Assessment of Field Machinery Performance in Variable Weather Conditions Using Discrete Event Simulation

A. de Toro A.
Department of Biometry and Engineering
Uppsala

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Abstract

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Daily field operations were simulated for 15 or 20 years with a model built using a discrete event simulation technique in order to analyse machinery performance on cereal farms as influenced by daily weather. Daily soil workability was inferred by means of moisture threshold values and simulated soil moisture contents from another model (the SOIL-model) using weather data from Malmö and Uppsala, Sweden.

The simulation model for field machinery operations had the capacity to determine operation dates for sowing and harvesting for individual fields and years. The dates were utilized to estimate annual timeliness costs, their mean and variance for each of the machinery sets assessed. Using this procedure to determine timeliness costs, total machinery costs (specific machinery + labour + timeliness costs) were also estimated for varying machinery set sizes, farm sizes, number of drivers and locations.

Some of the findings were: (a) within certain limits of machinery size and for a given farm, there was not only one set identified as ‘the least-cost set’ but several; (b) sets with high daily effective field capacity showed low variation in annual timeliness cost; and (c) the machinery set to be selected should be the largest one among those with similar ‘least-cost’ on account of its lower annual variation, which in turn should lead to lower risks.

The simulation model for field operation was also applied to a case study where a machinery co-operative was evaluated. Machinery pooling enabled farms to reduce total costs by about 15% and investment requirements by about 50%. Average timeliness cost estimates were of some consideration and their annual range was large (10-120 EUR ha^{-1}), even for the machinery systems with sufficient capacity.

A seedbed field experiment on the effects of spring preparation date and associated soil water contents in a clayey soil found that preparation date had only a minor effect on soil compaction but the fraction of fine aggregates in the seedbed increased with time.

Keywords: discrete event simulation, field operations, machinery management, model, seedbed, seedbed properties, soil workability, Sweden, timeliness costs.

Author’s address: Alfredo de Toro, Department of Biometry and Engineering, SLU, P.O. Box 7032, SE-750 07 Uppsala, Sweden. E-mail: alfredo.de.toro@bt.slu.se

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Appendix

Papers I – IV

The present thesis is based on the following papers referred to by their Roman numerals:

I. de Toro, A. & Hansson, P.-A. 2004. Analysis of field machinery performance based on daily soil workability status using discrete event simulation or on average workday probability. *Agricultural systems* 79, 109-129.

II. de Toro, A. & Arvidsson, J. 2003. Influence of spring preparation date and soil water content on seedbed physical conditions of a clayey soil in Sweden. *Soil & tillage research* 70, 141-151.

III. de Toro, A. 2004. Influence of various factors o timeliness costs and their variability on arable farms (Manuscript)

IV de Toro, A.; Hansson. 2004. Machinery Co-operatives - A Case Study in Sweden. *Biosystems engineering*, 87(1), 13-25.

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Introduction

Agricultural production in Europe increased considerably during the past 50 years. Many countries that had a deficit in food production became self-sufficient or began producing a surplus, particularly cereals. This positive development was encouraged by governments with guaranteed agricultural commodity prices and/or subsidies (Witney, 1995). Mechanisation was an important contributing factor in achieving this development, particularly increasing labour productivity and helping to increase yields (Witney, 1995). Once food surpluses arose, governments started implementing policies to reduce them since several of these foodstuffs were produced at higher costs than world market prices. A result of these policies was a considerable decrease in prices for some food commodities in the European Union (EU) during the 1990s. The deflated producer price index for cereals and rice for the year 2000 was 54.6 (1990=100) in the EU (Eurostat, 2001). This trend was not limited to the EU but also applied in the rest of the world. Statistics for cereals show a price index of 80 in the year 2001 (index 1990-92=100) (FAO, 2002). On the other hand, the deflated price index for agricultural machinery in the EU remained at almost the same level during the period (Eurostat, 2001). In consequence, cereal producing farmers have been facing a decreasing margin between gross revenues and machinery costs, not only in nominal terms but also in real terms.

Swedish farmers have been subjected to a similar trend (Fig. 1). Producer prices have decreased while machinery and labour costs have increased, making it difficult to run cereal production in a profitable way.

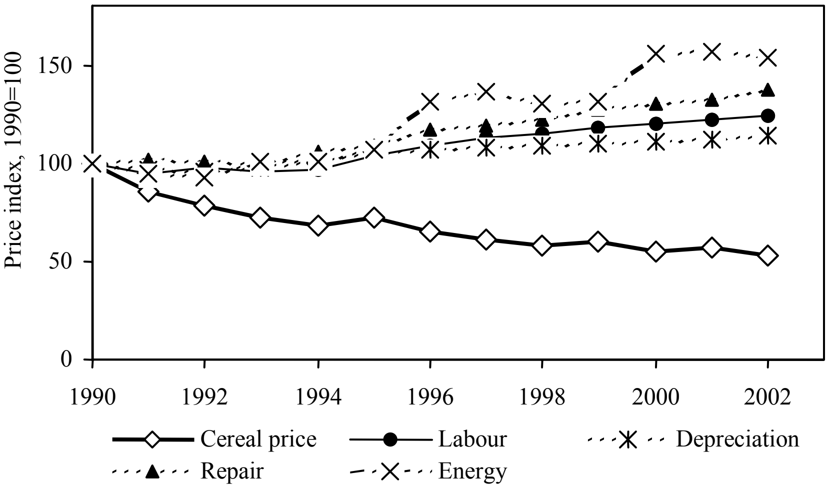

Fig. 1. Development of the deflated price indices 1990-2002 (1990=100) of the producer price for cereals, some items included in machinery costs (Jordbruksverket, 2001; Jordbruksverket, 2003) and labour costs (SCB, 2003) in Sweden.

Machinery costs are important in cereal production. Machinery costs of about €426 ha^{-1} (2003 price level) were estimated in Sweden based on data from 59 farms, most of them involved in cereal production, and variation was large (Laike & Einarsson, 1993). A similar cost level was found in a Danish study based on 116 arable farms, €379 and €544 ha^{-1} (2003 price level) excluding and including labour respectively, and variation was also large (Poulsen & Jacobsen, 1997). Regarding gross revenues obtained by cereal farmers, the above cost levels with their variations indicate that a considerable number of arable farms are facing serious difficulties in balancing their production system in economic terms. The large variation in costs also indicates that some farmers are not using their machinery very efficiently in economic terms and that there is a potential for improvement.

In this context of divergent development between cereal prices and machinery and labour costs, all measures to reduce costs are important in order to maintain the profitability and economic sustainability of cereal production in the long term. Machinery costs, as one of the main items in cereal production, are the central focus of this thesis, in which machinery performance is analysed.

However, specific machinery costs cannot be analysed independently from labour costs in any production system as they substitute each other. In addition, if operations such as sowing and harvesting are not accomplished on time, reductions on yields and/or produce quality can be expected. These reductions cause indirect costs and are known as timeliness costs. They can be considered as a charge against machinery due to its inability to complete operations on optimum time (Opara, 1999). In cereal production, significant timeliness costs mainly occur in regions with short periods for sowing and harvesting operations, generally subjected to annual variation in available workdays as they are affected by weather.

Taking into account that cereal production is the result of a sequence of operations, where several machines, labour and other factors are working together to affect production results and costs, the complete mechanization scheme has to be analysed as a whole, namely as a system. The optimum machinery scheme for such a system should be the one with the ‘least-cost’ when labour, specific machinery and timeliness costs are considered together. The sum of these three items is called ‘total costs’ (Siemens, 1998) and this meaning is used in the present work.

Specific machinery costs are relatively simple to estimate and there are standard methods for such estimations (*e.g.* ASAE Standards), although several parameters have to be assumed and each machinery system has to be treated as a special case (Hunt, 1995). Similarly, labour costs can be calculated, based on either hourly availability or longer employment periods. In contrast, timeliness costs are much more difficult to determine since they are related to available workdays, which in turn are influenced by the combined effects of soil, weather and machinery factors. As weather varies from day-to-day, the number of available workdays for field operations is difficult to assess in advance, introducing a source of uncertainty into any estimation. The preceding facts make timeliness costs the most uncontrollable and unpredictable variable affecting total costs (Edwards & Boehlje, 1980).

In addition, the schedule for a field operation usually depends on previous operations, particularly for sowing, making timeliness costs also influenced by the preceding operations (Oving, 1989). When several machinery units and labour resources are to be assigned to one or other operation option, timeliness costs are also influenced by management decisions.

Taking into account that:

- most field machines are expected to keep going for many years,
- variability of timeliness costs from year-to-year, and
- possible interactions between factors that may affect timeliness costs,

the 'least-cost' machinery system for a given farm should not be selected based on data for an 'average year' but in a long-term evaluation where all the factors affecting total costs, including their interactions, are considered simultaneously (Danok *et al.*, 1980). However, this kind of assessment is difficult to perform, mainly due to the difficulties in estimating timeliness costs under weather variability. Only a few studies were found in the literature where total costs, including timeliness costs, were assessed in a long-term evaluation including annual variation (for further details, see *Background* section)

Objectives

Considering the preceding analysis and issues such as:

- The importance of reducing costs in cereal production.
- The climatic conditions under which Swedish cereal production is carried out (short periods for field operations and affected by annual variation in available workdays).
- That timeliness cost is the component of total costs most difficult to estimate and the main source of annual variation in total costs.
- That large variation is usually associated with higher risk, particularly for systems with low security margins.
- That most of the cereal production in Sweden is carried out on farms less than 100 ha

the purposes of the present work were:

- To develop a method to estimate timeliness costs in detail based on a long-term assessment where annual variations were considered.
- To analyse the influence of daily weather on field machinery performance in general, and on timeliness costs in particular under Swedish climatic conditions for medium-scale arable farms using the method developed.
- To assess the effects of machinery co-operation in economic and social terms in a case study.

Boundaries

The following boundaries were considered important for implementing the work:

- The study was restricted to arable farms of medium-scale size, *i.e.* 200-600 ha, mainly with combinable crops; except for a case study which also included smaller farms (Paper IV).
- The assessment was restricted to those field operations competing for resources, *i.e.* spring and autumn tillage, sowing and harvesting. Operations such fertilization and pesticide applications as individual operations were not included in the analysis.
- Yield differences due to crop rotation or unusual cultivation techniques were not considered. The study was based on current practices for cereal production in the region of Uppsala (59^{o}49'N/17^{o}39'E).

Synopsis of the work

- A simulation model for field machinery operations was developed using a discrete event simulation technique in order to determine annual timeliness costs in a long-term assessment on cereal farms (Fig. 2), with the results compared with a simpler approach, i.e. the equation proposed by ASAE Standards (2000a) to estimate timeliness costs (Eq. 1) (Paper I).
- Taking into account the influence of soil water content on soil workability, which in turn is linked to timeliness costs, an experiment was carried out in order to gain understanding of this issue (Paper II).
- The influence on timeliness costs of daily weather in conjunction with machinery size, farm size, number of drivers and location was studied in order to assess their effects on field machinery performance (Paper III).
- The mechanisation systems of six arable farms, their creation of a co-operative and some mechanisation options were analysed using the simulation model for field machinery operations described in Paper I (Paper IV).

The methodology developed and parts of the conclusions are pertinent to cereal cropping in temperate countries with limited periods for field operations and annual variation in available workdays for spring and autumn field operations, provided that they have a similar economic framework for agricultural production to the locations used in the study.

Background

Selection of size or capacity of both tractor and equipment is a major decision that affects farm profitability (Witney & Eradat Oskoui, 1982) and field equipment size or capacity is the most pertinent selection variable to complete field operations on time (Hunt, 1995). The completion of an operation on time, *i.e.* timeliness, is directly related to machine capacity and available suitable working days. The factors determining timeliness are given by the equation proposed by ASAE Standards (2000a) to determine timeliness costs for one operation:

$$W = \frac{K \cdot A^2 \cdot Y \cdot V}{Z \cdot G \cdot C_i \cdot (pwd)} \qquad (1)$$

where: W = timeless cost for the operation (€)

where: W = timeliness cost for the operation (€)
K = timeliness loss coefficient (1 day^{-1})
A = crop area involved (ha)
Y = yield (kg ha^{-1})
V = value of the crop (€ kg^{-1})
Z = 4 if the operation can be balanced evenly about the optimum time and 2 for premature or delayed schedule
G = expected time available for field work each day (h)
C_i = effective machine capacity (ha h^{-1})
pwd= probability of a workday (decimal)

Management can more or less control machine capacity (machine width, speed, field efficiency) and daily working hours, but the probability or number of workdays for field operations are largely outside the farmer's influence as these depend on the complex relationship between machinery system, soil and weather (Edwards & Boehlje, 1980). This relationship is usually site-specific with respect to soil, climatic and management factors (Hadas *et al.*, 1988). In addition, the influence and interaction of the above factors on machinery costs implies that they should be considered simultaneously (Danok *et al.*, 1980). Weather uncertainty makes the analysis still more difficult.

Because simple mathematics are not a good tool to analyse the complex relationship between field machinery - soil conditions – weather, several researchers have developed diverse models to examine these relationships. Naturally, some of these instruments give more emphasis to soil conditions, including available workdays, while others focus on management aspects of field machinery.

Available workdays

Since available number of suitable field workdays varies from season to season and directly affects the operation schedule, which in turn influences timeliness costs, several approaches have been used to estimate suitable field workdays.

A very good approach, but not always possible, is to use annual series of actual field working days as Edwards & Boehlje (1980) did when they utilized 20 years of historical data series from the State of Iowa, USA. This method avoids possible bias and errors of methodology but these data are rarely available and changes in farming techniques can make them inappropriate.

Another approach is to determine soil workability by means of models, as reviewed by Rounsevell (1993). Most of these models assume that soil workability is a function of soil water content since water significantly regulates the forces between particles within the soil matrix (Rounsevell, 1993).

The simplest models were developed during the late 1960s and early 1970s, mainly based on climatic data, especially precipitation. Some of them also included a simplified soil grouping. The soil water threshold criteria for soil workability were based on empirical data. Good monthly predictions were possible with some of them but daily estimations were often erroneous (Rounsevell, 1993).

Other kind of models, which are more complex, are based on soil water budgets and include specific water threshold values for a number of soil types. Several researchers tried to extend the workability criteria based solely on water content with other soil parameters such as penetration resistance. Tests on this type of model also show good accuracy for monthly predictions but poor accuracy for daily predictions (Rounsevell, 1993).

Concerning the water threshold values for soil workability in field operations, Rounsevell (1993) concluded that the soil water content should be around field capacity, depending on soil type and machinery used. Witney (1995) stated that it should not exceed the lower plastic limit. Maximum soil friability has also been associated with the plastic limit (Utomo & Dexter, 1981b; Watts & Dexter, 1988). However, soil water contents from an equivalent to 5 kPa water tension to 115% of field capacity are also suggested (Witney & Eradat Oskoui, 1982; van Wijk, 1988; van Lanen *et al*., 1992; McGechan & Cooper, 1994; Droogers *et al.*, 1996; Earl, 1997).

Field machinery models

Machinery selection and associated costs comprise a recurrent, complex and important issue. This issue is recurrent because machines begin to deteriorate and/or become obsolete from purchase day and a decision on keeping, upgrading or replacing has to be taken by farmers periodically. It is complex since many factors are involved in the relationship machinery – soil – weather, with weather in particular being an uncertainty factor in the system. It is important considering the required investment for machinery and the related annual costs involved; furthermore, machinery influences crop management (Danok *et al.*, 1980).

The importance of machinery selection and performance, in addition to the complexity of the issue, have led to the development of numerous models, from calculator programmes to sophisticated simulation[1] models for the whole farm including expert systems (Kline *et al*., 1988; Lal *et al.*, 1992). Klein & Narayanan (1992) reviewed the whole farm models, most of them focused on economic issues and developed in Canada and USA. In general, two main approaches may be distinguished according to the technique models are founded on, *i.e.* static and

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[1] Kelton *et al*. (1998, p. 3) define simulation as ‘a broad range of methods and applications that mimic real systems, usually on a computer with appropriate software’.

In a few simple words, simulation consists of doing experiments with a model that mimics ‘the real system’ instead of the ‘real world’.

dynamic models[2]. Each approach has its own merits and limitations and it is difficult to state which of them leads to better results. None of the machinery models developed until now has had full success in terms of wide utilization (Recio *et al.*, 2003).

Static models

In this kind of model, the 'optimal set' for a given farm is found by representing the mechanization system by mathematical equations, which should yield an analytical solution. Generally, they are based on linear, integer, mixed integer or dynamic programming. Usually, weather uncertainty is included as a single probability value for each calendar period under study (Edwards & Boehlje, 1980). The result of this approach, in most of the cases, is an 'optimum machinery set' for an 'average season' or other workday probabilities, *e.g.* 80% of years. Linear programming models usually overestimate profit, not only in years with poor weather but also on average as well if more detailed rainfall patterns are not included (Etyang *et al.*, 1998). A pooled long-term assessment under variable weather conditions is difficult to include in this type of model.

In the literature review, a number of models were found that can be classified as static models (Hughes & Holtman, 1976; Nilsson, 1976; Danok *et al.*, 1980; Edwards & Boehlje, 1980; Pfeiffer & Peterson, 1980; Audsley, 1981; Whitson *et al.*, 1981; Witney & Eradat Oskoui, 1982; Ozkan & Edwards, 1986; Kline *et al.*, 1988; Oving, 1989; Jannot & Nicoletti, 1992; Jannot & Cairol, 1994; Lazzari & Mazzetto, 1996; Etyang *et al.*, 1998; Siemens, 1998; Opara, 1999; Ekman, 2000; Recio *et al.*, 2003; Sørensen, 2003; Gunnarsson & Hansson, 2004). The model presented by Kline *et al.* (1988) *i.e.* FINDS (Farm-level INtelligent Decision System) is not only an optimisation model but rather an expert systems model, which was developed for sizing and selecting machinery for whole-farm cropping systems.

Dynamic models

In this type of approach, machinery operations are modelled with a technique that simulates operations on a real farm, *e.g.* day-by-day, generally based on some kind of discrete event simulation and 'appears to be the most elegant' alternative (van Elderen, 1980). Output data such as field operation dates may be used to estimate timeliness costs for individual fields. Best performing machinery sets are found by simulating a series of sets, evaluating them and selecting the best option.

Simulation models are appropriate to test the feasibility of solutions attained with static models (*e.g.* models based on linear programming) because available workdays are better represented in simulation models as they are included in chronological sequences (van Elderen, 1980). Similarly, work organisation, resource matching and stochastic events can easily be incorporated into dynamic

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[2] A static model represents a system in which the outputs are always independent of the past input and state values. In contrast, the outputs in a dynamic model depend on past values of the inputs and states (Cassandras, 1993, p. 53).

models. Interactions and non-linear relationships can also be captured in a better way by this kind of model. Thus, static models designed to find ‘optimal solutions’ are complemented by simulation models (Jannot & Nicoletti, 1992).

Only a few studies found in the literature were based on dynamic approaches (van Elderen, 1980; Buck *et al*., 1988; Papy *et al*., 1988; Chen *et al*., 1992; Jannot & Nicoletti, 1992; Lal *et al.,* 1992; Parmar *et al*., 1994; Arjona *et al*., 2001).

The models developed by van Elderen (1980); Buck *et al*. (1988); Chen *et al.* (1992) and Arjona *et al.* (2001) were build to evaluate the harvesting operation for grain, forage, cotton and sugar cane, respectively. Van Elderen (1980) in a pioneering work simulated 12 harvest seasons using hourly weather data as input; thus an average cost and its variation was determined for the harvesting operation in a ‘long-term’ assessment.

The model built by Jannot & Nicoletti (1992) was able to simulate daily field operations on a farm for many years having as input daily workability based on a soil water content balance. Important outputs of the model were beginning and ending dates for each field operation. Similarly, the model of Papy *et al.* (1988) was used to simulate autumn field operations for a 15-year period on a 318 ha farm with daily workability inferred from climatic data. The model developed by Parmar *et al.* (1994) had the objective of aiding peanut farmers to select machinery. It simulated daily field operations including delays due to high soil water contents estimated from historical weather data and included crop growth, field operation schedule and cost estimation modules. Parmar *et al.* (1996) combined their daily machinery simulation model with an automatic search algorithm in order to find the ‘optimal set’ in a long-term assessment (15 years) within ‘all possible machinery set combinations’.

The simulation model for field operations reported by Lal *et al.* (1992) is a module of a larger system, FARMSYS, a whole-farm machinery management decision support system, which also includes an ‘info manager system’ and a yield estimation module.

The above simulation studies were implemented using different software. Buck *et al.* (1988) and Arjona *et al.* (2001) utilized languages for discrete event simulation, *i.e.* SLAM II and SIMACT, respectively. Chen *et al.* (1992) used the SIMLIB programming language (Law & Kelton, 1991) and sub-routines written in Fortran 77. The models developed by Papy *et al*. (1988) and Parmar *et al.* (1994) were written in C and Fortran language, respectively. Lal *et al.* (1992) developed their expert system in Prolog (PROgramming in LOGic), a software based on object-orientated programming and used for developing expert systems.

Discrete event simulation[3]

The state of a continuous model changes continuously over time (*e.g.* the level of a reservoir model as water flows in). In contrast, the state in a discrete model changes at discrete points in time, which physically correspond to discrete events *e.g.* clients arriving at a post office or the state change of a tractor to 'busy', 'idle' or 'down'. This has the implication that state changes in the model are driven by events (Cassandras, 1993).

The use of a discrete event simulation language facilitates the development of such models since many features required for mimicking the behaviour of real systems are incorporated in the language. Thus, models built with this technique are easier to develop, modify and less prone to errors when compared to those developed in a general purpose language (Law & Kelton, 1991).

The main components of a discrete event simulation language are usually (with examples related to agriculture machinery):

- *Entities* representing objects to be processed (*e.g.* fields to be cultivated). They may have:
    - *attributes* or specific characteristics (*e.g.* field size, ploughed state which may change as the field undergoes a ploughing process, crop to be cultivated, sequence of operations to be followed), and
    - the *ability* to trigger activities (*e.g.* the sowing operation), if
- *Resources*, or means are available (*e.g.* tractor, drivers), and if
- *Other conditions* are fulfilled (*e.g.* the field is already cultivated), then an *event* occurs, which may change the entity state (*e.g.* the sowing operation changes the 'sowing state' of a field).
- *An event scheduling device* that sort events to come and successively makes the *simulation clock* jump to the next event (*e.g.* stubble cultivation after harvesting), while
- *Statistical* accumulators keep track of what happens and when in the simulation (*e.g.* sowing date for 'field 1'), and
- *Global variables* store characteristics for the whole system (*e.g.* total number of hectares sown).

Using discrete event simulation techniques, daily field operations on a farm can be simulated with available resources (machines, labour), constraints (*e.g.* soil workability) and some management criteria. Valuable characteristics of this kind of technique, particularly when a language for discrete event simulation is utilized, are (Paper I):

- Each field can be treated as a 'distinct entity', making it possible to determine its operation start and finishing dates, which in turn enable timeliness costs to be estimated for the field in question.
- Sequence effects of operations are fully taken into consideration.

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[3] Cassandras (1993, p. 41) defines a discrete event system as a system whose 'states depend entirely on the occurrence of asynchronous events over time, being the state space a discrete set'.

- Eventual interactions and non-linear relationships can be taken into account (*e.g.* unique effects of a combination of machinery size-number of drivers-farm size).
- If simulations are run for long periods (15 or more years), timeliness costs are estimated not only for 'average weather' but also for extreme years.
- Stochastic events (*e.g.* machine breakdowns) can easily be incorporated into the model.
- Incorporation of some 'human decision patterns' is also feasible (Lal *et al.,* 1991).
- Constraints in the mechanisation system can easily be identified.
- Individual resource utilization can be monitored without difficulty.

Methodology

This thesis focuses on the analysis of field machinery performance in general, and annual timeliness cost variability as influenced by daily weather in cereal production in particular. Specific machinery and labour costs were determined using standard methods. The methodology utilized for calculating timeliness costs is outlined in Fig. 2 and described in Paper I, thus the following is a rather short account.

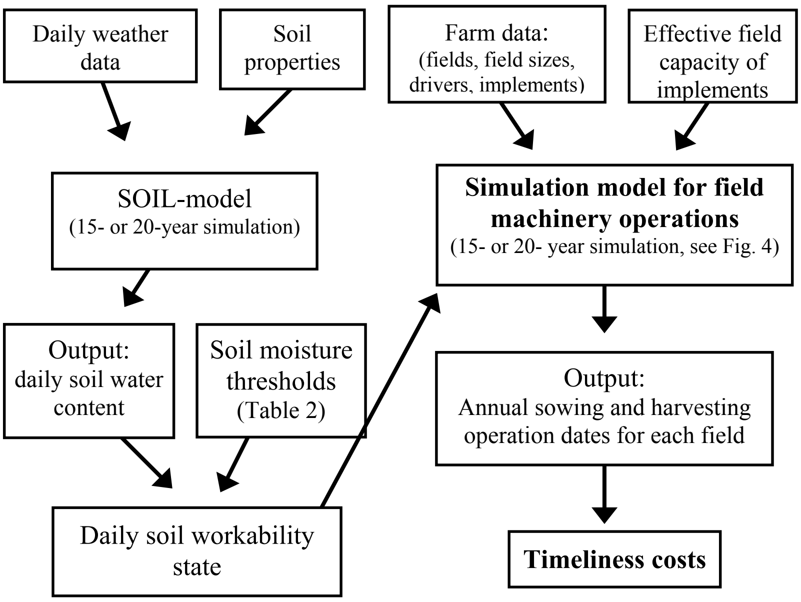


Fig. 2. Chart flow for the procedure to estimate timeliness costs based on 15- or 20-year climate data from Malmö and Uppsala, respectively (Paper I, modified figure).

Determination of daily soil workability

Since soil workability is linked to soil moisture content, which can be assessed through soil water models (Rounsevell, 1993), an existing soil model, namely the SOIL-model, was utilised to estimate soil water contents (Jansson, 1991a; b). This model has already been validated for certain soils and has produced satisfactory results (Eckersten & Jansson, 1991; McGechan & Cooper, 1994; Kätterer & Andrén, 1995; Cooper *et al.*, 1997; McGechan *et al.*, 1997).

Soil workability was only determined for one soil type (a clay loam soil with about 20 g kg^{-1} organic matter) for which the SOIL-model had already been calibrated and important soil parameters determined (McGechan *et al.,* 1997), some of them are shown in Table 1. The main weather variables used as input for the SOIL-model were daily air temperature, air relative humidity, wind speed, precipitation, global radiation and cloudiness. The model was run with weather data from Malmö (55^{o}36'N/13^{o}00'E) and Uppsala for fifteen years (1980-1994) and twenty years (1980-1999), respectively.

Table 1. *Some physical soil parameters and hydraulic properties of the clay loam soil used in the SOIL-model (Paper I)*

Parameters	Source	Surface layer 0-100 mm	Sub-surface layer 101-1200 mm
Porosity, %	Measured	45 (σ=7.7)	45
Dry bulk density, kg m^{-3}	Measured	1370 (σ=206)	-
Pore size distribution index	Fitted*	0.06	0.05
Soil water tension at air entry, Pa	Fitted*	49	49
Residual water content, % V/V	McGechan *et al.* (1997)	7.5	7.5
Saturated hydraulic conductivity, (including macropore), mm h^{-1}	McGechan *et al.* (1997)	57	57
Hydraulic conductivity at 590 Pa tension, mm h^{-1}	McGechan *et al.* (1997)	23	5

* Fitted according to the procedure proposed by McGechan *et al.* (1997).

From the many output parameters produced by the SOIL-model, water tensions for the two top layers and frost boundaries were selected for inferring soil workability. The applied water threshold values are presented in Table 2. Different soil moisture threshold values were chosen for the superficial soil layer (0-30 mm) and lower ones for secondary tillage, *i.e.* harrowing, rolling and sowing operations. The moisture content at the lower plastic limit was applicable as the soil workability threshold value for the superficial layer but it was not applicable for the deeper layers as they are usually much wetter in early spring or autumn. For these layers, a different approach was utilised. As the start dates of spring operations on a real farm were available for the past 30 years, the soil water tension outputs of the SOIL-model were matched with the dates for the most recent ten years and the average simulated tension for these dates was selected as the threshold value for secondary tillage. In this way, the threshold value selected was the result of this calibration.

Table 2. *Soil moisture threshold and non-frozen soil layer thickness values applied to determine soil workability for ploughing, secondary tillage and harvesting operations (Paper I)*

Field operation	Workability criterion; soil water tension, kPa (%FC)[a]		Non-frozen soil layer thickness, mm
	Soil layer, mm		
	0 - 30	31 - 70	
Ploughing	1.0 (110)	1.0 (110)	100 - 400
Secondary tillage[b]	60 (85)	2.0 (107)	0 - 100
Harvesting[c]	1.0 (110)	1.0 (110)	

[a] In brackets: % FC= % of field capacity (pF 2).

[b] Included sowing with a minimum–tillage seed drill. The values for secondary tillage were inferred from simulated moisture outputs and the start dates of the spring operation on a real farm, *i.e.* through a calibration procedure.

[c] In addition, a daily rain discount sum less than 1.3 mm was set for harvesting, with 20% as discount factor (Witney, 1995).

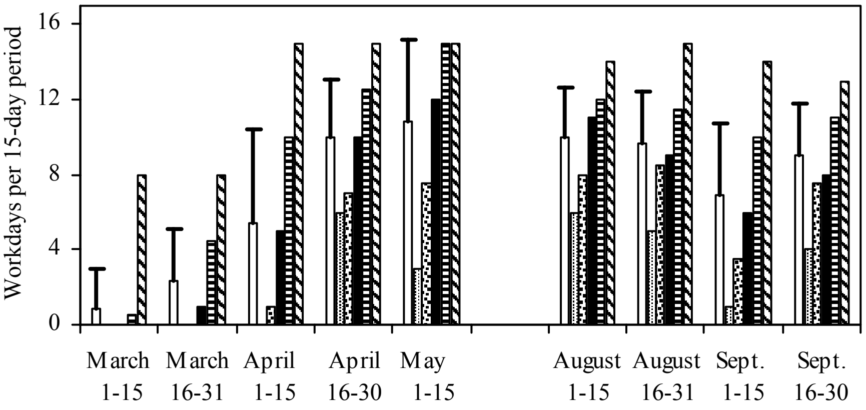
As ploughing and harvesting are less sensitive to soil moisture content than secondary tillage, the limit of 1.0 kPa water tension (110% of field capacity) was chosen as the limiting moisture content for soil workability. A daily discounted sum (20% as discount factor) of less than 1.3 mm rain was also set for harvesting (Witney, 1995).

Daily soil workability states for secondary tillage, ploughing and harvesting operations were inferred for 15 and 20 years in Malmö and Uppsala, respectively. Some of the results of soil workability are shown in Fig. 3. Average available workdays for the clayey soil increased in Malmö and Uppsala during spring from a very low level, reaching a level of about 50% at the beginning of April in Malmö and at the middle of April in Uppsala. Variation was large from year to year as shown by the standard deviations and quartile distributions. Under such climatic conditions, timeliness costs of some consideration should be expected, particularly during extreme wet years. Similar patterns occurred with available workdays for harvesting periods at both locations, with an average of some 60% available workdays.

The simulation model for field operations

The aim was to create a simulation model with the capability of mimicking main field operations of a cereal farm and producing the same work dates as a 'real farm'. The model was developed in Arena, which is a discrete event simulation language (Kelton *et al.*, 1998); a version of the model in the Arena software is presented in Appendix A. No stochastic feature was incorporated into the model, the results being determined by the input data, which included daily soil workability state, specific data on effective field capacity per hour for each machine involved in the simulation, number of drivers available and working time for each driver (Fig. 2). Most of the simulations were done assuming a 'virtual' farm comprising 30 fields divided into spring and winter-sown fields. To each field '*attributes'* like size, sequence of operations to follow and operation priority in respect to other fields were assigned in the model. In addition, each operation had a priority '*attribute*' when competing for resources with other operations, harvesting being the operation of highest priority for resource assignment; fields to be sown during autumn had the second highest priority. Main steps for a field to undergo from the start of a year to the harvesting operation are shown in Fig. 4 in a simplified way.

(a) Malmö



(b) Uppsala

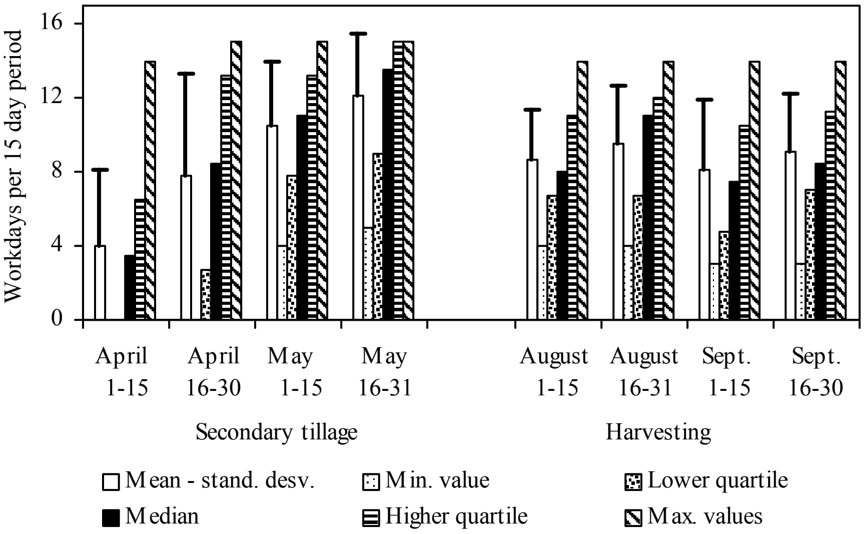


Fig. 3. Mean and standard deviation (error bars) of available workdays and their quartile distributions per 15-day periods for spring secondary tillage and harvesting periods in a clay loam soil in (a) Malmö and (b) Uppsala based on 15- and 20-year climate data, respectively (Paper III).

Estimation of total costs

Total costs, *i.e.* specific machinery + labour + timeliness costs, were estimated for each of the evaluated machinery sets in order to compare their economic performances.

Timeliness costs

Timeliness costs were estimated using the procedure delineated in Fig. 2. Field operation dates as day numbers, which were outputs of the simulation model for field machinery operations, were used in Eq. 2 to estimate annual yield losses for sowing and harvesting for individual fields.

$$Y_l = P_d\, A_f\, (D_s - D_o) \; + \; 0.5\, P_d\, A_f\, (D_f - D_s) \qquad (2)$$

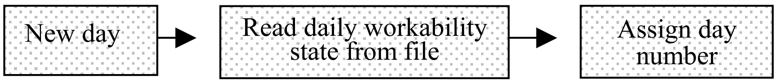
where:
Y_l = annual yield losses for each field for the sowing or harvesting operation, kg
P_d = penalty per day (Table 3), kg day^{-1} ha^{-1}
A_f = field area, ha
D_s = start day for operation, day number
D_o = optimum day for operation (Table 3), day number
D_f = finishing day for operation, day number

In cases where $D_f < D_o$, a value equal to *0* was assigned to yield losses (Y_l). In other cases where $D_s < D_o$ and $D_f > D_o$, D_s was assigned the value of D_o. This latter assignment introduced a small error to timeliness cost estimations for autumn sowing operation in some cases. Spring sowing and harvesting operations always started on the ‘optimum day number’ or later.

The yield losses estimated by Eq. 2 and the cereal price presented in Table 3 were utilised to estimate annual timeliness costs for the sowing operation. However, for the harvesting operation timeliness costs were calculated from maturation day for each field, which in turn was determined by the model using a procedure based on daily temperature and photoperiod (Angus *et al.*, 1981; Appendix B). Since the procedure only calculated maturation date for one cereal and as farmers usually grow several crops, the date estimates were modified by a random factor with uniform distribution, namely 0-5 days for winter crops based on the average maturity day ranges for 5 years for the current winter wheat cultivars (Fältforskningsenheten, 2002), and 0-13 and 0-6 days for spring crops based on the range of median harvesting dates for main spring cereals at the locations of Malmö and Uppsala, respectively, (Jordbruksstatistisk årsbok, 1989-1993). Thus, the maturation date of an individual field was the result of the climatic effects plus such random variation (Paper I).

Once timeliness costs were determined for sowing and harvesting on individual fields, overall annual timeliness costs were estimated for the whole farm for a 15 or 20 year period, after which mean timeliness cost and variance were calculated for each of the simulated sets.

(a) Every 24 h: read daily state of soil workability and assign day number



(b) Operation sequence

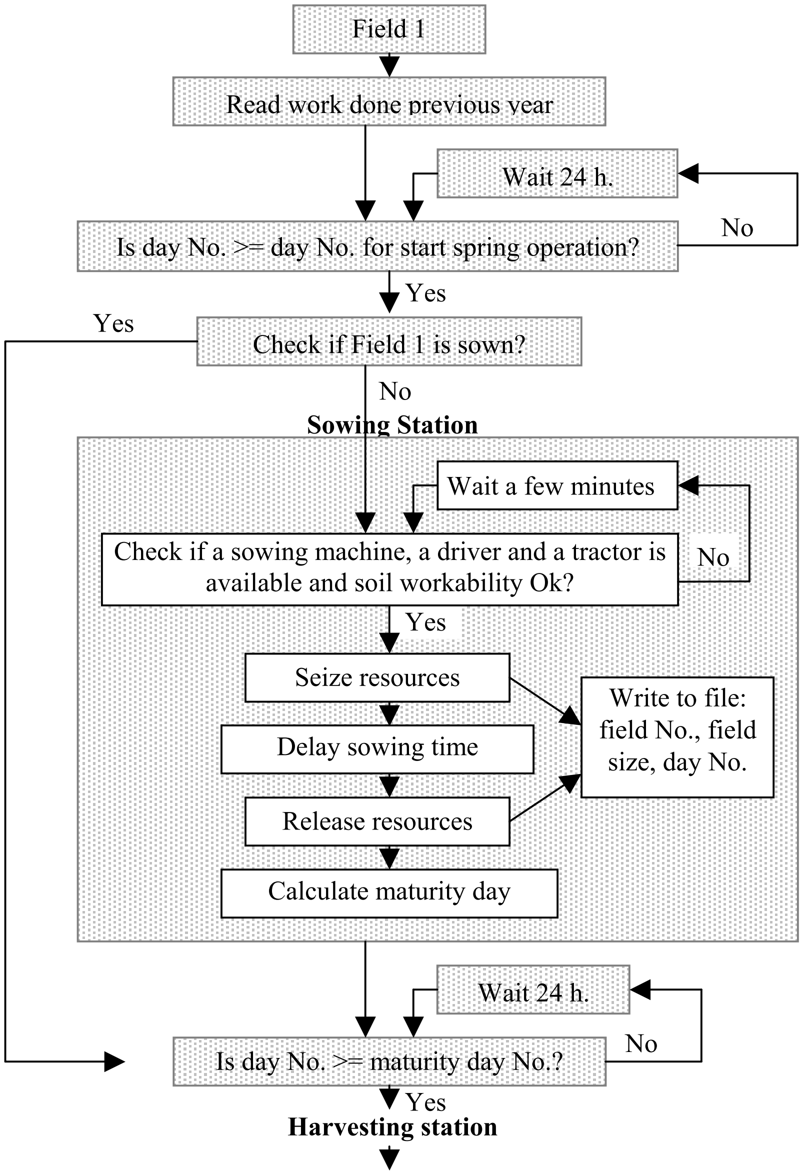


Fig. 4. Simplified sketch of the simulation model for field machinery operations from the start of the year to the harvesting operation, (a) reading soil workability state and assigning day number, and (b) steps to follow for a field in the model.

Table 3. *Some parameters and penalties used in estimating timeliness costs in the Malmö and Uppsala locations (Paper III)*

Parameter	Source	Malmö	Uppsala
Cereal price in the field, € kg^{-1}	Assumed	0.077	0.077
Penalty per day, kg day^{-1} ha^{-1}			
Spring-sown fields	Mattson (1990)	22	43
Autumn-sown fields	Andersson (1983)	17	30
Harvesting	Nilsson (1976)	42	44
Penalties applied from, date			
Spring-sown fields	Mattson (1990)	18 March[a]	19 April[a]
Autumn-sown fields	Andersson (1983)	25 Sept. [a]	15 Sept. [a]
Harvesting	Calculated by the model	Maturity day + random number[b]	
Random number added to harvesting date[b]	Agric. Statistics[b]		
Spring crops		0-13	0-6
Winter wheat		0-5	0-5
Autumn sowing period, date	Andersson, 1983	10 Sept .– 20 Oct.	1-30 Sept.
Penalty for a field planned to be sown in autumn but not actually sown until following spring, kg ha^{-1}	Agric. Statistics[c]	2383	1256
Penalty for a field not cultivated, kg ha^{-1}	Agric. Statistics[d]	3184	1411
Penalty for an unharvested field, kg ha^{-1}	Agric. Statistics[e]	5304	4401

[a] Penalty based on a delayed sowing schedule.

[b] Based on the average maturity day ranges for 5 years for the current winter wheat cultivars at the locations (Fältforskningsenheten, 2002), and for spring crops based on the range of median harvesting dates at the locations for main spring cereals (Jordbruksstatistisk årsbok, 1989-1993).

[c] Difference in standard yields for the year 2001 between winter wheat and spring cereals weighted by area (50% barley, 25% spring wheat and 25% oats) in the locations (Jordbruksstatistisk årsbok, 2002).

[d] Based on rental price for arable land for the year 2000 adjusted to 2003 price level and converted to equivalent kg cereal in the locations (Jordbruksstatistisk årsbok, 2002).

[e] Standard yields for the year 2001 for spring cereals weighted by area (50% barley, 25% spring wheat and 25% oats) in the locations (Jordbruksstatistisk årsbok, 2002).

Specific machinery costs

Specific machinery costs were calculated using standard methods (ASAE Standards, 2000a, b). Machinery depreciation was estimated employing the straight-line method with a salvage value of 10-35% of list prices (Paper I and IV) depending on machine type and annual use. In Paper III purchase prices for machinery were assumed to be 80-90% of list prices considering that dealers normally grant discounts. In those cases of short annual use, economic life of most implements was limited to 20 years and the repair and maintenance ASAE parameters were adjusted to a lower level assuming that new machines have lower breakdown rates. Fuel consumption per hectare was the normal value for Swedish farmers (Danfors, 1989), at a cost of some €0.66 l^{-1} fuel (diesel). The annual interest rate applied was 6%. The number of tractors was assumed to be equal to the number of drivers in order to reduce 'idle driver time' except in the case of shift work, where the number of tractors was equal to the number of drivers in each period of work.

Labour costs

Labour was assumed to be available on an hourly basis. In addition, it was considered that extra labour was always available for cereal transport and drying during harvesting, which could only be performed during daytime. This extra labour was not included in the simulations. In addition, it was assumed that drying capacity was sufficiently large to match harvesting capacity.

Daily working time during periods of peak demand was 10 hours for the first and second driver, and in those simulations with larger number of drivers, their time was reduced to 9 h per day for the third and fourth driver at a cost of €20 h^{-1} for normal working time (8.00–17.00 hours) and €30 h^{-1} for labour outside normal time.

Farming conditions

Simulation conditions in terms of machinery sets, working hours, cropping, field sizes, operation sequences, management principles, field operation parameters (operation speed, field efficiency), economic parameters and assumptions for estimating costs, etc. tried to be as representative as possible for the situation that medium-scale farmers face in Uppsala.

Paper I: Testing the methodology developed

The methodology developed to estimate timeliness costs previously described was tested by evaluating seven machinery sets on a 400 ha arable farm and comparing the results with those of a simpler method, *i.e.* the ASAE equation for estimating timeliness costs (ASAE Standards, 2000a). The sets (Table 4) and the simulated field operations (autumn ploughing, one harrowing, sowing with a minimum-tillage seed drill and rolling) were chosen to be representative for a combinable crop farm of this size in the region of Uppsala.

Table 4. *Composition and size of the implements, number of tractors and available labour of the machinery sets assessed with two methods, i.e. one based on an average probability value of available workdays, and the other based on daily state of soil workability*

Set	Implement and its width, m							Number of tractors or workers
	Plough		Harrow	Minimum till drill		Harvester		
	1	2	1	1	2	1	2	
C1:	2.4		10.5	3		5.4		3
C2:	2.4		10.5	3			7.2	3
C3:	2.4		10.5		4		7.2	3
C4:	2.4		10.5	3	4		7.2	3
C5:	2.4		10.5		4	5.4	7.2	3
C6	2.4		10.5	4	4	5.4	7.2	3
C7:	2.4	2.4	10.5	4	4	7.2	7.2	4

Paper II: An experiment on seedbed physical conditions of a clayey soil

Considering that daily soil workability was one of the main inputs of the simulation model for field machinery operations, a field experiment was carried out in order to gain understanding of the relationship soil water content – soil workability. Since soil water content usually decreases as spring advances under Swedish weather conditions, seedbed preparations conducted at various dates are usually performed at different water contents. Accordingly, a series of ten seedbed preparations were made in a field that had been ploughed the previous autumn, at different dates, starting at beginning of April until middle of May, considering each 'preparation date' a treatment. The treatments were randomised into a block consisting of ten plots, with a size 8 x 8 m, and the block was replicated three times. Three harrowing operations were performed on each plot as seedbed preparation. The measured parameters were thickness of the superficial dried layer, penetration resistance before and after harrowing, bulk density, aggregate size distributions in the seedbed and water contents at several depths before and after preparation.

Paper III: Influence of daily weather and other factors on timeliness costs and their variability

The influence of daily weather in conjunction with various other factors on annual timeliness costs and their variation was quantified using the method developed in Paper 1. At two locations (Malmö and Uppsala), seven machinery sets of different sizes (Table 5) with a varying number of drivers were tested on three farm sizes (200, 400, 600 ha). Basic assumptions in the evaluation were that (a) minimization of machinery costs is an important objective for farming (e.g. Burrows & Siemens, 1974) and (b) less variability is preferred than more since it implies less risk (Danok et al., 1980).

Table 5. *Composition and size of implements in each machinery set, number of tractors or drivers*

Set	Implement number and its width, m							Number of tractors or workers[a]
	Plough		Har-row	Minimum till drill		Harvester		
	1	2	1	1	2	1	2	
S1:	1.6		6	3		5.4		1-3, shift[b]
S2:	1.6		6	3		7.2		1-3, shift[b]
S3:	2.4		10.5	4		5.4		1-3, shift[b]
S4:	2.4		10.5	4		7.2		1-3, shift[b]
S5:	2.4	2.4	10.5	4		7.2		2-3, shift[b]
S6	2.4	2.4	10.5	4		7.2	7.2	2-4, shift[b]
S7:	2.4	2.4	10.5	4	4	7.2	7.2	2-4, shift[b]

[a] Power of tractor varies from 80 kW to 140 kW depending on the implement sizes included in the set.

[b] Shift work, with one or two drivers in each shift, depending on farm size.

Paper IV: Application of the simulation model in a case study

The mechanisation systems of six arable farms, their current joint machinery pool and some alternative machinery options were analysed in economic terms and operation times utilizing the simulation model for field machinery operations, with some social aspects also included in the study. The following steps were taken to carry out the evaluation:

- An existing production cooperation scheme of six combinable crop growers (59-164 ha) was selected in the region of Uppsala. Data were collected on their situation prior to cooperation and the current pool (Tables 6 and 7).
- Total costs (labour + specific machinery + timeliness costs), investment requirements and field operation times for crop establishment and harvesting were estimated for the farms prior to cooperation, for the present machinery pool and for three alternative options to it (Table 7).
- The farmers were interviewed regarding their views on the cooperation.

Table 6. *Basic data on the farms and their machinery before participating in the machinery pool*

	Farm no.					
	1[a]	*2*	*3*	*4*	*5*	*6*
Size, ha	164	74	100	74	59	141
Man hours[b], h day^{-1}	14	8	13	13	7	10
Tractors, no. x power, kW	1 x 90 1 x 103[a]	1 x 57 2 x 110	1 x 100 1 x 115	1 x 65 1 x 65	1 x 52 1 x 93	1 x 97 1 x 116
Ploughs, no. x furrows	1 x 4f	1 x 4f	1 x 4f	1 x 4f	1 x 4f	1 x 4f
Harrow, no. x width, m	1 x 6.6	1 x 8.1	1 x 8.1	1 x 6.6	1 x 6.6	1 x 8.9
Drill, no. x width, m	1 x 4	1 x 4	1 x 4	1 x 4	1 x 4	1 x 4
Roller, no. x width, m	1 x 12	1 x 6	1 x 4.5	1 x 5	1 x 4.5	1 x 10
Combine, no. x width, m	1 x 5.2[a]	1 x 5.2	1 x 5.2	1 x 3.7	1 x 4.8	1 x 5.2

[a] Farm 1 included a second-hand tractor and a second-hand combine harvester.

[b] Available staff hours per day during harvesting period.

Table 7. *Basic machinery data on the current machinery pool (Co) and three optional sets (Op1 - Op3)*

	Co	Op 1 (Shift)[a]	Op 2[b]	Op 3 (Shift)[a, b]
Cropped area[c], ha	560	560	560	560
Man hours[d], h day^{-1}	45-55	62	48	48
Tractors, no. x power, kW	2 x 60 1 x 90 3 x 115	2 x 60 1 x 90 3 x 115	1 x 115 1 x 160 2 old ones[b]	1 x 160 2 old ones[b]
Ploughs, no. x furrows	2 x 4f	2 x 4f	1 x 6f 1 x 7f	1 x 7f
Harrow, no. x width, m	1 x 8.1 1 x 8.9	1 x 8.1 1 x 8.9	1 x 10	1 x 10
Drill, no. x width, m	2 x 4	2 x 4	1 x 4 1 x 5	1 x 5
Roller, no. x width, m	1 x 6 1 x 12	1 x 6 1 x 12	1 x 12	1 x 12
Combine, no. x width, m	1 x 5.2 1 x 6.7	1 x 5.2 1 x 6.7	1 x 5.2 1 x 6.7	1 x 5.2 1 x 6.7

[a] Shift work system for tillage and sowing.

[b] This option includes two second-hand tractors mainly used for transporting grain during harvesting.

[c] Set-aside land not included.

[d] Available staff hours per day during harvesting period.

Results and discussion

The results concerning the development of the simulation model for field machinery operations and its applications are briefly discussed in this section as well as the seedbed experiment. An overall discussion on soil workability and timeliness costs is also included considering their close relation with the objectives of this work.

Paper I: The simulation model for field machinery operations

The building of the model was facilitated by the utilization of a discrete event simulation language, *i.e.* the Arena language (Kelton *et al.*, 1998). The model was validated in terms of daily field operation progress on a 367 ha farm for the spring and autumn field operations of the year 1999. Very good agreement was achieved in terms of progress between the model and the actual farm for spring operations and good enough for autumn-sown areas (Paper I). The good results were attributed to the facts that:

- The model was well adapted to the actual farm in terms of field capacity for the implements involved, daily effective field working hours for each driver, non-working days or free days, in addition to general data on the farm such as operation sequences, field sizes, alternative operations if one was not possible.

- Favourable weather conditions during the validation periods.

An important feature of the model was its capability to estimate timeliness costs for the harvesting operation under conditions of scattered field maturation times and possible overlaps between their harvesting periods since it included a module to estimate 'maturation time' for individual fields (Appendix B). Simpler approaches to estimate timeliness costs, *i.e.* ASAE equation (Eq. 1), require that an 'optimum time' should be identified for each 'operation' and no overlap should occur between different operation periods. Under Swedish conditions, these requirements are not fulfilled for harvesting. Usually fields are sown according to a crop rotation plan and as they dry in spring, leading to different field maturation times with a resulting overlap of their 'optimal' harvesting periods. In addition, field maturation times are difficult to predict, which implies that 'single harvesting' periods can hardly be identified with simple approaches.

The sensitivity of the ASAE equation (Eq. 1) for timeliness costs was tested for a varying number of harvesting periods. The results showed that timeliness costs were very sensitive to their number (Paper I). Thus, the correct identification of the number of harvesting periods and field involved is an essential pre-requisite to apply the ASAE equation.

Figure 5 displays total costs for tillage, sowing and harvesting operations estimated for seven machinery sets (Table 4) assessed on a 400 ha farm in Uppsala by means of the simulation model for field machinery operations and the ASAE equation (Eq. 1). Timeliness costs for the harvesting operation determined with the ASAE equation (second bar of each pair in Fig. 5) are not included since this method was not considered appropriate for estimating them.

Specific machinery costs were the main component of the total costs and they increased with machinery size. Timeliness costs decreased as machine size increased for sowing with both methods and for the harvesting operation estimated with the simulation model for field operations. As expected, set size had an effect on the variation of timeliness costs (Figs. 5 and 6). The smallest sets exhibited higher average timeliness costs and variance. The effect of set size on timeliness cost variability for single years was much larger, as reflected by the quartile distributions (Fig. 6).

In summary, the simulation model for field machinery operations developed using a discrete event simulation technique was able to simulate field operation progress on a real farm in a satisfactory way. The model allowed quantification of timeliness costs on a field basis during a series of years, since operation dates for sowing and harvesting in individual fields were outputs of the model. In addition, effects of operation sequences were captured. Average timeliness cost estimates were quantified in a long-term assessment (20 years) and their yearly variability determined. These features of the model were expected to lead to better accuracy when evaluating field machinery performance.

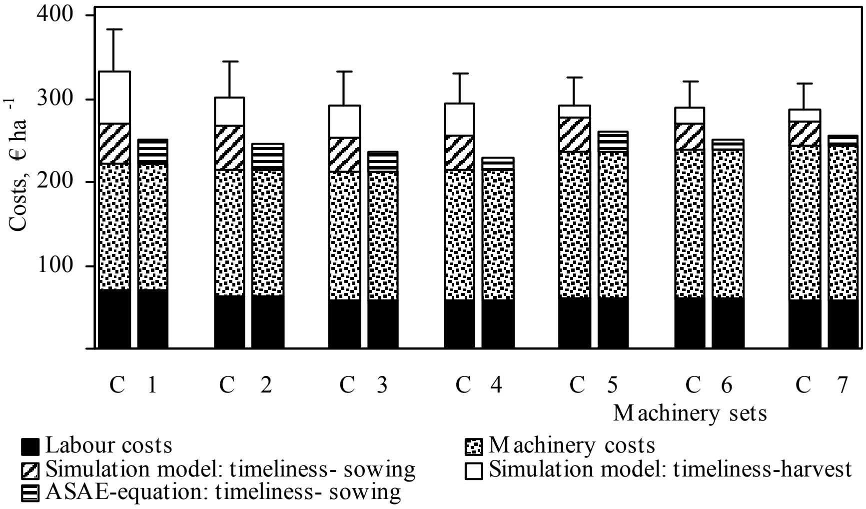


Fig. 5. Labour, machinery and timeliness costs for crop establishment (tillage + sowing) and harvesting for seven machinery sets determined with the simulation model for field machinery operations (first bar of each pair) and with the ASAE equation (Eq. 1) (second bar of each pair). The 'timeliness-sowing' and 'timeliness-harvest' legends indicate timeliness costs estimated for the sowing and harvesting operations respectively; the error bars indicate one standard deviation (n=20) of the annual timeliness costs estimated with the simulation model; for details on machinery sets, see Table 4 (figure source: Paper I).

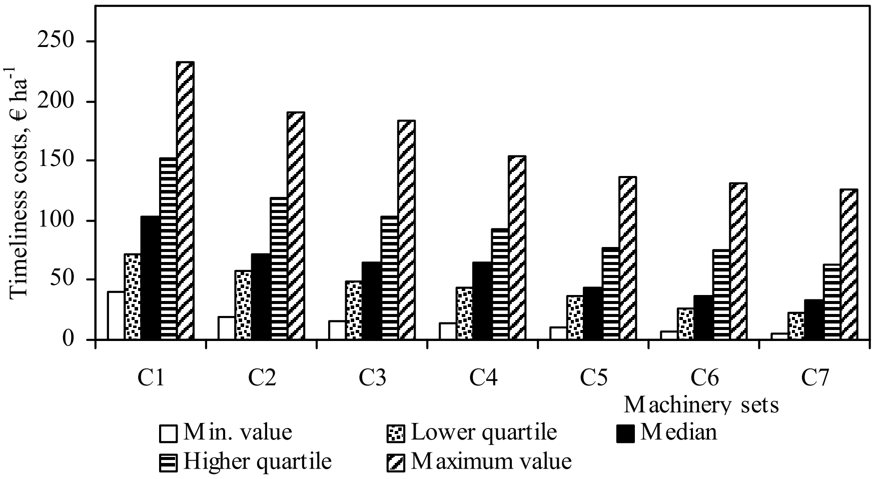


Fig. 6. Quartile distributions of timeliness costs for sowing and harvesting for the seven machinery sets assessed with the simulation model for field machinery operations. The sets are ordered from small to large; for details on machinery sets see Table 4 (figure source: Paper I).

Paper II. Influence of spring preparation date and soil water content on seedbed physical conditions of a clayey soil

The clayey soil (488 g kg^{-1} clay content) at the experimental site was well weathered after winter, exhibiting a granular structure in the superficial layer. Moisture stratification was already clear at the beginning of April and the same pattern continued during the whole experimental period with the exception of short periods after rain. The superficial dried layer (estimated visually) at the experiment start was still thin (less than 10 mm) while deeper layers were much wetter, drying slowly during the experiment period, *i.e.* the layer 40-50 mm dried from some 320 g kg^{-1} water content at the beginning of April to 280 g kg^{-1} at the middle of May. In contrast, the superficial layer (0-20 mm) was very dry most of the time, with a water content of some 50 g kg^{-1}.

As a result of the harrowing operation (three passes) the aggregate fraction less than 2 mm increased from about 40% at the beginning of the experiment to over 60% at the end, while the fraction of aggregates larger than 5 mm decreased considerably (Fig. 7). The largest fraction of small aggregates occurred when the average seedbed water content just after harrowing was about 150 g kg^{-1} or lower, which is about 50% of the water content at the plastic limit for this soil. This value is much lower than that generally found in the literature as the optimum water content for tillage.

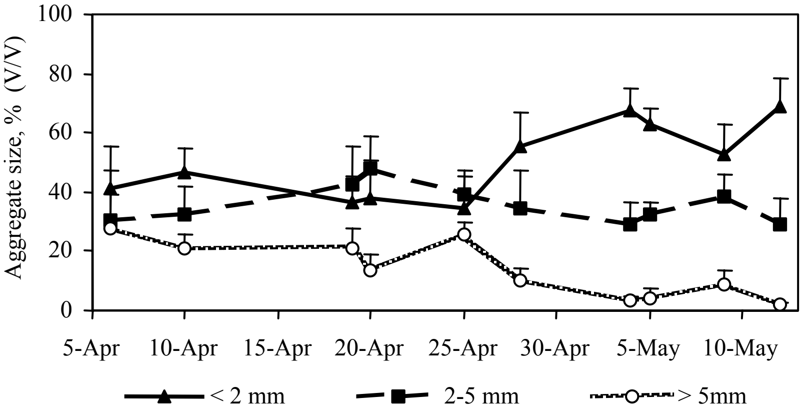


Fig. 7. Aggregate size distributions (%, v/v) of the seedbed (average of all layers) after seedbed preparation; the error bars indicate the coefficient of variation (figure source: Paper II).

The harrowing operations only produced a small increase in bulk density (Fig. 8), despite the fact that the first treatments at the beginning of April were performed when the soil was very wet, since it had just thawed. Then, the water content for the layer 50-150 mm was about 350 g kg^{-1}. A contributing factor to this result was the good tyre equipment of the tractor (dual tyres with a tyre inflation pressure of 40 kPa).

However, an increase in penetration resistance, including measurements before harrowing, occurred at 70 and 105 mm depth with soil water contents close to the plastic limit (300 g kg^{-1}) during May after a 2-week period with moderate temperatures (around 10 °C). This change in resistance can hardly be explained solely by variations in water content, as this remained almost constant, but it might be attributed to the 'strength regain' or 'age-hardening' phenomenon (Utomo & Dexter, 1981a; Dexter, 1988).

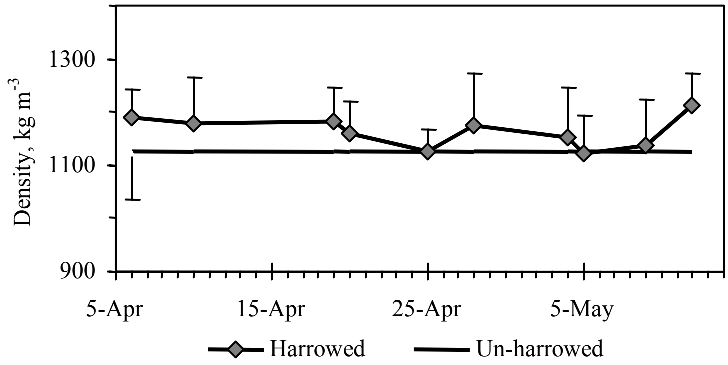


Fig. 8. Average bulk densities in the 50 - 150 mm soil layer for the plots harrowed at different dates and un-harrowed spots of the blocks; error bars indicate one standard deviation (n=9); the measurements were made at the end of the experiment (figure source: Paper II).

The increasing penetration resistance before harrowing in the layers with nearly constant water contents confirmed the dynamic property of soil structure. During winter time, freezing processes cause a disruption of soil structure, and after thawing in spring a subsequent structure recovery occurs, which is favoured by temperature and water content (Bullock *et al*., 1988; Utomo & Dexter, 1981b; Watts & Dexter, 1998). Such changes place additional difficulties on the determination of soil workability with static approaches.

Soil friability was the crucial factor for the timing of seedbed preparation and not soil trafficability or compaction risks. This can probably be applied to spring sowing on self-mulching soils with low evaporation losses and slow capillary rise. On such soils, compaction can only be avoided by technical measures, such as low inflation-pressure tyres, and not waiting for deeper soil layers (>50 mm) to become significantly drier.

Paper III: Influence of daily weather and other factors on timeliness costs and their variability

The objective of this study was to analyse the influence of daily weather linked to some major factors affecting timeliness costs and their influence on field machinery performance on cereal farms using the approach shown in Fig. 2 and described in the section '*Methodology*'.

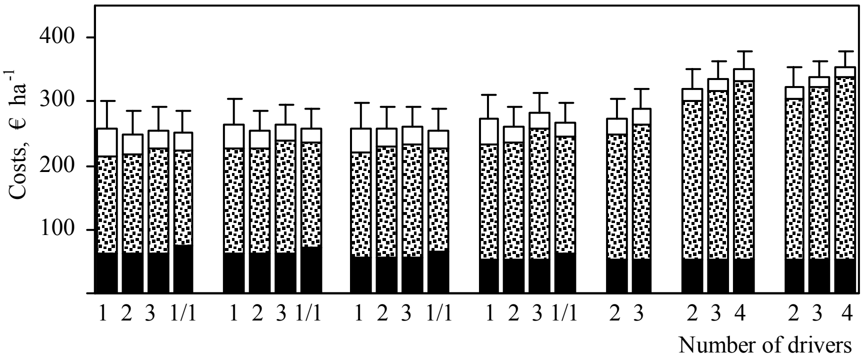
Total costs for crop establishment and harvesting for seven machinery sets (Table 5) with a varying number of drivers (or tractors) and three farm sizes in Uppsala are presented in Fig. 9. The quantitative relationships between machine, labour and timeliness costs were those expected according to established general farm management principles. The simulation results indicated that field operation costs and their variability were sensitive to the factors varied, *i.e.* cropped area, set size, labour availability and location (not shown in Fig. 9). Despite the fact that the 'optimal' set is usually 'site- and conditions-specific' in the case of the sets assessed, there was not just one set identifiable as the 'least cost' set for each farm size but several sets performed with similar low costs. A similar finding was reported by Edward & Boehlje (1980), who explained that within certain limits of machinery capacity, higher specific machinery costs of larger machinery sets are offset by their lower timeliness and labour costs, which can be clearly observed in the figure. Sets very different in size (*e.g.* set 'S1' and 'S7', 2 drivers, 400 ha farm case, Fig. 9) had similar total costs, since the lower specific machinery costs of set 'S1' were traded off by higher labour and timeliness costs and vice versa in the case of set 'S7'.

Annual variations in timeliness costs were lower for the larger sets as shown by the standard deviation values (Fig. 9). Correspondingly, higher daily effective field capacity was linked to lower variability in timeliness costs (Figs. 10a, b), which should lead to lower risks.

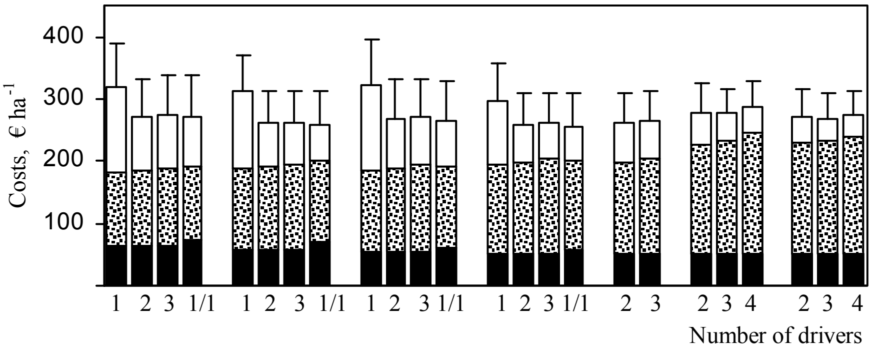
A step increase in daily effective machinery capacity had a lower effect on timeliness costs than a corresponding decrease in the same parameter (Fig. 10a), confirming the results reported by Danok *et al.* (1980), Oving (1989) and Sørensen (2003). Very low daily effective field capacity also led to peculiar effects on timeliness costs, particularly during rainy years when the 'weaknesses' of the smaller sets were revealed. Under such poor climate conditions, the effects of low machinery capacity were difficult to predict in advance since considerable areas were left un-worked or partially cultivated, *e.g.* ploughed but unsown.

The analysis found that timeliness costs of some considerable size (some €50 and €100 ha^{-1} in Malmö and Uppsala, respectively) were difficult to avoid during unfavourable climatic years on arable farms with clayey soils and reasonable machinery costs. This was associated with the low number of available workdays during those years (Fig. 3).

(a) 200 ha



(b) 400 ha



(c) 600 ha

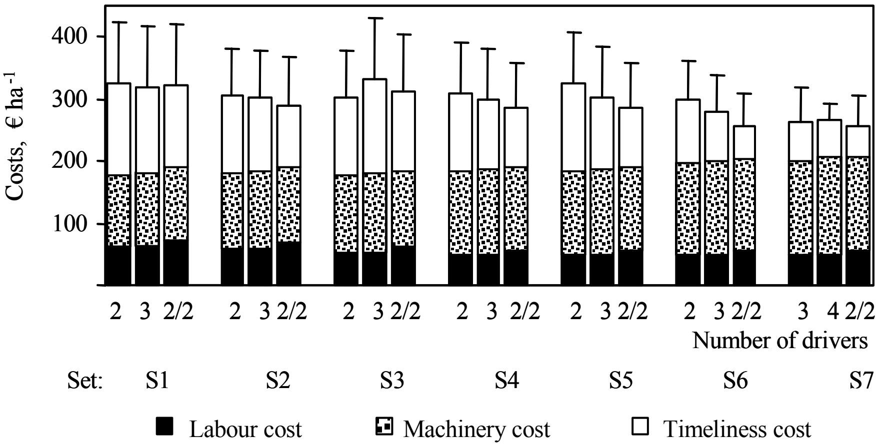
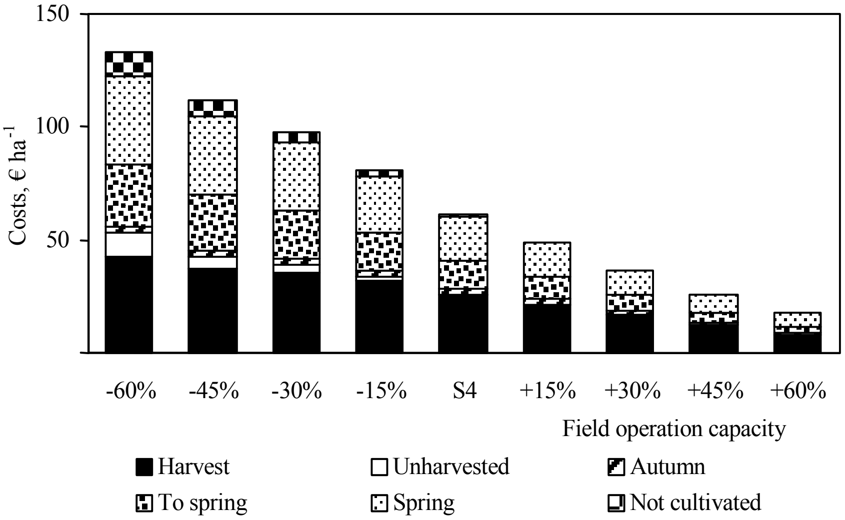


Fig. 9. Labour, machine and mean timeliness costs and their standard deviation (error bars, n=20) for crop establishment ((tillage + sowing) and harvesting for seven machinery sets working on a 200, 400 and 600 ha farm in Uppsala with a varying number of drivers (1 – 4; 1/1 or 2/2 refer to shift work); for details on machinery sets, see Table 5 (figure source: Paper III).

(a) Timeliness costs and their components for machinery set ‘S4’



(b) Mean and quartile distributions of timeliness costs for machinery set ‘S4’

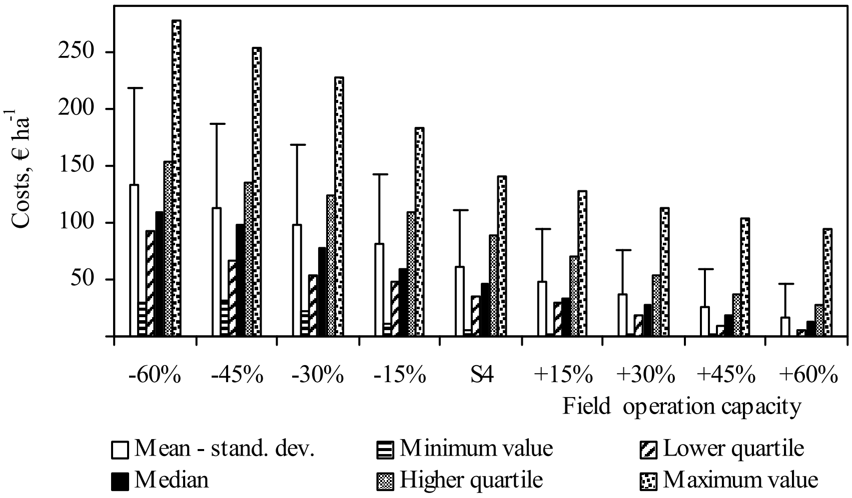


Fig. 10. (a) Average timeliness costs and their components for sowing and harvesting and (b) mean and standard deviation (error bars, n=20) of timeliness costs and their quartile distributions for the machinery set ‘S4’ when its daily effective field capacity was varied in 15% steps working on a 400 ha farm with two drivers (or tractors) in Uppsala; for details on set ‘S4’, see Table 5 (figure source: Paper III).

Paper IV: Machinery co-operatives – a case study

Labour, specific machinery and average timeliness costs per ha based on 20-year simulations for tillage, sowing and harvesting for the farms prior cooperation, current cooperation and three mechanization options are presented in Fig. 11. The average total cost was €370 ha^{-1} for the farms before cooperation (weighted by farm area), and €315 for the present pooling ('Co' in Fig. 11), *i.e.* a reduction of 15%. Total costs could be reduced still further; the estimate for the alternative 'Op2' is 30% lower than the average total cost for the farms prior to cooperation (weighted by farm areas).

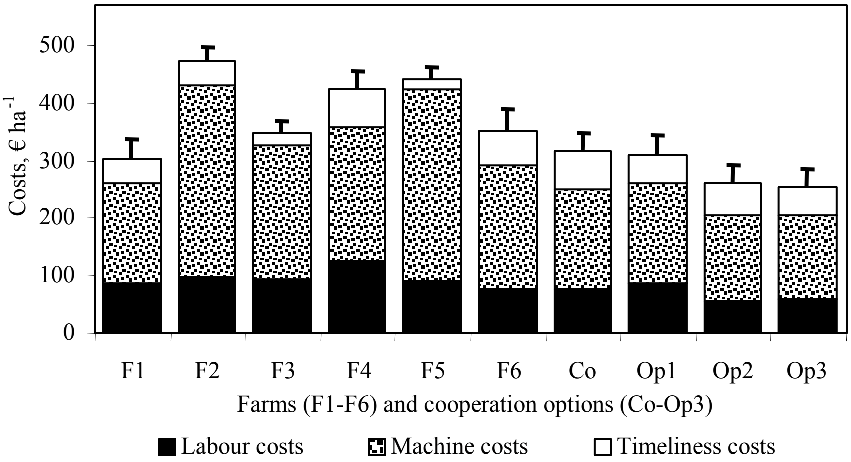


Fig. 11. Labour, machinery and average timeliness costs per ha for crop establishment (tillage + sowing) and harvesting for the mechanisation systems of the farms prior to cooperation (F1 - F6), the current cooperation (Co) and three options to the current pooling (Op1-Op3); the error bars indicate one standard deviation (n=20) of the timeliness costs; for details on machinery sets, see Tables 6 and 7 (figure source: Paper IV).

Timeliness costs of some consideration were found for all the mechanisation systems with 'no excessive capacity' (Fig. 11). They were difficult to avoid during those years with poor weather conditions during field operation. Their annual range was large, €10-120 ha^{-1} for most of the mechanization systems (Fig. 12). Timeliness costs and their variation were low for farms 3 and 5 for most of the years (Fig. 12) but the gains were offset by their high specific machinery costs (Fig. 11).

The machinery pool enabled the investment requirements to be reduced by about 50%. Similarly, field operation times were reduced to some extent but the gains were limited because the pool still mainly consisted of machinery from the time prior to cooperation (for further details, see Paper IV). Positive effects of machinery co-operation under Nordic conditions have been reported by Nielsen (1999) and Svendsen (1999).

Regarding non-economic aspects, all the farmers interviewed were satisfied with the results of the production cooperation scheme after three years of experience, pointing out that in addition to the economic benefits, it decreased their vulnerability and risks in cases where their own work availability for farming was affected, *e.g.* due to illness or other impediments. Furthermore, working in a team was also highly appreciated. Only minor disadvantages were expressed for the cooperation, *e.g.* decision processes took longer.

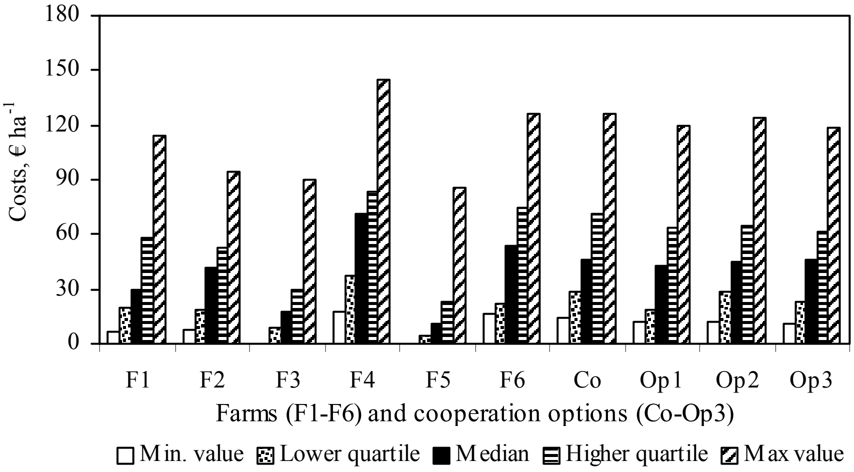


Fig. 12. Quartile distributions (n=20) of timeliness cost estimates for sowing and harvesting for the mechanisation systems of the farms prior to cooperation (F1 - F6), the current cooperation (Co) and three options to the current pooling (Op1-Op3); for details on machinery sets see Tables 6 and 7 (figure source: Paper IV).

The findings of the study on the co-operative, with a farming situation rather common in Sweden concerning soil type, farm size, crops and part-time farmers, led to the conclusion that more integrated machinery schemes are interesting options to consider for many farmers with similar conditions to those in the study.

Overall discussion

Soil workability

Rounsevell (1993) concluded in his review that most of the models inferred soil workability from soil water content, although in some cases other parameters such as penetration resistance were also included in the analysis. However, several studies indicate that water or penetration resistance are not the only factors influencing soil physical properties. Several other factors also affect it such as texture, organic matter, soil aggregation, processes influencing structure such as freezing-thawing, drying-wetting cycles, etc. In addition, soil structure is dynamic, changing during seasons and is influenced by agricultural practices (*e.g.* Chepil, 1954; Sillanpää & Webber, 1961; Utomo & Dexter, 1981b; Bullock *et al.*, 1988; Dexter, 1988; Watts & Dexter, 1998).

Consequently, soil workability, without any consideration of its eventual definition and soil heterogeneity in a field, is a result of complex processes where water is an important factor but not the only one. Thus, good accuracy for single days seems difficult to achieve and still remains a matter to be resolved in the future.

In this study, a sophisticated soil model, *i.e.* the SOIL-model (Jansson, 1991a, b), was utilized to estimate daily soil water content. Most of the soil input data for the SOIL-model were from a previous application on clayey soils where it had already been run with good results. However, some specific input data on physical and hydraulic properties were determined for the soil of the farm to be simulated (Table 1). The model proved to be very sensitive to small changes in hydraulic properties of soil, particularly for the parameter 'pore size distribution index' (for further details on this parameter, see Jansson (1991a) or McGechan & Cooper (1994)). Considering that soil characteristics in a field are heterogeneous, particularly for hydraulic properties, such sensitivity added a source of uncertainty to the results.

The calibration of the simulated moisture contents by the SOIL-model with the start dates of spring field operations on a real farm in order to infer soil workability for secondary tillage made it possible to bypass selection of moisture threshold values from general considerations of soil properties and reduced effects of possible errors in the simulated water tensions. However, this solution was not general, since the soil workability estimated in this way was related to the specific soil conditions and management policies of the farm where calibration was done. This sets up limitations on the estimated soil workability to conditions that are similar to the 'real farm'.

Due to the complexity of soil physical processes, particularly after freezing and thawing cycles in early spring and their effects on soil physical properties, the author of this work considers the applied procedure to estimate daily soil workability as the 'weakest point' of the thesis. Undoubtedly, this topic deserves further research in order to find better solutions.

Timeliness costs

The application of the simulation model for field machinery operations compared with simpler approaches provided three main advantages concerning estimation of timeliness costs, *i.e.* it enabled the operator to (a) capture sequence effects of operations, particularly for autumn sowing; (b) quantify timeliness costs for the harvesting operation when independent harvesting periods are difficult to identify and overlaps may occur between them; and (c) carry out a long-term assessment under variable weather conditions. In consequence, better timeliness cost estimates were expected, which almost certainly led to a more accurate evaluation of the machinery sets assessed.

In Paper III factors such as machinery size, operation area, number of drivers were varied in order to assess their effects on timeliness costs. These factors were those considered most feasible to be influenced by farmers. Other parameters also affecting timeliness costs, including working speed and field efficiency (which in turn depends on several other factors such as theoretical spot rate of work, field shape and size, fieldwork pattern, turning technique and speed, and time required for minor machinery adjustments), were assumed to be the normal values for the farming conditions in the regions of the study and were maintained unchanged in the simulations.

Similarly, the tillage technique and operations evaluated were the usual operations carried out on cereal farms; as was the soil type of the farms evaluated, a clayey soil, the common soil type in Uppsala. The basic idea behind this approach was that the simulated 'virtual farms' were as representative as possible of 'real farms'.

The timeliness penalties applied may be a matter of concern (Table 3). They were based on experiments carried out at least 15 years ago. During this time, crop varieties have changed and cereal yields have increased considerably. In addition, the timeliness penalties were based on data of different reliability. A considerable number of experiments lay behind the penalties applied to spring sowing, while the penalties for autumn sowing were based on much more limited statistics. The penalties charged for delays during harvesting were founded on data from the beginning of the 1970s, which were confirmed by some data from the experiments reported by Andersson (1983).

The procedure to estimate yield losses was based on a fixed penalty per day (Table 3), *i.e.* a linear relationship between losses and delays. This approach was chosen because the available data on yield losses for untimely sowing of spring cereals were from the study of Mattson (1990), who inferred such linear relationships. A similar approach was applied for the sowing operation of winter cereals and harvesting because of the limited data available. Such a linear approach has also been suggested by ASAE Standards (2000a) and has been applied in several studies (*e.g.* Burrows & Siemens, 1974; Nilsson, 1976; Parmar, *et al*., 1994; Siemens, 1998; Sørensen; 2003; Gunnarsson & Hansson, 2004). However, other researchers have proposed or utilized curvilinear relationships, *e.g.* a quadratic equation, for yield losses due to untimely operations (*e.g.* Tulu *et al*., 1974; Jarvis, 1977; Edwards & Boehlje, 1980; Witney & Eradat Oskoui, 1982; Witney, 1995). The determination of such 'average' curves requires considerable experimental data during a series of years because losses and their curve forms are specific for each year (Witney, 1995). This latter approach is more consistent with those observations where daily yield losses are very low a few days around the 'optimum time' but increase considerably as operation time deviates from it.

In effect, yield losses for the harvesting operation and single years seem to be more related to 'rainy days', which usually have more detrimental effects than extended periods of favourable weather. Consequently, timeliness costs for this operation are to a greater extent linked to these 'wet events' than just the passage of time as assumed when they are estimated with equations based on operation duration.

Cereals reach their physiological maturity at water contents above 30%, which is inadequate for harvesting and storage. The period between physiological maturity and 'harvesting maturity' is mainly a drying period, the duration of which is related to the water content that grain has to reach according to the farmer's policy to start the operation, varying from year to year and farmer to farmer.

Consequently, the water content that grain has to reach for ‘harvesting maturity’ is also a variable that should be analysed together with harvesting and drying capacity for a given farm in order to find an ‘optimal solution’ for these three items, which interact and largely affect harvesting costs. Simulation using hourly weather data has been utilized for predicting moisture content of field grain (*e.g.* Atzema, 1993; Sørensen, 2003).

Concerning spring sowing operations, extended delays in a given year do not necessarily lead to considerable timeliness costs if the growing season is favourable during that year. Consequently, a yield reduction resulting from an untimely sowing operation is itself a stochastic event (Pfeiffer and Peterson, 1980) if detailed weather data are not included in the analysis.

Simulation and reality

As already mentioned in the B*ackground* section, several researchers have taken advantage of simulation to analyse field machinery performance. A number of benefits have been pointed out, *e.g.* models are less expensive to construct and easier to modify than real systems, potential alternatives can be tested many times and with many modifications, hypothetical systems can be assessed (Buck *et al.*, 1988). However, simulation does not provide solutions to all problems as it mainly detects the state of a system over time within given assumptions (Lal *et al.,* 1991). The drawing of inferences from simulation is usually left to the user’s capabilities or to a software package, *e.g.* an expert system, where simulation is usually part of a larger system such as a module (Lal *et al.,* 1991; 1992). In the case of the machinery systems analysed in this work (Papers I, III and IV), simulation was used to determine field operation dates and timeliness costs were calculated by means of a spreadsheet programme.

Simulation models are a simplification of reality, including many assumptions, either implicit or explicit. The following were important simplifications made in this work:

- Daily soil workability was determined with data from one soil type when in reality soil characteristics on any farm are heterogeneous. In addition, its determination was made through calibration from only one farm.
- Only a few variables were varied to study their effects on timeliness costs. There are perhaps hidden interactions from other variables affecting these costs, such as field efficiency, working speed, working hours, *etc*., but they were maintained at constant levels during the simulations (for further details, see *Methodology* section).
- The model for field machinery operations had little flexibility to change ‘cropping plan’ in cases of major delays, which heavily penalized those sets with low capacity.
- The economic conditions for cereal production were those prevailing in Sweden at the time of the study, *i.e.* 2003.

Despite the above limitations, the model developed for simulation of field machinery operations made it possible to analyse the sensitivity of field machinery to daily weather in conjunction with other important parameters influencing timeliness costs. The study of machinery sensitivity to climatic variability makes necessary to develop such models. Papy *et al.* (1988) stated that it would be 'illusionary to believe that the problem could be solved by observing a large number of years, because in the meanwhile, farmer's objectives as well as the economic, environmental and technological factors would have changed'.

Environmental aspects and usefulness of the model to practical farming

The present work is in the area of farm machinery management and focuses on economic aspects, particularly on timeliness costs. Consequently, environmental issues were an implicit condition with the meaning that they were not affected very negatively in the cases analysed. Generally, management of farm machinery influences environmental issues more in an indirect way rather than directly.

An indirect issue worth mentioning is that farms with a better economy have the means to finance more efficient machinery, eventually with lower negative environmental effects, *e.g.* up-to-date tractors with a lower fuel consumption, advanced sprayers in order to reduce pesticides doses; equipment in the concept of 'precision agriculture'.

A direct way that machinery management influences the environment is through operation timing, particularly for sowing, fertilization and pesticide application operations. Appropriate timing for these operations usually allows pesticide and/or fertilizer requirements to be reduced. Similarly, a proper matching of implement size (draught requirement) to tractor makes best use of fuel (Hansson *et al.*, 1999; Lindgren & Hansson, 2002).

The value of the simulation model developed for field machinery operations to practical farming is related to the main findings resulting from the analysis of timeliness costs in Paper III and the case study of the cooperative machinery scheme in Paper IV. New findings and/or future utility of the model depend on its utilisation in new studies where sensitivity of field machinery to daily weather or annual timeliness cost variations are important aspects to include. However, the model is mainly a research tool and not sufficiently user-friendly to be utilised as a general tool for advisers.

Future research

Considering: (a) the high cost of harvesters; (b) the high drying costs and grain deterioration that a few wet days may cause to mature grain; and (c) the insufficient data on timeliness penalties for harvesting under Scandinavian climate conditions, better estimators of timeliness costs are necessary in order to select harvester size properly. In addition to data from field experiments, the following studies might be useful for the task:

- Atzema (1993), who developed a model for the prediction of field moisture content for cereals at harvesting time.
- The model of Abawi (1993), which had the capability of assess the effects of harvester size, speed, drying capacity, shedding losses and maturity date on

harvesting costs using daily simulation for 30 years with historical weather data from northern Australia.
- The work of Sørensen (2003), who adapted existing models to predict grain moisture status for different crops through simulation and to infer available workdays for harvesting at several grain moisture threshold values. The available workdays determined were utilized to analyse several economic parameters for the harvesting operation in Denmark.

The development of a dynamic model with the capability to analyse the relationship between field grain moisture content and grain losses might help to reduce the number of field experiments. Once better estimates of grain losses are determined, the entire system (field grain moisture - harvester size - drier size) could be optimized for various farming situations.

The assessment of mixed farm systems, *i.e.* farms with animal and crop production, is also an interesting study as regards: (a) the importance of animal production in Sweden, particularly milk, (b) the proportion of medium-scale farms, and (c) the increasing gap between cereal price development and machinery costs that occurred during the past decade (Fig. 1). The mechanization system and machinery utilization of these mixed farms has a different pattern than farms specializing only in combinable crops. Machinery optimization of such systems would require consideration of the whole system, wherein four main sub-systems may be differentiated, *i.e.* crop production, forage production, forage handling and specific activities related to livestock husbandry. Only two studies with such an approach were found in the literature (Jacobsen *et al., 1998;* Shaffer *et al.,* 2000). The analysis should include options for common use of machinery and some higher degrees of integration such as joint production systems as both schemes are interesting alternatives to reduce machinery costs.

Another issue quite relevant for field machinery management is soil workability. There is still not a generally accepted and accurate methodology to estimate available workdays for field operations. Already two decades ago, Pfeiffer & Peterson (1980) stated that ‘the days available for fieldwork were clearly the most import constraint in determining the optimum machinery size’. Their determination still seems difficult, particularly considering the complexity of soil processes and soil variability, which was summarized by Witney (1995) in the following statement ‘soil workability varies from soil to soil, machine to machine and farm manager to farm manager’. The author of the thesis has no suggestion on a possible approach to the issue.

Conclusions

The experiment on spring seedbed preparation on a clayey soil showed that date had only a minor effect on soil compaction but the fraction of fine aggregates increased with time. Thus, the optimal time for seedbed preparation depended more on soil friability than on the risks of compaction.

Despite the numerous efforts to develop a methodology to determine available field workdays, there is still not a generally accepted method.

The simulation model for field machinery operations developed using a discrete event simulation technique enabled timeliness costs and their annual variability to be estimated in a long-term assessment. The model was particularly appropriate for estimating timeliness costs for the harvesting operation in conditions of scattered field maturation times and probable overlapping of their ‘single harvesting periods’, where simpler approaches are difficult to apply.

Timeliness costs were an important component of total costs (specific machinery + labour + timeliness costs) for field machinery in Malmö and Uppsala. The estimations varied from a low value for years with favourable weather conditions to more than €100 ha^{-1} during rainy years, even for those machinery sets performing relatively well at both locations.

Machinery sets with high daily effective field capacity not only showed lower timeliness costs but also lower annual variation. Timeliness costs were more affected by a stepwise reduction in daily effective field capacity than a stepwise increase of the same magnitude.

For given farming conditions and within certain limits of machinery capacity, there was not just one set identified as the ‘least-cost’ option. Instead, several sets performed at a similar low cost level. Higher specific machinery costs for the larger sets were offset by lower timeliness and labour costs, and the converse was equally true. The machinery set to be selected should be the largest set among those with a similar ‘least-cost’ on account of its lower annual variation, which usually implies lower risks.

Machinery co-operation proved to be advantageous in economic terms for medium-scale cereal producing farmers (50-200 ha) in the region of Uppsala. Machinery sharing enabled costs to be reduced by about 15% and investment requirements by 50% compared to the situation prior to co-operation, and both items could be reduced still further by fewer but larger machines. At the same time co-operation was highly appreciated in social terms by the farmers in the study.

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Appendix A. The structure of the simulation model for field machinery operation in the Arena software

The model was developed in the Arena software, which is a discrete event simulation language (Kelton *et al.*, 1998). Version 3.01 was used but newer versions of Arena (*e.g.* 7.01[1]) have been released and are compatible with the code of Version 3.01. Only the structure of the model is presented in the following pages due to space restrictions. Arena programmes are mainly built on the basis of modules, each of which contains more detailed information on parameters, equations, batch sizes, routes, etc. If the reader is interested in details or the whole programme, please contact the author.

The model consists of modules, which can be grouped as follows:

(a) Declaration modules for defining general variables, simulation time (*e.g.* 175 000 h), attributes of entities (field), resources etc. (Page 48).
(b) Initiation of variables, field attributes, work done in previous year, delays of operation start, calculation of maturity day, read daily soil state (Page 51).
(c) 'Stations' for each field operation: stubble cultivation, ploughing, cultivator, harrowing, rolling, sowing and harvesting (Page 55).
(d) Animation of resources, some variables and counters (Page 62).

The main features of the model are:

- It starts simulation at the beginning of the year, reading data saved from the previous year.
- It includes a *Sequences* module where a succession of field operations are defined for each field.
- Daily input data on the soil workability state read from an input file.
- Delays for winter and summer seasons.
- Resources: 4 tractors, 4 drivers, implements for soil tillage, sowing and harvesting (two of each type). 'Ghost' resources were added for control of the programme. The programme is flexible enough to add new machines and new operations.
- Field specifications: each field has a set of attributes which determine its size, sequence of operations, priority of the operations in relation to other field when competing for resources.
- Operation 'stations' where ploughing, harrowing, rolling, planting and harvesting operations are simulated.
- Calculation of harvesting date (Appendix B).

---

[1] Rockwell Software, Inc., 2002-2003. http://www.arenasimulation.com/

(a) Declaration modules

Simulation model for field machinery cooperations

Read field data from file ""C:\Alf03\Arena\uppsala\rapid_400ha.wks""
Read soil state from file "c:\arena\tem\weather.wks"
Read file for Visual Basic proced. "c:\arena\tem\tem_day_80_upp.prn"

Operation periods for machine cooperation, Uppsala
Spring start operation: April 19 (Day No: 109)

Autumn seeding period: Sep 1 (Day No: 244) --- Oct. 1 (day no 274)
Harvesting: August 1 (Day No: 213) --- Oct. 15 (day no 288)
Maturity limits: August 5 (Day No: 217) --- Sept. 7 (day no 250)

General declarations

Expressions
- stubbling time
- plowing time
- harrowing Time
- RollingTime
- Cultivator Time
- Sowing time
- Combining time
- Workers
- MaxFieldNo

Initiate these variables

Variables
- Aux1
- No_D
- No_T

Attributes
- field
- fieldSize
- Priority

Sequences
- Win_trad6
- cul_trad7
- Spr_trad8
- Win_Rapid1
- Spr_Rapid3
- Cul_rapid2

Sets

■ 175000

Simulate

Program S4_uppsala.doe

Variables
- PlowedHa
- HarrowedHa
- CultivatorHa
- RolledHa
- SowedHa
- CombinedHa
- year
- dayNo
- p_ok
- H_ok
- c_ok
- other
- doneThisYear

Queues
- opera_q
- PlowingQueu
- P2Queu
- P1Queu
- H1Queu
- H2Queu
- St1Queu
- St2Queu
- CU1Queu
- CU2Queu
- R1Queu
- R2Queu
- Sw1Queu
- Sw2Queu
- C1Queu
- C2Queu

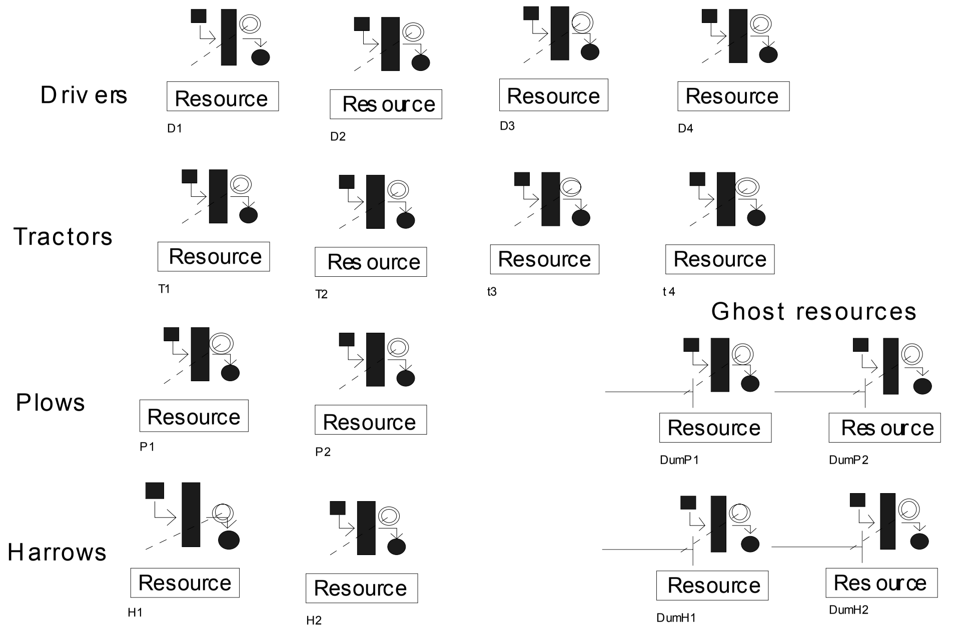
Memory variable: Donethisyear(1..40, 1..10)

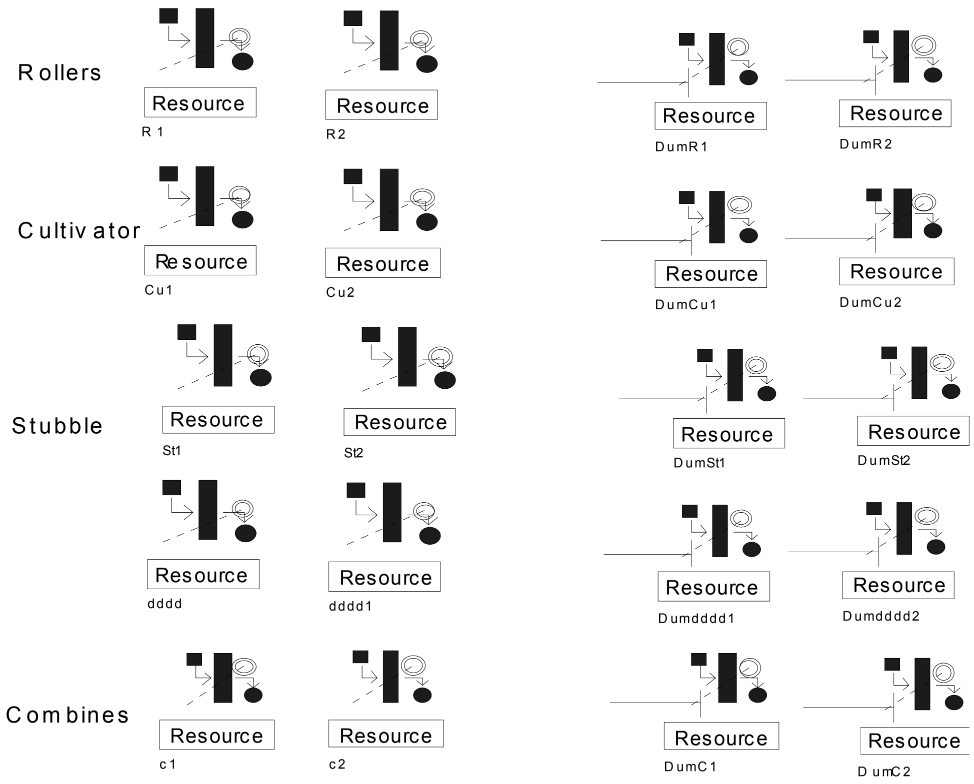
Rows: fields

Sequence: AssignLastYearDone, Winter delay, AssignStepServer, Harrowing1, Sowing1 Calcul_comb_day, Rolling1, Summer delay, WaitingMatureDay, Combining1 Plowing1, Harrowing1, Rolling1, Sowing1, Calcul_comb_day, NextYearInitiate

Resources

(D_=Driver T_=Tractor P_=Plow H_=Harrow S_= Sowing machine)

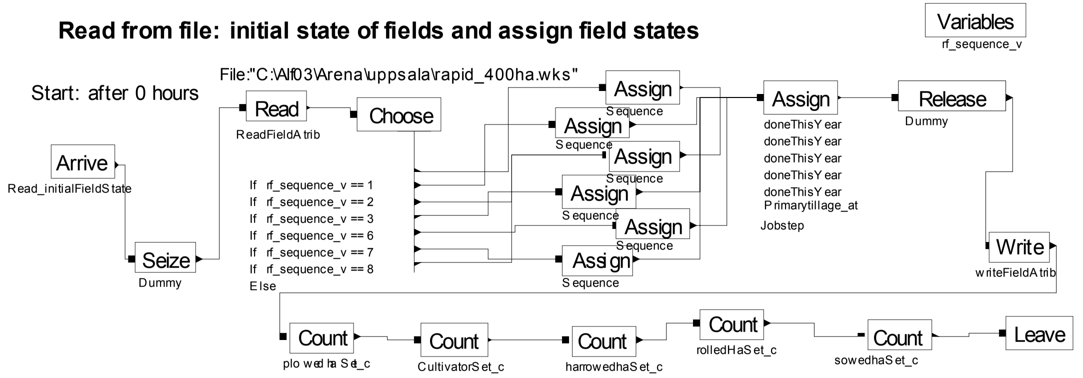



Rollers
Resource
R 1
Resource
R2
Resource
DumR1
Resource
DumR2
Cultivator
Resource
Cu1
Resource
Cu2
Resource
DumCu1
Resource
DumCu2
Stubble
Resource
St1
Resource
St2
Resource
DumSt1
Resource
DumSt2
Resource
dddd
Resource
dddd1
Resource
Dumdddd1
Resource
Dumdddd2
Combines
Resource
c1
Resource
c2
Resource
DumC1
Resource
DumC2

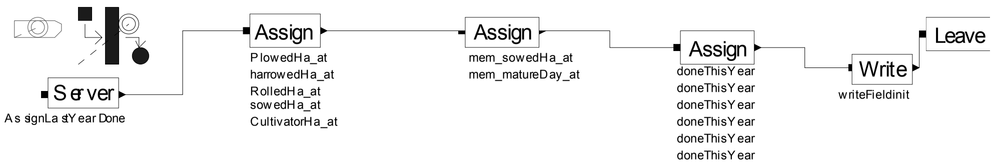
(b) Initiation of variables, delays, calculation of maturity day, read daily soil state

Initiate: field states, working conditions, delays

Read from file: initial state of fields and assign field states

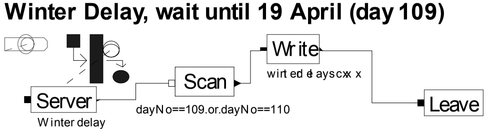


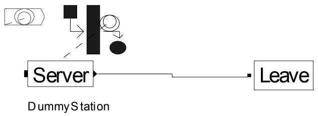
Initiate attributes, variables with the work done the previous year



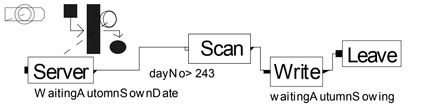
Delays: winter, summer, mature day, autumnSownDate

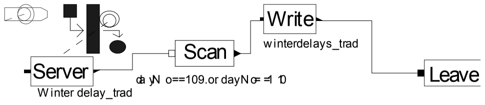
Winter Delay, wait until 19 April (day 109)





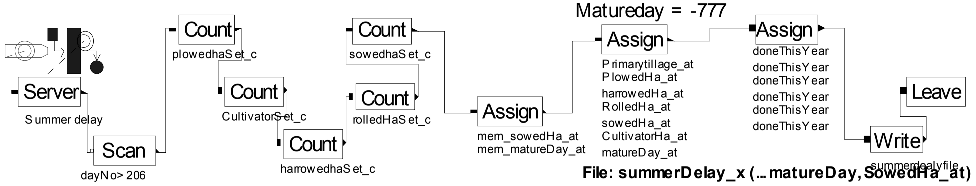
Waiting automn sowing date: 1 Sept. (day 244)





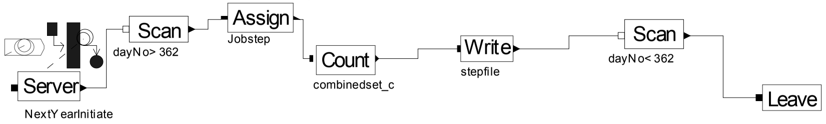
Summer Delay, wait until July 25 (day 206) and initiate winter variabels

Initiate to 0: counters, doneLastYear, doneThisYear arrays and fieldSize

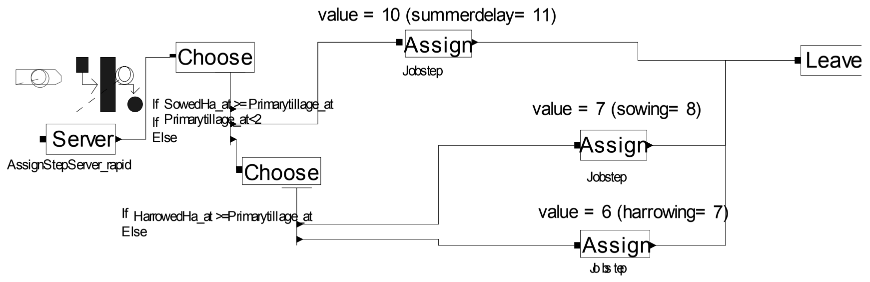


Re-initiate sequences and variables for next year (day 363)

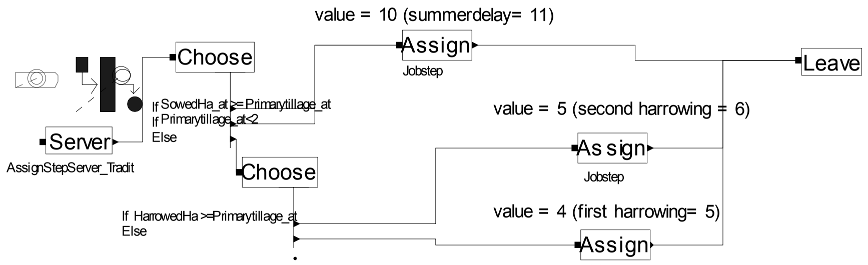
value = 0 (assignLastYearDone = 1)



Step operations at the beginning of a new year for reduced tillage



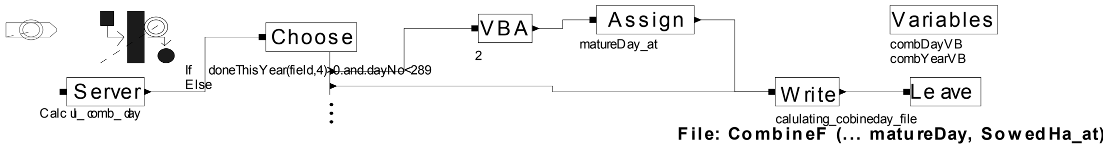
Step operations at the beginning of a new year for traditional seedbed preparation



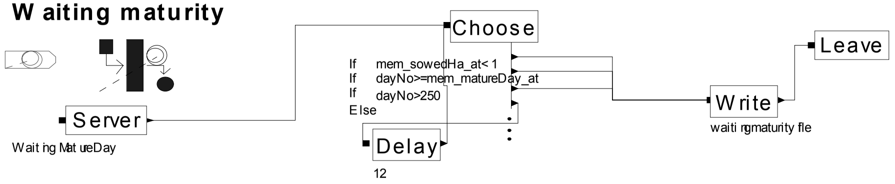
Info on sequence identification: NS(ident)= "sequence namn"

Calculating maturity day

In the VBA code maturation limits are set to: 217 (5 august) and 250 (7 Sept)



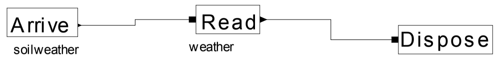
Waiting maturity



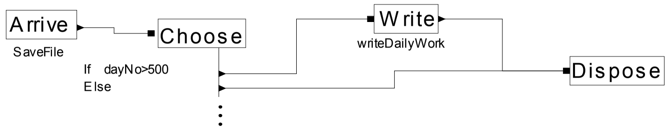
Read and write files

Read from file: daily soil states for field operations

Start: after 24 hours

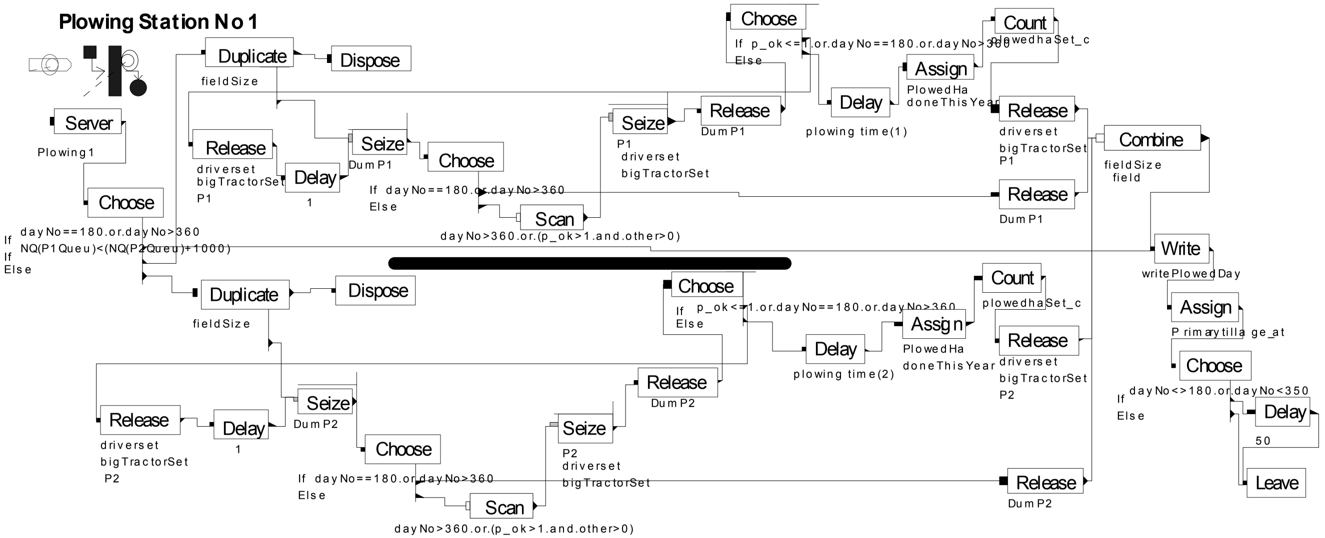


Save to file daily work done:



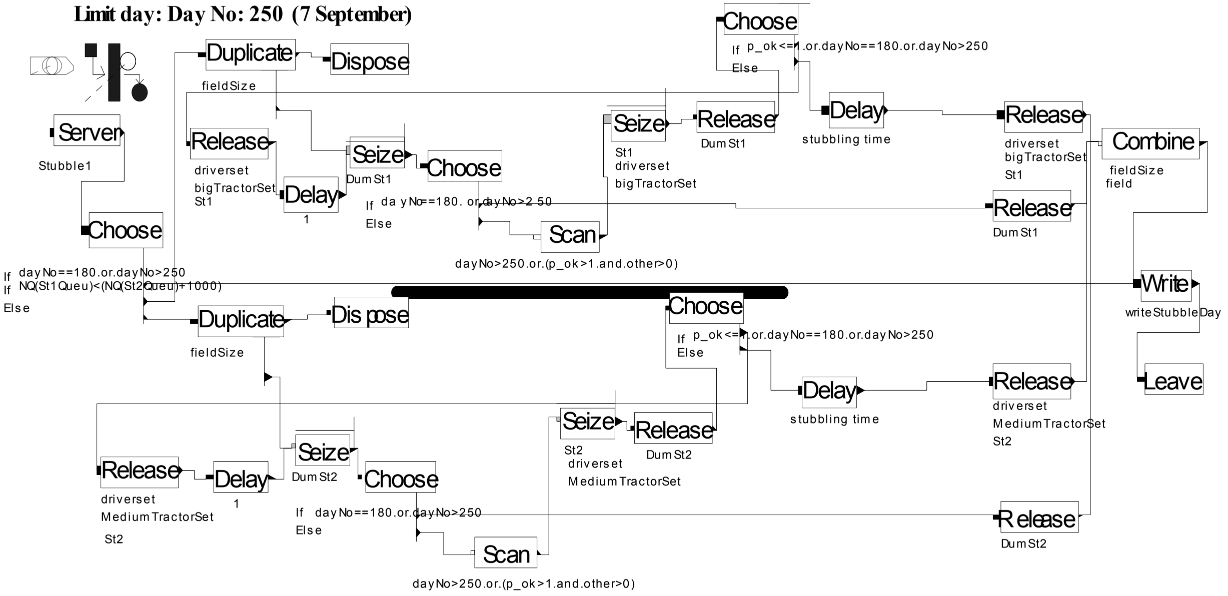
(c) ‘*Stations*’ for field operations

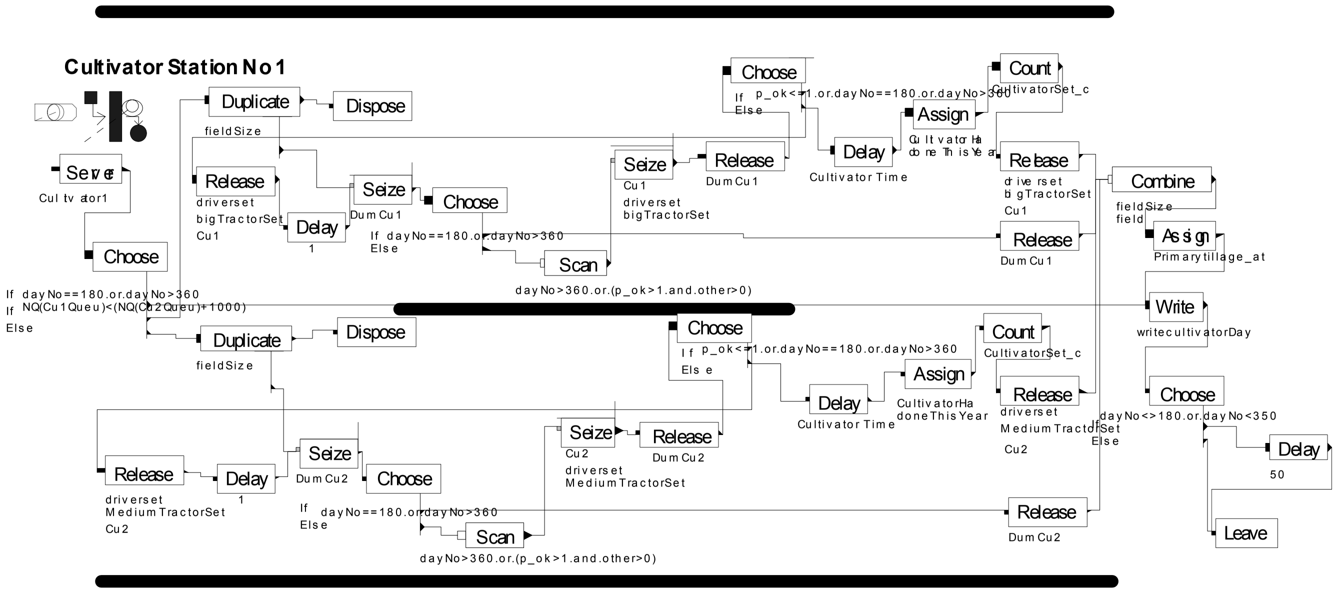
Field operations



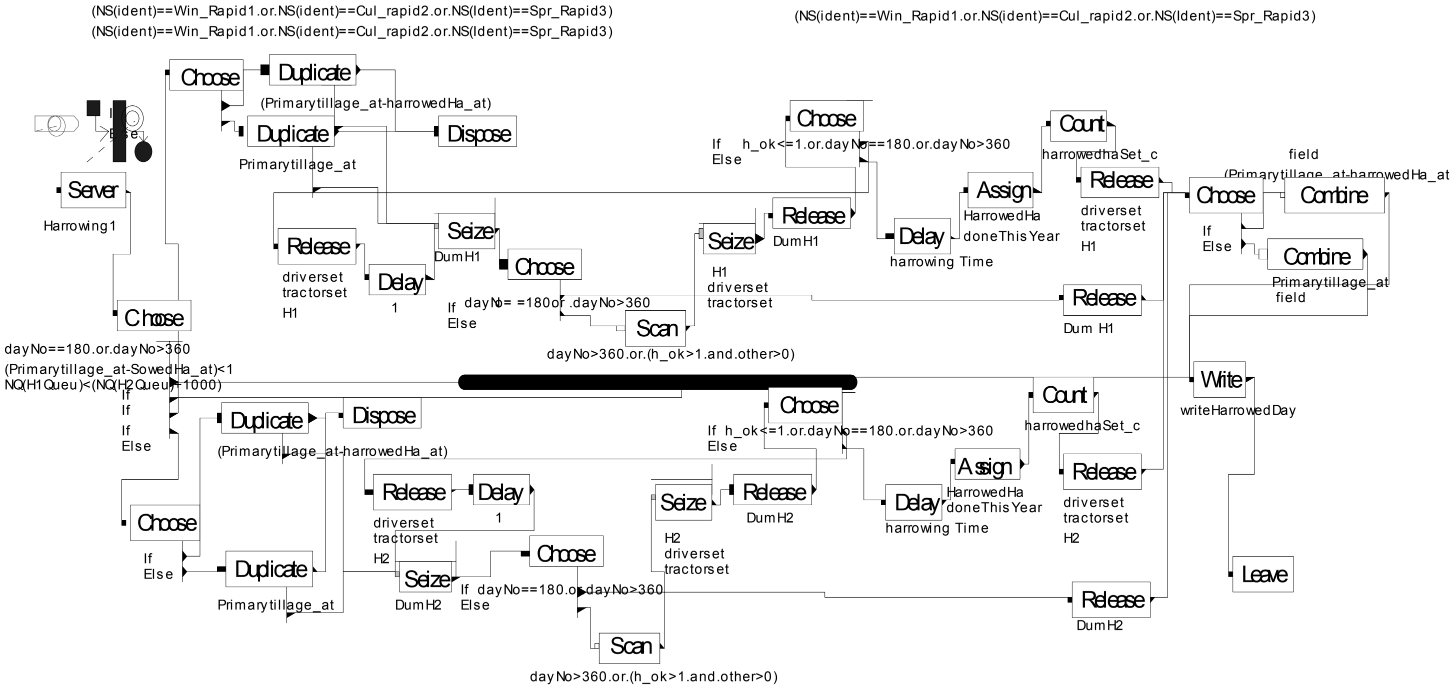
Stubble Station No 1

Limit day: Day No: 250 (7 September)



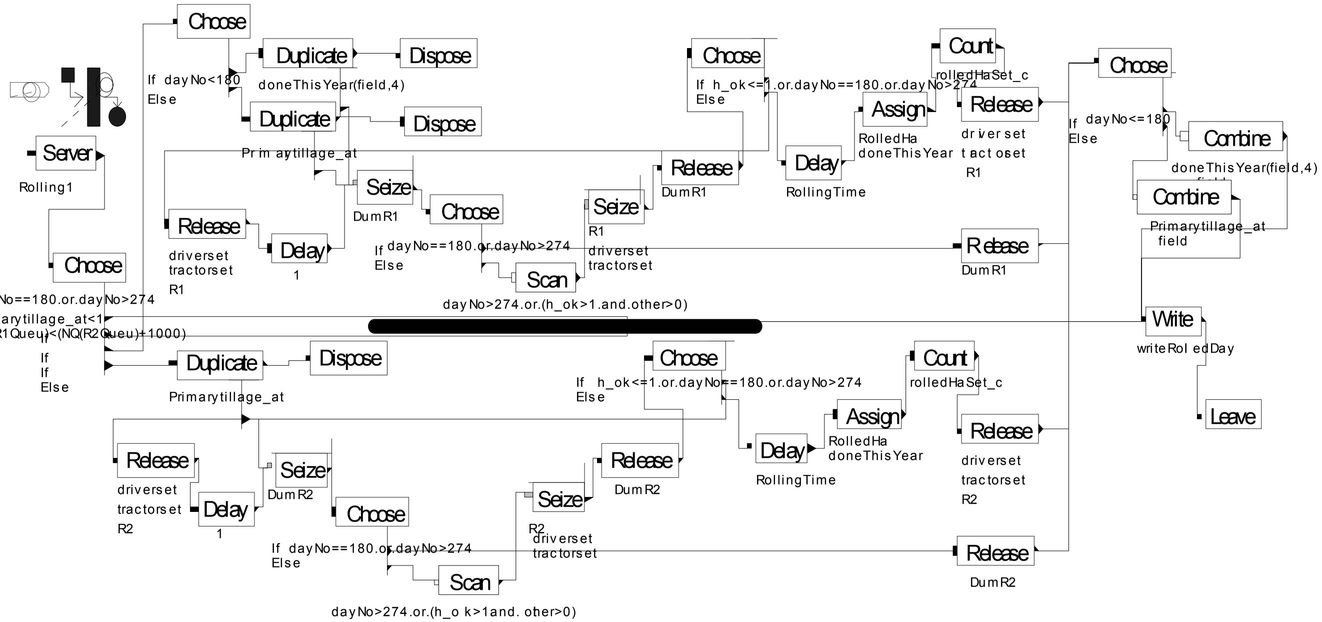

Cultivator Station No 1
Server
Cultivator1
Choose
If dayNo==180.or.dayNo>360
If NQ(Cu1Queu)<(NQ(Cu2Queu)+1000)
Else
Duplicate
fieldSize
Dispose
Release
driverset
bigTractorSet
Cu1
Delay
1
Seize
DumCu1
Choose
If dayNo==180.or.dayNo>360
Else
Scan
dayNo>360.or.(p_ok>1.and.other>0)
Seize
Cu1
driverset
bigTractorSet
Release
DumCu1
Choose
If p_ok<=1.or.dayNo==180.or.dayNo>360
Else
Delay
Cultivator Time
Assign
CultivatorHa
doneThisYear
Count
CultivatorSet_c
Release
driverset
bigTractorSet
Cu1
Release
DumCu1
Duplicate
fieldSize
Dispose
Release
driverset
MediumTractorSet
Cu2
Delay
1
Seize
DumCu2
Choose
If dayNo==180.or.dayNo>360
Else
Scan
dayNo>360.or.(p_ok>1.and.other>0)
Seize
Cu2
driverset
MediumTractorSet
Release
DumCu2
Choose
If p_ok<=1.or.dayNo==180.or.dayNo>360
Else
Delay
Cultivator Time
Assign
CultivatorHa
doneThisYear
Count
CultivatorSet_c
Release
driverset
MediumTractorSet
Cu2
Release
DumCu2
Combine
fieldSize
field
Assign
Primarytillage_at
Write
writecultivatorDay
Choose
dayNo<>180.or.dayNo<350
Else
Delay
50
Leave

HarrowingStation
Limit day: Day No: 360



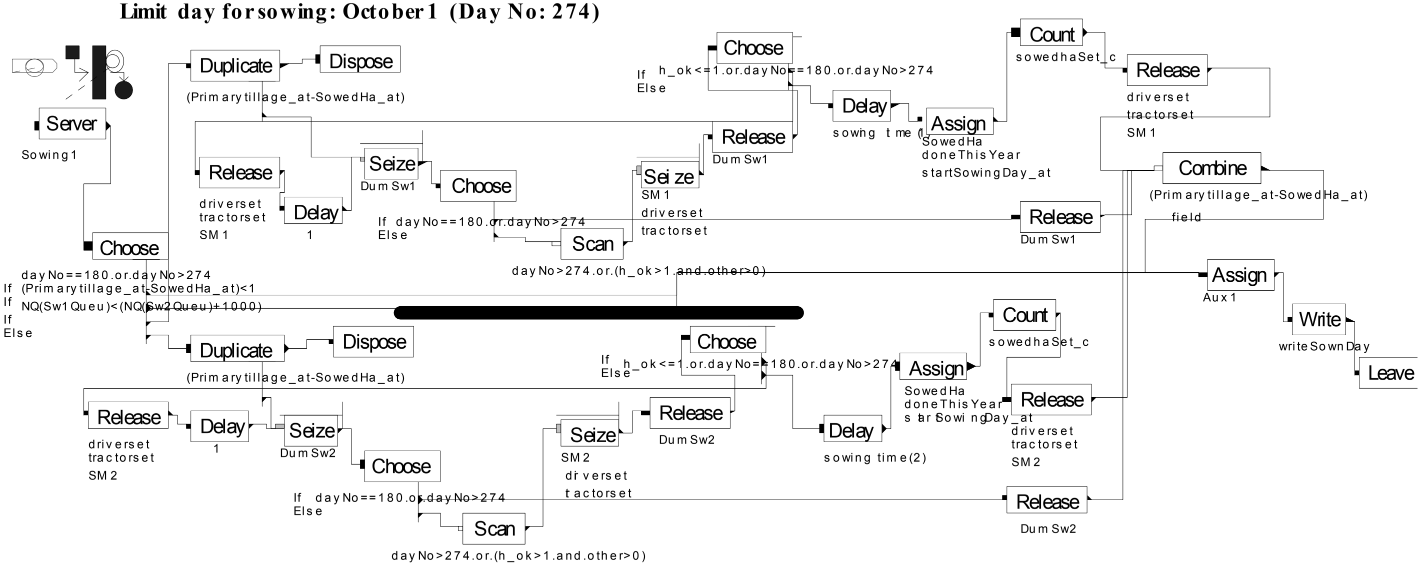
Rolling Station

Limit day: October 1 = Day No: 274



Sowing Station

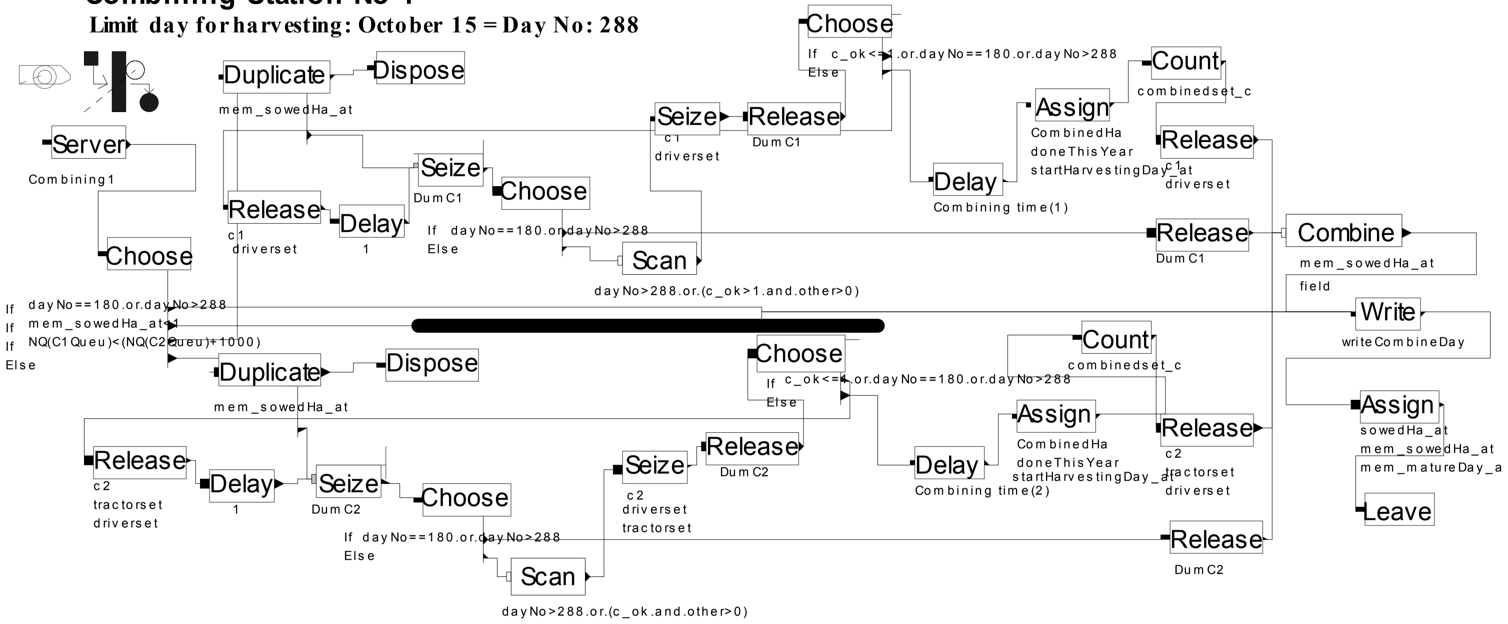
Limit day for sowing: October 1 (Day No: 274)



File SownDay.wks : year, startDayNo, Dayno, Field, Fieldsize, SowedThisYear, totalsowed

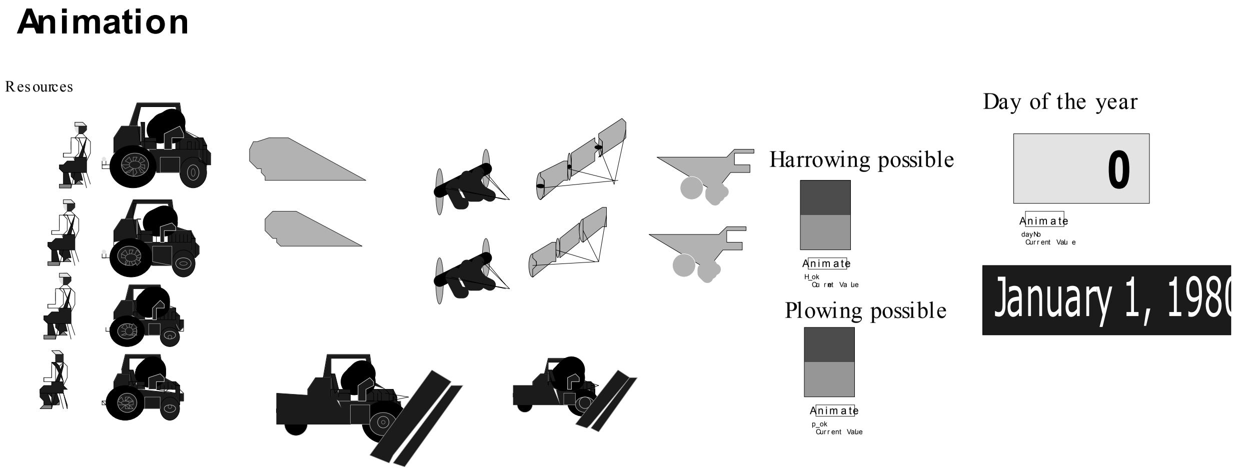
Combining Station No 1

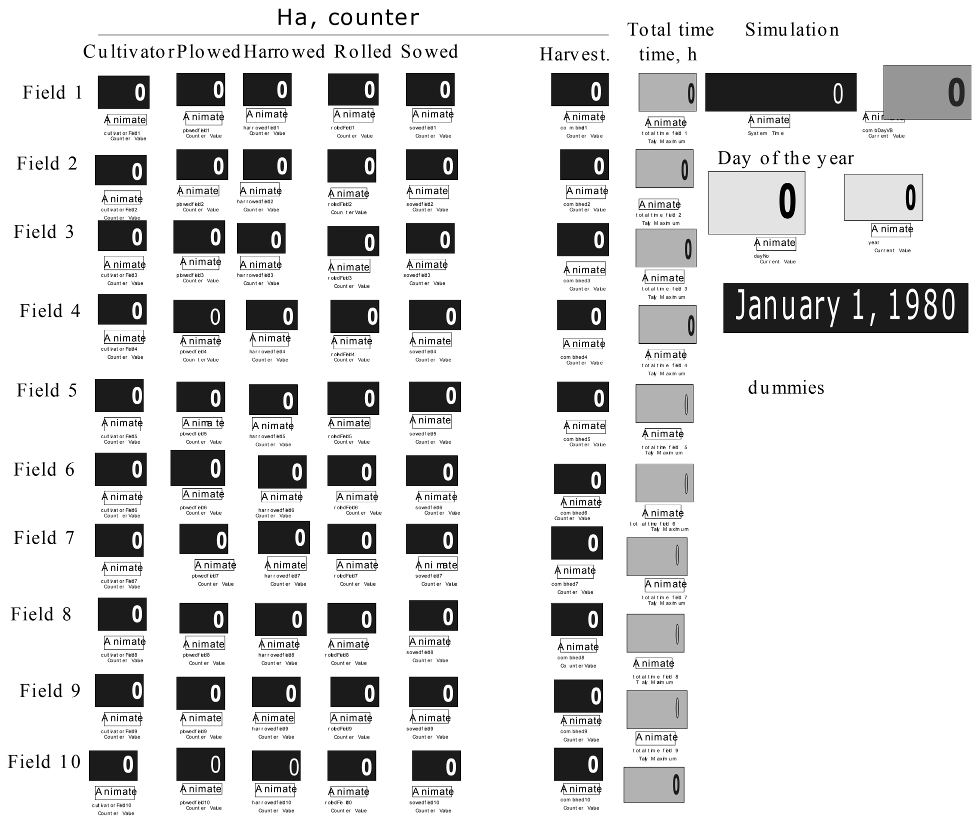
Limit day for harvesting: October 15 = Day No: 288



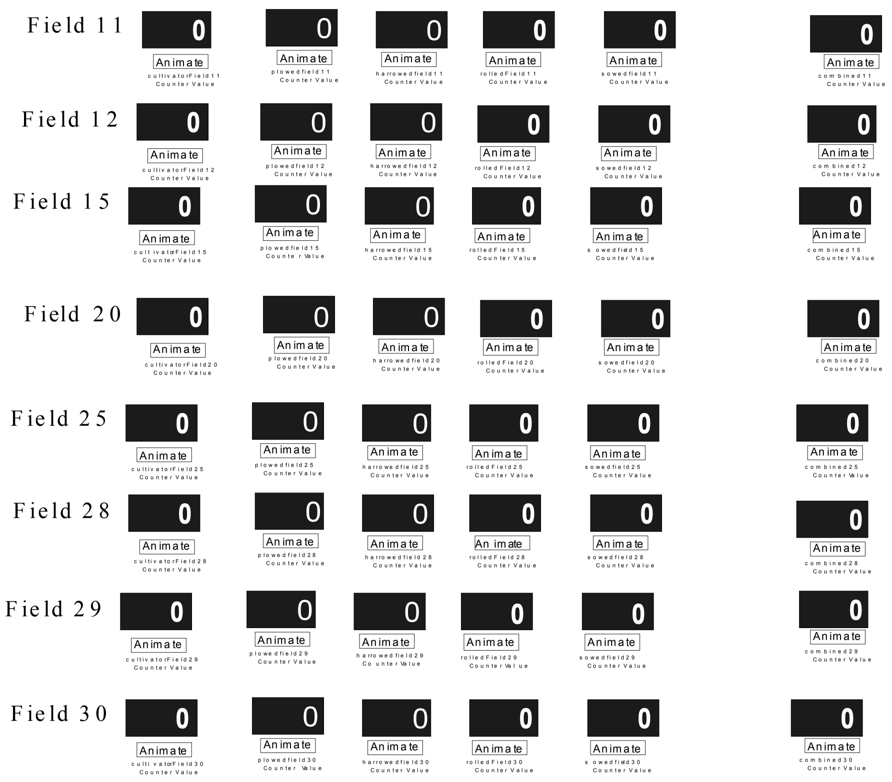
File Combinedav.wks: year, startDayNo, Dayno, Field, Fieldsize, SowedHa, Combined ha, MatureDay

(d) Animation of resources, some variables and counters





	Cultivator	Plowed	Harrowed	Rolled	Sowed	Harvest.	Total time time, h
Field 1	0	0	0	0	0	0	0
Field 2	0	0	0	0	0	0	0
Field 3	0	0	0	0	0	0	0
Field 4	0	0	0	0	0	0	0
Field 5	0	0	0	0	0	0	0
Field 6	0	0	0	0	0	0	0
Field 7	0	0	0	0	0	0	0
Field 8	0	0	0	0	0	0	0
Field 9	0	0	0	0	0	0	0
Field 10	0	0	0	0	0	0	0


Field 11
0
Animate
cultivatorField11 Counter Value
0
Animate
plowedfield11 Counter Value
0
Animate
harrowedfield11 Counter Value
0
Animate
rolledField11 Counter Value
0
Animate
sowedfield11 Counter Value
0
Animate
combined11 Counter Value
Field 12
0
Animate
cultivatorField12 Counter Value
0
Animate
plowedfield12 Counter Value
0
Animate
harrowedfield12 Counter Value
0
Animate
rolledField12 Counter Value
0
Animate
sowedfield12 Counter Value
0
Animate
combined12 Counter Value
Field 15
0
Animate
cultivatorField15 Counter Value
0
Animate
plowedfield15 Counter Value
0
Animate
harrowedfield15 Counter Value
0
Animate
rolledField15 Counter Value
0
Animate
sowedfield15 Counter Value
0
Animate
combined15 Counter Value
Field 20
0
Animate
cultivatorField20 Counter Value
0
Animate
plowedfield20 Counter Value
0
Animate
harrowedfield20 Counter Value
0
Animate
rolledField20 Counter Value
0
Animate
sowedfield20 Counter Value
0
Animate
combined20 Counter Value
Field 25
0
Animate
cultivatorField25 Counter Value
0
Animate
plowedfield25 Counter Value
0
Animate
harrowedfield25 Counter Value
0
Animate
rolledField25 Counter Value
0
Animate
sowedfield25 Counter Value
0
Animate
combined25 Counter Value
Field 28
0
Animate
cultivatorField28 Counter Value
0
Animate
plowedfield28 Counter Value
0
Animate
harrowedfield28 Counter Value
0
Animate
rolledField28 Counter Value
0
Animate
sowedfield28 Counter Value
0
Animate
combined28 Counter Value
Field 29
0
Animate
cultivatorField29 Counter Value
0
Animate
plowedfield29 Counter Value
0
Animate
harrowedfield29 Counter Value
0
Animate
rolledField29 Counter Value
0
Animate
sowedfield29 Counter Value
0
Animate
combined29 Counter Value
Field 30
0
Animate
cultivatorField30 Counter Value
0
Animate
plowedfield30 Counter Value
0
Animate
harrowedfield30 Counter Value
0
Animate
rolledField30 Counter Value
0
Animate
sowedfield30 Counter Value
0
Animate
combined30 Counter Value

Appendix B. Procedure for determining maturation day

The determination of maturation day for a field is based on daily average temperature and day length (Angus *et al.,* 1981) using a procedure written in Microsoft Visual Basic for Application (VBA), which is an integrated application in the Arena language. The original source of the procedure is the SOIL-N model (Eckersten *et al.,* 1998) and was written in Fortran. The author of the thesis translated the Fortran-code to Visual Basic code, making no change to constants, variables or equations. The translation of the code was necessary for integrating the procedure to the Arena model for simulation of field machinery operations (Appendix A).

The procedure is started by the Arena programme, which passes to this procedure the variables *day number* and *year* corresponding to the sowing date of a field. Then, the procedure determines maturation day for the field from daily *temperature* and *day length* data read from an input file. Once the maturation *day number* and *year* are determined they are returned to the 'ordinary' Arena programme.

The procedure consists of 5 main sub-routines:

- CalculateStage_1: for determining the stage 'sowing to emergency'.
- CalculateStage_2 for determining the stage 'emergency to start grain filling'.
- CalculateStage_3 for determining the stage 'start grain filling to finish grain filling'.
- CalculateStage_4 for determining the stage 'finish grain filling to maturity'.
- SetLimitsForMaturationDay: in cases where the above sub-routines do not succeed in determining 'maturation date' within a certain period a maturation range is set (this sub-routine was added by the author of this work).

Visual Basic code

```
' Procedure for calculating MATURATION DAY
' fired from the ‘ordinary’ ARENA Program.
' Passed values from ARENA: "year" and "DayNo", and
' returned values to Arena: "combYearVB" and "combDayVB".
' Input file: "c:\arena\tem\ tem_day_80_upp.prn "
' Please control that input file has only four data columns
' with the variables: year, dayNo, temperature, daylength
' Read from file: year_f, DayNumber_f, Ta_f, dayLength_f
'
' By Alfredo de Toro, 2001-08-12
------------------------------------------------------------------------

Option Explicit
Dim m As Arena.Model
Dim s As Arena.SIMAN
Dim sameStage, ready As Boolean
Dim sowingDay, sowingYear As Integer
Dim growthStage As Long
Dim ytaAccem, yhelp1a, yhelp1 As Double
Dim ydevacc, vdev, yhelp2a, yhelp2 As Double
Dim ytaAccgr, ytaccma As Double
Dim year_f, dayNumber_f As Integer
Dim ta_f, dayLength_f As Double
Const taphenol_2 = 90, graini3 = 9.1, ygraini1 = 0.0252
------------------------------------------------------------------------

Private Sub init_Var()
   growthStage = 1
   ytaAccem = 0
   yhelp1a = 0
   yhelp1 = 0
   ydevacc = 0
   vdev = 0
   yhelp2a = 0
   yhelp2 = 0
   ytaAccgr = 0
   ytaccma = 0
  End Sub
------------------------------------------------------------------------
```

```
'Stage sowing to emergency
Private Sub calculateStage_1()
    If ta_f > 1 Then ytaAccem = ytaAccem + ta_f - 1
    If ytaAccem > taphenol_2 Then
       growthStage = 2
       sameStage = False
      End If
   End Sub
---------------------------------------------------------------------------
'stage emergency to start grain filling
Private Sub calculateStage_2()
    If (ta_f - 3.51) > 0 Then
                     yhelp1a = ta_f - 3.51
                    Else
                     yhelp1a = 0
       End If
    yhelp1 = (1 - Exp(-0.153 * yhelp1a))
    If (dayLength_f - graini3) > 0 Then
                               yhelp2a = dayLength_f - graini3
                              Else
                               yhelp2a = 0
       End If
    yhelp2 = (1 - Exp(-0.301 * yhelp2a))
    ydevacc = ydevacc + (ygraini1 * yhelp1 * yhelp2)
    If ydevacc > 1 Then
      growthStage = 3
      sameStage = False
   End If
  End Sub
  ---------------------------------------------------------------------------

  'stage start grain filling to finish grain filling
  Private Sub calculateStage_3()
     If ta_f > 9 Then ytaAccgr = ytaAccgr + ta_f - 9
     If ytaAccgr > 260 Then
       growthStage = 4
       sameStage = False
      End If
  End Sub
  ---------------------------------------------------------------------------
```

```
   'stage finish grain filling to maturity
   Private Sub calculateStage_4()
      If ta_f > 9 Then ytaccma = ytaccma + ta_f - 9
      If ytaccma > 60 Then
          growthStage = 5
          ready = True
          sameStage = False
        End If
      If year_f > (sowingYear + 1) Then
          growthStage = 5
          ready = True
        End If
   End Sub
   --------------------------------------------------------------------
Private Sub calculateStage()
   sameStage = True
   If (growthStage = 1) And sameStage Then calculateStage_1
   If (growthStage = 2) And sameStage Then calculateStage_2
   If (growthStage = 3) And sameStage Then calculateStage_3
   If (growthStage = 4) And sameStage Then calculateStage_4
 End Sub
--------------------------------------------------------------------

   'Sub-routine added by the author of this thesis
 Private Sub SetLimitsForMaturationDay()
     ' set  maturation limits for Uppsala: day 217 (8 august) and 250 (7 Sept)
  If sowingDay < 180 Then
     If year_f > sowingYear Then
          dayNumber_f = 250
          Beep
       End If
    Else
     If year_f > (sowingYear + 1) Then
          dayNumber_f = 250
          Beep
       End If
  End If
  If dayNumber_f > 250 Then dayNumber_f = 250
  If dayNumber_f < 217 Then dayNumber_f = 217
End Sub
--------------------------------------------------------------------
```

```
Private Sub star_1()
  Dim msg As String
  Dim startCalc As Boolean

  init_Var
  Open "C:\arena\tem\tem_day_80_upp.prn" For Input As #1

   ready = False
   startCalc = False
   Do While Not EOF(1) And (ready = False)
      Input #1, year_f, dayNumber_f, ta_f, dayLength_f
      If (startCalc = False) And (year_f >= sowingYear) And
                    (dayNumber_f >= sowingDay) Then
           startCalc = True
         End If
      If startCalc = True Then
          calculateStage
        End If
   Loop
----------------------------------------------------------------------

Private Sub VBA_Block_2_Fire()
  Dim msg As String
  Dim index As Long

  Set m = ThisDocument.Model
  Set s = m.SIMAN

  index = s.SymbolNumber("year")
  sowingYear = s.VariableArrayValue(index)
  index = s.SymbolNumber("DayNo")
  sowingDay = s.VariableArrayValue(index)

   ' msg = "Sowing day  " & sowingDay & " year:" & sowingYear
   ' MsgBox msg
  star_1
   ' msg = "combining " & dayNumber_f & " year:" & year_f
   'MsgBox msg

  SetLimitsForMaturationDay

  index = s.SymbolNumber("combDayVB")
  s.VariableArrayValue(index) = dayNumber_f

  index = s.SymbolNumber("combYearVB")
  s.VariableArrayValue(index) = year_f
End Sub
```

Reference

Eckersten, H., Jansson, P.E. & Johnsson, H. 1998. SOIN model, user's manual; version 9.2. *Swedish University of Agricultural Sciences, Department of Soil Sciences,* Communications 98:6.