system switches to "sleep mode" if it is not used for an extended period (< 10 min), or the weighing system battery is discharged, and the operator has not noticed it. To prevent this issue, the operator must continuously monitor whether the weighing data is being recorded in the system's interface and must reactivate the weighing program after prolonged pauses.

Based on the weighing process, the total calculated transportation distance was 345 km, with an average forwarding distance of 796 meters at the felling site. The travel distance significantly affects overall productivity. If the average distance exceeds 1 km, additional compensation is usually applied, such information can also be obtained from the weighing system.

When using the John Deere weighing system, data recording occurs at the moment when the loaded material bundle is at a specific height above the ground, and the manipulator is positioned at a predefined angle relative to the cargo space:

- during loading, this occurs before the cargo compartment stanchions, when the material is fully lifted;
- during unloading, the recording takes place when the material is outside the cargo compartment.

This mechanism nearly completely eliminates the possibility of counting the same bundle multiple times during the loading process while collecting material. Unlike the Intermercato XP 50 PS weighing system, the John Deere grapple scale does not provide information about the placement of transported material within the felling site. Therefore, it is not possible to assess whether the prepared material has been transported from all parts of the felling area. The recorded volume can be accounted for either at the felling site or at the upper storage site (AGK). Incorporating boom scales into forwarders within the CTL system can enhance the accuracy of biomass accounting during extraction [8]. This integration facilitates better resource management and supports sustainable practices by providing precise data in the quantity of extracted residues.

Based on the experience gained from trials with different weighing systems, the key aspects that need attention in the planning process for transportation of logging residues have been identified:

- periodic calibration of forwarder weighing systems;
- compliance of the forwarder data system with the StanForD 2010 data standard, ensuring data compatibility [12] and further usability;
- weighing at the upper storage site (AGK) reduces risks associated with;
  - the use of logging residues for reinforcing technological roads,
  - repeated material weighing, if it falls off the forwarder at the felling site.
- equipping the weighing system with global navigation satellite system (GNSS) enables data recording at both the felling site and AGK. This allows for more efficient tracking of biofuel feedstock deliveries from the entire site and determines the exact storage location, especially when multiple storage sites are combined.
- operator training – operators must be informed about the purpose and necessity of data collection. There is a risk that the weighing system may fail to record the entire transported volume, for example, due to temporary data transmission failures, and operators need to have backup with manual records of transported volumes.
- weighing system functionality – integrated weighing systems within the forwarder's computer system ensure more detailed data recording, allowing the operator to avoid additional manual actions while maintaining an uninterrupted workflow.

Based on the study results, a forecasting equation has been developed to convert the transported biomass feedstocks from mass units (tons of naturally moist material) to volume units (loose cubic meters, LV).

The relationship between transported volume and mass is described by a linear regression equation (2) with a determination coefficient $R^2 = 0.89$. The model's accuracy was evaluated using statistical indicators:

- Mean Absolute Error (MAE) 22.73;
- Mean Squared Error (MSE) 904;
- Standard Deviation (RMSE) 30.65;
- Percentage Root Mean Squared Error (RMSE%) 20.6%;
- Mean Residual Error (MRES) 0.00;
- Mean Absolute Residual Error (AMRES) 1432;
- Model Efficiency Index (MEF) 0.899;
- Variance Ratio (VR) 0.899.

These statistical parameters confirm the high reliability and accuracy of the developed conversion model (2), making it suitable for practical application in biomass transportation planning.

$$LV = 20.32 + 1.50 * m \quad (2)$$

where LV – volume of logging residues transported to the upper storage site (AGK), loose cubic meters;
m – forwarder system fixed weight, in tons;
20.32 and 1.50 – coefficients.

The data analysis reveals that the measured and predicted volumes are mostly similar (Table 1), but deviations depend on the month (January -11%, February -28%, March -11%, April -17%, July -10%, October -13%, and November -10%), with an average difference close to zero, but significant fluctuations ranging from -70.1% to + 51%. On average, the forecast accuracy is high, but in some cases, the models significantly overestimate or underestimate the extracted volume, particularly in winter and spring months. This is probably due to changes in humidity during storage [13]. The largest discrepancies were observed in specific periods, which may indicate seasonal or methodological influences. Overall, the data provide valuable insights into forecasting accuracy and can help improve future predictions.

Table 1

Summary of measured and predicted volume statistics

Units of measurement	Measured volume, LV.m^3	Predicted volume, LV.m^3	Difference between measured and predicted volume, %	Difference between measured and predicted volume, *LV*, m^3
count	62	62	62.00	62.00
mean	148.96	148.96	0.01	0.00
std	97.36	92.33	22.18	30.90
min	22.0	32.7	-70.00	-96.70
25%	63.5	66.1	-14.00	-9.10
50%	133.0	125.2	3.40	4.70
75%	206.0	212.1	13.60	21.30
max	386.0	380.2	51.00	52.70

The developed equation is based on the data set obtained using the John Deere integrated weighing system. During the testing process of the weighing system, several potential risks were identified that could affect data accuracy:

- the volume of logging residues used for improving bearing capacity of striproads;
- temporary loss of the weighing system data transmission signal;
- the density and orientation of the pile of logging residues.

Conclusions

The integrated weighing system provides comprehensive information not only about the transported material but also about other key indicators (e.g. fuel consumption, work time distribution, traveled distance, equipment utilization rate, etc.). Therefore, this weighing system offers significant advantages in production conditions. The only drawback is that it does not allow the assessment of the initial distribution of transported material in the felling area, making it impossible to determine whether the entire site has been fully extracted.

Considering the successful results obtained in the trials, it is recommended to continue using the John Deere weighing system in production conditions and to evaluate other manufacturers' integrated solutions (e.g. Ponsse, Komatsu) for biomass weighing during transportation. In addition, IT solutions for transferring weighing data from the forwarder and for automated accounting of material stored in warehouses should be evaluated.

The current methods used in production (measuring at storage sites) and weighing both have limitations, meaning neither method ensures a 100% accurate forecast of the wood chip volume. The most effective approach is to record volumes based on operator-reported data, while simultaneously tracking the mass of the transported materials. Mass recording should be the priority, as it offers higher accuracy under optimal conditions and eliminates human error as a source of miscalculation. However, due to potential interruptions in operations of weighing systems, it is also necessary to collect transported volume data to adjust transportation reports in case of significant discrepancies.

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Author contributions

Conceptualization, A.Z.; methodology, A.Z. and S.K.; investigation, A.Z., S.K. and J.C.; data curation, A.Z.; writing – review and editing, A.Z.; All authors have read and agreed to the published version of the manuscript.

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