Optimizing operational performance of field spraying from a task time and capacity perspective

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Title: Optimizing operational cost of field spraying from a task time and capacity perspective

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External/internal contributions:
Arhus University (AU) developed all models and model background used in this report. The input parameters selected and the case farm specifics for the example model calculations was discussed and agreed upon by AU and Danfoil A/S. AU performed and presented the results of the model output. AU evaluated the results and concluded the report

Abstract:

An important aspect of managing a farm is to acquire and operate the optimized machinery items in terms of size and capacity. This decision should be supported by analyzing the capacity and costs (variable and fixed costs) of the operation. This optimizes the operational performance (capacity) and contribution margin (costs) for the specific machine and thus optimizing the life-time overall performance of the operation. However, farmers tend to forget this long term aspect of the operational costs and instead focus on the initial investment of the

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equipment. This runs the risk of over time employ ineffective machinery, resulting in loss of overall farm competitiveness. As an example, often only the in-field tasks are taken into account, which distort the overall effects of changed spraying speed and application rate.

The focus of this report is to develop a model to determine how the parameters: i) tank size, ii) spraying speed and application rate, affect the capacity, CO_2 emission, amount of road transport, total spraying cost including depreciation and interest, total time consumption and initial investment of the sprayer. Thus giving informed guidelines from which the farmer can decide how the optimal sprayer for his farm should be specified from an operational aspect. The agronomic aspect is outside the scope of this article, but is well documented in the literature (e.g. Matthews et al., 2014).

Results show that lowering the application rate (water volumen) is a key factor in optimizing the operational performance and costs for the spraying operation. It is shown that in conventional crops, reduction of the water volume rate can provide an additional contribution margin of between 15 to 18% depending upon 5 or 6 treatments in the season. Furthermore, a reduction of the CO2 emission by 29% can be achieved at the same time due to reduced transport to/from the filling location.

Introduction

Task time models allow users to estimate how much time can be expected to be spent in the field for specific machine operations. It is the key tool for assessing the capacity of different machine types or machines of different sizes or setups. The user can change a number of input parameters so that the labour requirement and machine capacity can be adapted to the conditions and requirements on the individual farm.

Plant care in the form of pesticide application by spraying is one of the key operations executed during the cropping season. Even if the spraying operation has unique characteristics in the form of combined filling, transport and in-field work, the spraying operation as such are described by the same general features and model elements as other field operations. The following below model can describe all work processes involved with in-field work, here spraying [see for example Sørensen et al., 2014]:

$$A = \left(\frac{h * 600}{v * e} + \frac{p * b * n}{e * (1+a)} + k + s * h\right) * (1 + q) \qquad (1)$$

where ***A*** is the labour requirement in [min]; ***h*** is the size of the field in [ha]; ***v*** is the effective working speed in [km/h]; ***e*** is the effective working width in [m]; ***p*** is the time for turning in [min per turning]; ***b*** is the field width in [m]; ***n*** is the number of turnings per pass (normally n = 2); ***a*** is a model parameter dependent on field shape and travel pattern (a = 1 in the case of driving back and forth in the track); ***k*** is the turnings on headland in [min per field]; **s** represents the stochastic crop and soil stops, adjustments, control, tending of machine in [min/ha]; and ***q*** is

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an assessed rest allowance time amounting to 5% additional time in min. A further description of the model can be found in the appendix.

The objective of this report is to adapt the above model structure to be able to utilize georeferenced field data from a given farm, and then next, analyze what effect changing inputs of tank size, water volume rate, forward speed during spraying, and initial investment of the sprayer has on the following output parameters which is of key interest to the farmer:

- Capacity in [ha/hour]
- CO_2 emission per hectare [CO_2/ha]
- Amount of road transport
- Total spraying cost incl. depreciation and interest
- Total time consumption
- Investment of the sprayer

The agronomic requirement as determining for the actual required value of the input parameters is outside the scope of this article, but is well documented in the literature (e.g. Matthews et al., 2014). By performing a parameter variation on the model, it is possible to calculate what the relative impact of each parameter is on the mentioned outputs. This will provide new knowledge and in turn give farmers a tool for better understanding and adapting the sprayer operation to the individual farm, optimizing for both time consumption, cost and impact on fossil fuel consumption.

Model structure

The model for spraying is divided into the following sub models and subtasks:

- Filling
- Road transport
- Field work

As the size of the tractor required to pull the sprayer is dependent upon the size of the sprayer, specifically the tank size, it's assumed that a 150 hp tractor is sufficient to pull a 3.000 l trailed sprayer - whereas a 250 hp tractor is required to pull a 10.000 l trailed sprayer. For the calculation of other tank sizes and their effects on the CO_2, fossil fuel consumption and operational cost of the tractor, simple linearization is used.

It is assumed that a 3.000 l sprayer can be filled with a filling capacity of 150 l/min and a 10.000 l sprayer can be filled with 500 l/min.

The purchase price of the sprayer will also vary with the size and whether or not the sprayer is equipped with air spraying technology - see below table. The air spraying technology will allow the sprayer to utilize less water than a sprayer without air spraying technology, thus increasing the capacity of the sprayer by reducing the water volume rate and the number of fillings.

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Sprayer tank size [L]	With air [DKK]	Without air [DKK]
1.000	400.000	250.000
3.000	650.000	500.000
6.000	950.000	750.000
12.000	1.500.000	1.200.000

Table 1: Overview of the initial price for sprayers of different tank sizes and with/without air spraying technology.

Initial filling of sprayer tank

Initially, the model assumes that the sprayer is empty and needs to be filled with water and addition of pesticides into a tank mix. Dependent upon the input parameters, this will have an effect on the temporary model outputs

- CO_2 emission
- Diesel consumption
- Salary to the driver
- Cost of service to the tractor
- Time required to perform the task

Driving on the road to the first field

As the sprayer is initial filled with water and a tank mix with pesticides, it needs to be transported to the field. Based on the geolocation of the farm, the Google route API is utilized to calculate the optimal route from the filling point to the field, thus providing the distance in meters. Again dependent upon the input parameters, a given effect can be calculated on the temporary model outputs. At this point, the outputs only holds the values for the filling, subsequently, they are now updated with the drive contribution, as shown in Equation 3 for the time parameter:

$$\text{(3)} \qquad Time\_New = Time\_Current + Time\_Driving$$

Field work

As the sprayer has now reached the field, it can start executing the spraying, described by Equation (1) with the given input parameters. It can be calculated whether or not the entire field can be sprayed with the current amount of water in the tank. If the entire field can be sprayed, the model outputs are updated with the task times for the fieldwork, as shown in Equation 4 for the time parameter:

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(4) Time_New = Time_Current + Time_Field_Work

If the whole tank amount of water is used for the current field, the calculations follow Equation (1) regarding task times, etc. However, if only a certain amount of water is used for this specific field, this amount is deducted from the current tank amount, as shown in Equation 5. This reduced amount is then used for a second field.

(5) TankVolumen_New = TankVolume_Current - WaterUsedInField

Driving on the road to the next field

If the sprayer still contains a certain amount of water, it can continue to the next field. As before, the distance is known from the geolocation of the farm and the fields utilizing the Google route API. As before, the temporary model outputs are updated.

Next field work

When the sprayer has arrived at the next field and it is ready for spraying, it can be calculated whether or not the entire field can be sprayed with the specific amount of water left in the tank. If there is sufficient water to spray the entire field, the sprayer will spray the field and continue to the next field. However, at some point, a field cannot be completed with the water amount left in the tank, and in this case, only part of the field will be sprayed - then the sprayer needs to be transported back to the filling point for refilling. The amount of hectares not treated will be stored in the model as a variable.

Driving on the road to the filling point

As the sprayer needs refilling with water and tank mix of pesticides, the distance from the current field to the filling point is now calculated using the Google API. The effect of the transport is stored as temporary model variable.

Re-filling

As with the initial filling, the sprayer will be completely filled - and the temporary model variable is updated with the contribution of this operation.

Driving to the partly sprayed field

The sprayer now needs to return to the partly sprayed field, and finish the remaining area. When the job is completed, the temporary model outputs are updated and the sprayer needs to be transported to the next field.

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Calculation of temporary model variables

Based on the georeferenced data for the specific farm (field locations, field sizes, etc.), the model will incrementally keep updating the temporary variables mentioned above, based on each sub models contribution and the specific input parameters. The calculations will be based on average values for the operational parameters, and these values may not be numerically correct with what can be achieved on the specific farm - as more detailed logistic optimized planning is typically applied. However, multiple calculations may be used to relatively calculate the impact of changing a specific parameter. For this purpose, a benchmark is required, and in the following, the benchmark sprayer is described together with the georeferenced data from a real farm.

Case farm and benchmark sprayer

A case farm in terms of field sizes, field locations, etc. is specified. For GDPR reasons, the identity of the farmer cannot be disclosed - however the georeference data on field locations can be seen in figure 1:

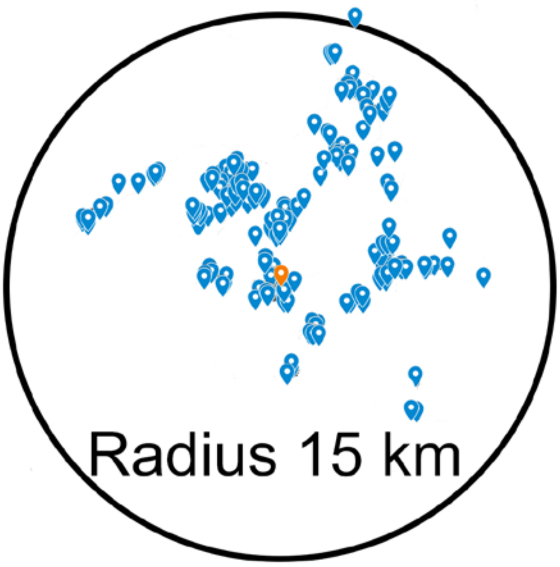

Figure 1: Georeferenced data from a farmer, where the filling point is located at the orange marker, where the sprayer is refilled with water and addition of pesticides. Each of the farmers fields is represented with a blue marker. All fields are located within a radius of 15 km from the filling point, however most fields are located to the North-East and all closer than 15 km to the orange filling point.

The farmer used for benchmarking grows the following crops: 640 ha potato, 135 ha seed grass, 787 ha regular crops, like cereals and rape. The farm has a total of 1.562 ha divided into 164 fields all within 15km of the filling point. The average distance to the filling point from the field is 8,8km. The average distance between fields is 1,8km. The average field size is

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9,52 ha, ranging from 0,21 ha to 51,49 ha. The farmer only uses one filling point, which is marked with the orange marker. It's estimated that the farmer can average 15 km/h on the road, including public roads and field roads

In order to perform a parameter variation, a benchmark sprayer setup is selected composing of:

- Boom width of 36m
- Tank size 4.000 l
- Application rate 175 l/ha for general crops and 200 l/ha for potatoes. For simplicity, only 200l/ha is used in the remainder of this report
- Average spraying speed of 8 km/t
- Investment cost 577.155 DKK - without air spraying technology

Effects of various parameters on sprayer capacity

By varying the benchmark sprayer parameters above, the influence of these parameters on the model output parameters as compared with the benchmark sprayer can be seen in Table 2. The table show the change (%) of varying the parameters (tank size, working speed, application rate, tank size + application rate) one at a time.

Parameter	Tank Size	Spraying speed	Application rate	Tank Size and application rate
Benchmark value	4.000 L	8 km/h	200 l/ha	4.000 L and 200 l/ha
Actual parameter value	12.000 L	14 km/h	50 l/ha	12.0000 L and 50 l/ha
Results of parameter variation				
Capacity [ha/hour]	+ 47%	+ 11%	+ 55%	+ 77%
CO_2/ha	+ 18%	N/A	- 29%	+ 2%
Road Transport	- 56%	0 %	- 62%	- 76%
Total spraying cost incl. depreciation and interest	- 6%	- 9%	- 26%	- 10%
Total time consumption	- 32%	- 10%	- 36%	- 44%

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Initial investment of sprayer	208%	0%	130%	260%

Table 2: Key model output change based on sprayer parameter variation,. The last table column represents the combined effect of a 12.000 l sprayer with an application rate of 50l/ha.

Capacity

The capacity of the sprayer needs to be sufficient for timely spraying in a year with a limited number of spraying hours. However, it can be difficult to obtain precise quantitative numbers on what capacity is needed for different types of farm size and for different crops in terms of timeliness, besides general guidelines. However, it is widely recognized that timeliness is a very important aspect of maintaining maximum effect and limiting use of pesticides (e.g. Landforsøgene 1999). As can be seen from Table 2, reduction of application rate is the single most efficient way of increasing the capacity. However, the marginal gain is reduced as the capacity increases - increasing the tank size provides 47% gain and lowering the application rate provides 55%, respectively. However, a combined change only increases the capacity by 77%.

Emission of CO_2/ha

The model does not account for a possible increase in the diesel consumption as the spraying speed is increased from 8 km/h to 14 km/h, thus this is omitted from the table. However, increasing the tank capacity will increase the emission of CO_2/ha by +18%, whereas decreasing the water volume rate will reduce the emission of CO2 by -29%. Also, if the tank size is increased and the application rate is lowered, the CO2 emission is almost equal to that of the benchmark sprayer (-2%) even though the capacity is increased by 77%.

Road transport

As sprayers are large and relatively slow machines, farmers should minimize road transport in order to minimize the disturbance of the regular faster traffic. Minimization of road transport is achieved by minimizing the water volume rate and maximization of the tank size, as this will minimize the amount of water transport on the road from filling point to field. Reducing the water volume rate to 50 l/ha and increasing the tank size to 12.000 l, reduces the road transport by 76%.

Total spraying cost including depreciation and interest

A key aspect is the total cost of the spraying operation. Often farmers tend to focus on the initial investment of the sprayer alone, however, the operational cost incl. depreciation and interest is a better way to compare costs and technology. For the benchmark sprayer, the operational cost is 71% of the total cost including depreciation and interest, whereas it is only 56% for the setup with a lower application rate. As can be seen from table 2, this reduced the operational cost incl. depreciation and interest by 26%, which is a significant saving.

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The 26% savings in total operational cost including depreciation and interest is equal to a reduced cost of 0,22 kr/l for each ha pr. treatment. If a field needs e.g. 5 treatments in a year, and the average water consumption can be reduced by 150 l/ha, this will amount to a saving of 168 kr/ha. If a field needs 6 treatments, the saving will be 202 kr/ha. This is a significant saving in regular crops (cereal and rape) where the surplus might average 1.133 kr/ha. (Statistics Denmark, 2021). So even though the initial cost of the technology is 130% more expensive, it will still provide the farmer with an additional contribution margin of 14,8% for 5 treatments and 17,8% for 6 treatments.

If the interest rate will continue to drop as has been the case in the recent years, the overall savings will be even bigger if the farmer reduces the water volume rate for spraying.

For the calculation of the initial investment, the following basic values have been used: interest including inflation is set at 2%; estimated scrap value 10% of initial cost after 12 years or 1.800 hours of usage (Farmtal Online, SEGES, 2019). Maintenance of the sprayer is set to 109 dk/hour (Farmtal Online, SEGES, 2019). Tractor costs including maintenance, depreciation and interest are estimated to be in the range of 200 - 279 dkk/hours for the 150hp tractor and 238 - 339 dkk/hour for the 250hp tractor.

Total time consumption

As can be seen from table 2, it is more effective to lower the application rate than increase the tank size However, increasing the spraying speed is significantly less effective. This illustrates the importance of applying a total operation perspective, instead of limiting the scope to the in-field operation. Almost doubling the speed to 14 km/h only provides a timesaving of 10% and corresponding increase of the capacity. By increasing both the capacity and lowering the application rate, it's possible to decrease the time consumption by 44%, whilst maintaining a safe working speed of 8 km/h.

Initial investment of sprayer

The initial investment of the different setups vary significantly, and therefore it is an important parameter. However, as can be seen, the less expensive sprayer is actually the one with the highest operational cost - the by far most cost effective parameter is lowering the application rate. Even though it is 30% more expensive, the total operational cost including the depreciation and interest of the sprayer is 25% cheaper. The additional fuel consumption used by driving faster in the field is not included in the calculations, whereas the 9% reduction in operational cost by increasing the spraying speed to 14km/h might be slightly lower than shown in table 2.

Discussion

Results from the model show that increased tank size, increased spraying speed and reduced application rate all increase the capacity and reduce the total spraying costs including

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depreciation and interest of the sprayer. Increased working speed is often used as a simple way to increase capacity, however, the model shows that increasing the speed from 8 to 14 km/h only provides a total time saving of 10% and corresponding capacity increase. In comparison, the drift from the sprayer increases significant when increasing the spraying speed from 8-12 km/h (Syngenta, 2021).

Increasing the tank size from 4.000 to 12.000 l reduces the time consumption by 32%, which is significantly more than increasing the speed, and it also reduces the total spraying costs including depreciation and interest of the sprayer by 6%. However, increasing the tank size has a negative impact on the CO_2 footprint of the spraying operation increasing the output of CO_2/ha by 18%. Furthermore, heavy machinery will result in structural damage to the soil and increase the emission of climate gasses.

Reducing the application rate from 200 to 50 l/ha provides a time saving of 36%, while reducing the total spraying costs including depreciation and interest of the sprayer by 26% and the emission of CO_2/ha by 29%. The model showed that by both increasing the tank size and reducing the application rate, the CO_2/ha remained near neutral at +2% while reducing total spraying costs including depreciation and interest of the sprayer by 10% together with a a reduction of the time consumption by 44%. For various arable crops, reduction of the application rate can provide an additional contribution margin of between 14,8% to 17,8% depending upon 5 or 6 treatments per crop per year. In conclusion, the optimal way to increase capacity whilst lowering operational costs and reducing the impact on the environment is to reduce the water volume rate, but with a specific consideration to obtain sufficient spray deposit on the spray target.

Parameter change	Tank Size	Spraying speed	Application rate	Combined tank Size and application rate
Total time consumption	++	+	++	+++
CO_2/ha	--	N/A	+++	-
Drift	0	---	0	0
Total spraying cost incl. depreciation and interest	+	+	+++	+

Table 3: Based on the parameter variation, the effect of the various parameters are shown on relevant output parameters. The effect of each parameter is represented by + and -. For a very good performance +++ is given, the performance decreases to --- which is a very poor performance.

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Conclusion

There is a general agreement that timeliness of the spraying operation is an important factor, both in maximizing yield - but also in reducing the amount of pesticides that is necessary to effectively protect the crop. However, it is difficult to obtain precise quantifications of the timeliness effects and calculate the savings and pesticide reduction based on an increase in capacity. This is to a high degree a result of varying conditions (weather, disease development, etc.) associated with each spraying operation. If available, the inclusion of a comprehensive timeliness function would improve the model and enable more efficient management and optimization of the spraying capacity. Further research and studies are required in order to uncover the important effects and implement them into the model in a way that can quantify the economics and environmental impact.

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Appendix

Description of the variables:

The first part of the Equation (1) expresses the net work of the sprayer. The effective working speed will be lower than the theoretical one displayed by the tractor speedometer, for example as a result of wheel slip. Also, in some cases the effective working width will be smaller than the theoretical one caused by overlap.

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The second part in Equation (1) expresses the estimation of turning times excluding turnings in the connection with the working of the headlands, as these are estimated separately. The width of the field, *b*, is the actual width of the field minus potential side headlands, which is present in the case of initial driving around the field. The width of the field is estimated as a function of the shape and size of the field. The turning time, *p*, is defined as a weighted average of all turning times.

The parameter, *a,* denotes the number of turnings in relation to the working width, *e,* and the parameter, *n,* equals the number of turnings per driving round. In the case of a rectangular field, *a* equals 1, if the driving path is forth and back, in subfields or around the field. In the case of an right-angled triangle, *a* also equals 1, if the driving path is forth and back along one of the catheters, while it will exceed 1 in case of a driving path around the triangle or along the hypotenuse. As an example, for a right-angled triangle, *a* is estimated as:

$$a = \frac{\cos B + 1}{\sin B}$$

where *B* is the angle in degrees to the adjacent angle of the field width *b*. In many cases, *n* equals 2 and *a* equals 1, indicating that Equation (1) is relaxed

Turnings as part of working the headings are modelled with the parameter *k*. This parameter sums the number of turnings at the start and finish of the operation in question and is independent of the size of the field and as such constant for a given field and implement. The total turning time for the headings is the sum of the individual specific turnings.

The parameter, *s,* sums the operational interruptions caused by crop and soil conditions, time for adjustments, maintenance, control, *etc*., which is assumed to be area dependent and it is a multiplex of the workable area. The indications are that *s* is highly variable and dependent on the local conditions, like the presence of stones in the field, soil characteristics, terrain, machine capability and the ability of the machine operator.

The rest allowance, *q,* amount to 5 % of the direct estimated labour requirement. Often, the models also are extended with supplemental labour requirements for daily preparation and transport of material and crew to and from the fields. Normally, this addition is assessed to 10 %, but is not used in the case of relative comparisons.

Additional model elements needed for the spraying operation

As mentioned, the spraying operation requires auxiliary works, like filling of the tank with water and chemicals and transport to and from the field, which must be added to Equation (1) to get the total work for the sprayer.

Transport:

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$$T1 = \left(\frac{t2 \ x \ n \ x \ 0{,}12}{v3 \ x \ h2}\right) x \ (1+q)$$
(2)

Number of fillings:

$$N = \frac{h2 \ x \ z}{w}$$
(3)

Filling time:

$$l1 = \frac{(m \ x \ n)+(c1 \ x \ h2 \ x \ z) x \ (1+q)}{h2}$$
(4)

where,

T1 = work needs for transport by spraying, min pr. ha

l1 = work needs for filling water and chemicals, min pr. ha

t2 = transport distance, meter

v3 = driving speed on road, km pr. hour

n = number of fillings, increased to an integer

h2 = area sprayed without emptying and cleaning the sprayer, ha

z = dosage, liter pr. ha

w = filling in tank, liters per time

m = drive to and from filling + prepare and finish, min per time

c1 = filling, min pr. 100 liter

q = personal breaks usually 5 % addition

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