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Analysis of cost and performances of agricultural machinery: reference model for sprayers

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Abstract. Management of agricultural operations is currently rapidly changing caused by increased attention to the concepts of sustainable development and sustainable intensification. Enhancement of productivity and efficiency of agricultural machinery are the leading factors in sustainable agriculture. The complete application and exploitation of engineering advances require the revision of traditional agricultural machinery management process. The definition of the farm fleet (tractors and implements), as well as machinery planning and management, must consider different parameters, including not only the cost of the machines but also their dimensions, weight, working width, needed power, etc. All of this information related to an agricultural machine is eventually influencing the impact on productivity, on the return on the investment, and also on the environment.
The present work is aimed at identifying the most relevant parameters which are influencing costs and performances of sprayers, including tank volume, maximum flow, needed power, weight and price. The different parameters are analysed in a correlation matrix, in order to allow identification of dependencies and to extract reference models.
The study is based on linear and multiple linear regression analysis carried out on technical specifications of about 700 models of sprayers. Relevant correlations were highlighted between price and weight, between weight and tank capacity and in some cases between power and weight. Following such correlations, models have been proposed, which can be implemented in order to support the decision making phases.

Key words: agricultural machinery, sprayer, optimization model, stepwise regression, correlation analysis.

INTRODUCTION

Agriculture is moving toward sustainable intensification. Information technology developments applied in agriculture production are called to ensure sustainable development of the sphere and solve the main challenge of last decades – to produce more. According to the Strategic Research Report provided by the European Union for Agriculture and Rural Development nowadays agricultural production currently directs research towards increasing production per unit area, caused by population growth at the global level, the consequent increase in food requirements and limited resources (Zarco-

Tejada et al., 2014). Information-based and decision-making approaches of farm management are designed to improve the agricultural process by precisely managing each step, thus optimizing both agricultural production and profitability, leading to cost savings and also environmental benefits (Sopegno et al., 2016; Dubbini et al., 2017). However, the full exploitation of engineering advances requires the revision of traditional agricultural machinery management processes, such as:

- agricultural machinery planning methods (tractors and implements) (Bochtis et al., 2014);
- combination of different and appropriate technological operations (choice of machine or implement) (Fountas et al., 2015a);
- characterization of multiple parameters for ensuring the balance between economic, environmental and social issues (Fountas et al., 2015b).

Application of proper decision parameters in agricultural mechanization is not trivial since it supposes balanced choices and trade-off between proper machinery and technological operation based on the actual needs arising from farm size, crop or management approach, and other factors (Søgaard & Sørensen, 2004). The definition of the farm fleet (tractors and implements), as well as machinery planning and management, must consider different parameters, including not only the cost of the machines but also their dimensions, weight, working width, working speed (or efficiency), needed power, etc. All of this information related to an agricultural machine is eventually influencing the impact of that machine on productivity, on the return on the investment, and also on the environment.

One of the most critical agricultural operations is connected with plant protection: in particular, there is a wide variability of machines and implements devoted to the application of pesticides. The success of crop protection products (herbicides, pesticides and fungicides) depends on the effectiveness of their timely application and plays a vital role in ensuring better yields. Mechanization of application and correct selection of the appropriate equipment are the most important key issues of plant protection.

Sprayers play essential importance both for the cultivation of herbaceous crops, and for fruit tree crops or viticulture, as protection from adversity is, in many cases, a determining factor not only of quantity but also of production quality (Matthews & Thornhill, 1994; Matthews, 2000). The performance of crop protection machines and implements is estimated by relative balance between environmental contamination and biological efficacy (Duga et al., 2013). Which are caused by construction and operational parameters of the sprayers, treated plant features and environmental conditions.

The sprayers on the market are characterized by a considerable variety, both in terms of size and components, which makes them suitable for every type of crop and situation. Based on the cultivated crop, in general, the sprayers can be divided into two groups: ground sprayers and orchard sprayers. Representatives of the first group by themselves can be designed as attachments to tractors (mounted or trailed) and as individual machines (self-propelled) (Hunt, 1983), the second group include trailed or mounted mistblowers and tunnel sprayers.

The basic structure, however, proves to be substantially constant despite this variety and is characterized by some fundamental components that are always present regardless of the specific machine. The necessary components of any sprayer are a tank with agitator and strainer, a pump, a filter, a pressure regulator, valves, piping and nozzles

(Pimentel, 2002). Depending on the crop being treated, the applied protection and technology the main technical parameters are accordingly changed (weight, power, dimensions, etc.). Thereby contributing to a variation in productivity and performance, which are the fundamental factors for price formation.

The decision on the best solution for a farm is not easy since many variables are influencing costs and performances. Therefore the aim of the present work is to identify the most relevant functional parameters determining the performances and costs of sprayers. In particular, the study pays specific attention to tank volume, maximum flow, needed power, weight, working width and price. Regression analysis was then applied in order to determine the dependencies of the variables and to extract reference equation models, which can be implemented in order to support the decision making phases and optimize the choice of the machine.

MATERIALS AND METHODS

Reference database

The reference database was populated with the support of Edizioni l'Informatore Agrario: it reports the main technical characteristics and list prices of all the categories of machines on the Italian market and is updated annually thanks to the close collaboration with the main companies of the agricultural sector. The categories of agricultural machinery include tractors, harvesting machines, implements for tillage and sowing, spraying and crop protection, mineral and organic fertilization, hay-making, trailers, etc. Data (relating to over 6,000 machines in total) concern the technical characteristics in numerical or category format.

The work here presented is based on main technical specifications of 729 commercial sprayers of 26 different machine producers from Italy, Germany, Netherlands, Norway and Denmark. Considered data were as follows: constructing company, type of machine (field or orchard), model/series name, type of attachment to the tractor (self-propelled, mounted or trailed), weight, tank capacity and materials, maximum pump flow rate, working width, number of sections and spray nozzles, standard tires, list price, type of fan and diameter for atomizers, minimum power required and nominal engine power, or engine characteristics for self-propelled machines. Data provided were sorted, edited from errors, completed and a single database for the study was created. The range for minimum and maximum values of the considered variables in accordance with available dataset is presented in Table 1, which additionally helps drawing a brief picture of the machinery considered within the current work.

Table 1. The range for minimum and maximum values of the considered variables according to dataset

	Power, kW	Tank capacity, L	Pump flow, L min^{-1}	Working width, m	Weight, kg	Price VAT excl., k€
Mistblower	10–70	300–4,000	50–250	-	100–1,700	2–38
Tunnel	5–40	300–3,200	60–250	-	900–2,800	23–73
Field sprayer	5–100	120–6,000	40–520	9–32	200–5,000	1–100
Self-propelled	45–180	1,200–5,000	120–400	16–40	3,000–10,000	80–420

The dataset includes 453 implements for orchard crop protection and vineyards, 19 of which are tunnel machines. The designed and homogenised dataset for orchards is constituted by 143 mounted, 5 semi-mounted, and 305 trailed implements. The remaining 276 sprayers in the dataset are intended for field crop protection and are available in all possible varieties (35 self-propelled, 156 mounted, 8 semi-mounted, 77 trailed). Available data represent a clear figure of the present plant protection machine market and allow to produce comparisons and models for different groups of commercial sprayers.

Data analysis

This study investigates the correlation between functional parameters of commercial sprayers and their influence on the performance of the machines and price. To this purpose, data were classified into four main groups according to the type of machine (mistblowers, tunnel sprayers, self-propelled field sprayers, mounted/trailed field sprayers) and analysed separately. Main parameters were investigated: power, working width, weight, tank capacity, pump flow rate, price.

Statistical analyses were applied in order to design models describing the relationship between technical characteristics of sprayers. The relevance of the models was quantified by means of correlation studies and dependences modelled according to linear (1) and multiple linear (2) characteristic equations:

$$y = m_1 \cdot x + q \quad (1)$$

$$y = \sum_i m_i \cdot x_i + q \quad (2)$$

where x – and y – represent respectively independent and dependent variables; m_i – is the slope (or linear coefficient) related to the i-th independent variables; q - is the intercept between y and x variables.

For model development and analysis, Microsoft Excel program and tools were used. Excel spreadsheet was implemented to analyse data, to create the correlation matrices between abovementioned six parameters, and to carry out and interpret regression analysis. On the first step, simple linear regression was applied in order to understand correlations and dependencies between selected variables. Data are reported in simplified tables in terms of Pearson correlation coefficient r, slope m and intercept q of the linear models. As a second step, one of the methods of multiple linear regression (specifically stepwise regression analysis) was applied for estimating the relationships between the dependent and independent variables as an alternative to linear regression. Multiple linear equations are more complex and their implementation might be more difficult in simulated scenarios where optimization or definition of break even points are needed, however, they can be useful whenever a deeper description is needed for different parameters. The applied stepwise regression analysis allows to identify and avoid misleading regression of variables and overfitting of data. The regression model explains the relationship between response and explanatory variables. In our study case, the response variables were represented by power, weight and price; explanatory variables converged time by time to tank capacity, working width, weight, power and pump flow rate. Price was not included between independent variables, being itself a function of machines performances. Multiple linear regression output was evaluated in terms of adjusted multiple coefficient of determination (adjusted R^2).

RESULTS AND DISCUSSION

Linear modelling

Mistblowers

For the group of orchard sprayers, a linear regression analysis performed comparatively high Pearson coefficients in particular between weight and tank capacity ($r = 0.88$) and also between price and weight ($r = 0.82$), as reported in Table 2. Slightly lower correlation was also found between price and tank capacity ($r = 0.67$), as well as between price and pump flow ($r = 0.55$).

Table 2. Correlation matrix of Pearson coefficient for functional parameters of orchard atomizers

r	Required power, kW	Tank capacity, L	Pump flow, L min^{-1}	Weight, kg	Price VAT excluded, €
Required power	1				
Tank capacity	0.458	1			
Pump flow	0.467	0.41	1		
Weight	0.448	0.884	0.465	1	
Price VAT excl.	0.427	0.672	0.558	0.818	1

As a result of the linear regression, linear coefficient and intercept were estimated for all of the variables combinations. Results are summarized in Table 3. It can be noticed how a power supply of about 9.5 kW is needed for each additional cubic meter of tank capacity, while for the same volume, a weight of about 0.34 tonnes has to be taken into account. With regard to needed investment, a starting price of at least 4.7 k€ has to be considered, increasing by 4.8 k€ for each cubic meter of tank capacity.

Table 3. Linear coefficient and intercept matrix for functional parameters of orchard atomizers

		Required power, kW	Tank capacity, L	Pump flow, L min^{-1}	Weight, kg	Price VAT excl., €
m	Required power		0.0095	0.209	0.024	0.0012
	Tank capacity	22.04		8.819	2.275	0.094
	Pump flow	1.046	0.019		0.056	0.0036
	Weight	8.367	0.343	3.884		0.044
	Price VAT excl.	147.1	4.812	85.91	15.08	
q	Required power		30.46	16.79	28.25	28.53
	Tank capacity	208.3		88.84	-102.8	164.4
	Pump flow	73.19	94.91		86.39	79.51
	Weight	191.1	152.4	83.49		85.96
	Price VAT excl.	4,082	4,764	142.8	2,061	

Tunnel machines

Linear regression analysis on orchard tunnel implements gave lower evidence of a high correlation with respect to other implements analysed here (Table 4). This is most probably ascribable to the reduced number of models available in the market and a progress stage still under development. However, a relatively high Pearson coefficient was found between weight and tank capacity ($r = 0.88$) and also between price and tank capacity ($r = 0.70$). Slightly lower correlations were also found between pump flow and power needed by the machine to operate in standard conditions ($r = 0.54$), and also between price and weight ($r = 0.55$).

Table 4. Correlation matrix of Pearson coefficient for functional parameters of orchard tunnel sprayers

r	Required power, kW	Tank capacity, L	Pump flow, L min^{-1}	Weight, kg	Price VAT excluded, €
Required power	1				
Tank capacity	0.492	1			
Pump flow	0.538	0.309	1		
Weight	0.323	0.884	0.234	1	
Price VAT excl.	0.367	0.703	0.114	0.547	1

Estimated linear coefficients and intercepts are summarized in Table 5. It can be noticed how a power supply of about 8.4 kW is needed for each additional cubic meter of tank capacity, while for the same volume, a weight of about 0.7 tonnes has to be taken into account. With regard to the price, a starting investment of at least 27 k€ has to be considered, increasing by 13.6 k€ for each cubic meter of tank capacity.

Table 5. Linear coefficient and intercept matrix for functional parameters of orchard tunnel sprayers

		Required power, kW	Tank capacity, L	Pump flow, L min^{-1}	Weight, kg	Price VAT excl., €
m	Required power		0.0084	0.171	0.007	0.0003
	Tank capacity	28.65		5.731	1.130	0.0363
	Pump flow	1.694	0.017		0.016	0.0003
	Weight	14.73	0.691	3.385		0.0221
	Price VAT excl.	414.6	13.62	40.99	13.55	
q	Required power		8.11	-5.370	6.132	4.301
	Tank capacity	714.4		444.3	-745.5	-351.2
	Pump flow	108.7	119.5		111.8	126.3
	Weight	1,490	901.7	1,290		791.2
	Price VAT excl.	36,309	2,7030	38,290	20,120	

Field sprayers (trailed/mounted)

Relatively higher correlations between the considered parameters have been recognised after linear analysis in the case of trailed and mounted implements. As can be seen from the Table 6, there high correlations arise between weight and tank capacity ($r = 0.95$), price and weight ($r = 0.91$), working width and pump flow ($r = 0.87$); slightly lower values can be recognised between price and working width ($r = 0.85$), price and tank capacity ($r = 0.83$), weight and pump flow ($r = 0.83$), weight and working width ($r = 0.83$), working width and tank capacity ($r = 0.82$), pump flow and tank capacity ($r = 0.82$). The robustness of these results is supported by the numerosity of the related starting data set.

Table 6. Correlation matrix of Pearson coefficient for functional parameters of trailed/mounted field sprayers

r	Required power, kW	Tank capacity, L	Pump flow, L min^{-1}	Working width, m	Weight, kg	Price VAT excluded, €
Required power	1					
Tank capacity	0.505	1				
Pump flow	0.543	0.822	1			
Working width	0.569	0.822	0.870	1		
Weight	0.480	0.948	0.833	0.833	1	
Price VAT excl.	0.579	0.830	0.791	0.854	0.910	1

Estimated linear coefficients and intercepts are reported in the Table 7. With regard to the weight, about 0.94 t is needed for each additional cubic meter of tank capacity, or 0.15 t for each additional meter in working width. With regard to the price, a starting investment of about 1.2 k€ is needed, increasing by 21.2 € per kilogram. Alternatively, the price can be expressed also through the tank dimension, with about 18 € per litre of capacity. For working width L larger than 9 m, the price Pr can be expressed also as $Pr = 3{,}671 \cdot L - 29{,}552$.

Table 7. Linear coefficient and intercept matrix for functional parameters of trailed/mounted field sprayers

		Required power, kW	Tank capacity, L	Pump flow, L min^{-1}	Working width, m	Weight, kg	Price VAT excl., €
m	Required power		0.012	0.159	2.486	0.010	0.0006
	Tank capacity	21.88		10.01	152.8	0.951	0.038
	Pump flow	1.850	0.067		12.11	0.066	0.003
	Working width	0.130	0.004	0.062		0.004	0.0002
	Weight	22.29	0.945	10.56	154.2		0.039
	Price VAT excl.	589.3	18.03	209.4	3,671	21.17	
q	Required power		34.83	24.06	14.06	40.51	37.84
	Tank capacity	356.5		-308.2	-840.5	374.7	551.1
	Pump flow	80.41	79.37		-4,690	99.24	106.2
	Working width	8.977	8.904	4.181		10.21	10.23
	Weight	54.70	-235.2	-687.7	-1,145		156.0
	Price VAT excl.	-4,935	-2,115	-12,839	-29,552	1,207	

Self-propelled

In comparison with above mentioned three groups, for self-propelled sprayers, the high correlation is mainly associated with the power of the machines (Table 8). High Pearson coefficients were found between tank capacity and power ($r = 0.93$), price and weight ($r = 0.85$), as well as between weight and power ($r = 0.83$) or weight and tank capacity ($r = 0.83$). Slightly lower correlations performed between price and working width ($r = 0.79$), working width and tank capacity ($r = 0.75$), price and tank capacity ($r = 0.75$) or weight and working width ($r = 0.75$).

Table 8. Correlation matrix of Pearson coefficient for functional parameters of self-propelled field sprayers

r	Nominal power, kW	Tank capacity, L	Pump flow, L min^{-1}	Working width, m	Weight, kg	Price VAT excluded, €
Required power	1					
Tank capacity	0.932	1				
Pump flow	0.412	0.382	1			
Working width	0.733	0.750	0.208	1		
Weight	0.834	0.835	0.508	0.747	1	
Price VAT excl.	0.728	0.748	0.206	0.790	0.853	1

Estimated linear coefficients and intercepts are summarized in Table 9. Self-propelled machines exhibit a nominal which is typically higher than 42 kW and increases by 26 W per litre of tank capacity. The weight M ranges between 4 t and 10 t, and is about 54.5 kg per kilowatt of nominal engine power; related price can be expressed as $Pr = 37.6 \cdot M - 60{,}020$.

Table 9. Linear coefficient and intercept matrix for functional parameters of self-propelled field sprayers

		Nominal power, kW	Tank capacity, L	Pump flow, L min^{-1}	Working width, m	Weight, kg	Price VAT excl., €
m	Nominal power		0.026	0.258	4.951	0.013	0.0002
	Tank capacity	33.05		8.457	179.8	0.453	0.009
	Pump flow	0.660	0.017		2.255	0.012	0.0001
	Working width	0.108	0.003	0.019		0.002	0.00004
	Weight	54.55	1.539	20.73	330.2		0.019
	Price VAT excl.	2,095	60.75	369.5	15379	37.55	
q	Nominal power		42.58	52.20	8.803	37.37	74.47
	Tank capacity	-1,003		729.7	-1,085	21.98	1,291
	Pump flow	194.9	223.2		224.1	192.4	254.1
	Working width	9,725	13.49	17.77		11.71	15.26
	Weight	6,705	2,005	997.7	-900.1		2,994
	Price VAT excl.	-65,548	6,189	90,337	-162,680	-60,020	

Multiple linear modelling

In the simulation of different scenarios for optimization of agricultural machinery management (Boscaro et al., 2015; Pezzuolo et al., 2014), some variables play a particularly important role.

The needed power is relevant to understand the suitability in relation to the available tractors fleet and other available agricultural machinery. Also needed or nominal power have a major influence on fuel consumption, which is eventually determining the environmental impact in terms of gas emissions. Carbon footprint related to implemented machinery has to take into account also the mass of the machines, which is indeed another relevant characteristic. The latter is additionally important to foresee and possibly prevent soil stress, which is of major concern in the case of tank equipped machinery. Finally, the price is needed in many applications (Sopegno, 2016), where optimization of costs is needed to schedule most profitable management conditions. Thus, power, weight and price underwent multiple linear modelling. The table below (Table 10) reports the results of stepwise regression analyses, considering power, weight and price as response variables. In some cases, the relevant correlations revealed after the linear regression were sufficiently high to properly describe model equations, as was in the case of power for tunnel, self-propelled and field sprayer machines and in the case of weight and price for tunnel machines. The most frequent independent variables are tank capacity and pump flow, which appear in over 50% of the equations; in the case of the price, a relevant influence is determined by the weight of the sprayers, while the working width can be relevant for field and self-propelled machines. In most of the cases the models demonstrate reasonably high predictive ability, in particular in the case of weight and price estimation.

Table 10. Equation models for response variables (power, weight, price) determined by stepwise regression analyses

	Power	Adjusted R^2	Standard error
Mistblower	$P = 16.2 + C \cdot 0.007 + N \cdot 0.15$	0.300	11.8
Tunnel	$P = -5.37 + N \cdot 0.17$	0.248	10.7
Field sprayer	$P = 14 + L \cdot 2.49$	0.320	19.9
Self-propelled	$P = 42.58 + C \cdot 0.026$	0.864	12.4
	Weight	Adjusted R^2	Standard error
Mistblower	$M = 54.7 + C \cdot 0.32 + N \cdot 1.03$	0.792	120
Tunnel	$M = 901.7 + C \cdot 0.69$	0.768	271
Field sprayer	$M = -493 + C \cdot 0.77 + N \cdot 1.4 + L \cdot 29.47$	0.918	294
Self-propelled	$M = -11.23 + C \cdot 1.382 + N \cdot 9.03$	0.722	1,156
	Price	Adjusted R^2	Standard error
Mistblower	$Pr = -1121 - C \cdot 1.65 + N \cdot 34.9 + M \cdot 16.9$	0.718	2,586
Tunnel	$Pr = 27030 + C \cdot 13.6$	0.465	10,200
Field sprayer	$Pr = -13407 + P \cdot 217 – C \cdot 6 + L \cdot 895 + M \cdot 20.1$	0.850	9,127
Self-propelled	$Pr = -31142 – N \cdot 446.9 + L \cdot 4877 + M \cdot 34.87$	0.806	42,600

where C – tank capacity, L; M – weight, kg; P – power, kW; N – pump flow, L min^{-1}; L – working width, m; Pr – estimated price for different groups of machines, €.

Proposed equation models can constitute a reference for practical implementation of simplified forecasting and optimization approaches. Specifically, an application of the proposed price models is now ongoing in connection with estimation of costs connected with agricultural machinery. The models are being used by some regional Italian authorities to estimate supports for investments in modernization of agricultural fleets, in connection with the European Rural Development Programmes 2014–2020 (Zarco-Tejada et al., 2014).

CONCLUSIONS

One of the most important and at the same time vulnerable aspects of agricultural fleet management organization is the decision-making process, due to the wide range of machinery types and performances. The current study was carried out in order to investigate the correlation between functional parameters of commercial sprayers and their influence on the performance and price of the machines. Based on the output of two approaches (linear and multiple linear regression) it can be noted that the examined parameters revealed especially in some cases relevant correlations, which enable to model the most relevant characteristics of sprayers and the corresponding prices based on weight, power and tank capacity as explanatory variables.

Based on the proposed analysis, it can be highlighted how power has relevant influence only in the case of self-propelled machines where it highly correlates with tank capacity, weight and price. For other implements, power plays only a secondary role: this is mainly ascribable to the fact that needed power is not easily measured but is just estimated by manufacturers. Conversely, the weight has a rather relevant influence and is clearly correlated with tank capacity, in a different way according to the type of the studied machines. For the price, which is a target parameter for our study, all the considered parameters have quite an essential influence depending on the type of sprayer. From the Pearson correlation coefficient it can also be noticed some expected high correlation between weight and tank capacity, which eventually play a key role and impact on the price formation and on the performance of the machines.

The applied stepwise regression analysis proposed as an alternative option to linear regression, show a slight increase in correlations (quantified through adjusted R^2) thus providing more detailed prediction models. The developed multiple linear models are comparatively more complex (mostly not linear), however are intended for deep analyses and more accurate forecasting of required variables. In both cases the equation models resulting from the study can be implemented by agricultural machinery and farm management applications, programs or software as an initial reference for optimization of simulated scenarios.

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