Workability and Machinery Sizing for Combine Harvesting

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Abstract

Harvesting costs make up 30% of overall in-field machinery costs. In addition to this, indirect machinery costs may be incurred through timeliness effects, i.e., reduction in crop yield and quality caused by inefficient scheduling of machinery operations. Optimal work organization and machinery utilization are essential elements in achieving cost reductions, requiring detailed quantifications of harvesting workability and machine performance. This study has adapted models predicting harvesting workability as governed by the crop moisture status. The hourly course of grain moisture status after maturity was simulated for a 30-year period, allowing for the prediction of the number of workable harvesting hours under different weather conditions, at different moisture thresholds, and for different localities. A farm-level optimization model has been used to depict the potential effects of different economic-incentive options. Results show that the utilization coefficient, expressing the potential harvesting time as a fraction of total daytime, varies considerably depending on the type of crop and moisture thresholds, e.g., ranging across types of crops from an average 21 to 36% for the 18% moisture threshold. Additionally, indications are that winter barley may permit 15–25% more harvesting hours than spring barley. The influence of the geographical locality indicates 15–40% higher utilization for western Denmark than for eastern Denmark due to climatically differences. Independently maturing crops, dispersion of maturing periods, harvesting time, and in-field machinery efficiency all affect work organization and optimal machinery size and may reduce the capacity demand and costs considerably.

Keywords: combine harvesting, grain moisture, timeliness, workability, machine sizing, machine costs

1. Introduction

Labor and machinery dominate all other cost categories in arable farming and much is to be gained by adapting and balancing resources according to the actual needs arising from farm size, crop plan, etc. In this context, grain harvesting is a good example of compromise machinery management, highlighting the inherent complex evaluations. The harvesting costs make up 30% of the total machinery costs, ranging from 404 euro to 943 euro per hectare (Jacobsen, 2000). This emphasizes the need for developing robust methods for choosing the optimal harvesting equipment.

The analysis and prediction of agricultural machinery performance are important aspects of all machinery management efforts (Witney, 1995). Although there are numerous data depicting the net capacity of combines, on-farm surveys show that the actual field performance differs considerably. Elrick (1982) stated that the slowest 10% of combine operators are only half as fast as the fastest 10% over the whole harvest season when the same combine model is used. When field operations, such as harvesting, are analyzed the primary activity is that of carrying out the operation. Although some nonproductive activities (turning time, adjustment time, etc.) are unavoidable, the goal is to minimize the sum of these nonproductive activities, as they may total as much as 40% (Henrichsmeyer et al., 1995). In order to fully capture the structure of a predictive combine performance measure, the notion of separated work elements and task times relying on detailed time measurement must be invoked. The quantified work elements may be used for aggregation in work-budgeting models.

Previous efforts have included a number of modeling approaches to support farm machinery selection. The approaches involved simulation (e.g., Audsley and Boyce, 1974; McClendon et al., 1987; Abawi, 1993), linear programming techniques (e.g., Nilsson, 1972; Bender et al., 1990; Jannot and Cairol, 1994; Parmar et al., 1996), or a combination of these modeling and solution techniques (Tsai et al., 1987). Glen (1987) concludes that machinery requirement models often become very complex, requiring large quantities of input data that are not easily available.

One of the most crucial pieces of information for determining machinery sizes is the number of potential field working hours (e.g., Audsley, 1984; Ekman, 2000) contained within the term *workability*. Previous working-days criteria for combine harvesting include threshold values for past amounts of rainfall (Audsley and Boyce, 1974) and the combination of rainfall thresholds and algorithms for grain moisture content (e.g., Philips and O’Callaghan, 1974; Atzema, 1994). Explanatory models suggest that prediction using grain moisture content, in conjunction with meteorological data, is the most promising working-day criterion, especially if operates on an hourly basis (e.g., Goense, 1987; Atzema, 1990).

The approach described here involves an analysis and modeling of the harvesting operation based on a level of aggregation consistent with the accessible data related to machinery performance and workability. The machine performance is based on detailed farm-specific task time models and the workability is based on physical-biological crop moisture content models.

2. Objectives

The objective of this study was to optimize harvest machinery. This included investigating and modeling the operational performance of the harvesting process and the derivation of preharvest crop moisture models, specifying a number of crops and based on a comprehensive number of parameters affecting the moisture content. The latter effort included developing a specific model for dew occurrence. The objective also included estimating a utilization factor, defined as the potential operation time as a percentage of the total time, for different moisture content thresholds, types of crops, and geographical locations. The specific objectives were:

1. to analyze and model the technical and operational characteristics of the combine harvesting process
2. to analyze and develop simulation models for predicting crop moisture and harvesting workability
3. to develop harvesting strategies for minimized costs.

3. The model

The comprehensive analysis of the harvesting process involves a number of modeling approaches and the variables included in the models fall into the following categories:

1) Machine performance
    a) machine capacity
    b) labor requirement

2) Workability
    a) length of harvesting period
    b) potential harvesting hours
3) Economics
    a) fixed costs
    b) operating costs
    c) optimal harvesting capacity

3.1. Machine performance

The basis for the operational data used in the quantification of the harvesting capacity was 65 on-farm surveys. The surveys entailed detailed time-motion and method studies with specific reference to the labor and machinery requirements. The total time for each machine used in the harvesting process was divided into time elements. These time elements included operation time (effective field time, turning time, unloading, etc.), ancillary time (adjustments, repairs, disturbances due to crop or soil, relaxation allowance, etc.), waiting time and preparation time.

The collected data were used to develop a planning model for the harvesting capacity:

$$OC = \frac{60}{(((\frac{h\times 600}{v\times e} + \frac{p\times b\times n}{e\times(1+a)} + k + (s\times h))\times\frac{1}{h}) + (\frac{m\times u\times 1000}{l} + (u\times c)))\times(1+q)} \qquad (1)$$

where OC is the overall capacity (ha h^{-1}), h is the size of field (ha), v is the working speed (km h^{-1}), e is the effective working width (m), p is the time for turning (min per turning), b is the field width (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 swath), k is the turnings on treatment of headland (min per field), s represents the stochastic crop and soil stops, adjustments, control, tending of machine, etc. (min ha^{-1}), m is the preparation for unloading (min $load^{-1}$), u is the expected yield (t ha^{-1}), l is the net tank size (kg), and c is the net unit of unloading time (min t^{-1}), q is an assessed rest allowance time amounting to 5% additional time

Most statistical information on combines presents the combine net capacity in terms of the width of the swath. Another measure is the potential input of MOG (material other than grain, i.e., straw, chaff, etc.) (Elrick, 1982; Lundin and Claesson, 1985). The MOG capacity may be determined as proportional to the width of the drum. The following function is based on testing results from the Swedish Machinery Testing Institute (1970–1990):

$$MOG = 1.4\times\Theta - 55.5 \qquad (2)$$

where MOG is the potential throughput (t h^{-1}) and Θ is the drum width (cm). The constraints are 1–2% grain loss and the model explains 77% of the variation of the MOG capacity.

3.1.1. Model calibration

Table 1 gives the parameter estimations of p, k, s, and m based on the measured on-farm data. Specifically, the parameter s is stochastic in nature and may depend on crop conditions, machine reliability, etc. The average value of the parameters is considered sufficient for strategic machinery selection problems, whereas operational scheduling problems might require that the uncertainty of the parameters be explicitly stated (e.g., Sørensen, 1999).

Table 1. Fixed values of parameter estimations

Parameter	*p* (min)	*k* (min)	*s* (min)	*m* (min)
Average	0.40	5.81	2.09	1.62
Standard deviation	0.13	3.30	1.96	0.49

In cases where the harvester is unloading on-the-go the *m* parameter has an average value of 0.25 min.

3.1.2. Harvesting efficiency

Based on the developed model, the harvester performance in terms of theoretical and gross capacities was estimated. The theoretical capacity was determined as the capacity when driving in the swath with full header width and average working speed at standard loss levels (<2%). Overall, the gross capacity takes into account the complete operational cycle, including all turnings, unloading, occasional stops, rest allowances, etc., as identified by the on-farm measurements. Summarizing, the efficiency of the harvesting operation is expressed by the field efficiency factor (*FE*). This factor, denoting the fraction of the actual operational combining time spent on productive work, was estimated as the ratio of the gross capacity to the theoretical capacity.

3.2. Workability

Different approaches concerning the prediction of moisture content in preharvest crops from weather data such as temperature, humidity, precipitation, etc. have emerged. These include both empirical models (e.g., van Kampen, 1969; Crampin and Dalton, 1971; Smith et al., 1981) and physical-biological explanatory models (Heger, 1973; van Elderen and van Hoven, 1973; Atzema, 1993). This topical approach has been derived from the principles stated by Heger (1973) and Olesen and Mikkelsen (1985), and modified to include a submodel for dew occurrence and a comprehensive set of explanatory variables including wind speed.

The mathematical description of the model includes both ambient physical parameters and biological parameters. Model assumptions are summarized thus:

- there is a proportionality between the absorption/desorption of moisture and the difference between the current moisture content and the lower/upper thresholds ($M_{\min}/M_{\max}$) for the moisture content in the crop
- the desorption of moisture is proportional to the quadratic wind speed, $\sqrt{\eta}$
- there is a proportionality between temporal change in the moisture content in the crop and the deficit of reduced saturation (negative or positive), ΔE
- the absorption of moisture into the kernels of the crop is proportional to the amount and duration of precipitation and dew, ω and D
- the individual parts of the plant are independent from one another
- the description of the processes is concentrated on the uptake and the evaporation of moisture
- all parts of the plant – the kernel, the upper and lower parts of the straw – involve the same basic physical processes as far as change in the moisture content due to weather is concerned
- the assumptions will apply to the full or over-ripeness maturity states of the grain kernel.

Based on these adapted assumptions, a model depicting the temporal change of the moisture content of the grain was formulated. The baseline differential model depicts the temporal change in the moisture content as proportional to the present moisture content, positive or negative deficit of reduced saturation, precipitation, dew occurrence, wind speed, etc. The differential equations were solved following the principles for solving a general nonhomogeneous first-order linear differential equation. The overall model was divided into four phases following the actual weather conditions. Table 2 gives the differential equations, the constraints governing the alternation between phases, and the matching solutions.

Table 2. Model equations

	Conditions	Differential equation	Solution
1)	$\omega \le 0 \wedge D \le 0 \wedge \Delta E > 0$	$\frac{dM(t)}{dt} = c_1 (M(t) - M_{min}) \sqrt{\eta}\, \Delta E$	$M(t) = (M(t-d) - M_{min}) \exp(c_1 \sqrt{\eta}\, \Delta E d) + M_{min}$
2)	$\omega \le 0 \wedge D \le 0 \wedge \Delta E < 0$	$\frac{dM(t)}{dt} = c_2 (M(t) - M_{max}) \Delta E$	$M(t) = (M(t-d) - M_{max}) \exp(c_2 \Delta E d) + M_{max}$
3)	$\omega > 0$	$\frac{dM(t)}{dt} = c_3 (M(t) - M_{max}) \sqrt{\omega\, d}$	$M(t) = (M(t-d) - M_{max}) \exp(c_3 \sqrt{\omega d^2}) + M_{max}$
4)	$\omega \le 0 \wedge D > 0$	$\frac{dM(t)}{dt} = c_4 (M(t) - M_{max})\, d$	$M(t) = (M(t-d) - M_{max}) \exp(c_4 d^2) + M_{max}$

$M(t)$ is the moisture content at time t, M_{min} is the lower threshold for moisture content, M_{max} is the upper threshold for moisture content, ΔE is the deficit of reduced saturation (Pa), η is the wind speed (m s^{-1}), ω is precipitation (mm h^{-1}), D is the amount of dew (abstract number), d is an incremental time step (d=1), c_1, c_2, c_3, c_4 are the crop-specific parameters depicting the phases of drying, moisturizing in dry weather, moisturizing in the event of precipitation, and moisturizing in the event of dew.

3.2.1. Dew occurrence

The grain moisture model requires that the formation of dew is known. Atzema (1990) describes the processes involved in dew formation as the radiation exchanges between the earth and the atmosphere, between turbulent heat and water vapor transport within and above the plant canopy, and between the heat and vapor transport in the underlying soil. The occurrence of dewfall can be estimated by setting up energy balance equations between net radiation, soil heat flux, evaporation, latent heat, etc. However, the current model following the diurnal pattern of dew occurrence should be developed requiring fewer explanatory variables.

The occurrence of dew or humidity on plant surfaces has only been recorded during the last 10–15 years. A set of such observations from the location at Research Centre Foulum (56°29′N, 9°34′E) was used to develop a model predicting dew occurrence. The observations were collected for 5 years for the months of June, July, August, and September. The measured parameters included in the data set were air temperature (° C) at 200 cm, air temperature (° C) at 20 cm, relative humidity (%), wind speed (m s^{-1}) at 10 m, and precipitation (mm).

A logistic regression model was used to predict the state of the binary dependent variable (dew) from a set of independent variables (time of day, air temperature, relative humidity, and wind speed). Based on probable influences on dew formation, assumptions were made regarding the diurnal pattern of dew occurrence as well as the possible interactions between variables. The diurnal pattern of meteorological variables was simulated using a linear combination of *cos* and *sin* time-dependent curves. For further refinement of the model, a quadratic regression formula was added. The complete logistic analysis gave the following model:

$$P(dew) = \frac{1}{1 + e^{-Z}} \tag{3}$$

where
$$\begin{aligned} Z = &-4.7915 - 0.5604 * T_1 + 0.4726 * T_2 + 0.1871 * T - 0.0410 * Rh + 0.1174 * \eta \\ &-0.0094 * T^2 + 0.0010 * Rh^2 + 0.0302 * \eta^2 + 0.0010 * T * Rh - 0.0192 * T * \eta \\ &-0.0026 * Rh * \eta \end{aligned} \tag{4}$$

and where T_1 is cos(π/12*Ω), Ω is the hour of the day (1–24), T_2 is sin(π/12* Ω), T is temperature (° C), Rh is relative humidity (%), η is wind speed (m s^{-1}).

A maximum-likelihood method was used to estimate model parameters. For the binary categorical variable of *dew*, dew formation will occur if the probability exceeds 50%. Using this decision rule, model calibration gave 4174 occurrences of dew formation and 6528 occurrences of no-dew formation, yielding an 80.5% correct prediction rate. For testing purposes, the model was applied to a different weather data set for the months of June, July, August, and September and from the location of Research Centre Årslev (55°28′N, 10°19′E). The model gave 76.8% correct predictions of dew formation.

3.2.2. Model calibration

The algorithms detailed in table 2 all contain parameters specific for different harvestable crops. Those parameters were estimated on the basis of measured moisture contents of nonharvested crops and measured meteorological variables, such as temperature, relative humidity, wind speed, and precipitation occurrence. Measurements of moisture contents were carried out over four consecutive years for crops grown at Research Centre Bygholm (55°52′N, 9°47′E) in central Denmark. The moisture content was determined in ripe and standing crops at 2-hour intervals by collecting small samples from randomly selected parts of the field and subsequently measuring the moisture content in these samples. The meteorological variables were measured by means of a mobile weather station unit located in the field.

The goodness-of-fit was evaluated by calculating the RMS value as a term for the root mean square of the relative discrepancy between the measured and the simulated values (table 3). The parameters c_1, c_2, c_3, and c_4 depicting the phases of drying, moisturizing in dry weather, moisturizing in the event of precipitation, and moisturizing in the event of dew are listed together with RMS values.

Table 3. Model calibration

	c_1	c_2	c_3	c_4	M_{max}	M_{min}	RMS_{est}	$RMS(2)$	$RMS(3)$
Barley	0.006	0.02	0.15	0.01	35	11	0.079	0.083	0.091
Wheat	0.005	0.04	0.15	0.01	35	11	0.045	0.087	
Rye	0.006	0.02	0.1	0.01	35	11	0.036	0.062	0.075
Rape	0.008	0.001	0.08	0.001	40	4	0.063		0.054
Peas	0.005	0.01	0.03	0.01	34	11	0.032	0.057	

M_{max} is the estimated upper threshold for moisture content, M_{min} is the estimated lower threshold for moisture content, RMS_{est} is the relative discrepancies between measured data and model for year 1, when the parameters c_1, c_2, c_3, and c_4 are estimated, $RMS(2)$; $RMS(3)$ are the relative discrepancies between data and model, when the model is validated on data for years 2 and 3.

RMS_{est} gives the minimized relative discrepancies for the data set, which are used for the parameter estimation. The model was used and validated on the other data set, and the corresponding RMS(2,3) values express the expected discrepancy when the model uses historical weather data. The range for all RMS values is 3.2 – 9.1% .

3.3. Economics

The current economic model focuses on the system costs, including both machinery costs (fixed and variable) as well as timeliness costs. The model is derived from theories described by Nilson (1972), Have (1991) and Hunt (1995), and expresses the total yearly fixed and variable costs as a function of machine capacity:

$$C=\psi\times\rho\times\theta+\frac{A\times U}{\theta\times FE}\times(r\times\rho\times\theta+L+\delta\times\theta+C_t) \tag{5}$$

where C is the total yearly costs (euro year^{-1}), ψ is a factor expressing depreciation and interest as a fraction of the purchase price, ρ is the purchase price per unit capacity (euro t^{-1} h^{-1}), □ is the machine capacity (t h^{-1}), A is the treated seasonal area (ha year^{-1}), U is the expected crop yield (t ha^{-1}), FE is the field efficiency expressing the ratio between gross and theoretical capacity, r is a factor expressing repair and maintenance costs as a fraction of purchase price, and δ is the fuel costs proportional to the capacity (euro h^{-1}). The unit price of MOG capacity was derived from relating Equation (2) to the purchase price of combines on the market with varying drum widths (Agrimach, 2002).

C_t is the total estimated timeliness costs and is expressed as:

$$C_t=R\times A\times U\times\frac{V}{X}\times UC \tag{6}$$

where R is a timeliness factor set to 0.01–0.04% crop losses per hour (Olsen and Hansen, 1977; Nilsson, 1972; Hunt, 1995), U is the expected yield (t ha^{-1}), V is the value of the harvested crop (euro t^{-1}), X is a planning factor expressing the relative placement of the harvesting period in relation to the optimal harvesting point in time, and UC expresses the utilization in terms of available operational time for harvesting as a fraction of the total time.

The costs are minimized by the optimal capacity and they are derived by the following equation:

$$K_{optimal}=\sqrt{\frac{A\times U}{\psi\times\rho\times FE}\times\left(L+\frac{R\times A\times U\times V}{X\times UC}\right)} \tag{7}$$

where $K_{optimal}$ is the optimal machine capacity (t h^{-1}). The optimal machine size is increased when timeliness costs are included and repair and maintenance costs do not influence the optimal capacity, assuming that these factors are equal for a given area independent of the used capacity. The model may be extended to include multiple crops by indexing the equations within the square root.

4. Simulations

4.1. *Potential harvesting hours*

The grain moisture model was used for simulating the potential harvesting hours for certain upper moisture thresholds. Historical weather data were obtained for the years 1961–1991 for the locations of Karup (56°18′N, 9°07′E) in western Denmark and Værløse (55°45′N, 12°18′E) in eastern Denmark. The data included temperature, humidity, and wind speed every 3 hours, and precipitation data every 12 hours. Hourly values and missing values for temperature, humidity, and wind speed were estimated by linear interpolation. Based on weather codes (dry weather, rain, or fog) hourly weather types were determined (WMO, 1974), and the accumulated amount of precipitation was distributed evenly across the periods when rain had actually occurred.

The simulations were run from 15 June to 15 September using the models for dew occurrence and moisture content (fig 1). The early start date ensured that the initial conditions did not affect the model results in the "real" harvesting period from July to September. Data on maturing dates for different crops were acquired in order to include this effect in the simulations

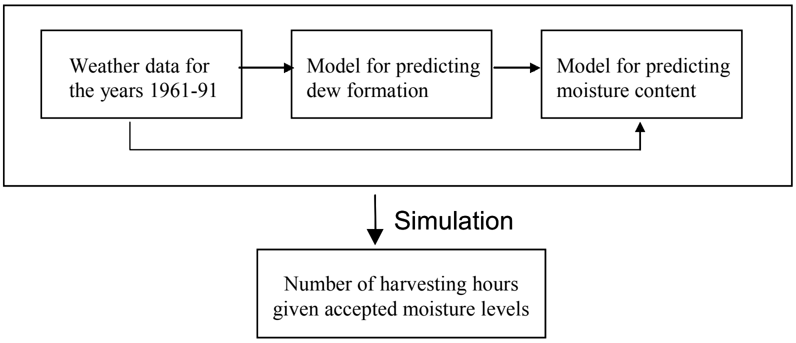

Figure 1. Model structure for simulating harvesting hours for different crops

The harvesting period was arbitrarily constrained to a time span around the optimal harvesting time, where the crop might be harvested without the total yield loss exceeding 10%. Results from timeliness studies (Nilsson, 1972; Olsen and Hansen, 1977; Hunt, 1995) predict yield loss amounts of 0.01–0.04% h^{-1}, indicating that the average length of the harvesting period could be set to 10 days commencing from the maturing date.

4.2. *Field efficiency*

It is important that unproductive work be minimized. The proportion of the productive time during the operational cycle is expressed as the field efficiency factor (*FE*). The *FE* was estimated for the ranges of capacities measured in the on-farm studies. Average results from these estimations were used for the machinery sizing scenario.

5. Results and discussion

5.1. *Potential harvesting hours*

The average utilization coefficient (*UC*), expressing the potential operational time as the ratio of the total day length, for a number of crops and for two locations is shown in table 4. The *UC* varies significantly between years and is very much dependent on the moisture thresholds. In addition, the utilization coefficient seems to be of similar magnitudes for cereal crops, while this is not the case for rape, peas, and seed grass. It is important to note that the variation of the *UC* between crops originates both from a difference in the biological reaction to the meteorological variables and from a difference concerning the temporal displacement of the maturity period.

Table 4. Average utilization coefficient (*UC*)

Location	West Denmark, Karup			East Denmark, Værløse		
Moisture threshold	14%	18%	22%	14%	18%	22%
Spring barley	3.5	20.7	32.2	5.8	26.6	37.4
Winter barley	4.1	22.9	35.9	7.2	30.4	42.3
Winter wheat	2.8	21.1	32.6	4.8	27.2	40.5
Winter rye	5.6	28.6	38.3	7.9	33.8	42.5
Spring rape	12.2	28.4	35.3	14.0	34.2	41.9
Winter rape	13.4	28.0	37.4	18.9	35.9	42.7
Peas	1.8	24.0	35.9	2.1	28.9	42.2

The *UC* is 15–25% higher for winter barley than for spring barley because of an earlier maturity date for winter barley. Also, the *UC* for low moisture contents is significantly higher for oil-seeds than for cereals. Finally, the *UC* for low moisture content is significantly lower for peas than for cereals and rape and, in general, the geographic location influences the *UC* such that the *UC* for eastern Denmark (Værløse) is 15–40% lower than for western Denmark (Karup), indicating the difference in amount of precipitation. This is similar to results presented by Olesen and Mikkelsen (1985) focusing exclusively on spring barley. Multiple harvesting hours are gained (2–13 times) when accepting 18% moisture threshold as compared to 14%.

The individual simulation results for each year in the 30-year period may generate *UC* frequencies related to crops, locations, and moisture thresholds. For example, the cumulative relative frequency for the *UC* and winter wheat is shown in figure 2.

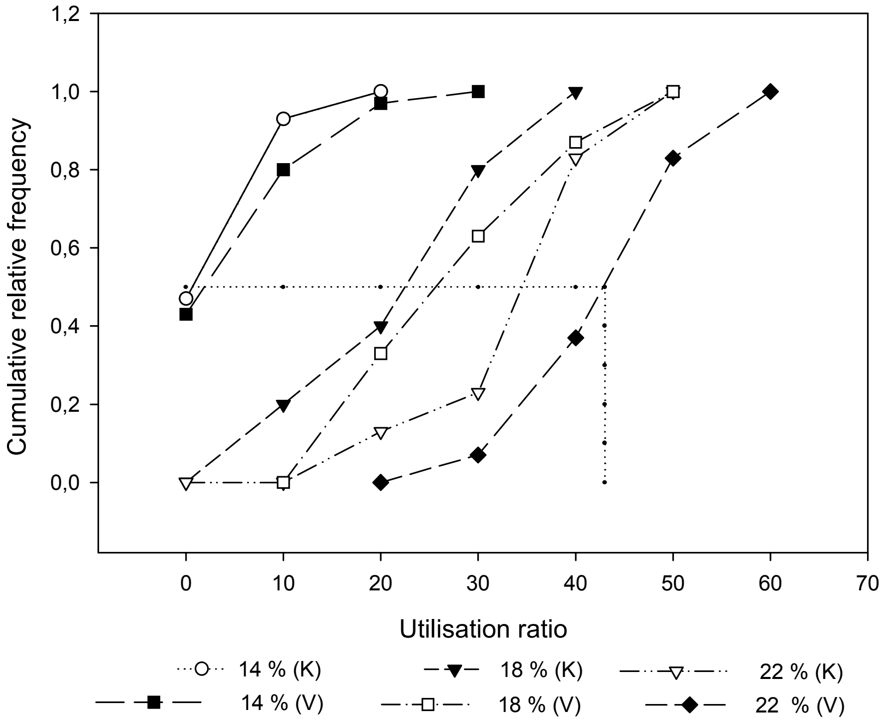

Figure 2. Estimated frequencies for the utilization ratio for the harvesting of wheat. *K* denotes the results for Karup, *V* denotes the results for Værløse and 14%, 18%, and 22% denote the moisture thresholds. Example with the dotted straight lines for 22% (*V*): in 50% of the seasons the utilization ratio will be 43 or less.

5.2. *Machine performance*

Based on the on-farm time motion studies the field efficiency factor together with the capacity measures was estimated.

Table 5. Average field efficiency factors across a range of capacities from on-farm measurements

Type of crop	ε ⁽¹⁾	Yield (t)	e ⁽²⁾ (m)	Working speed (km h^{-1})	Gross capacity ⁽³⁾ (ha h^{-1})	Theoretical capacity (ha h^{-1})
Barley	0.68–0.76	6.0	2,70–6,00	4.58–5.85	0.94–2.40	1.24–3.51
Wheat	0.68–0.75	8.3	4.20–6.00	4.10–5.95	1.29–2.42	1.72–3.57
Rye	0.69–0.81	4.5	2.70–6.00	2.68–5.69	0.58–2.36	0.72–3.41
Rape	0.68–0.77	3.8	2.70–6.00	3.72–6.29	0.81–2.40	1.05–3.52
Peas	0.69–0.76	4.6	4.20–6.00	4.03–5.95	1.28–2.45	1.69–3.57
Seed grass	0.63–0.72	1.6	3.60–6.00	2.70–3.28	0.70–1.24	0.97–1.97

(1) ε = average field efficiency factor, (2) e = effective working width in meters, (3) unloading on-the-go.

The field efficiency varies from 63 to 81% and is influenced by a number of technical and biological factors. These factors include the basic theoretical capacity as determined by the machinery size and the working speed, the shape and size of smaller fields, the traveling pattern in terms of subdivisions of the field, combine maneuverability, crop conditions, operator skill, etc. In comparison Grisso et al. (2002) measured field efficiencies for combining of soybeans and corn in the range of 35 to 70%.

5.3. Machinery sizing

The machine performance model, the workability model, and the costs model were used to estimate the optimal sizing of the harvesting equipment under specific circumstances. A typical farm crop plan was set up as a scenario for the simulations (table 6).

Table 6. Summary of scenario input data

Parameter	Description	Winter wheat	Spring barley	Spring rape	Peas
A (ha)	Area	50	25	50	25
U_m (t ha^{-1})$^{(1)}$	Straw yield	4.3	3.1	3.2	2.1
E $^{(2)}$	Field efficiency	0.72	0.72	0.73	0.73
R (h^{-1})$^{(3)}$	Timeliness factor	0.0004	0.0004	0.0004	0.0004
U_k (t ha^{-1})$^{(1)}$	Kernel yield	7.7	5.6	2.6	4.1
V (euro t^{-1})$^{(4)}$	Value of produce	115.7	113.1	234.2	157.5
UC (18%)$^{(5)}$	Utilization factor	0.21	0.21	0.28	0.24
X $^{(6)}$	Planning factor	2	2	2	2
i	Crop index	1	2	3	4
ψ	Cost fraction	0.14			
ρ (euro t^{-1} h^{-1})	Unit price	10045			
L (euro h^{-1})	Wages	20.2			
δ (euro t^{-1} h^{-1})	Fuel	0.96			
r	Repairs	0.00042			

(1) Average kernel and straw yield for Danish acreages and for the years 1994–1996.

(2) Average field efficiency based on results from table 6.

(3) Based on Olsen and Hansen (1977).

(4) Market prices for 2001.

(5) Average utilization values for the 18% moisture threshold based on results from table 5.

(6) The planning factor indicates that the harvesting period exclusively extends from the initial optimal harvesting time.

By extending Equation (7) to include i=1,…4 independently maturing crops the optimal machinery size was derived. The UC in table 6 is a key factor to the sizing of the harvester, as UC varies considerably from year to year. Based on an averaged UC the average optimal capacity needed is 5.2 t h^{-1} in terms of MOG, equaling a net area capacity of 1.2 ha h^{-1} or a gross area capacity of 0.9 ha h^{-1} for wheat. Based on an average value of 0.21 for UC, the length of the operations period is 166 hours. The costs sum to 108 euro ha^{-1}, included the timeliness costs amounting to 24 euro ha^{-1}.

The harvester is sized according to average conditions, implying that those humid years with few operational working hours can not be matched with sufficient capacity. In such cases the timeliness costs will increase, unlike in dry years. Simulations show that it may be beneficial to size the harvester above the optimal recommendations, as overcapacity seems to be cheaper than undercapacity. It is estimated that a surplus capacity of 1 unit (t h^{-1}) results in extra costs of 1.3 euro ha^{-1} while a deficit capacity of 1 unit (t h^{-1}) results in extra costs of 1.9 euro ha^{-1}.

This case was used as the outset for examining a number of aspects on optimized harvesting operations, such as the effect of dispersion of maturity periods, the effect of varying potential operational time, the effect of varying field efficiency for the harvesting machine, etc.

5.4. Effect of maturing date

The type and number of different crops significantly affect the timeliness losses. Ideally, the maturing dates of the different crops should be independently dispersed across the entire harvesting period. The harvesting costs may be reduced by 19–57% dependent on the number of independently maturing crops and different cropping areas (fig. 3).

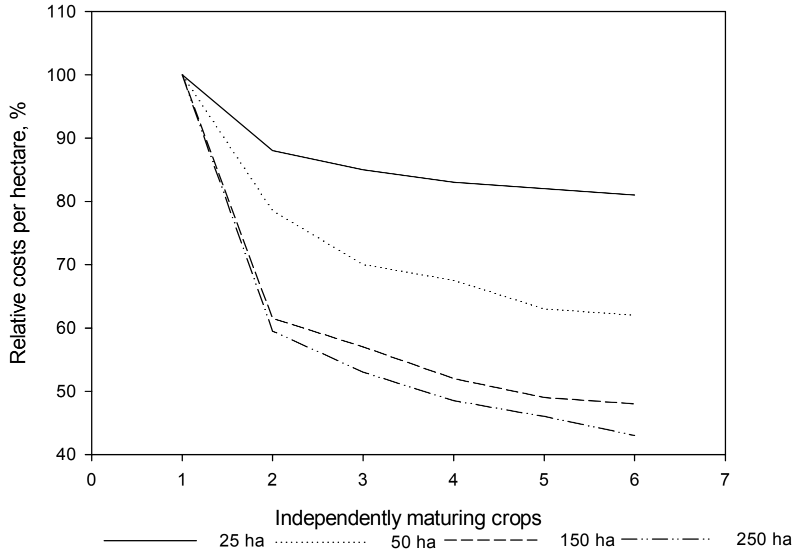

Figure 3. Costs and dispersion of maturing crops related to independently maturing crops and acreage.

Normally it will difficult to establish crops with entirely independent maturing dates. Some degree of overlap between maturing periods will be unavoidable and this will affect the harvesting costs. Model calculations show that an increased dispersion of the maturing date between three crops from 0 days to 9 days reduces the harvesting costs by 20%.

Crop composition within Danish agriculture has for many years been tending toward an increased share of winter crops (Danish Agricultural Council, 2000). By 1995 this transition had entailed a considerable dispersion of the maturing dates, implying a reduction in the necessary optimal capacities of 20% (Sørensen, 1996). Compared with this, the number of combines had been reduced by 11% but the overall capacity had only been reduced by 7% as the individual combines became larger. Hence, a tendency toward a reduced utilization of the available combine fleet was observed, as the increased dispersion of the crop maturing dates stipulated a larger reduction in the number of combines than has been experienced.

5.5. Effect of utilization coefficient

As explained, the utilization coefficient (*UC*) denotes the fraction of potential available operation time. This factor is influenced by the weather, demands on moisture thresholds at harvest time, labor availability, etc. (see table 4). The harvesting costs and the optimal capacity are influenced to a great extent by the utilization factor (fig. 4). An increase in the *UC* from 20 to 40% will reduce the optimal capacity by 20% and a 16% reduction in the costs is observed. Relatively speaking, the most significant changes in the capacity demand and costs are observed when the *UC* varies within the range of 10–20%.

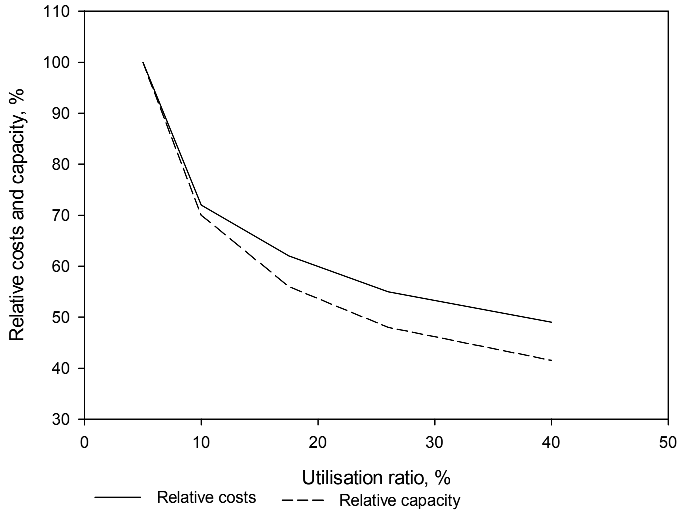

Figure 4. Effect of utilization ratio on optimum capacity and costs.

5.6. *Effect of field efficiency*

The field efficiency for the combine harvester affects the necessary capacity and the costs. Often it will be as important to obtain a high field efficiency as to choose the correct capacity (table 7). An increase in the field efficiency from, for example, 0.5 to 0.9 in terms of a combine with improved maneuverability, better reliability of the technical components, increased field size and more regular field shape, etc. implies a 30% reduction in costs, all other things being equal.

Table 7. Harvesting costs as a function of varying field efficiency

Field efficiency	Relative cost per hectare
0.5	123
0.6	110
0.7(1)	**100**
0.8	92
0.9	86

(1) Initial optimization conditions.

5.7. *Effect of crop value*

Changing relations between labor and machinery costs as compared with the value of produce also affect the optimal machine capacity. A reduction in the value of produce implies a reduced optimal capacity, because of an increased operation period due to the lesser economic value attributed to the timeliness effects. When for example the value of the produce is reduced by 30%, the optimal capacity should be reduced by 15%.

6. Conclusion

Detailed on-farm studies of harvesting operations have formed the basis for the aggregation and development of operational models for the analysis and prediction of labor requirements and machine performance for combine harvesting. Results show that the field efficiency may vary from 63 to 81%, indicating the importance of quantifying and minimizing the nonproductive part of the operations cycle.

A model for the prediction of the moisture content in a standing crop as a function of meteorological variables has been adapted. The model parameters express the individual characteristics of a crop as related to moisture absorption and desorption, respectively. Calibrations have been carried out for barley, wheat, rye, rape, peas, and seed grass.

The utilization coefficient (*UC*), expressing the potential harvesting time as a fraction of total daytime, has been simulated based on 30-year meteorological data. The *UC* varies considerably depending on the type of crop, moisture thresholds, etc. For example, the *UC* varies from 21 to 36% for the 18% moisture threshold and seems to be 15–25% higher for winter barley than for spring barley. In addition, the *UC* is 15–40% lower for eastern Denmark than for western Denmark.

The optimal machinery size is determined by balancing machinery costs and timeliness costs. A model estimating the optimal capacity is denoted, expressing this capacity as a function of fixed and variable costs including costs per unit of capacity, crop area, crop yield, field efficiency, timeliness effects, workability, etc.

A generalization of the case-specific optimization indicates that:

- undercapacity is 50% more costly than overcapacity
- the harvesting costs will be reduced by 19–57% if for example a given area is grown with six independently maturing crops rather than one crop
- dispersion of maturing periods from 0 days to 9 days reduces the harvesting costs by 20%
- an increase in the utilization factor from 20 to 40% implies a reduction in the optimal capacity and costs of 20% respectively 16%
- an increase of the field efficiency from 0.5 to 0.9 gives a 30% cost reduction
- a reduction in the value of produce by 30% lowers the optimal capacity by 15%.

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Nomenclature

The following list denotes the mathematical symbols and notations used. The units associated with the symbols are given in square brackets, if relevant.

Symbol	**Definition**
OC	overall capacity [ha h^{-1}]
h	size of field [ha]
v	working speed [km h^{-1}]
u	expected yield in terms of material other than grain (MOG) [t ha^{-1}]
e	effective working width [m]
p	time for turning [min per turning]
b	field width [m]
n	number of turnings per pass (normally n=2)
a	model parameter dependent on field shape and travel pattern (a=1 in the case of driving back and forth in the swath)
k	turnings on treatment of headland [min per field]
s	stochastic crop and soil stops, adjustments, control, tending of machine, etc. [min ha^{-1}]
q	assessed rest allowance time amounting to 5% additional time
m	preparation for unloading [min load^{-1}]
l	net tank size [kg]
c	net unloading capacity [min t^{-1}]
Θ	drum width [cm]
MOG	potential throughput [t h^{-1}]
$M_{\min}$	lower threshold for grain moisture [%]
$M_{\max}$	upper threshold for grain moisture [%]
η	wind speed [m s^{-1}]
ω	precipitation amount [mm h^{-1}]
D	amount of dew [abstract number]
ΔE	deficit of reduced saturation [Pa]
d	duration of precipitation period [h]
$M(t)$	moisture content at time t
t	current time [h]
c_1, c_2, c_3, c_4	crop-specific parameters specifying drying and moisturizing
T_1	$\cos(\pi/12*\Omega)$
Ω	hour of the day (1–24)
T_2	$\sin((\pi/12* \Omega)$
T	temperature [° C]
Rh	relative humidity [%]
RMS	root mean square
UC	utilization coefficient, the potential harvesting hours [%]
FE	field efficiency factor, ratio of gross capacity to theoretical capacity [%]
C	total yearly costs [euro year^{-1}]
ψ	depreciation and interest as a fraction of the purchase price
ρ	purchase price per unit capacity [euro t^{-1} h^{-1}]
□	machine capacity [t h^{-1}]
A	treated seasonal area [ha year^{-1}]
U	expected d crop yield [t ha^{-1}]
r	repair and maintenance costs as a fraction of purchase price
δ	fuel costs expressed as proportional to the capacity [euro h^{-1}]
C_t	timeliness costs [euro year^{-1}]

R	timeliness factor set to 0.01–0.04% crop losses per hour
V	value of the harvested crop [euro t^{-1}]
X	relative placement of the harvesting period to the optimal harvesting time
$K_{optimal}$	optimal machinery capacity [t h^{-1}]