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Modelling of Harvesting Machines' Technical Parameters and Prices

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Abstract: Technical and performance parameters of agricultural machines directly impact the operational efficiency and entire crop production. Sometimes, overestimation of technical and dimensional parameters of harvesting equipment is carried out with the intention of enhancing the operational efficiency, but this approach might turn out to negatively impact productivity due to unbalanced system design, and ultimately lead to financial losses. Therefore, a balanced preliminary estimation of technical parameters of equipment needs to be carried out before investment quantification, especially on the large capital-intensive machinery units, such as harvesting systems. In addition, availability of ready to use, simplified models for the price estimation from input technical parameters would reduce the complexity involved in this latter analysis. The current study is an attempt to provide tools to address these issues. A large dataset of combine and forage harvesters has been analyzed to investigate relevant parameter-to-parameter and parameter-to-price relations. The study of the available data allowed the determination of indicative models for the estimation of machine price, power, weight, tank capacity and working width. A significant correlation between power and price ($R^2 > 0.8$) has been observed for two groups of harvesting machines. For combine harvesters, satisfactory correlations were found between power and weight, and power and tank capacity. A regression model for combine harvesters showed a satisfactory behavior at predicting the average working width that can be operated by a given power. On the other hand, for the forage harvesting group, the relation between these quantities has lower values; therefore, for better accuracy of the association, more sophisticated considerations should be incorporated, taking into account other parameters.

Keywords: cost modelling; harvesting operation; combine harvester; forage harvester; machinery price; farm management; decision support

1. Introduction

A key step for the development of agricultural processes is the mechanization of operations. It is a complex activity toward farm value enhancement that is meant to provide a financial return above the sustained costs [1]. This activity requires a careful selection and efficient management of mechanical units and large capital investments; thus, it affects not only on-farm productivity but all agri-food production.

Management of agricultural machinery is based on a composite of available farm data and resources, and relies on the complete understanding of farm potential and the technical quantification of units and operational functions [2]. Identification of optimal synergy is very complex due to machinery's interactions with agronomic, biological and climatic features [3,4]. Therefore, fleet management decisions require understanding and proper planning of farm development scenarios with the considerations of the technical and economic impacts of machinery units [5]. Thus, the provisional definition of the actual needs of the farm and the capacity of investments might increase operational performance and ensure sustainable production and profit [6].

Farm management and fleet accomplishment are focused on the maximization of efficiencies and optimization of costs, which is crucial in the case of large capital-intensive equipment such as harvesting machines. Development of harvesting equipment significantly changed agricultural production, and the harvesting operation of grain and fibrous biological materials [7]. It needs to be noticed that the technical development of combine harvesters has progressively increased over the last 25 years and resulted in remarkable capacities. According to the Fuchs study [8], the parameters of header width and grain tank capacity have almost doubled, and the engine power has increased approximately three times (from 147 kW to 434 kW). With the increase of engine power, the grain throughput of combines has also grown by reaching 10 t/h for last models [7,9]. The rapid expansion of dimensions almost reached its limits, and the focus turned toward optimization of the internal processes to maximally exploit the available capacity in terms of reducing the working time, harvesting losses and required driving power [7,9–11]. Modern tendencies for improving the use of the equipment are linked to the improvement of operation management and the need for understanding and quantifying a system's performance [12].

Combine harvesters are continuous-flow machines with a large operating adjustment potential. It is a multifunctional system that consists of the threshing, separation and cleaning processing units. A conventional combine is equipped with a tangential threshing system and straw walkers, while a rotary combine has an axial flow threshing system. The threshing unit is the key assembly of a combine harvester working process and the source of the power requirement [10]. The performance of combine harvester is characterized by the grain loss, grain quality and damage, cleanliness and straw quality, harvesting costs and environmental impact [10,11]. The efficiency of the machine and capacity are assigned to the balanced interplay between machine settings (driving speed, feed rate, material flow, rotor speed, material density within threshing unit, etc.), material quantities and properties and environmental parameters within threshing and separation section [11,12]. Many parameters might be conflicting (loss, throughput, straw quality, grain cleanness, power consumption, etc.); thus, a trade-off between capacity and/or power efficiency and performance with regard to losses has to be defined, especially in the case of high-value crop harvesting, such as corn harvesting [13]. Hence, the adjustments of the units (cutting, feeding, threshing, separating, cleaning) done with the purpose of increasing operational efficiency may reduce the productivity and lead to valuable losses [13,14]. Farmers are more interested in more substantial material efficiency of production and expected income greater than operating costs. Following that concept, the decisions regarding machinery selection usually are overestimated in terms of dimensions and parameters, which may lead to the disbalance of the operation flow (overload, etc.) and significantly change the expectations. Indeed, relatively high-capacity machines help to reduce yield losses but result in higher fixed costs. Proper selection of machine capacity is also a problem of balancing high fixed costs against losses; profits against investments. In addition, the short time window for harvesting and the moisture content of the crop creates a major impact on farmers' decisions related to the planning, and therefore, on the selection of the harvesting machines [11]. Thus, the choice of appropriate machine capacity and matching the requirements are important aspects of the decision-making procedure [6,15].

Forage harvesting is one of the most power-consuming operations on the farm due to the cutter mechanism speed and the shortness of the cut. Forage harvester power depends on throughput, moisture content, length of cut, crop type and blade sharpness [16]. Additionally, the capacity of a forage harvester is proportional to the available engine power. The power range for new commercial models reaches up to 800 kW with 18 t of weight without including the cutbar header. Self-propelled forage harvesters are adaptable with a range of headers from 630 to 850 mm in working width for the harvesting of various crops [7]. The choice of forage harvesting machine depends on many factors, such as harvested crop, the number and the size of fields, accessibility, time window available to perform the operation and the purchasing cost of equipment [7]. Additionally, in the case of the harvesting of voluminous low-value crops (for animal feed or energy source), the issues related to the selection and the purchasing of units are equivalent. Nevertheless, it represents the most highly mechanized operation; this system involves a large investment in equipment. Hence, it is economically practical only where a considerable volume of material is to be harvested each year [7,14]. Production of high-quality silage is an expensive operation, and poor selection of harvesting equipment may lead to an increase in farm costs and affect profitability significantly [7]. The increasing usage of renewable energy and diversity of used material sources are leading to the adaptation of harvesting machinery to the new forages and are evolving the harvesting operations into a complex system. Therefore, machinery is being lead toward universality and the increased requirements of available power and performance. Thus, consideration of fleet units involved in the silage production (trucks for transport, machinery for silage packing, etc.) and their suitability according to the field and machine capacity needs to be done during the investment planning and unit selection. Bottlenecks within transport or unloading operations can significantly impact the harvesting operation by reducing the operational capacity and increasing the production cost [7,16]. The balanced combination of forage harvesters and transport and storage units was discussed in the works of Buckmaster; Buckmaster and Hilton; Amiama et al.; Berruto and Busato; and Foulds: cycle analyses, spreadsheet implementation, simulation and linear programming models were applied for definition of the reasonable transport capacity requirements and to determine the suitable combination of resources according to the fields to harvest [16–20].

The increases in farm power through mechanization level enhancement and development of single farm use strategies of equipment lead to lower utilization rates and higher unit costs for agricultural machinery, thereby causing modifications of price policy and impacting decision-making regarding fleet management and machinery selection. At the same time, increasing demand and prices of machinery indicate that the volume of trade in agricultural mechanization inputs is large. Still, farmers face constraints that limit the profitability of their farming enterprises, and it is increasingly difficult to maintain and replace equipment [1]. The variability of choice and rapid development of new technologies facilitate the misconception of selection [21]. The key issue is how to enhance the efficiency and effectiveness of the machinery purchase and distribution of financial resources applied by farmers, regional economic communities and other cross-related trading mechanisms.

Various studies are dedicated to the cost-effective, continuous improvement of combine and forage harvester performance through modelling, simulation and optimization of both process design and component design. Harvesting performance evaluation, the impact of threshing, separation and cleaning systems, minimization of the grain losses, optimization of operation costs and logistic process have been discussed by Sørensen; Kutzbach; Bulgakov et al.; Philips; Sopegno et al.; De Toro et al.; Olt et al.; and others [6,22–27].

A workability prediction model and combine harvesting sizing were studied by Sørensen [6] based on grain moisture content. Harvesting cost and the efficiencies of different combine harvester fleets were discussed in the study of Olt et al. [27]. Impacts of machinery size on the optimization of timeliness losses and total costs of conventional cereal harvesting system were studied by Philips [24]. Regarding combine harvester fleet renewal, Bulgakov et al. [23] developed a mathematical model on the basis of integral equations with an unknown lower limit of integration. A web mobile application "Agricultural Machine App Cost Analysis" based on a cross-platform approach was developed by Sopegno et al. [25], allowing determination of machinery costs in different field operations, based on user expectations with customer-driven quality function deployment approach.

Models and software for the definition of farm needs and data elaboration for ensuring successful performance of farming operations are mostly conceptual ideas, rather than qualitative or quantitative ones; the diversity and complexity of available systems do not always meet the needs and expectations of real farms [5,25,28–32]. Therefore, farmers lack knowledge of up-to-date research, and lack simplified tools and methods for supporting the issues of merging production efficiency and optimization of costs. Simplification of the decision-making regarding machinery unit selection and acquisition remains unsolved. This emphasizes the importance of the development of provisional models for calculation and definition of optimal capacity of mechanical units according to the farm demands and financial resources assessment [6,12]. With that purpose in mind, economic evaluation with the consideration of technical parameters needs to take place before investment planning based on a complete estimation of the farm's development scenario and the role of machinery. Simplification of the practices for the definition of the eligible parameter–price relation for the machinery can reduce the complexity of the estimation, leading to the correct implementation of the resources [33].

The aim of the current study is to analyze the technical parameters of combine and forage harvesting equipment with the purpose of defining parameter-to-parameter and parameter-to-price relations so as to derive reference models for the definition of machine price, power, weight, tank capacity and working width that can be used as an indicative tool to estimate the required investments and resources.

2. Materials and Methods

The study is dedicated to the comprehensive analyses of high-performance self-propelled harvesting equipment for grain and forage crops. The reference database involves 155 commercial models of combine and forage harvesters' data concerning descriptive constructional and operational parameters and the list prices of the machines. The database has been created on the basis of harvesting equipment market analyses (market involved data from 2017), completed with machinery specifications provided by constructors and regularly updated thanks to the assistance of Informatore Agrario srl (Verona, Italy).

The collected information related to the producer, machinery system, design and performance were classified and homogenized for better understanding of the machine specifications and elements of the study (Table 1). The sorted data have been used for simulation of price/parameter prediction of harvesting machines with the application of a modelling approach. According to the initial evaluation of the dependencies, not all of the parameters were available or sufficiently characterized to provide predictive features; thus, they were not involved in further analysis. Specific reference for the study represents power, weight, grain tank capacity, working width and list price.

Table 1. Description of the considered data related to the harvesting machines according to the information provided by constructors.

Characteristic	Description/Type
Model	constructing company, series, name
Functional mechanism parameters	threshing, separation, cleaning (type, diameter, speed)
Type of threshing system	conventional, axial, hybrid
Levelling system	fixed, self-levelling, semi-levelling
Other parameters	tank capacity, power, pneumatics, etc.
Other equipment	standard tires, hydraulics, electronic controls
Dimensions	total length/height/width, weight
List price	basic machine configuration, without header

The study accounts for a large variability of models and constructors of harvesters available in the market, thereby allowing us to perform corresponding analyses and predictions. The range for minimum and maximum values of parameters gives evidence of the considered variables' scales within the current work (Table 2). Studied technical parameters and list prices of harvesting machines were set according to the manufacturers, set on the basis of unloaded weight without consideration of the header.

Table 2. The range for minimum and maximum values of the considered variables according to the dataset for combine and forage harvesters.

Variable	Value	
	Combine Harvesters	**Forage Harvesters**
Power, kW	110–480	300–790
Tank capacity, L	4200–14,500	-
Weight, kg	7600–19,500	11,000–17,800
Price VAT excl., k€	130–595	309–545
Weight power index, kg kW^{-1}	35.7–87.0	18.7–38.6

The dataset consists of the variation of combine harvesters with conventional, axial and hybrid threshing systems equipped for hillside harvesting with and without a self-levelling control system. The study includes 120 models of combine harvesters with an extensive range of power supplies of 110–480 kW needed for ensuring constant threshing and separating speeds of grain harvesting. In the case of forage harvesting machines, analyses based on 35 models involve the broad range of power from 300 to 800 kW needed for the provision of the specific length of the cut and speed rate of the cutting mechanism. Additionally, power high requirements are due to the universality of the forage harvester's application and their adaptation with various headers according to the cultivated crop specific needs.

For the definition of dependencies between variables and development of algorithms, data were studied with the application of linear and multiple linear regression analyses. The application of statistical analyses has been performed for the combine and forage harvesting equipment subgroups correspondingly. Microsoft Excel (Microsoft Corporation, Redmond, WA, USA) was used for the performance of statistical analysis, for the definition of the relevance of numerical/non-numerical variables and for their impacts on the price. The power, weight and tank capacity variables of the machines exhibited high relations and impacts on price formation; thus, we proceeded with regression analyses and elaboration of equation models.

According to the linear regression analysis data reported regarding coefficient of determination R, standard error and *p*-values. Linear models are considered as not-large models with a high degree of precision; nevertheless, the models are based on the defined functional parameters and represent robust and realistic outputs, and provide simplified details for decision-making and selection optimization. The simplicity of linear models allows for their broad application and integration by interested parties and farm management software (farmers, farm management applications and agencies, stakeholders, etc.) for evaluation and justification of machine parameters, requirements and forecasting.

For a complete evaluation of the parameters' predicational capacities and improvement of the forecasting features of the linear models, stepwise regression analysis was applied. The application of multiple regression analysis includes the consideration of qualitative parameters' impact on the price formation. Differently from linear regression models, multiple linear analysis allows one to identify and avoid misleading regression of variables and overfitting of studied data. Power, weight, working width and price underwent stepwise regression analysis; the list prices of the machines were not included between independent variables by being a function of machine performance. Application of stepwise regression analyses allowed us to increase the precision of the calculation of the variables and provided a better predicational output for decision support. Multilinear models of dependencies are considered more composite, and implementation may lead to several constraints, however—for definition or optimization of break-even points is needed. Multiple linear regression output was evaluated in terms of adjusted multiple coefficients of determination adjusted R^2 and standard errors.

3. Results and Discussion

3.1. Linear Modelling

3.1.1. Combine Harvesters

Applied linear regression analyses gave evidence of general trends and existing correlations valid for technical parameters of combine harvesters. Relatively high coefficients of determination were found between price and power (R^2 = 0.83), and between power and tank capacity (R^2 = 0.82). Slightly lower values could be recognized between weight and power (R^2 = 0.67), and between price and weight (R^2 = 0.65), as reported in Table 3.

Table 3. Linear models for technical parameters and prices of combine harvesters.

Power	R^2	**St. Error**	***p*-Value**
P = 0.00077Pr + 23.1	0.828	33.7	<0.01
P = 0.026M − 124	0.674	46.5	<0.01
P = 0.035C − 63	0.821	34.5	<0.01
Weight	R^2	**St. Error**	***p*-Value**
M = 0.022Pr + 8120	0.653	1510	<0.01
M = 25.8P + 8020	0.674	1460	<0.01
M = 0.98C + 5740	0.644	1530	<0.01
Capacity	R^2	**St. Error**	***p*-Value**
C = 0.018Pr + 3680	0.676	1200	<0.01
C = 23.4P + 3130	0.821	891	<0.01
C = 0.66M − 486	0.644	1250	<0.01
Price	R^2	**St. Error**	***p*-Value**
Pr = 1070P + 28,000	0.828	39,600	<0.01
Pr = 30.2M − 139,000	0.653	56,400	<0.01
Pr = 37.5C − 38,300	0.676	54,500	<0.01
Working Width *	R^2	**St. Error**	***p*-Value**
L = 0.0216P + 1.29	0.803	0.785	<0.01

C—tank capacity, L; M—weight, kg; P—power, kW; L—working width, m; Pr—estimated price, €. * Estimated from power model.

Compared to previously published linear regression analyses performed on seeding machines [34] and sprayers [35], combine harvesters models have, in general, a higher correlation between performance related parameters. This can be probably explained as a consequence of the lower number of companies that compete in the market: such a condition most probably reduces competitiveness and increases homogenization of performances and constructive principles.

The threshing unit is the dominant source of power consumption, and according to the types of combines, the requirements are different [10]. According to the studied database, conventional harvesting machines require less power (110–300 kW) than rotary ones, and have limited performance due to relatively limited material throughput (up to 9 kg/s), caused by the sizes of threshing-separating and straw walker systems, which led to the increasing of axial-flow threshing system application trends. The rotary combines provide better performance in terms of grain loss and grain damage but have an increased power requirement (230–480 kW). Due to a higher separating intensity in rotary threshing-separating system, the axial threshing units provide 50%–90% higher throughput capacity than the tangential ones, even though the specific power requirement (kW/(kg/s)) of the axial threshing system is higher by 16%–20% [10]. However, a combination of a tangential threshing and an axial threshing-separating systems, hybrid models have a higher material throughput, cause less mechanical damage of the grains and minimize threshing and separation losses. Prices for the corresponding types of models are identical due to the defined high correlation between power and price. Thus, during the selection procedure, considerations of the threshing and separating system need to take place not only for combine's capacity evaluation and the effective performance of an operation, but also for investments regarding the design.

Linear models were estimated for all the variables' combinations according to the linear regression analysis. Regarding the reference parameters, for each additional 1000 kg of the harvesting machine, a power supply of 26 kW has to be counted, while for the same weight (1000 kg), a volume of tank capacity of about 660 L has to be considered. The equation represents an approximate relation between weight and power that can be used to derive quick dimensioning of the expected power needed to operate a machine with a given weight according to current industrial practices.

Concerning needed investment, the average value of 1070 € has to be considered for each kW of engine power. Dealing with linear models, coefficients of determination are obviously in agreement with Pearson coefficients. Standard errors are in general relatively low, with higher uncertainty levels, especially in the case of linear regressions based on weight. However, the models provide good forecasting results, particularly in the case of high power/high weight machinery.

3.1.2. Forage Harvesters

The correlation matrix for forage harvesters has a slightly lower appearance in comparison with that of grain harvesters; however, the dependencies represent reliable values for further elaboration. Defined linear correlations represent the holistic view of the market; nevertheless, there is a limited number of observation models due to the small volumes of specialized machines produced (Table 4). However, developed linear dependencies allow one to perform a simplified calculation of variables, and can be considered as reference equations for model-based algorithms and software for farm management.

Table 4. Linear models for technical parameters and prices of forage harvesters.

Power	R^2	**St. Error**	***p*-Value**
P = 0.00172Pr − 266	0.894	39.3	<0.01
P = 0.0547M − 250	0.444	90.4	<0.01
Weight	R^2	**St. Error**	***p*-Value**
M = 8.14P + 9270	0.444	1100	<0.01
M = 0.0155Pr + 6470	0.488	1060	<0.01
Price	R^2	**St. Error**	***p*-Value**
Pr = 519P + 182,000	0.894	21,600	<0.01
Pr = 31.4M + 13,000	0.488	47,600	<0.01
Working Width *	R^2	**St. Error**	***p*-Value**
L = 0.011P + 2.61	0.558	0.83	<0.01

M—weight, kg; P—power, kW; L—working width, m; Pr—estimated price, €. * estimated from power model.

As a result of linear regression analyses, a strong correlation has been found between power and price (R^2 = 0.9); relatively low correlations were found between price and weight (R^2 = 0.5) and power and weight (R^2 = 0.44).

As has been stated, power availability is a very important factor for whole silage harvesting operation planning and management, performance efficiency and expected profit. However, a decision on the acquisition of a harvesting machine based on the power supply is not a guarantee of highly productive chopping or capacity. The operation performance and machinery adjustment (speed of cutter mechanism, feed ratio, length of the cut, etc.) have dominant impacts according to the crop and harvested field [13]. Producers launch harvesting machines with various large power supplies (up to 800 kW), but the operation of such a power sink has significant importance for the economic and environmental sustainability of the farm, which needs to be considered in the phase of decision-making regarding fleet renewal. Hence, with reference to the power–price correlation, approximately 519 euros per kW has to be considered in the phase of selection and purchase of forage harvesting equipment. Regarding the weight and power relation, 55 kW has to be considered per additional 1000 kg of a self-propelled forage harvester.

The capacity of the harvester is limited by engine power, feedrate and header capacity. The grain feedrate determines the actual yield rate [16]. The size of the header, machine speed, crop density and cutting height determine the federate, and therefore impact the performance of the header and header losses. Large working width is the simplest way to increase performance. But in the case of combine harvesters, it is also important to consider the type of the threshing-separating unit, which can compensate for the space limitation and allow one to achieve higher performance [9]. The basic composition of the harvesting equipment provided by constructors does not include the association with the cutbar header, and thanks to the large power supply availability, the same machine model can be flexibly equipped and operated with different headers for a variety of crops. Type of header, working width and number of rows are determined by the cultivated crop type, harvesting area, available time window, engine power, capacity of the harvester, available fleet and previous operation. Therefore, a priori it is not possible to have defined association of the harvesting machine and header with effective working width. On that note, the study of technical parameters was performed without the consideration of working width variation impact and correlation.

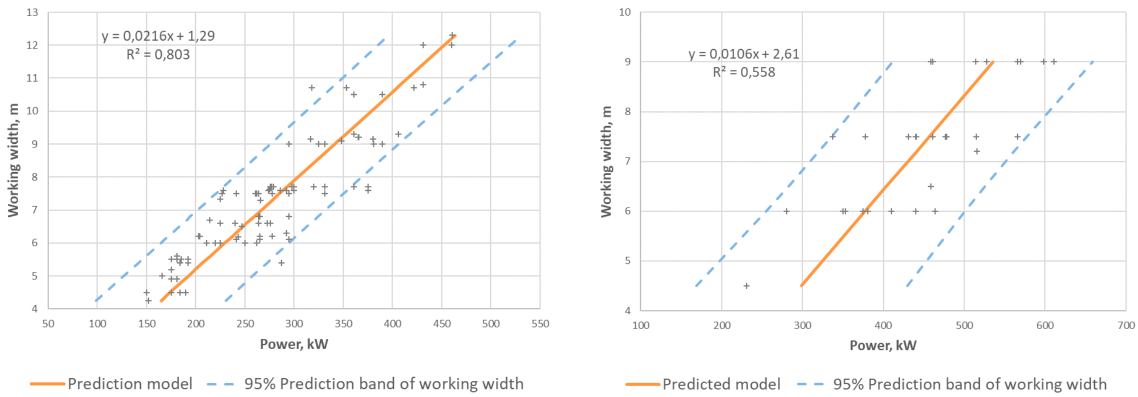
For the definition of reference working width size and possible association with harvesting machines, the used market of harvesting systems (including the combination of machine and header) was analayzed based on 165 models of the combine and forage harvesters. Data included a range of headers intended for the harvesting of different crops, available with working widths from 4.5 to 12 m and from 3 to 9 m for combine and forage crop harvesting correspondingly. The power range available for the current models of the study was in the frame of the general trend considered for the main studied database of machines (230–600 kW).

Regression model based on the used market of combine harvesters showed a satisfactory behavior at predicting the average working width that can be operated by a given power ($R^2 = 0.8$; p-value < 0.01). Prediction bands highlight how the potential of the model can be employed as a quick reference tool to get preliminary estimates on operable working width for a given power, even though for better accuracy of the association, more sophisticated consideration should be carried out taking into account other parameters different from the power of the machine (Figure 1). The low value of prediction ($R^2 = 0.6$) for forage harvesters is most likely due to the limited number of considered models. The model provides the possibility to assess the suggested working width parameter in the early stage of the machine selection and to avoid overestimation of power distribution related to the adjustment of cutter bar parameters. That allows performing complete planning of the reference parameters of the harvesting system and investment boundaries according to one's needs and preferences.

3.2. Multiple Linear Modelling

Progressive advances of technology applied in agriculture lead to the modification of operation planning and management [36]. In order to carry out correct planning, it is essential to determine the right combination of the resources, and to define the influences of parameters on the machine performance and price. Simulation models are considered balanced regulatory frameworks to support appropriate selection and help to shape sustainable distribution of resources.

The application of stepwise regression analyses allowed us to carry out a detailed evaluation of harvesting equipment technical parameters and their impacts on price formation. The multilinear modelling allowed us to elaborate equations with robust forecasting qualities with considerations of interdependencies of variables, including qualitative ones as well (Table 5). Models for the combine harvester group have higher precision of prediction due to the larger number of included variables. In the case of forage harvesters, the models have linear values, due to the limited number of the variables and models studied. All the final p-values for all of the coefficients are lower than 0.01.



(**a**) (**b**)

Figure 1. Linear regression models for working width on the base of the used market state for combine (**a**) and forage (**b**) harvesting machines.

Table 5. Equation models for response variables (power, weight, working width, price) determined by stepwise regression analysis.

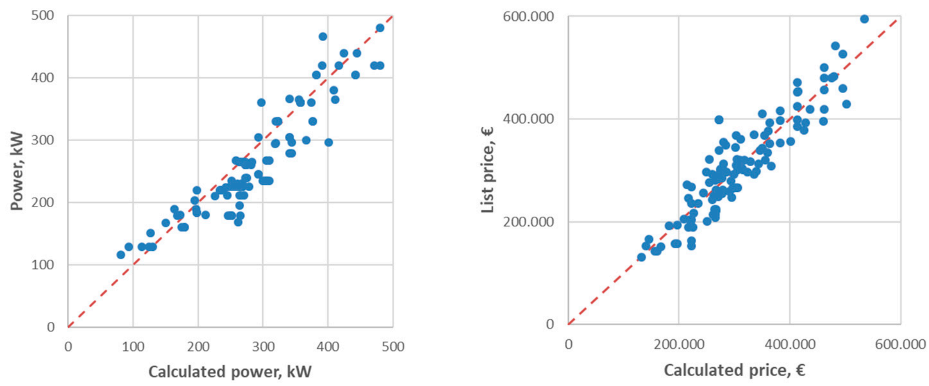
	Power	**Adjusted R^2**	**Standard Error**
Combine harvester	P= 0.0084M + 0.027C − 110	0.843	32
Forage harvester	P = 0.055M − 249	0.428	90.4
	Weight	**Adjusted R^2**	**Standard Error**
Combine harvester	M= 16.6P + 0.39C + 6780	0.688	1430
Forage harvester	M = 8.14P + 9270	0.428	1100
	Working width *	**Adjusted R^2**	**Standard Error**
Combine harvester	L = 0.00017M + 0.00065C − 1.11	-	-
Forage harvester	L = 0.0005M − 0.15	-	-
	Price	**Adjusted R^2**	**Standard Error**
Combine harvester	Pr= 890P + 6.9M – 28,000	0.837	38,500
Forage harvester	Pr = 519P + 182,000	0.892	21,600

C—tank capacity, L; M—weight, kg; P—power, kW; L—working width, m; Pr—estimated price, €. * estimated from power model.

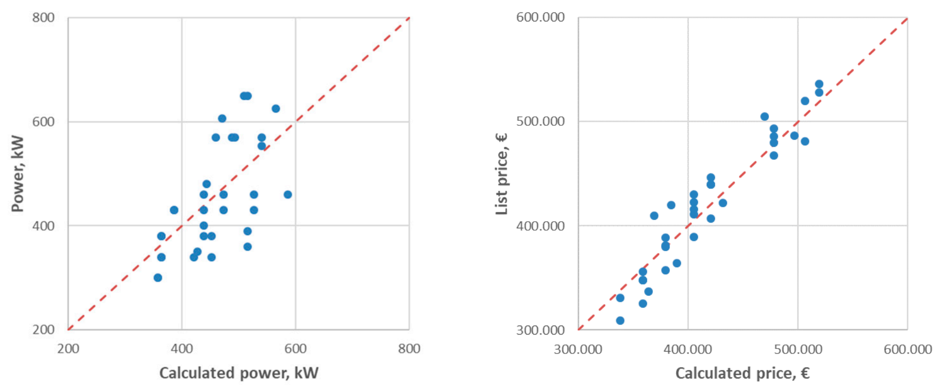
The impact of the self-levelling system (presence and type) on the price of the machinery was studied as a qualitative parameter. The study showed that investment planning regarding grain harvesting operation in the hillside landscape requires consideration of additional 40 thousand euros for the effective operational performance of the machine.

The increase of the throughput capacity of conventional combines can be achieved by the increase of the diameter (up to 800 mm) and the number of cylinder-concave units (two and more), the increase of the width of the tangential threshing unit (0.7–1.7 m and more) and other internal changes. As a consequence, the design changes will lead to an increase in the weight of the machine and power requirements. Rises in power requirements and the precision of the performance of the machine provided by various technical advances lead to the increase of the price of the machine. Accurate prediction of parameters is very important; however, it is very complex due to constantly changing throughput and machine settings during operation. Indicative models of technical parameters obtained in the study might be applied as references for the definition of the relative values of power, weight and price of harvesting equipment.

Model performance has been assessed for the parameters with the highest predictive qualities and importance in the phase of machinery unit selection (Figure 2). According to qualitative evaluation, the models can be suitable for the estimation of reference parameters and calculation of the initial investments contributing to fleet renewal.



(**a**)



(**b**)

Figure 2. Qualitative evaluation of the multilinear models for combine (**a**) and forage (**b**) harvesting machines.

4. Conclusions

The technical parameters of combine and forage harvesters were analyzed and reference models for definition of machine price, power weight and capacity were developed. For each group of harvesting equipment, linear and multilinear equations allow one to calculate the indicative values for highly correlated parameters and their relations to the price of the machine.

The developed linear models can be considered as reference models for definition of the machinery size and parameters that play key roles in the selection and purchasing of the machinery units. The proposed simplified solution can reduce the complexity of the estimation and lead to the correct implementation of the resources, thereby contributing to the sustainable management of economic and environmental resources. Multilinear models are more complex but provide a better prediction for the definition of the parameters and can be applied whenever more precise calculation is needed.

According to the analyses, with reference to the power-price correlation, for each kW of power, 519 euros needs to be considered for forage harvesters, and 1070 euros for combine harvesters; 95% of predictions are within ±20% of the actual value. Regarding weight and power relation, the operation of each 1000 kg of requires a 26 kW power supply for forage harvesters, and 55 kW for grain harvesters. The impact of design features of harvesting equipment in terms of threshing-separating system, and the presence of levelling control and their relations to the technical parameters were discussed. Working width's relation to the power was defined based on the used market analyses of harvesting equipment.

Regression model for combine harvesters showed satisfactory behavior when predicting the average working width that can be operated by a given power (R^2 = 0.8; p-value < 0.01).

Although harvesting represents a most highly mechanized operation, these machines involve large investments. Thus, the purchase is economically practical only where a considerable volume of material is to be harvested, for individual ownership of middle/big farms. Models might be applied for definition of the machinery management approach (machine purchase, rent or leasing) based on the farm actual economic evaluation and reference overview of the required investments. Furthermore, one might apply them to have a better arrangement of work, timeliness and independence in scheduling individual operations.

The linear and multilinear models herein allow for further implementation and combination with farm management systems and decision-making approaches as initial data for machinery performance assessment and cost predictions. Hence, price forecasting and definitions of initial investments might allow the parties involved to arrive at an economically practical decision regarding the operation management, and thus, to increase the efficiency and effectiveness of the machinery, purchasing and distribution of financial resources applied by farmers, regional economic communities and other cross-related trading mechanisms.

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