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An Integrated Simulation Model of Hay Growth, Harvesting and Barn Drying

Åke Axenbom

Institutionen för lantbruksteknik

Swedish University of Agricultural Sciences
Department of Agricultural Engineering

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PREFACE

The purpose of this report is to present a detailed model of hay harvesting and conservation, which also includes detailed sub-models of grass growth, field losses, conservation losses, and forage evaluation.

The model is validated in parts and as a whole, the importance of the model structure is discussed, and examples of how to use the model as an extension or management tool are demonstrated.

This project was financed by the Swedish Council for Forestry and Agricultural Research. The general simulation model of field operations, described in another report, was further developed using funds from the National Energy Administration.

The author is indebted to professor Bruno Nilsson for his support, the patience shown and the resources allocated, without which this project would not have been completed.

Åke Axenbom

SUMMARY

Because of the interactions between machinery, biological material, weather and management, many problems related to hay-making can not be properly analyzed unless the entire hay production and utilization process is considered. The only way of covering all of this process is to use a calculation model which includes the whole process.

It was found that the models available was not readily available for Swedish conditions, but would have to be modified. To some extent their resolutions were also lower than the one aimed at in this project.

The hay production and utilization system was modelled as three models being parts of the integrated model of hay production and utilization, a growth model, a harvesting model and a hay-to-milk conversion model. The harvesting model consists of a model of field operations and management, a field drying model and a barn drying model. It is also complemented with models of field losses (shatter losses, respiration losses, leaching losses) and a field loss model.

The model of field operations and management was designed as a discrete-event driven simulation program. It was developed using Simula, an object-oriented programming language, and DEMOS, a package for discrete modelling on Simula. The field operations model uses a statistical capacity calculation model rather than a detailed simulation model of the movements of field machinery. The management model concerns itself only with the general behaviour of the manager, leaving open the decision process for the application in question.

The growth model used was adopted from Torssell et al (1982). In addition to simulating the dry matter growth, it also calculates the protein and energy content using a "quality" model described in Torssell et al (1983).

The field drying model was adopted from Thompson (1981). This is a multi-layer model based primarily on meteorological laws.

The barn drying model was developed earlier in this project by Jónasson (1983), further developed by Sundberg (1985). In adapting it to the integrated model, the resolution has been significantly improved.

A hay-to-milk conversion model based on Linear Programming has been developed. Due to the fast development on the fodder ration calculation methods, this model is however not currently being used.

Most of the models being parts of the integrated model was already validated. The field drying model was however calibrated and validated against Swedish experimental field drying data, resulting in a very good agreement between simulated and experimental values.

The integrated model was also validated as a whole, using data from the hay harvesting at a real farm in 1981. The results of these were mixed. The growth model did underestimate the growth rate significantly, probably due to an unusually high nitrogen mineralization rate of the soil. The field operations and management model was instructed

to follow the known behaviour of the real farmers as closely as possible, which it did quite well. The field drying model could not be evaluated in this validation due to lack of data. The barn drying model, finally, seemed to predict the drying process in the two barn dryers quite well, but the data available was insufficient to confirm such a conclusion.

The integrated model is useful for analyzing a large class of problems requiring that the entire hay production and utilization process is considered. Its complexity however results in the model being useful primarily for research problems, whereas the extension service needs simpler tools.

1 INTRODUCTION

1.1 Background

Milk and beef production traditionally have a great economical importance especially in the forestry regions of Sweden, where the farms are generally smaller than the average acreage of 25 hectares of cultivated land. Although an increasing part of the forage is conserved as silage, hay-making will still be the dominating conservation method on these farms for many years. Elderly and small-scale farmers seem to be particularly reluctant to investing in the expensive equipment and know-how required when converting into a silage-making system.

In most parts of Sweden the summer climate is fairly favourable for hay-making. In conjunction with the nowadays wide-spread practice of barn-drying, hay-making is considered a relatively safe forage harvesting method.

Therefore modifying the existing haying system is for many farmers a more attractive alternative than switching to silage. The modification can include either the equipment or the harvesting strategy, or both. The costs could be reduced by minimizing the labour, machinery and energy costs, and the income could be increased by maximizing the net harvest after losses and by optimizing its nutritional value.

Extensive research on different practical aspects of these problems has yielded partial results to many of them. For example, it has been investigated which capacity and amount of shatter loss one can expect from different hay-making machinery. Also the barn-dryers, in which about 60 % of the hay conserved in Sweden is dried, are thoroughly dimensioned and tested to minimize respiration losses and to avoid moulding.

In haymaking, significant interactions take place between the haying equipment and management on one hand, and the growing and/or drying hay on the other. For example, the shatter losses and the drying rate are affected by the design of the machine as well as the way to run it, and not least, the timing of the operation. Of course, the properties of the biological material also affects the work (capacity, energy consumption, losses, breakdowns etc) so the interactions are in fact two-way.

There are important interactions also in the hay utilization process. For example, a change in the nutritive value of the hay means that the optimal fodder rations also changes. A changed optimal fodder ration in turn affects the optimal strategy in haymaking.

To consider the total effect of an adjustment of the equipment or management of a farm, the calculations have to consider the entire hay production and utilization process. Since this is a conceptually complex problem, few attempts have been made to develop a method with which the effects on the farm enterprise as a whole can be penetrated.

During the last few years the extension service has however requested an advisory tool for optimization of forage systems, where the dependencies between the different parts of the hay production and utilization system can be considered. To fulfil this need, the project "Optimization of Hay Harvesting Systems" was started.

1.2 Problem

Since the hay conservation process relies on not one, but a number of operations on the drying material, the interactions between man-machine system and biological material are more important in hay-making than in most other crop harvesting operations. They are also more complex, being sensitive to the properties of the machinery, the operating practice and the biological and environmental conditions at hand during the operation.

Although it has not been proved, it is commonly believed that these interactions have a significant effect on the economical result.

In order to appropriately consider these dependencies, the calculation model must include the entire hay production and utilization process. It is also essential that the model has a high resolution.

The problem was that no standard method to develop such a model was available, and that the models developed elsewhere would not be readily usable under Swedish conditions, due to climatical and cultural differences.

1.3 Objective

The main purpose of the project was to develop a high resolution model of hay growth, harvest, field drying, barn drying and utilization. The model was intended to be useful for optimizing haying machinery systems at the research level, and in the long term also on the extension level.

Note that the project did not aim at solving specific problems in conjunction with haymaking machinery, but instead aimed at developing a general tool for solving such problems.

Some examples of reqired results from the model are:

- the number of days needed to complete the harvest
- the number of hours used for different men and machinery
- energy consumption for drying
- hay quantities and qualities produced
- the value of the hay when converted into milk

with different harvesting systems and capacities under varying weather conditions.

The objective was that the model would be a valuable tool in the optimization of hay harvesting systems at individual farms as well as improving the general practice in conjunction with harvesting of hay. The model was aimed to be directed primarily towards research and extension purposes.

Within this work a major objective was to find an appropriate way to take into account the interactions between management, man-machine system, biological material and weather in hay-making.

It is a common experience that modelling pin-points the problem areas in which the current knowledge is unsatisfactory. In this project it was choosen not to concentrate on research on such areas, but rather to retain a holistic approach. Instead the identification of lack of knowledge areas might lead to future projects.

Extra emphasis was laid on the modularization problem. The objective was to divide the computer program into modules, making each module as easily interchangeable as possible. This would simplify the maintenance of the program according to the development of the knowledge within the area.

In addition to researchers and extension officers, also individual farmers in possession of on-farm computers was expected to become potential users of the model developed. Thus it should be as simple as possible to use.

2 LITERATURE REVIEW

2.1 Earlier work on machinery selection

Nilsson (1972) compared different Operations Research (OR) methods for planning of agricultural machinery systems. A system for dimensioning the machinery on individual farms was developed, built upon Mixed Integer Linear Programming (MILP) (Nilsson, 1976). He suggested future development to deal with the interaction between the machinery and the biological materials, so as to overcome the lack of knowledge in this area.

van Elderen (1977) developed a simulation model of farm operations and compared it with LP models. He found that the simulation model could achieve a much better model description than the LP model, since it actually followed the entire event chain. It also proved to give better possibilities to include biological submodels into the model. The major drawback of the simulation concept is that it is not optimizing.

Both of these authors utilized the timeliness concept.

Also Amir et al. (1978) used MILP, in this case for selection of hay-making systems.

2.2 Integrated models of hay growth, harvesting and utilization

2.2.1 Early hay harvesting models

There is an impressing amount of models describing either the growth or the harvesting and drying of hay crops in the literature. However, quite few authors have taken a multi-disciplinary approach to connect such sub-models into a common, "integrated" model.

One of the earliest integrated models was developed by Millier and Rehkugler (1972). The growth model was a static one, calculating alfalfa yield for up to three consecutive cuttings. Also the harvest model was a simple static one, using a predetermined harvest rate. The influence of the weather on the harvest was included by randomly drawing "good" and "bad" harvesting days, using the probability of bad weather in different periods of the summer and a computer random number generator. The forage-to-milk conversion model calculated the milk yield as a function of dry matter intake and total digestible nutrients (%). The model assumed a fixed alfalfa acreage and a variable cow herd size.

Cunney & Von Bargen (1972) developed a stochastic simulation model of alfalfa growth and harvest, using a constant half-day time-step. The performance of haying systems was measured in terms of dry matter yield and time consumption.

2.2.2 The "Parke et al" model

Parke et al (1978) presented an important integrated model of ryegrass growth, harvesting, conservation and conversion into milk. The growth sub-model calculates dry matter yield, digestible organic matter yield, "D value" (digestibility) and percent crude protein as a function of harvesting date, for the first cut only. The harvesting sub-model uses an hourly time-step and is controlled by a set of decision rules. The field drying sub-model is a modification of a simple but widely used model originating from Spatz et al (1970). Included are also equations to calculate rewetting caused by rain, drying of intercepted water and dry matter losses in the swath and in store. The minimum-cost feed ration is determined by a linear programming (LP) model.

The Parke et al model is restricted to one-harvest haying systems, and to dairy cattle utilizing the hay. The purpose of the model was to investigate the effects of changes in the performance and use of different conservation equipment. It has been used to evaluate barn-drying (Dumont & Parke, 1978) and the use of preservatives.

Recently the Parke et al model was investigated by McGechan (1985), who suggested several improvements. The improved sub-model is briefly described by McGechan (1986). The growth sub-model uses manure and fertilizer application level as well as daily weather data as input. Yields are calculated for the regrowth as well as for the first cut.

In the McGechan (1986) model, a mechanistic sub-model developed by Smith (1985) is used for the simulation of field drying. Both windrowed and spread swaths are considered in the model. Since the model is not a multilayer one, the effect on conditioning is only considered by means of a reduction in bulk resistance to drying, based on results from the multilayer model developed by Thompson (1981).

The field and conservation losses throughout the hay-making and ensiling processes are considered in the model, using published data. The ration formulation sub-model maximises the proportion of farm produced forage.

2.2.3 The "Lovering & McIsaac" model

Another interesting integrated forage model was developed by Lovering & McIsaac (1981). Their model allows two harvests per season, and permits silage-making as well as hay-making as conservation methods. Several optional growth sub-models for timothy was developed. The one used in the article is a static one similar to the one used in the Parke et al model.

Also the Lovering & McIsaac harvesting model operates at a hourly basis. The drying equation for hay and wilted silage is adopted from Dyer & Brown (1977), the drying constant fitted for the actual region.

The shatter losses due to mechanical treatment of the drying hay are not considered by Lovering & McIsaac. However, a 10 % dry matter loss is assumed during the storage of the hay. Like the Parke et al model, an optimizing model is used to determine the maximum return over feed costs.

2.2.4 The "Savoie et al" model

An integrated simulation model of alfalfa and corn growth, harvest and feeding is described by Savoie et al (1982a). They used a physiological model of alfalfa growth and regrowth.

The model allows a choice between a static harvest model and a more extensive one calculating the harvest rate as a function of yield. The conservation methods considered for alfalfa are hay and haylage.

The drying equation is an empirical one described in Savoie et al (1982b). Also, a empirical dew absorption model was developed.

Also in this case, harvesting losses and a feeding model are parts of the model. In addition, an extensive economical analysis is made within the model.

2.3 Comparison of the integrated hay-making models

The three models described above are quite similar concerning the hay harvest and ration formulation sub-models. The growth and drying sub-models tend to be more and more sophisticated in the more recently developed models. As a whole, however, the three models compared offer the same possibilities and suffer from the same shortages. In particular, their usefulness in evaluating different short-term management policies are all very limited, since the resolution of the harvesting, field loss and field drying models do not allow realistic comparisons between for example different tedding strategies.

All the models described above are coded in FORTRAN, a third generation programming language not well suited for programming of discrete event simulation models, since it lacks data types suited for queue handling and event sequencing. This may be a reason to why they all stick to static harvesting models with a constant time step. If this is the case, the choice of programming language does seem to have restricted the resolution and design of the models.

The models described above tend to be over-simplified in at least some respect in order to avoid time-consuming and expensive calculations. Since very powerful portable personal computers are now available, such considerations are no longer any excuse for over-simplifying computer-based models.

3 SYSTEMS ANALYSIS

3.1 Model concepts

Generally, field work means that a man-machine system performs some process on a material in possession of certain biological and physical properties. This process involves complex interactions between the man-machine system and the material. The properties of the man-machine system controls the process on the material. On the other hand, the properties of the material, often affected by the environment (notably the weather), influences the capacity and quality of the process performed on it. See figure 1.

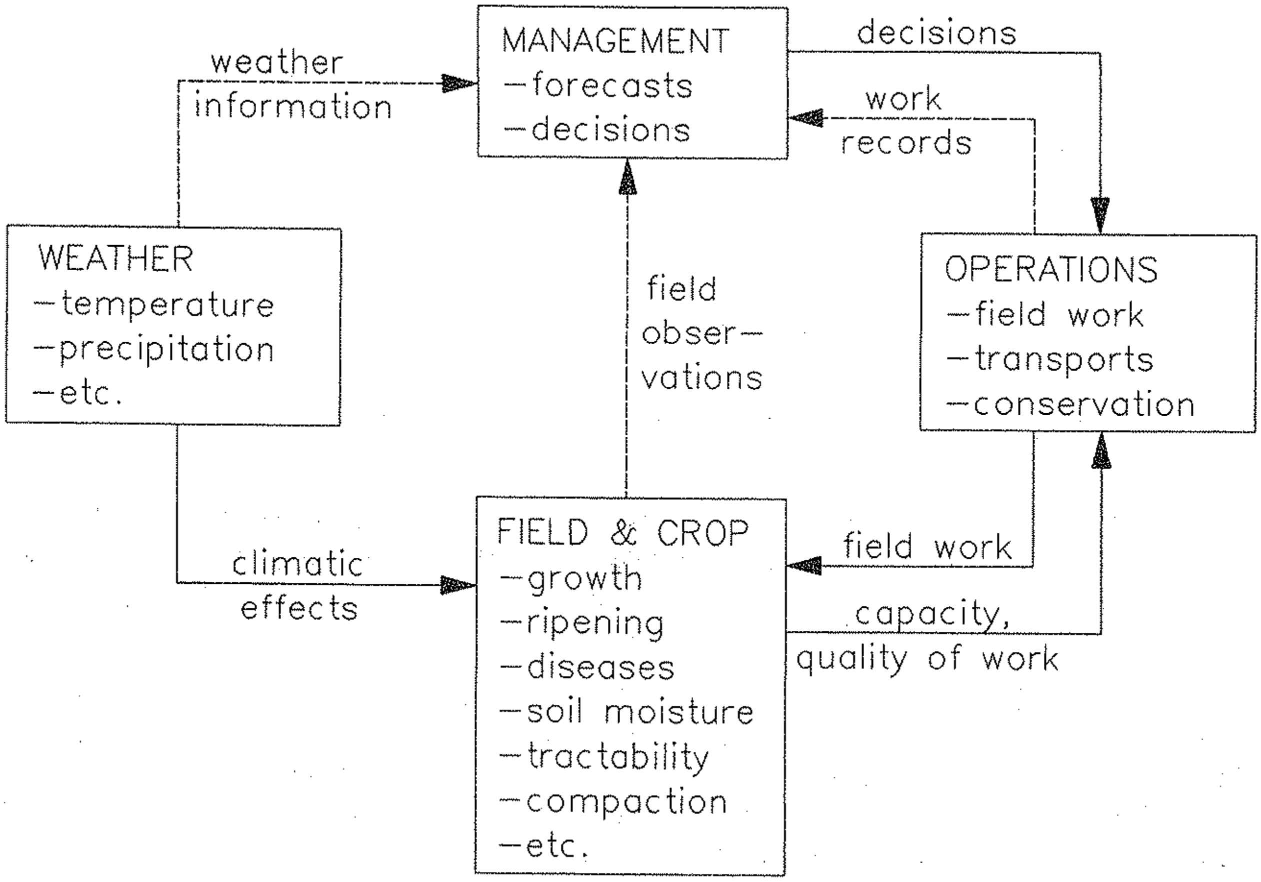

Figure 1. The general problem of interactions between the man-machine system and the biological material at field operations. Solid arrows indicate influence, dotted arrows indicate information.

A common way to model the effect of the biology on the economical result is to make the expected yield a function of the date of performing the operation in question. This function is called a timeliness function. Typically, the timeliness function has one maximum point, with a slope on each side.

The shape of the timeliness function is arbitrary, but it is very often approximated by some simple mathematical function for calculating convenience (Figure 2).

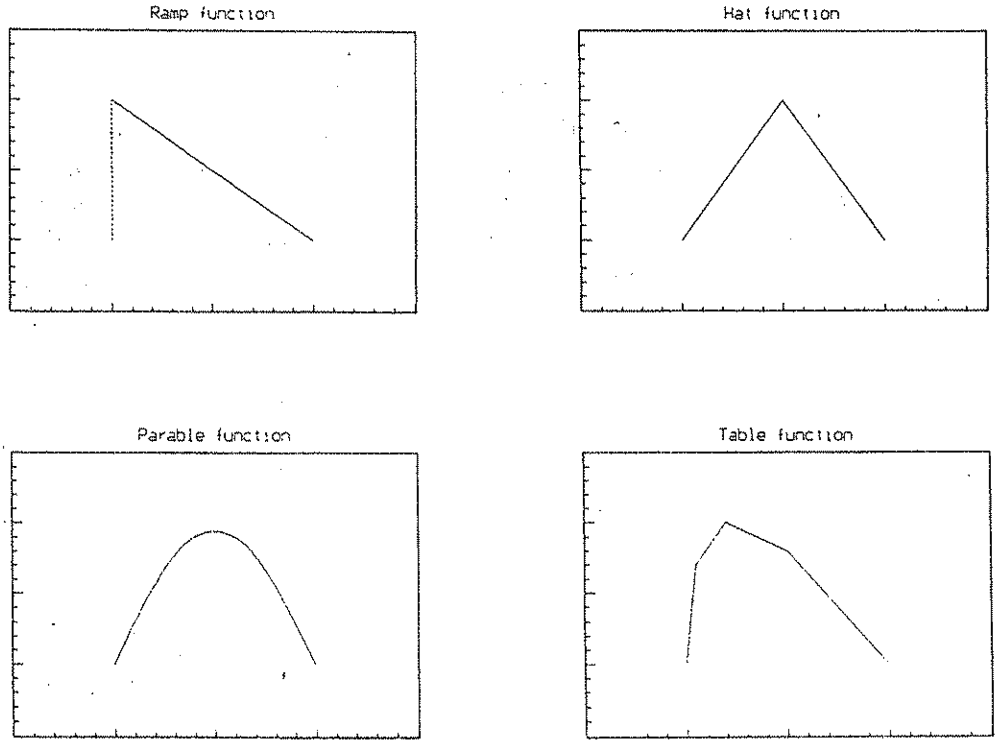

Figure 2. Some mathematical functions often used to represent the timeliness function.

The timeliness concept is a simple and straightforward way to model the impact of the man-machine system on the biological material. Works by e.g. Nilsson (1976) and van Elderen (1977) prove that the concept is useful in an optimizing Linear Programming (LP) model as well as in a simulation model, using a heuristic strategy.

The drawback of the timeliness concept is that it is static, unable to model the impact of the state of the biological material upon the capacity of the work performed by the man-machine system, and also unable to model the interactions between a series of operations on the same material, such as repeated teddings of hay. However, no other "standard" method is available with which these interactions could be taken account of.

3.2 System delimitation

In this phase of the systems analysis work it is decided which parts of the system are to be included in the model, and which are to be considered as part of the environment.

The primary problems to study were related to the mass-, energy- and information flows relevant to haymaking into, through and out of the system. This means that the entire farm did not have to be modelled. Only the men, machinery and fields involved in haymaking needed to be included. For example, the breeding and harvesting of grain for concentrate could be omitted.

Two activities related to haymaking were excluded from the model, as they were identified in advance as "lack of knowledge" areas, while it was yet considered possible to achieve the goals reasonably well. These areas were grazing management and fertilizer management, including spreading of manure.

Due to lack of knowledge, the effects of the harvesting on the future condition and productivity of the grassland was neglected.

The value of the hay produced must be evaluated to enable an economical analysis of the haying system. Since hay is not generally marketed, this should be done at farm level by calculating the milk-over-concentrate margin. Generally, practical considerations on the feeding work affect the actual rations significantly, making them non-optimal from a nutritional point of view. So there was a choice between including a farm-specific feeding model, or calculating the potential margin assuming an optimal ration formulation. The latter alternative was chosen, yielding a simpler and more general model. Neither of the "by-products" beef, calves or manure were considered.

Except for the milk-over-concentrate margin, no economical calculations were to be included in the model. The financial aspects of the farm - cash flows etc. - should preferably be considered in a separate economic module, using output data from the different parts of the model as indata.

Due to the phenological development and the varying weather conditions during the harvest, the nutritive and hygienic quality of the hay harvested will vary from day to day. It is therefore presumed that the total available amount of hay may be divided into batches with different nutritive and hygienic value, and treated as such in the milk-over-concentrate calculations. For example, if early-harvested and late-harvested hay are stored separately in the barn, they should be treated as two batches.

The weather is conceptually not a part of the model, just a source of indata.

3.3 System structure

The "system", being defined as all hay-related activities on the farm enterprise, was divided into the following sub-systems, each representing a certain process or activity in the flow of forage on the farm from production to utilization:

- grass growth and regrowth,
- forage harvesting and conservation,
- cattle feeding and conversion into milk.

On a small farm, the three processes are generally controlled by a common farm manager, aiming at optimizing the economical result of the entire production rather than of the different sub-systems (see figure 3).

The growth sub-system and the harvesting and conservation sub-system are interconnected, because the mowing dates on the different fields affect the next growth. The feeding activities are assumed not to affect the growth or the harvesting activities. If

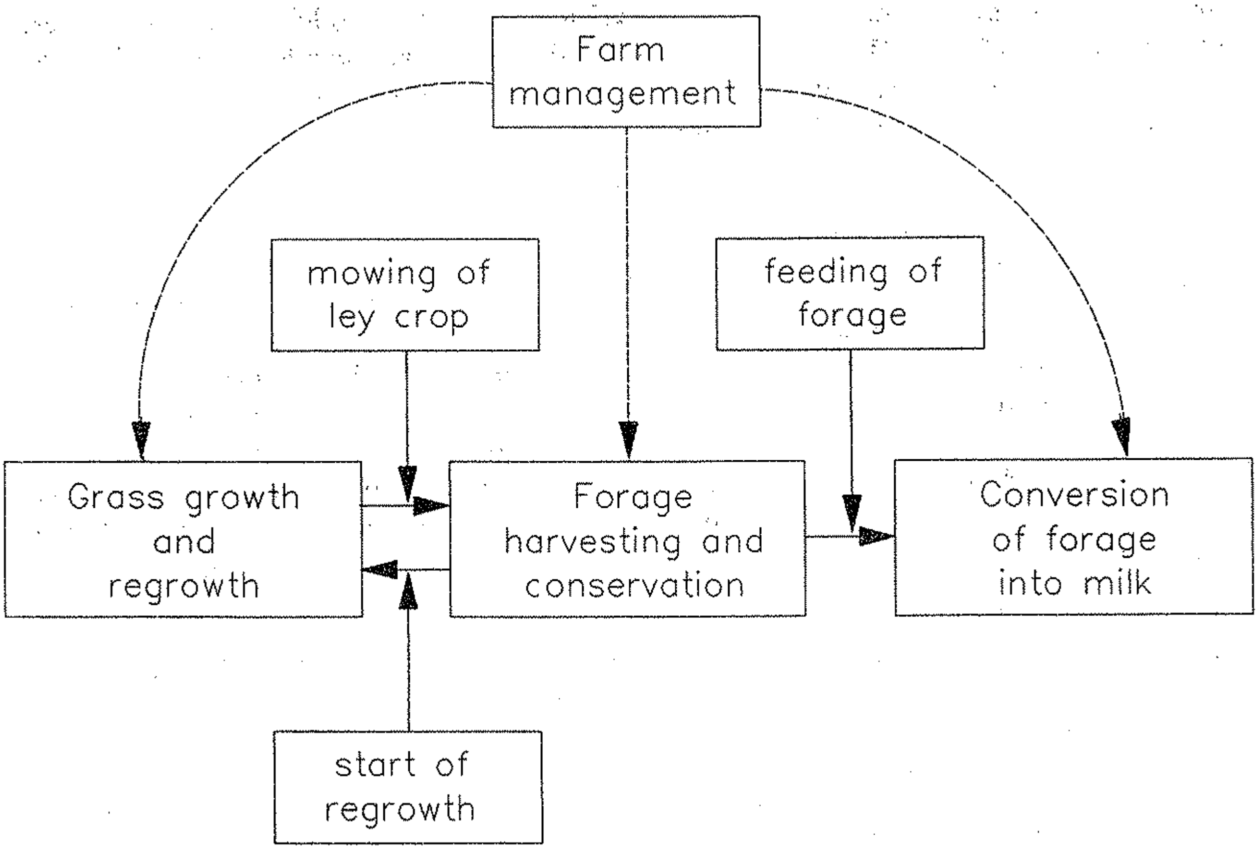

Figure 3. The hay-related activities on a dairy farm, and their division into three sub-systems, controlled by a management sub-system.

grazing had been included in the model, the allocation of grazing areas and forage harvesting areas could have been affected by the growth of the grazing areas, thereby making also this sub-system interconnected with the other ones.

The harvesting and conservation sub-system consists of several processes (see figure 4):

- field operations and management,
- field drying,
- field (respiration and leaching) losses,
- conservation (barn drying),
- conservation losses.

In the following it is presumed that the four sub-systems shown in figure 3 are represented by a growth model, a harvesting and conservation model, a hay-to-milk conversion model and a management model. In cases where the harvesting and conservation model and the management model are considered as one model, this one will be called the "model of field operations and management".

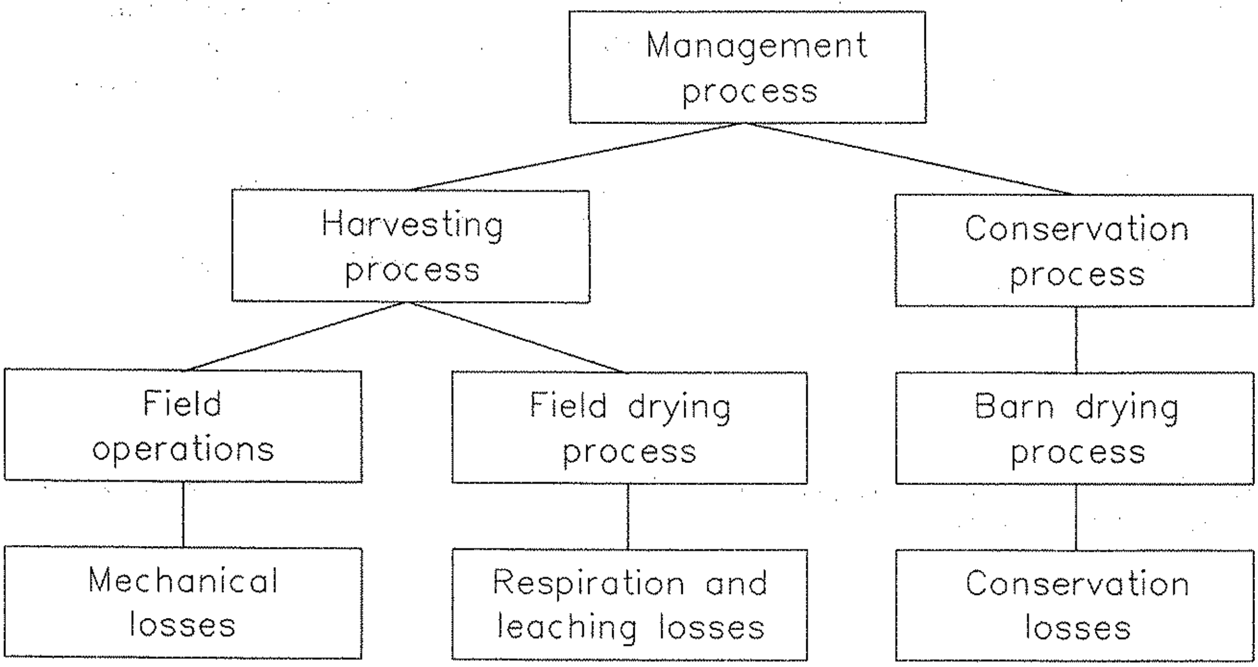

Figure 4. The relationships between the different processes of the forage harvesting and conservation sub-system.

3.4 State variables

All attributes of the hay field or batch affecting the field drying rate of the hay should be passed from the growth model to the harvesting and conservation model. The ones needed to constitute an appropriate set of variables are:

- the dry matter yield at cutting,
- the moisture content at cutting,
- the LAI (Leaf Area Index, crop surface/m^2 of land),
- the soil surface wetness.

As the forage is to be converted into milk, it is necessary that the variables describing the properties of the forage from the feeding point of view are passed all the way from growth to feeding. The set of variables necessary to make a simple ration composition (energy and protein balances) are:

- available amount	(kg of dry matter)
- crude protein content	(g/kg of dry matter)
- metabolizable energy content	(MJ/kg of dry matter)

for each available feeding-stuff. So these "state variables" are attributes of each hay field or batch.

Commonly also other variables are used for ration compositions. The reasons to include only these as state variables are in general terms that the energy and protein balances are the most important and most expensive requirements to fulfil in ration formulation. This is further discussed in 4.4.

There is a risk that bad weather during the field drying period enables a field fungi growth. The barn drying is however a much greater problem from the fungi point of view. Therefore an attribute expressing the hygienic quality must be passed from the conservation model to the hay-to-milk conversion model.

The attribute variables just mentioned conforms the interfaces between the models of the sub-systems shown in figure 3. The interfaces between the different processes of the forage harvesting and conservation sub-system are discussed in conjunction with the presentations of the sub-models.

3.5 Input data

The set of input variables and interface variables between the different parts of the integrated model is shown in figure 5.

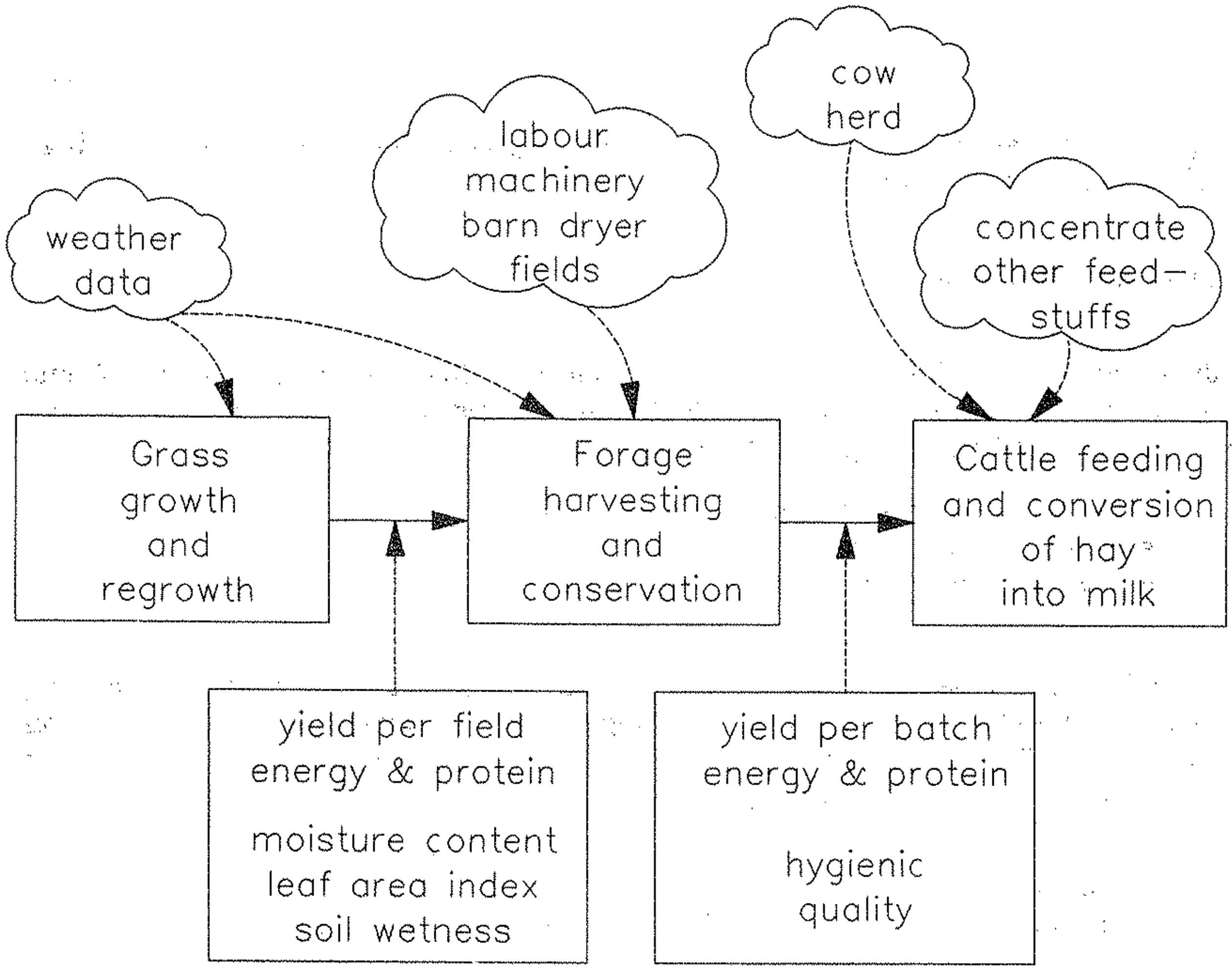

Figure 5. The input into, and the interactions between the different models of the integrated hay production and utilization model.

The weather is of course a very important factor for both growth, harvesting and conservation, so weather data must be available to these models. The specific weather variables by which the different sub-systems are most strongly affected will be discussed later in conjunction with the sub-models in question.

The harvesting and conservation processes are very much dependent on the actual farm size and structure, the men and machinery available and the design of the barn dryer. These parameters should be specified as input data rather than specified within the model.

The hay-to-milk conversion model needs a description of the actual cow herd (distribution of cow ages, yields and lactation dates) and a list of which other feeding-stuffs that is available.

3.6 Output data

The output variables should be as closely related to the model as possible. Thus figures describing time or energy consumption, losses etc. are preferred to monetary ones. This is because the prices are often dependent of the total set of quantities and qualities, thus they can not be determined until after the physical quantities are determined. Therefore the economical analysis should be made in a separate module.

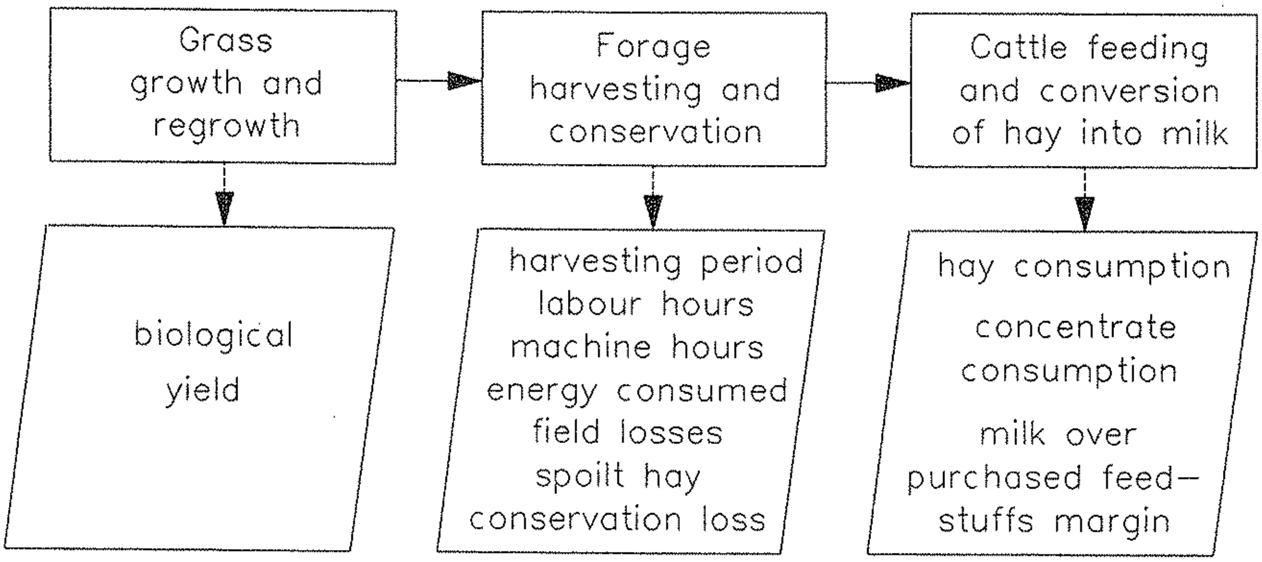

Figure 6. Output variables from the hay production and utilization model.

The parameters of the harvesting and conservation system selected as output variables are (see also figure 6):

- harvesting period (days)
- labour consumption per man (man hours)
- work hours per machine (machine hours)
- energy consumption for barn drying (kWh)
- field losses (kg of dry matter)
- amount of spoilt hay (kg of dry matter)
- conservation losses (kg of dry matter)

The growth model calculates the estimated biological (gross) yield, while the hay to milk conversion model calculates the estimated feeding-stuff consumption and milk over purchased feeding-stuffs margin. Note that this is the only monetary one of the output variables.

4 MODEL DESCRIPTION

4.1 Model design

It soon became evident that the mutual and relatively complex dependencies between machinery, biology and weather could not be appropriately described by the static timeliness function.

As a result of this, an LP model was out of the question, since such models are static to their nature. Among the two alternative types of dynamic models, Dynamic Programming also was considered too restrictive. The only alternative remaining was to develop a detailed simulation model of the entire hay production and utilization process.

The model of hay production and utilization logically consists of three models (growth, harvesting and conversion into milk). Each sub-model is physically separated from the other ones in the computer program, with well-defined interfaces between them.

The three models may be run as separate programs. Most of the submodels building up the harvesting and conservation model, i.e. the field operations submodel, the management submodel and the field drying submodel, however need to be coupled together to work. Nevertheless, each of them are quite easily replaceable since the interfaces between them are well defined.

So the computer program physically consists of a number of interchangeable modules. See figure 7.

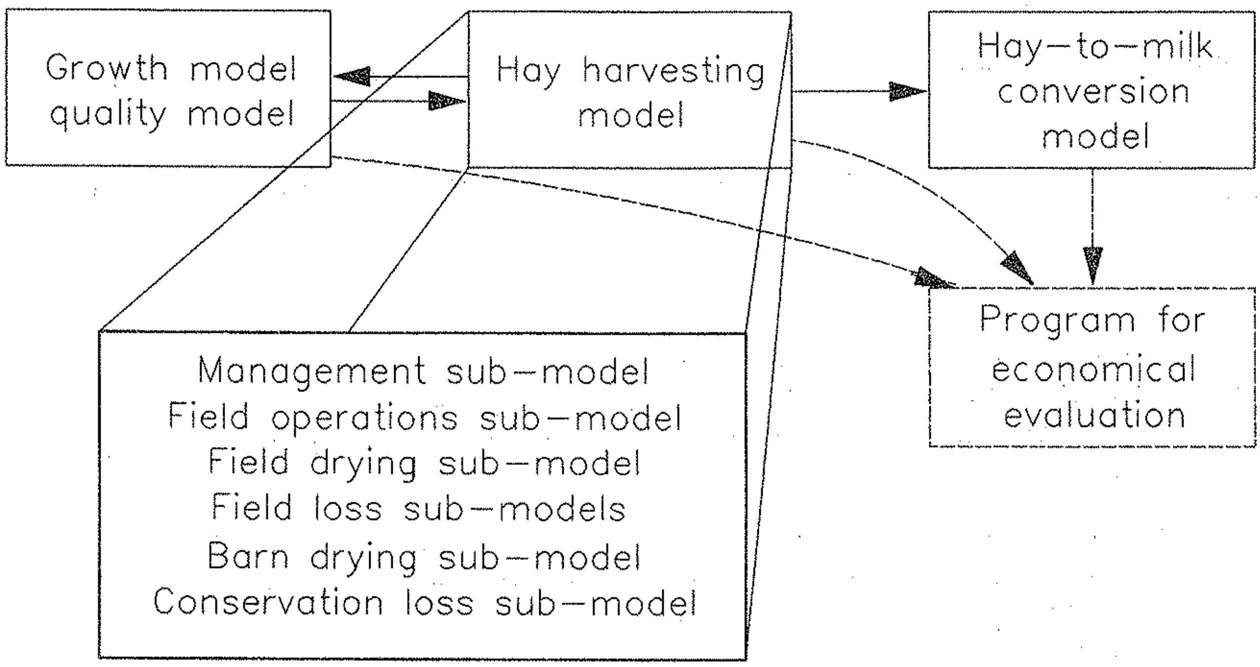

Figure 7. The computer program modules in the implementation of the hay production and utilization model. The program for economical evaluation is not included in the present work.

The hay-to milk conversion model was developed during an early stage of the present work. The methods of calculating fodder rations have however developed rapidly during the last few years. When this is written changes can be expected in "coarseness" analysis methods as well as in protein analysis and calculations. For these reasons, the hay-to-milk conversion model has been left outside the integrated model for the time being.

4.2 The growth model

The model of ley growth and regrowth is developed by Torssell et al (1982). Essentially it consists of the simple differential equation

$$\frac{dy}{dt} = k \times y$$

describing an exponential growth (if $k > 0$) of the yield y.

The equation is solved numerically, by means of Euler's commonly used integration method

$$y(t_1) = y(t_0) + \frac{dy(t_0)}{dt} \times (t_1 - t_0)$$

$$= y(t_0) + k \times y(t_0) \times (t_1 - t_0)$$

where k is assumed to be constant throughout the integration time step ($t_0..t_1$).

Two different time steps have been used by Torssell et al, namely one day and one week.

The variable k, determining the rate of the exponential growth, is the product of three factors:

$$k = GI \times AGE \times R_s$$

The first factor, GI, is called the growth index. It is defined as the product of the radiation index (RI), the temperature index (TI) and the water index (WI), each of these having a magnitude of 0.0..1.0. Consequently, so has the growth index. It describes the actual growth rate in relation to optimal conditions.

The second factor is the AGE function, dampening the exponential growth. The function value is dependent on the leaf area index (LAI), which in turn is estimated from the dry matter yield. The shapes of the growth index functions and the AGE function are shown in figure 8.

The third factor, Rs, determines the initial potential growth rate. It is implemented as a table function dependent on a number of parameters:

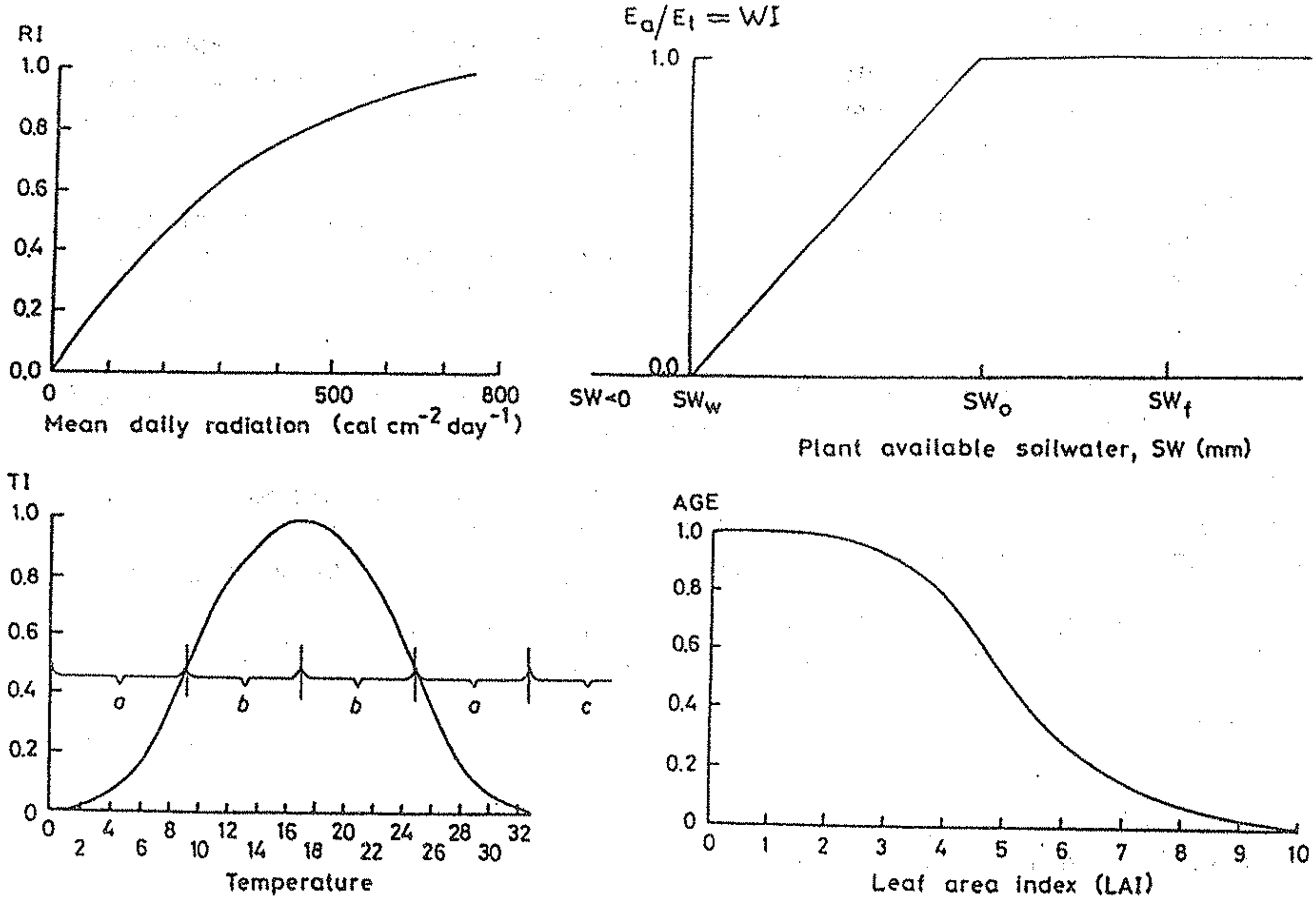

Figure 8. Outline of Torssell's growth model. The growth rate $\frac{dy}{dt} = y \times R_s \times RI \times WI \times TI \times AGE$ where WI is the ratio between actual and potential evaporation. The AGE function causes a negative feedback loop since the LAI is estimated to $\sqrt{c \times y}$. Rs and c are constants.

- growth number (1, 2, 3),
- planned number of cuts (2-, 3),
- percentage of clover (0..100),
- ley age (1, 2+),
- annual nitrogen rate, kg (0, 60, 120, 180, 240).

The growth model concerns itself exclusively with the dry matter (DM) yield. To permit estimation of the energy and protein contents, it has been complemented with a model of the quality development with time (Torssell et al, 1983).

The forage quality model is quite loosely attached to the growth model. It does not use any weather data. Neither is the quality related to the actual yield. Thus, the quality model cannot be characterized as a simulation model, but rather as a statistical one.

The quality model actually consists of four independent models, since the contents of energy and protein are calculated independently of each other, and for grass differently from clover. The figures on energy and protein for the actual mixture of grass and clover are obtained by means of linear interpolation.

The four quality models are similarly constructed in the sense that they are all quadratic functions of the time elapsed since a 'trigger' date. The 'trigger' date is defined as May 25 for the first cut, and as the cutting date of the previous cut for the subsequent ones.

The coefficients of the quadratic functions are dependent of a number of factors in addition to the species (clover or grass) in question.

The energy coefficients are dependent of the harvest number. For first-cut grass, the intercept is also dependent of the yield at May 25. Note however that the energy content of grass is considered independent of the nitrogen rate and of the age of the ley.

The coefficients for the contents of crude protein of clover are the same for the second and the third cut, but different from those for the first cut.

For grass, the crude protein coefficients are different for all cuts. Furthermore, they are dependent on:

- the planned number of cuts (2-, 3),
- the age (in years) of the ley (1, 2, 3+),
- the annual nitrogen rate (0, 60, 120, 180+ kg/year).

4.3 The harvesting and conservation model

The harvesting model consists of a discrete event model of field operations, connected to a continuous-type field drying model and a static model of harvesting losses. The field operations model is controlled by a model of the manager's decision process. Finally there is a continuous-type simulation model of barn drying and conservation losses, containing a static, qualitative model, which warns for risk for fungi growth.

4.3.1 The field operations sub-model

The model of the field operations is a general discrete event simulation model, called FIELD_OP, developed within this project. It is detailedly described in Axenbom (1988).

It is programmed in DEMOS (Birtwistle, 1979), a simulation package for discrete event models, written in the object-oriented programming language Simula. The field operations model consists of a number of gang objects performing operations on the different field objects. A gang is defined as the set of men and machines required to perform an operation or process on a specific set of materials, according to a method (Oving, 1971; van Elderen, 1977), so there is one gang for each operation or process.

4.3.2 The shatter loss sub-model

Attached to the field operations sub-model is a shatter loss sub-model developed by Jónasson (1983). This model calculates the increase in shatter losses for every mechanical treatment of the drying hay. The shatter loss percentage from mowing and tedding is assumed being dependent of mower and tedder type and a linear function of moisture content (see figure 9).

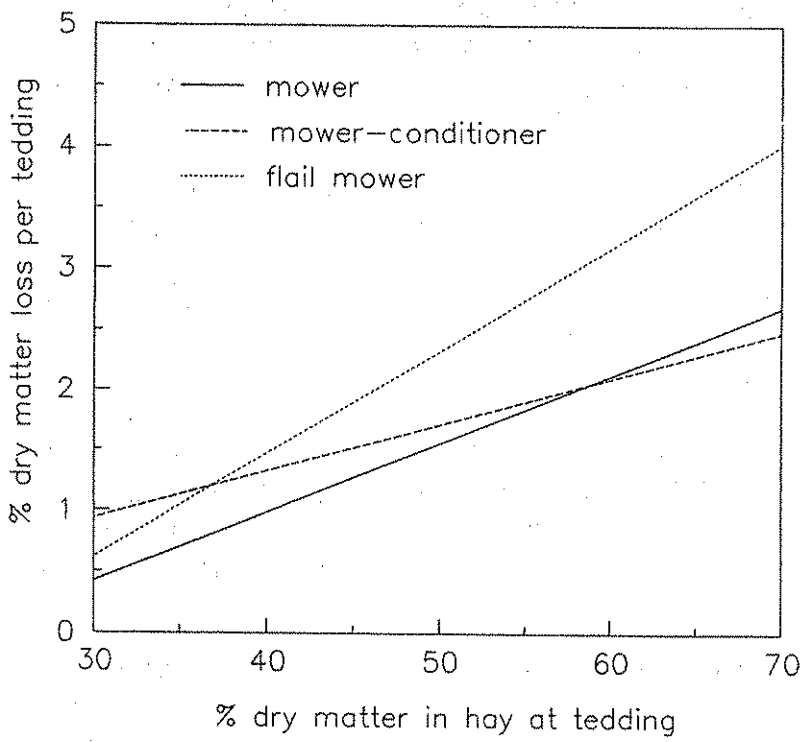

Figure 9. Expected shatter losses from mowing and tedding of hay, mowed with different mower types, and tedded with a rotary tedder. For gentler tedder types, the expected shatter losses are reduced with 35%.

Table 1. Expected shatter losses from raking and collecting hay with different types of raker and pickup, in kg of dry matter/hectare. Source: Jónasson (1983).

type of raker	low loss pickup type	high loss pickup type
low loss type	20	90
medium loss type	50	110
high loss type	80	160

The shatter losses occurring at collection are considered dependent of raker type and pickup type, but independent of mower and tedder type. The expected figures are shown in table 1.

The differences between grass leys and grass-clover mixture leys have not been accounted for by Jónasson because of lack of data on losses from mixture leys.

4.3.3 The field drying sub-model

Earlier work (Axenbom, 1983b) indicated that no single-layer drying models have the ability to appropriately model the non-steady-state drying behaviour of a hay swath tedded at certain points of time. It was concluded that a multilayer model was needed to accomplish this.

Of the two multilayer field drying models found in the literature, one was a two-layer model developed by Brück & van Elderen (1969). The second one, developed by Thompson (1981), largely based on micro-meteorological laws, allowed an arbitrary number of layers. This model was considered the only field drying sub-model having a sufficiently high resolution to be appropriate for the integrated model.

The Thompson model is a mechanistic model of the energy and moisture flow in the swath. A uniform swath layer is assumed, which simplifies the problem to one dimension. The space between the ground and the top of the swath is divided into a number of layers with equal heights. A layer may contain swath or stubble, or both. For each of these layers, the model calculates its energy absorption from radiation, and the division of the energy into sensible and latent heat. The proportion of the energy transformed into water vapour is a function of the relative humidity of the air in the layer and the moisture content of the drying hay in the layer. The relative humidity in a layer is in its turn determined by the wind speed, the temperature gradient above the swath, the proportion between sensible and latent heat production, and the water vapour flow from layers underneath, coming from the stubble, the drying hay, and the ground. See figure 10.

Rewetting during rainy hours is calculated using a rewetting sub-model originating from van Elderen et al (1972), modified by Thompson. The intercepted water is assumed to be more loosely attached to the drying hay than the "original" water, thus drying faster.

The evaporation losses of a field should be updated every time the moisture content is updated by the field-drying model. Within the present work, the Thompson model has therefore been complemented with an evaporation loss submodel, originating from Honig (1979). The evaporation loss rate is assumed to be a function of moisture content and temperature. Every time the moisture content is updated, the accumulated evaporation loss is also calculated.

The Thompson model was re-coded from FORTRAN into Simula to simplify its attachment to the field operations model. The integration routine was changed, from a fixed time-step to a variable one, to allow updating of the moisture content at every decision date during the simulation.

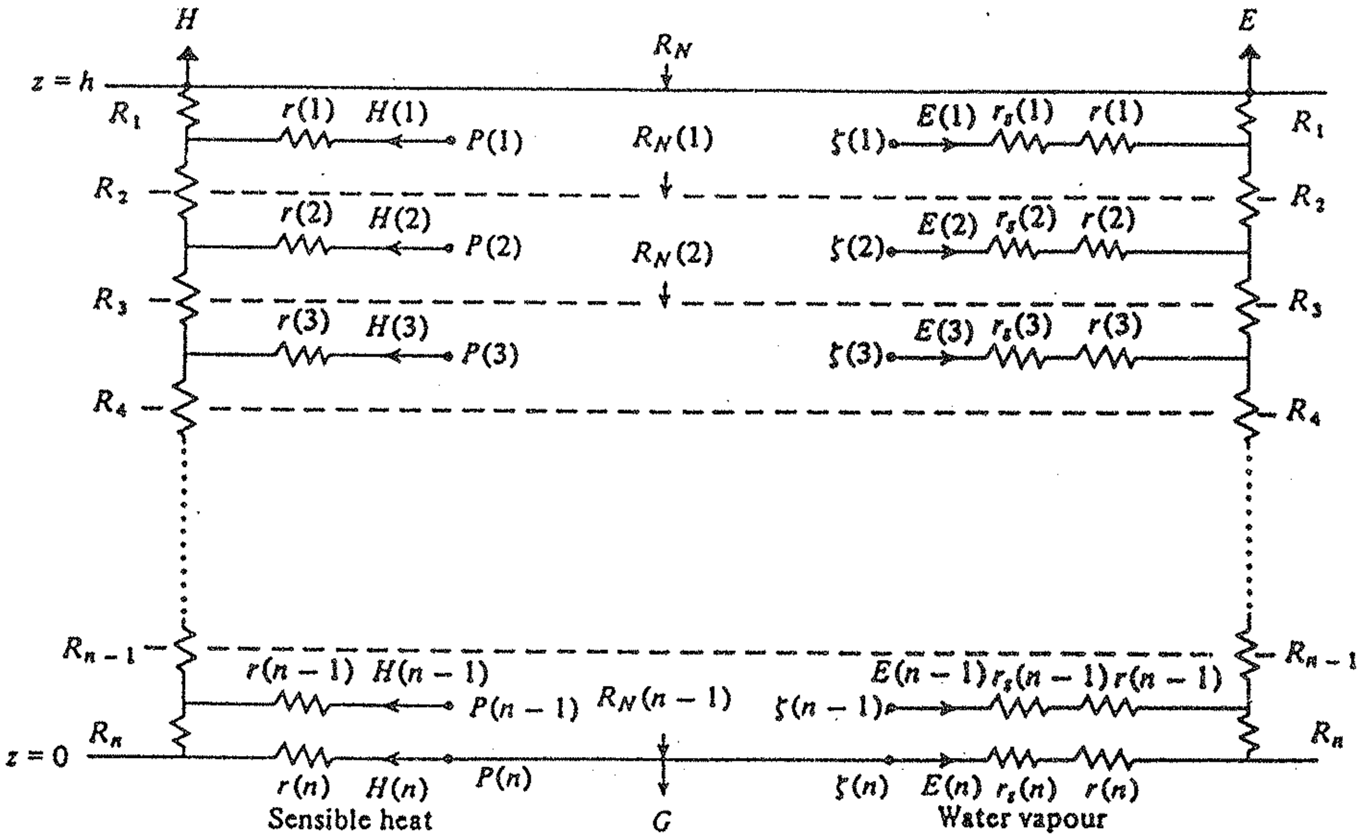

Figure 10. Outline of Thompson's model of hay drying in the field. The model uses resistances, flows and potentials in the same way as in electric circuits. The net radiation (R_N) is absorbed in the different grass layers, and the energy is converted into flows of sensible heat (H) or water vapour (latent heat) (λ*E), or absorbed by the ground (G). The proportions of sensible and latent heat produced in each layer is determined by the potentials of heat (P(i)) and water vapour (ζ(i)), respectively. The potentials are built up by the flows of energy through the resistances. The resistances Ri apply to transfer of water vapour and heat between adjacent layers, r(i) are boundary layer resistances, and r_s(i) are the resistances to water vapour flow from within the plant tissue to the surface of the plant. The calculation of the latter one is explained later. The model assumes that no heat is stored within the hay swath. Source: Thompson (1981).

4.3.4 The leaching loss sub-model

A leaching loss submodel, developed by Jónasson (1983), has been attached to the rewetting submodel. Jónasson assumed a linear relationship between leaching loss rate and moisture content at the time the rain starts and fitted this model to results by Møller & Skovborg (1971), as shown in figure 11.

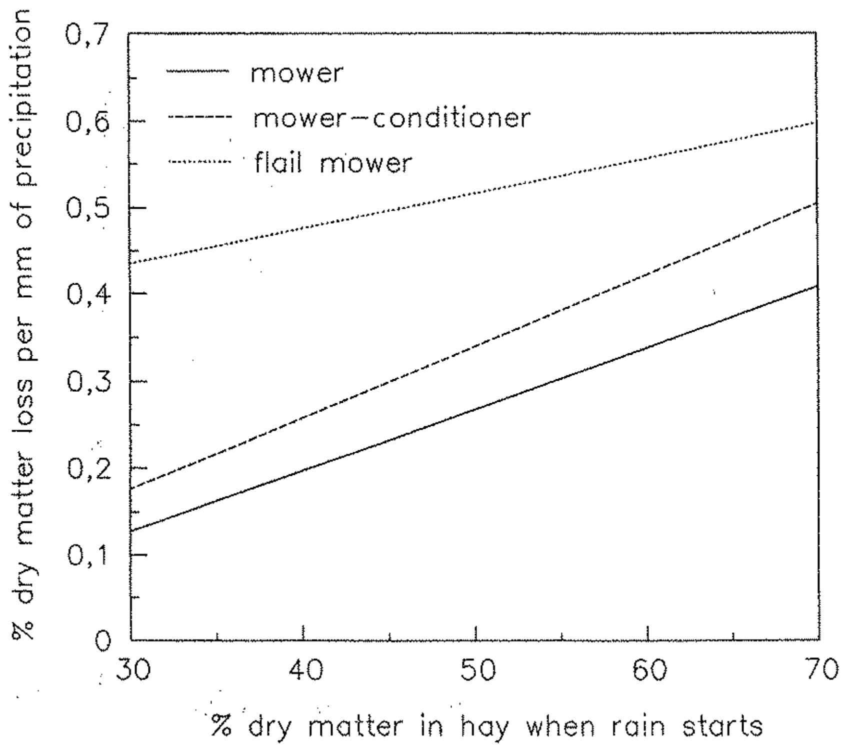

Figure 11. The leaching loss model. Source: Jónasson (1983).

4.3.5 The management sub-model

The management sub-model handles the decision-making process of the field operations model. Thus the simulation is essentially controlled from this sub-model.

The management sub-model is called whenever a decision date occurs. Decision dates occur when certain events happen, such as when an operation is started, or finished or when something else happens that may affect the planning of field operations.

The FIELD_OP package is flexible concerning the management sub-model, leaving the entire definition of the management strategy to the application developer. The general behaviour of the management sub-model is shown in figure 12.

In this project, the emphasis was laid more upon the planning of farm machinery and less on the short-term decision making. Therefore, no attempt was made to develop any model of a "real-world" haying farmer's strategy. Nevertheless, the model had to be defined somehow to enable the experiments to be performed. The obvious solution was to develop an interactive interface, permitting the person running the program to take control over the entire management process. This interface includes a procedure for presentation of the most important model data on the screen. A flowchart of the redefined DetermineAction routine is shown in figure 13.

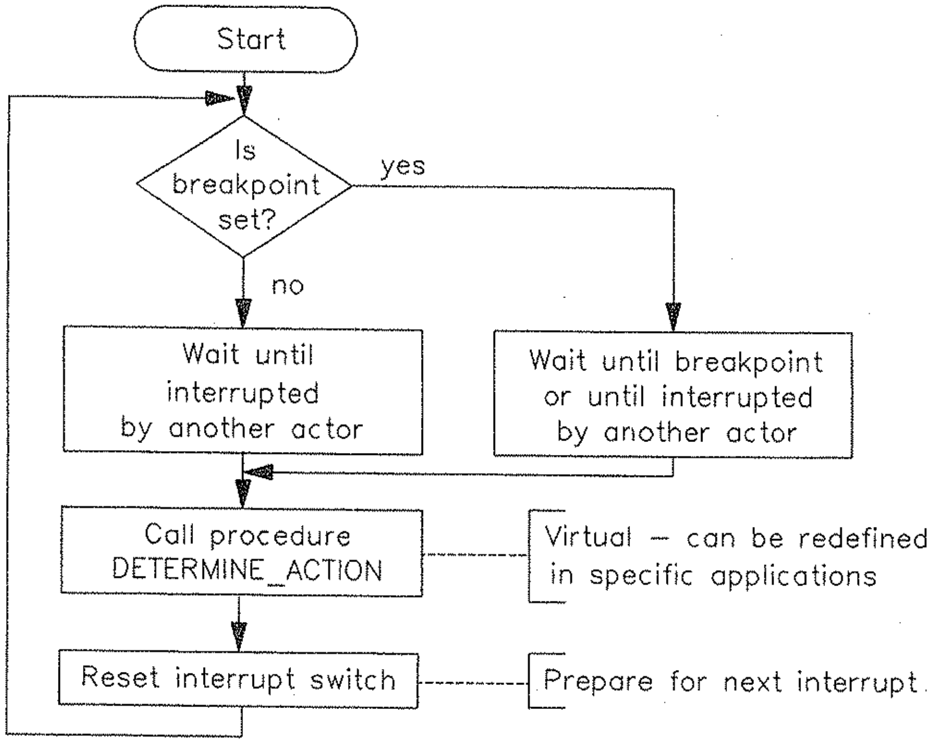

Figure 12. Flow chart of the general behaviour of the management sub-model.

The communication between the program and its user works as follows: The display presents the gang currently active and the gangs possible to start (i.e. the gangs for which the men, machinery and field required are available). The program user is prompted to select one of these.

If the gang selected is currently active, it is torn down. The men and machinery presently acquired are released. If the field on which the operation has been performed is only partially finished, it is automatically divided into two parts, each of which conforming one field, one finished and one not.

If the selected gang is not currently active, but possible to start, then the user is prompted to accept the field placed first in the queue from which to pick the field. (There is one queue for each field state, in this case one for growing fields, one for cut but not tedded ones, one for tedded ones and one for windrowed ones.) If the proposed field is rejected by the user, he is prompted to accept the next field in the same queue, as long as there are more fields.

As a part of starting or stopping a gang, the manager holds for a moment. Instead the gang is activated so it can acquire or release its resources, respectively. After having done this, the gang always hands back the program control to the manager. Consequently, the user will be prompted as long as he keeps on starting or stopping gangs at one single decision date.

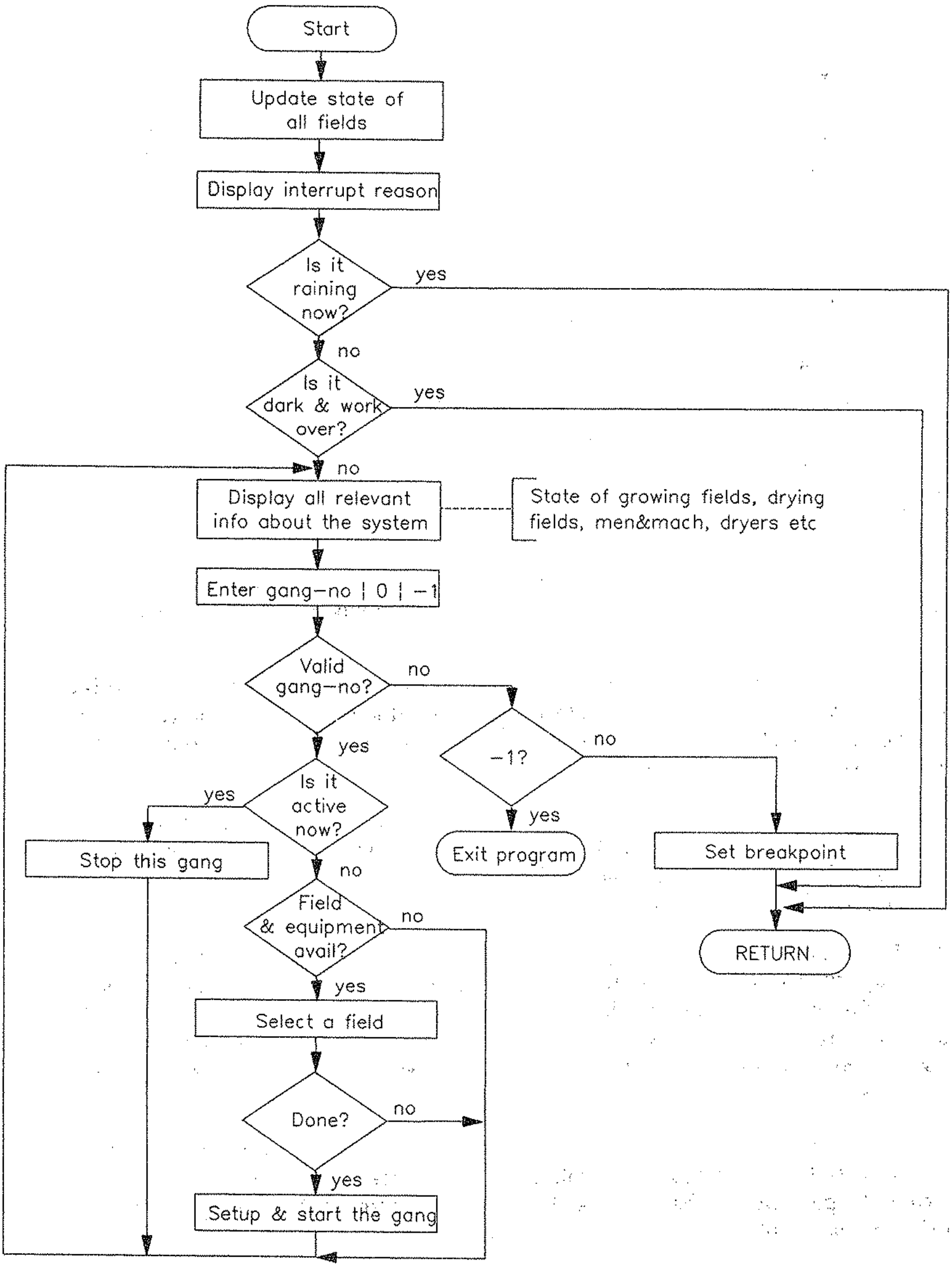

Figure 13. Outline of the redefined DetermineAction procedure.

4.3.6 The barn-drying sub-model

The barn-drying sub-model is originally developed by Jónasson (1983) who gives a detailed description of the barn-drying model and the validation of it. The model has later been modified and used by Sundberg (1986), who updated the model in accordance with results from new experiments.

The aspects of barn-drying for which the barn drying model was developed to examine are the conservation losses, the risk for moulding and the energy consumption for drying, as well as the sensitivity of these to the carting rate, the moisture content at carting and the ventilating strategy.

The original model, as well as Sundberg's modified one, used a constant 24 hr time step. They were both implemented as stand-alone computer programs.

To fit into the integrated model, the barn drying model was further developed. The new model version was developed in the form of a module with the ability to update the state of the dryer up to an arbitrary point of time. This model version is implemented as a Simula CLASS. After initializing the dryer object(s), all access to it is performed through its member procedure CalcBarnDrying. The flow chart of this procedure is shown in figure 14. As the figure shows, the maximal iteration time step may be adjusted to achieve the desired resolution. A value of about 1 hour should normally be appropriate.

The air flow of the fan is dependent of the air pressure. It is calculated by means of an iterative procedure searching the air flow for which the pressure of the fan equals the pressure fall over the hay bin as a function of the flow rate. For this purpose, a small data base with pressure and effect curves for a number of fans is available to the model.

The model does not explicitly calculate the position of the drying front. Instead each day's carting is treated as a batch, which is assumed to dry uniformly.

The drying rate is calculated using the psychrometric chart of air in conjunction with the equilibrium humidity of the air surrounding the hay as a function of its moisture content. The drying process results in the air being cooled and partially saturated with water vapor under constant enthalpy. The air is however also heated by the fan and as a result of respiration heat.

A fraction of by default 20% of the air is assumed to be lost via leachage through the distribution system and along the walls. Furthermore, since also the air flow through the hay bin is typically far from even, the hay dries faster where the flow is higher. The fraction of the air passing where the drying front has reached the surface of the hay is not available for drying. This is modelled in the way that only a fraction of the air is considered to be used for drying. This fraction is defined as

$$fraction = \frac{1}{(1 + 1.96 \times C.V.)}$$

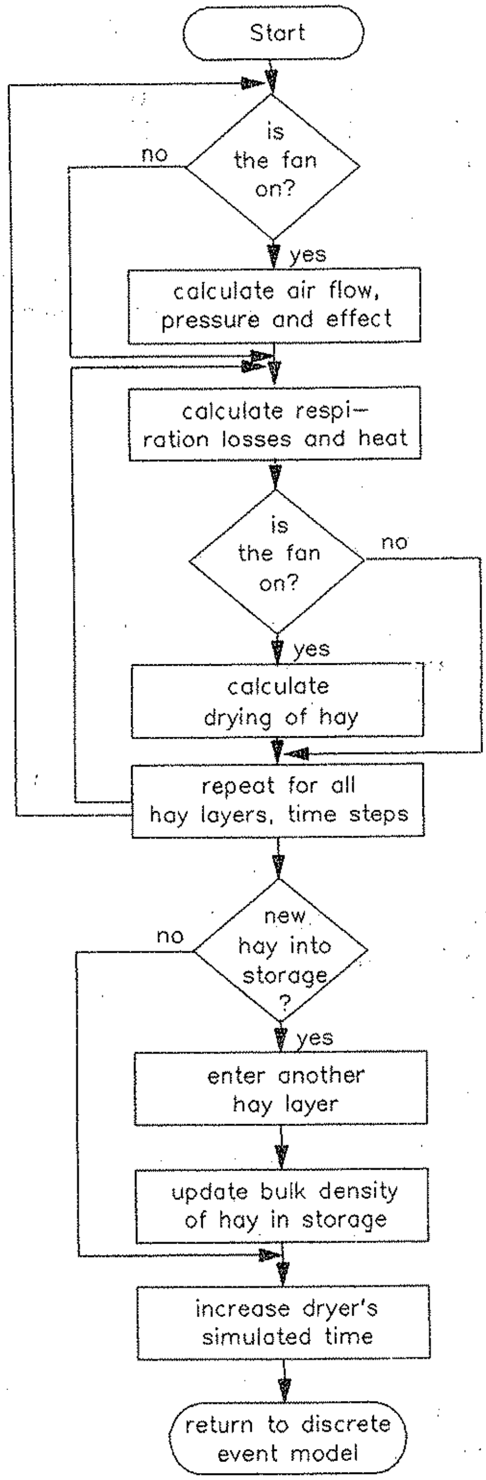

Figure 14. Flow chart of the dynamic part of the modified barn drying model.

where C.V. is the coefficient of variation of the air speed at the surface of the hay, typically in the range of 30 to 50% for loose hay and 65 to 70% for baled hay. The constant 1.96 is the z-value for a 95% confidence interval.

In the original (Jónasson, 1983) version the drying process was assumed to always take place in the innermost layer not completely dried. The fraction of the air used for drying was assumed to be saturated up to the equilibrium humidity under constant enthalpy. Combined these two air flow loss components implies that a constant fraction of about 30 to 40% of the air is utilized for drying.

In practice, the utilized fraction of the air is high as long as a thick layer of moist hay covers all of the surface, while it approaches 0 as the drying is being completed. This means that the original model under-estimates the initial drying rate, but over-estimates it at the end of the drying. This in turn leads to an over-estimation of the drying losses and of the risk for moulding.

The current model has been modified in this respect. Now all the drying calculations are performed for each individual layer. The utilized and non-utilized air is considered mixed as it flows from layer n to layer n+1. The equilibrium humidity is recalculated for layer n+1, and again the air is saturated only to the degree determined by the c.v. The consequence of this is that typically the undermost moist layer dries fastest, but also the succeeding layers to some extent since the air is not maximally saturated. It also means that a dry layer may be rewetted if the inlet air is very moist or if it lies above a more moist layer.

The Jónasson model of bulk density was further developed by Sundberg (1985). However, still only the average bulk density is calculated. The result is obtained through an iterative formula.

The model of respiration losses is originating from Wood and Parker (1971). Compared to the earlier versions of the model, the resolution has been improved. Now the respiration losses are calculated for each layer individually. Also the heat and moisture produced by respiration (15 to 75% of the heat energy for drying, according to Wood and Parker) is now added in each individual layer. (This is done before the drying calculation, resulting in that the heat is utilized for drying of the same layer as where it is produced.) Another improvement made is that the heat produced under periods when the fan is off now is accumulated in the tissue, resulting in a temperature increase. This in turn leads to an increase in the evaporation rate, so the evaporation loss rate accelerates. When the fan is turned on, the accumulated heat is cooled by the air flow.

The risk for storage fungi is expressed qualitatively, by a model telling if the forage batch may be mouldy as a result from too slow or incomplete barn drying or from storage at high moisture contents without barn drying.

4.4 The hay-to-milk conversion model

It is well known that Linear Programming (LP) is a suitable method to calculate fodder rations for animals. In this case the main goal is to calculate the economic potential of the hay available in a certain situation, i,e, each cow is fed with the optimal ration of each feeding-stuff from the nutritional and economical point of view. This problem can be solved using an ordinary LP model. If, however, the costs of feeding work would be included, whole number restrictions would have been needed, since it is normally faster to feed the same rations to each cow than to give every cow an individual ration. In this work it is not considered beneficial to consider the cost of the feeding work, since this cost is highly dependent of the conditions on the specific farm.

The hay-to-milk conversion model developed is built upon LP. It consists of four parts: a cow herd generator, an LP matrix generator, the solution (Simplex) algorithm and a report generator.

The cow herd generator requires as input the number of first-calvers and elderly cows respectively, the distribution of the calvings over the year and which months of the year the cows are housed. It outputs the number of cows in different lactation stages over the housing season. The lactation interval, which is assumed to be exactly one year, is divided into six lactation stages, within which the annual milk yield is distributed.

The reason to divide the lactation year into periods is that it is more difficult to fulfil the cow's nutritional needs during peak yield then else. The reason to divide the calendar year into periods is that most cows are grazing during the summer months. During that period they normally have no need of hay or silage.

The division into first-calvers and elder cows is requested by the much more flat lactation curve of the first-calvers. There are however also differences within these groups. Therefore, the elder cows and/or the first-calvers may also be divided into up to five sub-groups with different yields within each lactation stage. This causes, however, a bigger LP matrix. This means that the calculation requires more computer time.

In the model there are four sets of restrictions:

- herd restrictions, determining the number of cows in each group (and subgroup) and their maximum yields;
- energy- and protein balance equations, ensuring that the milk yield of each group is restricted by the intake of nutrients;
- fodder restrictions, determining the nutrient contents of the different feeding-stuffs available and the maximum quantity available;
- dietic restrictions, limiting the fodder intake of each cow and ensuring that she is served a well-balanced diet.

The first set of restrictions is generated using data from the cow herd generator. The last three sets of restrictions are partly adopted from Johansson (1980). They follow the Swedish recommendations from that time on feeding intensity and ration composition.

The model is designed to be robust against unfeasible solutions. For example, a shortage in energy or protein does not result in an unfeasible solution. Instead, the yield is adjusted down.

The dimension of the LP matrix is, with the maximum number of feeding-stuffs (10) and maximum number of subgroups of elderly cows as well as first-calvers (5 each), 182 rows (restrictions) and 133 columns (variables). This should be a reasonable size even for a personal computer.

The hay-to-milk conversion model is, and will remain, a separate program. The data required from the simulation model is manually entered into the input data file. This makes the hay-to-milk conversion model stand for itself.

Some nutritional parameters generally found in fodder ration calculations were omitted for different reasons:

- "coarseness"	(see below)
- moisture content	(% dry base)
- mineral content	(mg P.Ca. Mg etc/kg)
- price	(SEK/kg of dry matter)

The reason for neglecting the mineral contents is that the contents of different minerals are not of main interest in this project, its inclusion would be complicated due to lack of knowledge about how it is affected by the harvest and conservation. Furthermore, it is quite simple to complement the fodder rations with the necessary minerals, which means that its exclusion would only marginally affect the result. The price, valid for purchased feeding-stuffs as well as for cash-crops, is for forage an output variable rather than an input one, since it is worth as much as it pays to feed it to the cows. Its value may be determined in different ways depending on the actual situation.

The maximum daily fodder intake is dependent of the dietic properties of the different feeding-stuffs, notably its "coarseness" and moisture content. The "coarseness" is not easily defined. This is commonly handled by means of expressing the "coarseness" of the feeding-stuff as a function of some measurable variable. In Sweden, VOS (in vitro dry matter digestibility) energy content has been used. Another alternative is the fibre content, its use being restricted by the lack of appropriate methods of analysis. As this area of research is in fast progress, the coarseness problem has been neglected for now.

The effect of the moisture content on the maximum consumption is significant only for silage and is therefore not considered in the model.

5 METHOD OF CALIBRATION AND VALIDATION

The objective of the validation phase is to determine whether the model in fact mimics the reality sufficiently well. So the model is supposed to behave similarly to the reality, but to which extent, and in what respects?

In chapter 2 the importance of the interactions between the biological system, the man-machine system and the weather was emphasized. Consequently, these interactions have been a main reason for the efforts made toward a high resolution in the sub-models included in the integrated model.

The conclusion drawn from this was that the validation had to be performed on two levels:

1) the component level, where the sub-models are validated individually,

2) the system level, where the sub-models are assumed to work properly, and the validation is focused on the behaviour of the integrated model including the interactions between the sub-models.

No single experiment has been found, containing data appropriate for validating the field drying model (and the loss models) as well as the model as a whole.

For calibration and validation of the field drying model, excellent data was available from the JTI (Swedish Institute of Agricultural Engineering) drying and field loss experiment 1977-79 described below.

It was trickier to find appropriate data for validating the model as a whole. The best data found originates from a case study in the Skara region, where 6 milk farms were followed over a 3-year period 1981-83. Two of these were making hay of the first cut as well as the regrowth. These were selected for the validation.

5.1 Need of validation on the component level

In fact, most of the sub-models included in the integrated model were already validated to some extent. Below it is discussed to what extent further validation, and possibly calibration, was needed within this project.

5.1.1 The growth sub-model

This model was thoroughly validated by Torssell & Kornher (1983) under Swedish conditions. Within the present work, the model has been re-coded into Simula for compatibility reasons, but no changes have been made to its logic. Therefore it was not considered necessary to further validate this model on the component level.

5.1.2 The field drying sub-model

The field drying model was validated by Thompson (1981) under English conditions. He found that a constant leaf resistance gave an unrealistically high drying rate at low moisture contents. He therefore adopted the approach of an inverse relationship for crop resistance

$$R = \frac{R_0}{M}$$

or for a whole layer i,

$$r_s(i) = \frac{R_0}{2 \times LAI(i) \times M(i)}$$

where M denotes the moisture content (dry base) of the drying hay. He found that values of R_0 of 7500 and 15000 sec/m made the model fit well to drying curves of hay cut with flail mower and cutterbar mower, respectively. (Another relationship was used for the initial drying period, when stomata is still open.) He did not investigate the effects of different tedders, nor the effects of the botanical composition of the ley.

Obviously the values of R_0 had to be verified and complemented using Swedish experimental data. So the Thompson model had to be calibrated as well as validated.

5.1.3 The shatter loss, evaporation loss and leaching loss sub-models

All the field loss models was developed and validated by Jónasson (1983), as a part of a simple hay harvesting model developed earlier within the present project. Since the output data of these loss models are strongly dependent of the moisture content of the drying hay, they would be most appropriately validated in conjunction with the validation of the field drying model.

5.1.4 The field operations sub-model

The correctness of the logical behaviour of the field operations model was demonstrated in Axenbom (1988), using silage making as an example.

Provided the logical behaviour is correct, the only items needing verification are

1) indata,
2) the management sub-model.

As mentioned earlier, no attempt has been made to simulate the manager's decision process. Instead, the management process is controlled by means of indata. This reduces the task of validation of the management model into proving that the commands from the manager really control the simulation.

The validation of the field operations model as well as the indata verification needed is most appropriately performed on the 'system' level. This is therefore further discussed in chapter 5.2.

5.1.5 The barn drying sub-model

Jónasson (1983) performed some initial validation runs, but concluded that the experimental data available was not enough specified to allow for a complete description of the experimental conditions to be entered into the model. A sensitivity analysis by Axenbom (1983a) confirmed that the losses and mould risk increased sharply when a certain relation between specific air flow and carting rate was exceeded.

Since the modifications performed by Sundberg (1985), he (Sundberg, 1986) used the model to investigate the effects of development stage, carting moisture content climate (i.e. site), fan size, additional heating and in-barn transport method (hoist or pneumatic). The primary purpose was to investigate the system effects of the newly developed model of bulk density. Although the results were not compared with experimental results, the investigation confirms that the simulation results are realistic.

The barn drying model naturally has not been properly validated since the modifications performed within this project, because of lack of data. Since most changes are merely increases in the resolution, it is not likely that the present model would be less valid than its predecessors. Thus the barn-drying model should not have to be re-validated on the component level.

5.1.6 The hay-to-milk conversion model

The set of dietic restrictions is fetched from a quite widely used LP model, so the hay to milk conversion model may be considered at least partly validated in advance. Since the hay-to-milk conversion model has been left outside the present integrated model for the moment, it was decided not to try to validate it within the present work.

5.2 Need of validation on the system level

After successfully having validated all the individual sub-models on the component level, the validation of the integrated model is reduced into a verification of that the model as a whole works as expected, notably that all the sub-models interact properly with each other.

An exception was the field operations sub-model, which had to be validated on the system level for the reasons mentioned above.

5.3 Data available for calibration and validation of the field drying model and the field loss models

5.3.1 The JTI drying & field loss experiment 1977-79

During the years 1977-1979, the Swedish Institute of Agricultural Engineering (JTI) accomplished a series of 7 hay drying experiments, of which 3 was concerned with the first cut, and the other ones with the regrowth. The objective was to compare the drying rates and field losses between different mower types, tedder types and tedding rates.

Except for one second cut experiment located at Vapnö, Halland, all experiments were performed close to Uppsala, having similar soil conditions. Since the Vapnö experiment was performed under different conditions, it was omitted from the calibration and validation data set.

The 6 experiments used are presented in table 2.

Table 2. Some data characterizing the series of experiments used in the calibration and validation of the field drying model. The June experiments are first cut, while the August ones are second cut.

Exp. no.	Experimental site	Time of exper.	Clover rate, %	Yield, kg dm/ha	Initial m.c.d.b.
1	Sätuna	June-77	35	5500	-
2	Kungsängen	June-78	10	4800	3.17
3	Kungsängen	June-79	80	5000	5.0
4	Kungsängen	Aug.-77	35	4900	4.88
5	Kungsängen	Aug.-78	10	5300	-
6	Kungsängen	Aug.-79	10	4200	-

The mower types investigated was
- cutterbar mower,
- mower-conditioner with crimper rolls,
- flail mower.

The flail mower is nowadays very sparsely used in hay-making, so the plots concerned with this mower type was excluded from the data set used for calibration and validation.

The tedder types investigated was
- side rake tedder,
- rotary tedder.

The swaths were spread out shortly after mowing. Thereafter, they were tedded according to tedding rates once a day (in the morning) or twice a day (morning and early afternoon).

For the drying rate investigation, only one plot was used for each combination of mower, tedder and tedding rate, yielding 12 plots. From each of these, it was intended to collect samples 7 times a day (at 0700, 0900, 1100, 1300, 1500, 1700 and 1900) to determine the moisture content.

The sampling procedure was as follows: all hay within three squares 0.5 × 0.5 m was collected and mixed. 25 g of this was dried in an oven at 150°C for 30 min.

The evaporation at 1.5 and 0.5 m height above ground level was measured with the Andersson evaporimeter and registered in conjunction with the moisture content sampling. Also temperature, humidity, wind and cloudiness was registered, but only occasionally.

The field loss experiment in general used three plots per combination, to evaluate the shatter losses for three different target moisture contents: 20%, 30-35%, and 45-50%. The plots used for the field loss experiments were not the same ones as those used for the moisture content experiment. Not all combinations of mowers, tedders, tedding rates and target moisture contents were tested, limiting the number of plots to 26 (see figure 15).

There was one reference plot between each experimental plot. The gross yield of an experimental plot was estimated to the mean of the actual yields of the two adjacent reference plots plus the stubble losses of the reference plots.

Since the harvests of the reference plots were performed the day before the mowing of the experimental plots, the latter ones had another day's growth. Furthermore, some lossed did occur at the chopping of the reference plots due to windy conditions. Together these two factors lead to an under-estimation of the field losses (Jeppsson, 1981).

The experimental design did not permit estimations of the magnitude of the losses of the individual reference plots. This is therefore a major error source in the material, causing negative total loss figures in some cases. The extra one day's growth biases the estimates, but does not affect the relations between different treatments under the assumption that all plots within one experiment grow equally much.

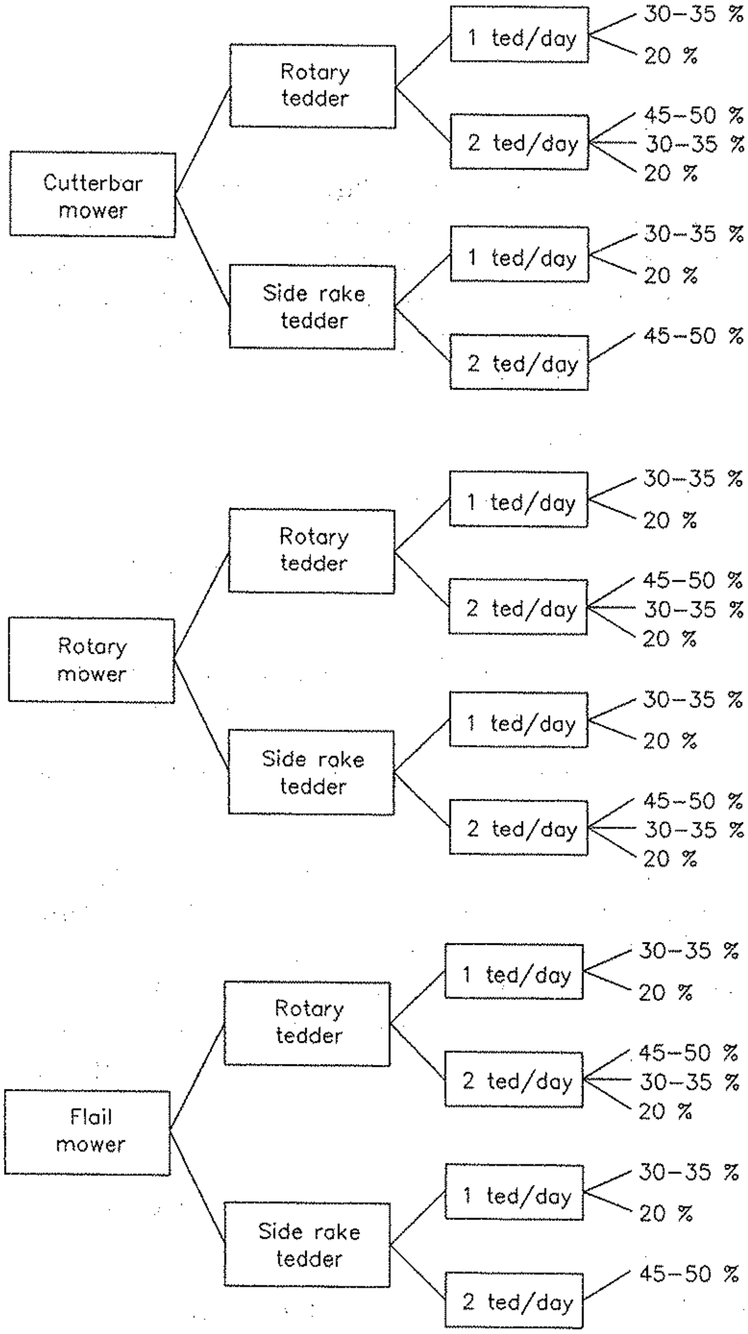

Figure 15. Outline of the design of the JTI field loss experiment. Source: Swedish Institute of Agricultural Engineering (unpublished material).

5.3.2 Weather data

For each time step, the field drying model requires the "current" values of the weather variables

- temperature at screen level,
- humidity at screen level,
- wind speed at 10 m level,
- short wave radiation.

The weather data registered during the experiments proved quite unsatisfactory. Therefore weather data had to be taken from the weather station in Ultuna, 4 km from Kungsängen. All the necessary weather parameters were available or could be derived from the data available. Unfortunately, observations were taken only at 0700, 1300 and 1900. This made it necessary to pay certain attention to the possibilities to calculate intermediate values. This aim was achieved in two ways:

1) an extra weather observation (at 0100) was generated,

2) interpolation was used for estimating intermediate values.

The reason to put an extra observation at 0100 is obvious: Then we have equidistant weather records, which simplifies the interpolation.

Linear interpolation was preferred in cases where a significant daily periodicity in the data could not be assumed, whereas quadratic interpolation had to be used elsewhere.

Temperature. - In addition to the ordinary temperature record, the daily max and min temperatures were registered.

A procedure to find the temperature at 0100 was developed as follows: A quadratic temperature curve between 1900 and 0700 was assumed. The min temperature was assumed to occur within this interval. From Gustafsson & Johansson (1977) was adopted a procedure calculating the x value of the min point of a quadratic curve, given three point coordinates. As the intermediate point was used (t(i), min temp). Iteratively the calculated time t(i+1) and the known min temp value was assigned to the intermediate point, and the x value was recalculated, until the result converged. Generally the procedure converged in less than 5 iterations. See figure 16.

Using quadratic Lagrange interpolation, the temperature at 0100 could now be calculated, using the calculated time and min temp as intermediate coordinates.

Since temperature varies in a sinusoidal manner, linear interpolation of temperature records was assumed inappropriate. Instead, quadratic Lagrange interpolation was used. The three points required were chosen as follows:

For simulated points of time between 0700 and 1900, the records of 0700, 1300 and 1900 were used. Otherwise the records of 1900, 0100 and 0700 were used. The reason for this choice was that the curvature can be expected to be different in daytime and in night time. It should be noted that Daylight Saving Time was not used in Sweden at that time.

Humidity. - The absolute humidity of the generated 0100 observation was calculated using linear interpolation. A test was performed to prevent the humidity to exceed the saturation humidity at the calculated 0100 temperature.

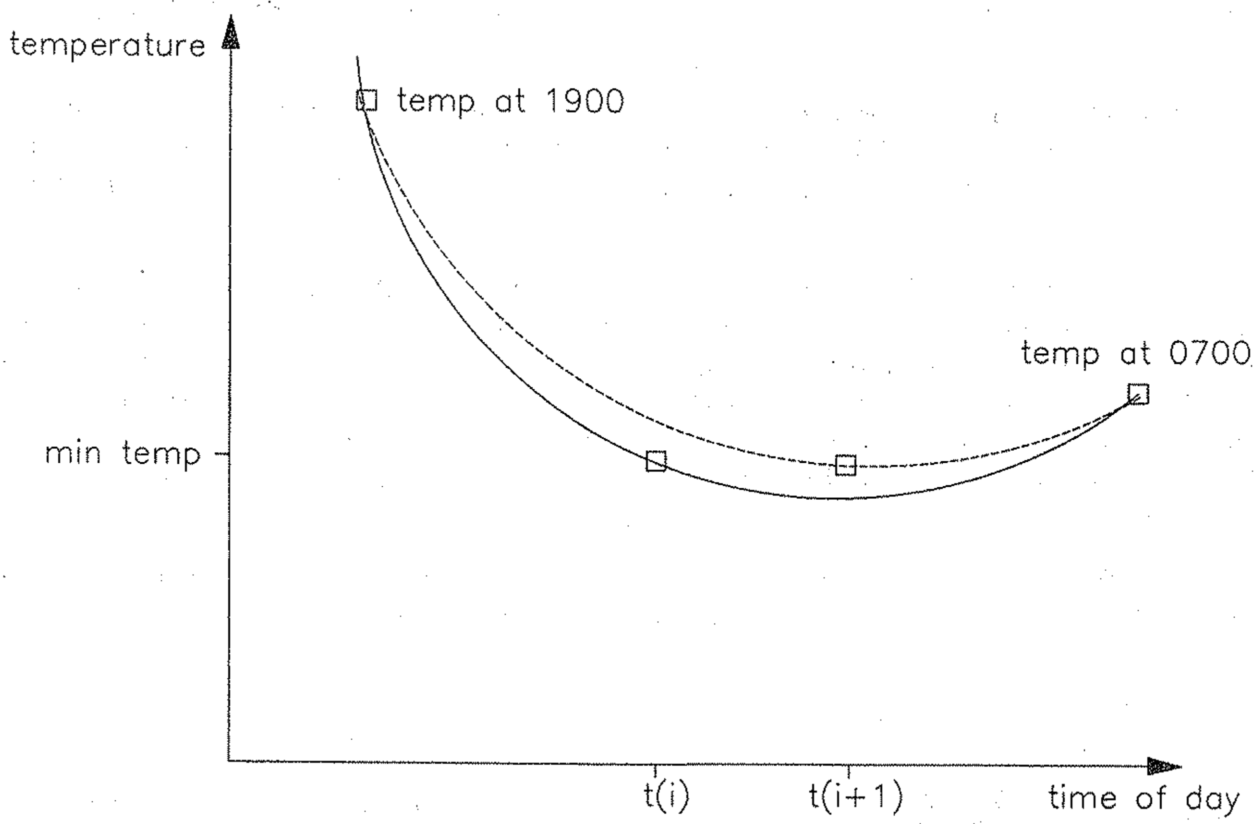

Figure 16. The iterative procedure to find the time for the min temperature. The solid line denotes the i^{th} iteration, and the dotted one the $(i+1)^{th}$ one, when the procedure has converged.

The absolute humidity at arbitrary times was derived using linear interpolation, since the absolute humidity is fairly constant from day to night. Note that the relative humidity varies considerably, but this is primarily due to the variation in temperature.

Wind. - It is well known to be less windy in the night than in daytime. A linear interpolation of the 0100 observation would therefore probably have been biased. The chosen approach was to assign the min value of the proceeding and the succeeding wind record to the 0100 observation.

Radiation. - The insolation was registered on a daily level. Furthermore, the number of sunshine hours was registered for a.m. and p.m. respectively.

To achieve the short wave radiation r for an arbitrary time of day, the formula developed by Josefsson (1987) was adopted:

$$p = -0.03702 + 1.62576\sqrt{\sin h} - 0.85513\sin h \qquad \sin h > 0.08$$

$$p = 1.0 - 8.07\sin h \qquad \sin h \le 0.08$$

$$r = \Phi \sin h\, p(1 - 0.75c^{3.4})$$

where sin h is the elevation of the sun, and c the proportion of the sky covered by clouds.

The first approach was to assign the a.m. value of cloudiness to the 0700 observation, and the p.m. value to the 1900 observation. The values of the 1300 observation and the 0100 observation was calculated as the average of the preceding and the succeeding observation.

This approach was checked by means of integrating the Josefsson formula over the bright hours of the day and comparing it with the observed insolation value. In average, the results were similar, but with a high variation. Therefore the 1300 cloudiness value was iteratively adjusted to make the Josefsson formula fit better. This approach worked well, except for some cases when the sky was clear and the observed value was higher than the estimated one. Thus the cloudiness could not be further adjusted downwards. In these cases, the difference could be around 10%.

The modified calculated insolation values was used all over. This implies that the model may slightly under-estimate the drying rate during very clear days.

5.3.3 Other sources of data

Initial moisture content. - The initial moisture content was missing for some of the experiments. Thus these values would have to be estimated. Table 2 shows that the variation in initial moisture content was considerable, and strongly correlated with the clover rate.

A simple regression model for the initial moisture content was developed:

$$M_0 = 3.0 + 2.0(c/100)$$

where c is the percentage of clover. The calculated values are showed in table 3.

Table 3. The observed and calculated values of the initial moisture content M_0.

Exp. no.	Time of exper.	Clover rate, %	Initial m.c.d.b. observed	calculated
1b	June-77	35	-	3.70
2	June-78	10	3.17	3.20
3	June-79	80	5.0	4.6
4	Aug.-77	35	4.88	3.70
5	Aug.-78	10	-	3.20
6	Aug.-79	10	-	3.20

The material is too small to validate this equation. Furthermore, other factors also affect initial moisture content. Anyway, no better alternative could be found, so the calculated values were used where observed ones were missing.

Leaf Area Index. - No figures of the leaf area index was available, so it had to be estimated. As a part of the growth model, a regression model of the LAI as a function of yield was used:

$$LAI = \sqrt{0.01\,y}$$

where y is dry matter yield in kg/ha.

The measured yield excludes the stubble, but the equation above includes it. Therefore, the stubble was assumed to be 10% of the total dry matter. Thereafter, the LAI was calculated and divided into living stubble LAI and swath LAI in the same proportion as the dry matter content. The LAI of dead stubble was assumed to equal the LAI of living stubble.

5.4 Method of calibration and validation of the field drying model and the field loss models

5.4.1 General

The field drying model was calibrated and validated against experimental data by means of simulating the different treatments, and ocularly comparing the historical and simulated moisture contents plotted against time. The moisture content was calculated dry base, since wet base is not linear with respect to the water content of the drying hay.

Since the main part of the field model deals with micro-meteorological laws, there are only a few empirical variables.

The calibration procedure comprised of determining the one empirical variable R_0 (leaf resistance at M=1.0). The assumption of the leaf resistance being inversely proportional to M was retained.

For the other empirical variables, the values used by Thompson were retained. The accuracy of the experimental data was not high enough to reliably permit the calibration of more than one variable at a time.

The material was divided into 2 halves, one for calibration, and one for validation. The experiments used for calibration were the ones where the initial moisture content was registered, i.e. exp. 2, 3 and 4.

5.4.2 Calibration of crop resistance

The objective of the calibration was to find plausible values of R_0 for all combinations of mowers and tedders, and possibly as functions of the percentage of clover. The effects of different tedding rates are supposed to be reflected in the drying model itself.

No optimizing procedure was used in order to find the appropriate values of R_0. Rather, a combination of results from a statistical drying model developed from Axenbom (1983b), and repeated simulations, was used. The statistical model yielded the relationships between the drying rates after different treatments and biological compositions, whereas the simulation runs were used to find the overall level minimizing the error.

Based on a non-linear statistical model by Axenbom (1983b) of the drying rate as a function of clover rate (c), conditioning treatment (m), tedder type (t) and harvest number, the following model was developed:

$$R_0 = \frac{P}{(1 - 0.77c)mth}$$

where m = 1 for mower, 1.23 for mower-conditioner and 1.69 for flail mower; t = 1 for side rake tedder and 1.09 for rotary tedder; h = 1 for the first cut and 1.10 for the regrowth. (P is a constant.) These figures denote the expected drying rate related to mower, side rake tedder and first cut.

Sample simulations showed that the effects of different equipment and harvest numbers were appropriately reflected, but that the effects of clover rate was not simulated properly. The drying rate was underestimated at high and low clover rates.

An alternative model was developed:

$$R_0 = \frac{P(1 + Qc)}{mth}$$

with the same values of m, t and h. Thus the parameters remaining to estimate was the constants P and Q. Values of 12000 and 0.75, respectively, were found to give a good agreement between measured and simulated drying curves.

5.4.3 Procedure for validation of the field drying model

Since the experiments 2, 3 and 4 was used for the calibration, the experiments 1, 5 and 6 remained for validating the calibrated field drying model.

The data available does not allow the validation of the model in general, just for the conditions under which the series of experiments have been performed. However, in some respects general conclusions can be drawn from the validation. These are:

- does the model dynamically behave similarly to the experiment?

- has the model got good prediction properties?

Undoubtedly, there are statistical procedures available to compare the behaviour of a number of time series. It was however considered just as appropriate just to look at the curves to answer the questions above.

Therefore, it was decided to plot the simulated and experimental drying curves in the same diagrams, and study them ocularly.

In addition to the comparative study, it would have been most valuable to perform a sensitivity analysis, investigating the effects of varying the values of certain empirical variables of the model. Such a sensitivity analysis should precede any further research aimed at improving the estimates of the data.

5.4.4 Procedure for validation of the field loss models

The field losses (evaporation losses, shatter losses and leaching losses) were simulated in the same runs as the field drying model calibration and validation runs. The loss figures were recorded over the entire drying process, so the figures at any pre-determined moisture contents could be extracted from the output lists. The simulated shatter losses did not include the losses occuring at windrowing and baling. The shatter loss model however assumes this component to be a constant, so the only effect of this is that it partly offsets the errors caused at the harvest of the reference plots.

In practice, the simulated loss figures were not recorded at a specific moisture content, but rather at the latest point of time with the number of teddings corresponding to the experimental sample. Since the shatter losses increase only at field operations, and the evaporation losses are insignificant at low moisture contents, this procedure gives better estimates of field losses than matching the simulated and the experimental moisture content would do.

From the total losses of the experimental plots (the difference in yield between reference plots and experimental plots) the stubble losses were subtracted, the rest being an estimate of the sum of the evaporation losses, shatter losses and leachage losses. These estimates were compared with the sum of the corresponding simulated figures. There was no means of validating the three loss models individually, since the different loss components could not be separated.

5.5 Data available for calibration and validation of the integrated model

5.5.1 The Skara case study

In the Skara case study, six dairy farms were closely followed by a group of researchers during three years, from 1 May 1981 to 30 April 1984. The farms were selected so that two of them harvested both the first and second cut as hay, two took the first cut as hay and the regrowth as silage, and the last two ones harvested haylage, stored in steel tower silos.

The objective of the study was to examine the entire milk production organization on the individual farms by means of following the flow of forage from growth to conversion into milk. From the study, its technical feasibility, its robustness to disturbance, the results of the different sub-processes growth, harvesting, conservation and feeding as well as result of the production as a whole was judged. During the experiment, the farmers were encouraged to improve their production by means of offering them advisory service, and the results of these attempts were followed up.

A multitude of registrations was performed on the farm. The ones related to the plant growth were the following: The soil type was analyzed. The condition of the ley crop was registered in the beginning of the growth seasons. The fertilizer rate was registered. Just before the harvest, the botanical composition and development stage was registered. The development of the biological yield was however not registered.

The types and sizes of the hay-making equipment was registered. During the harvests the points of time for the starting and finishing of every field operation was registered, as well as for the barn dryer fans. Also the weights of every load of hay were registered, and the average moisture content at carting was analyzed for each field. The amounts of rain were registered daily.

During the feeding season, the fodder rations were followed up twice a month.

Of the two "hay only" farms, one ("Tomten") performed the hay harvest in co-operation with a neighbour. This made it difficult to follow the work organization. Therefore the other one ("Storegården") was chosen for the validation of the integrated model.

Of the three harvesting seasons, 1981 was very wet, 1982 was normal, and 1983 was very nice. The first two years the equipment was the same, but in 1983 a mower-conditioner replaced the old mower. The capacity of the equipment had to be calculated from the time registrations. To avoid using the same data twice, it was decided to use 1982 data to calculate the capacities of the equipment and use 1981 for the validation. The calculated capacities are shown in table 4.

Table 4. Calculated capacities from the 1982 hay drying season at Storegården.

Operation	Hours / ha
Mowing	1.60
Spreading, tedding	0.57
Windrowing	0.86
Carting	4.00

The fertilizer levels used at Storegården are moderate. See table 5.

Arnesson et al (1986) claims that the N mineralization rate is high due to the high humus rate and the spreading of manure, although it is never spread on grassland. Therefore the annual N rate figures to the growth model was increased with 50 kg/ha all over.

There was no information about the proportion of hay put into each of the two barn dryers, so the actual amounts was manually divided according to the assumption that about 40% of the hay was put on the small dryer in each carting.

Table 5. The nitrogen (N) fertilizer levels used at Storegården.

Crop	N level, kg/ha
1st cut, 1st years ley	48
1st cut, elder ley	64
2nd cut	31

5.5.2 Other sources of data

Daily weather data for the growth model were fetched from a database, located at the Swedish University of Agricultural Sciences, containing daily weather data for a large number of locations. The location most close to the farm was the town of Skara.

Weather data for the field drying model was taken from a synoptic weather station situated in Borgunda (close to Skara), some 20 kilometres from the farm. This station was selected because it takes 7 observations a day (0100, 0400, 0700, 1000, 1300, 1600 and 1900). The data used in the simulation were temperature, humidity, wind speed and cloudiness. From the cloudiness the radiation was calculated using Josefsson's (1987) formula (see above). The differences from the validation of the field drying model was that

- the daily radiation was not registered, so the cloudiness was not adjusted

- no extra observation was generated. Instead the interpolation procedure was adapted to handle non-equidistant observations.

The field drying model requires the amount of rain for every rainfall, as well as the points of time it starts and stops. Since this was not available, the rainy hours had to be "guessed". This was done by plotting the temperature and humidity as a function of time. The rainy hours were assigned to periods with lower temperature and higher humidity than the preceding and following observations. These hours were adjusted with respect to the registered work hours, using the assumption that it did not rain since the work went on. If more than one shower a day was indicated, the precipitation was distributed between them.

5.6 Method of validation of the integrated model

The validation method chosen was to simulate the growth season and harvesting period of the first harvest of Storegården, and to compare the simulated results with the data available. The aim was to follow the harvesting work on the farm as close as possible.

Since the growth model and the harvesting model in integrated into one model, the output data from the former one was to be used as input data to the latter one. In the same way, the output data from the harvesting model was to be used as input data to the barn drying model, although the barn drying model is a separate program due to computer memory limitations.

All data required for the simulation could be made available. However, some key data needed to compare the model with the experiment was missing, the most important of these being the biological yield at cutting. This made it impossible to validate the field loss models, although the yield and moisture content at carting was registered, let be only at an aggregate level.

Now, since the field loss models have earlier been validated on the component level, it was decided to accept this imperfection. The main objective with the validation on the system level was after all to prove that the sub-models work appropriately together.

6 RESULTS

6.1 Calibration of the field drying model

For each of the experiments 2, 3 and 4, every combination of mower type, tedder type and tedding rate was simulated, i.e. 2 x 2 x 2 = 8 combinations.

With the constants P and Q set to 12000 and 0.75 respectively, this model resulted in simulated data generally in good accordance with experimental data. See figure 17 (exp. 2), 18 (exp. 3) and 19 (exp. 4).

The difference in simulated moisture content between plots tedded once a day and plots tedded twice a day was negligible, just as was the case with the experimental data. Therefore drying diagrams are showed only for plots tedded once a day.

The simulated moisture content measurements were taken at the same times as the experimental ones. Additional simulated measurements were however performed at each tedding, rain start, rain stop and sun set.

As is seen in figure 17 and 18, the simulated data of the experiments 2 and 3 shows an excellent fit to the experimental data. The only major deviation is during the first night of experiment 2. Such a deviation could have been caused by early dew. There is however no support for this assumption in the weather data available. Another possible reason is the fact that these plots were not spread out until the next morning, since they were mowed in the afternoon.

Figure 19 shows that in experiment 4, the model predicts too high moisture rates all over the experiment. There could be several reasons for this. For one thing, the regrowth is more leafy and might have a higher LAI than the estimated one. Another assumption could be that the initial moisture rate is erroneous. The large deviation between the measured and the estimated value for this experiment at least does not contradict this. To test the latter hypothesis, the simulations were repeated, but with the initial moisture content set to 3.7. The results are shown in figure 20.

Now the fit became much better, almost as good as for experiments 2 and 3. In particular, the simulated drying curves follow the experimental ones very closely at moisture contents below the stomatal closure moisture content, which is fixed to 75% of the initial moisture content. This indicates that if the moisture is correctly estimated at stomatal closure, the rest of the drying curve will follow the experimental curve closely.

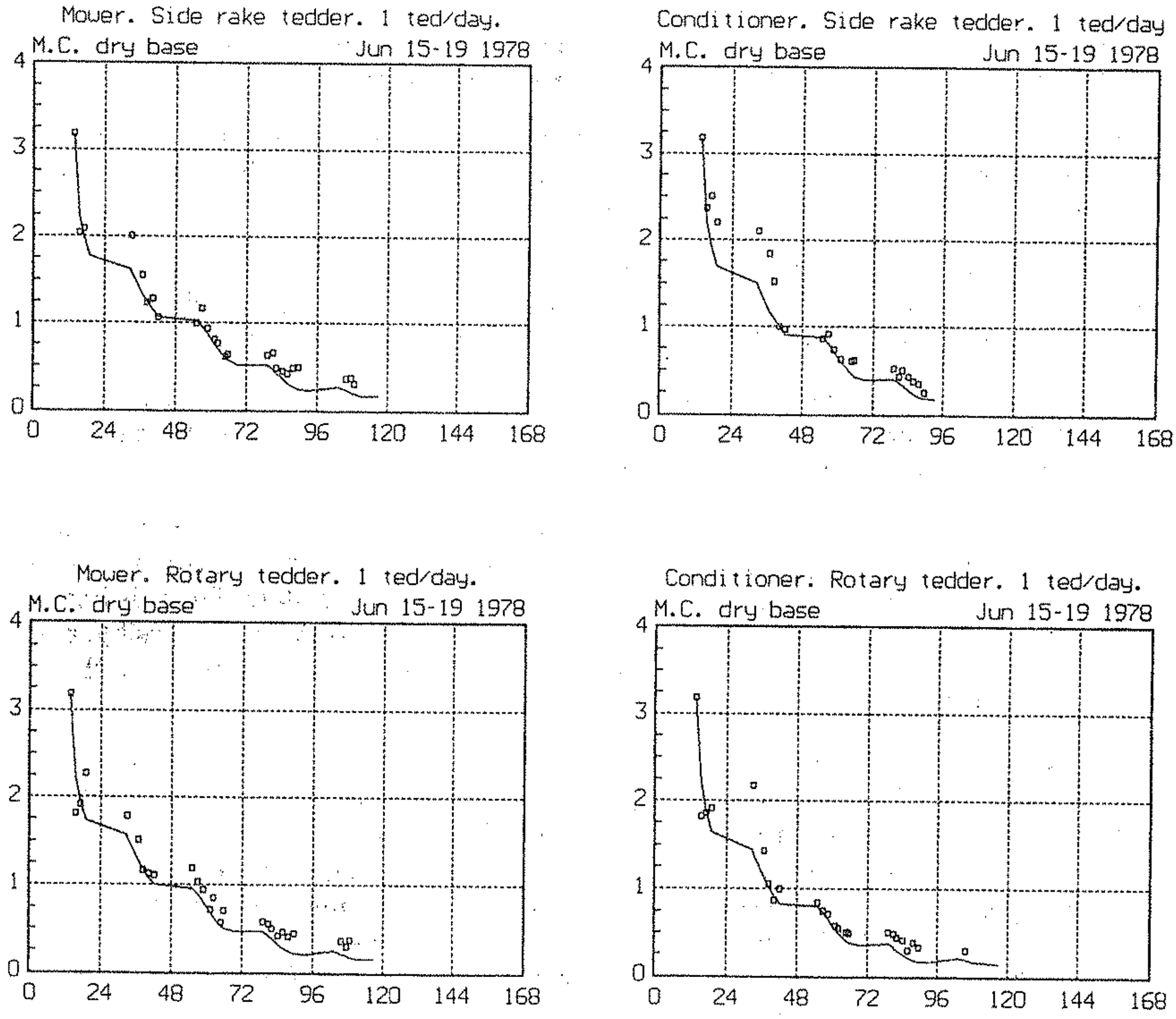

Figure 17. The measured and simulated drying curves with different combinations of mower type and tedder type for the first-cut experiment 1978. Legend: Observations ▢, simulated _____, simulated incl. rewetting by rain or dew ..... .

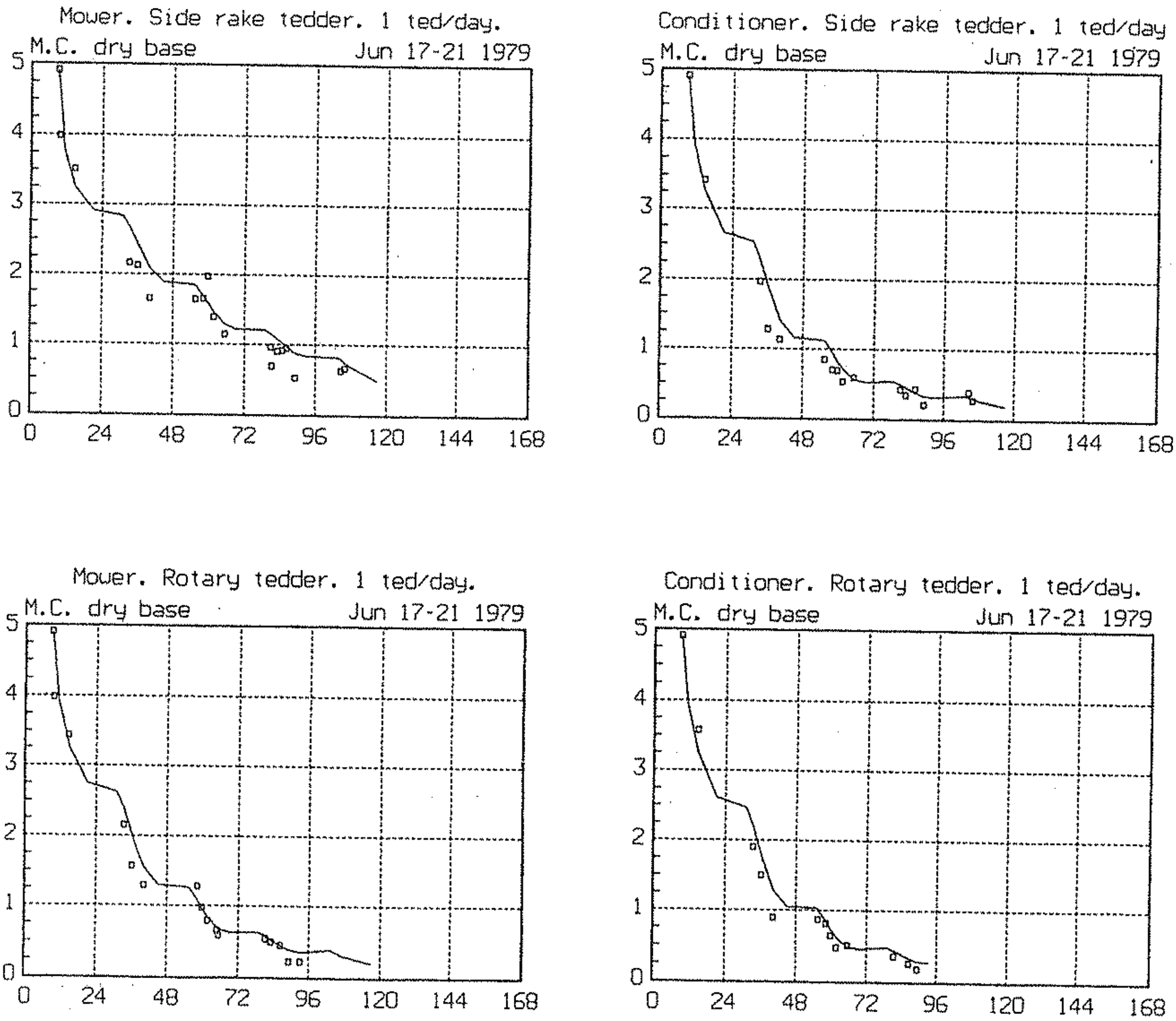

Figure 18. The measured and simulated drying curves with different combinations of mower type and tedder type for the first-cut experiment 1979. Legend: Observations ▢, simulated _____, simulated incl. rewetting by rain or dew ..... .

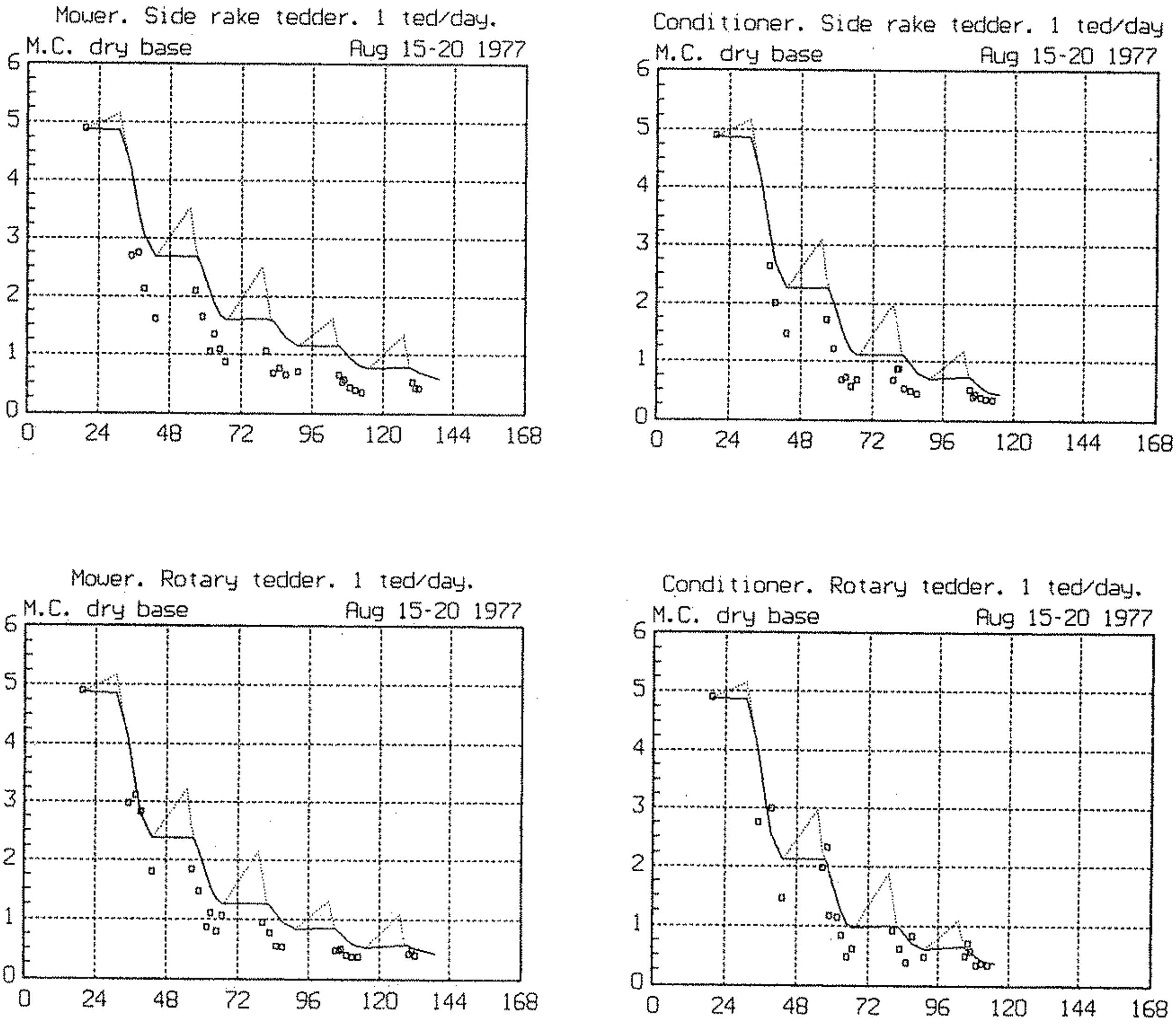

Figure 19. The measured and simulated drying curves with different combinations of mower type and tedder type for the second-cut experiment 1977, using the measured initial moisture content. Legend: Observations ▢, simulated _____, simulated incl. re-wetting by rain or dew ..... .

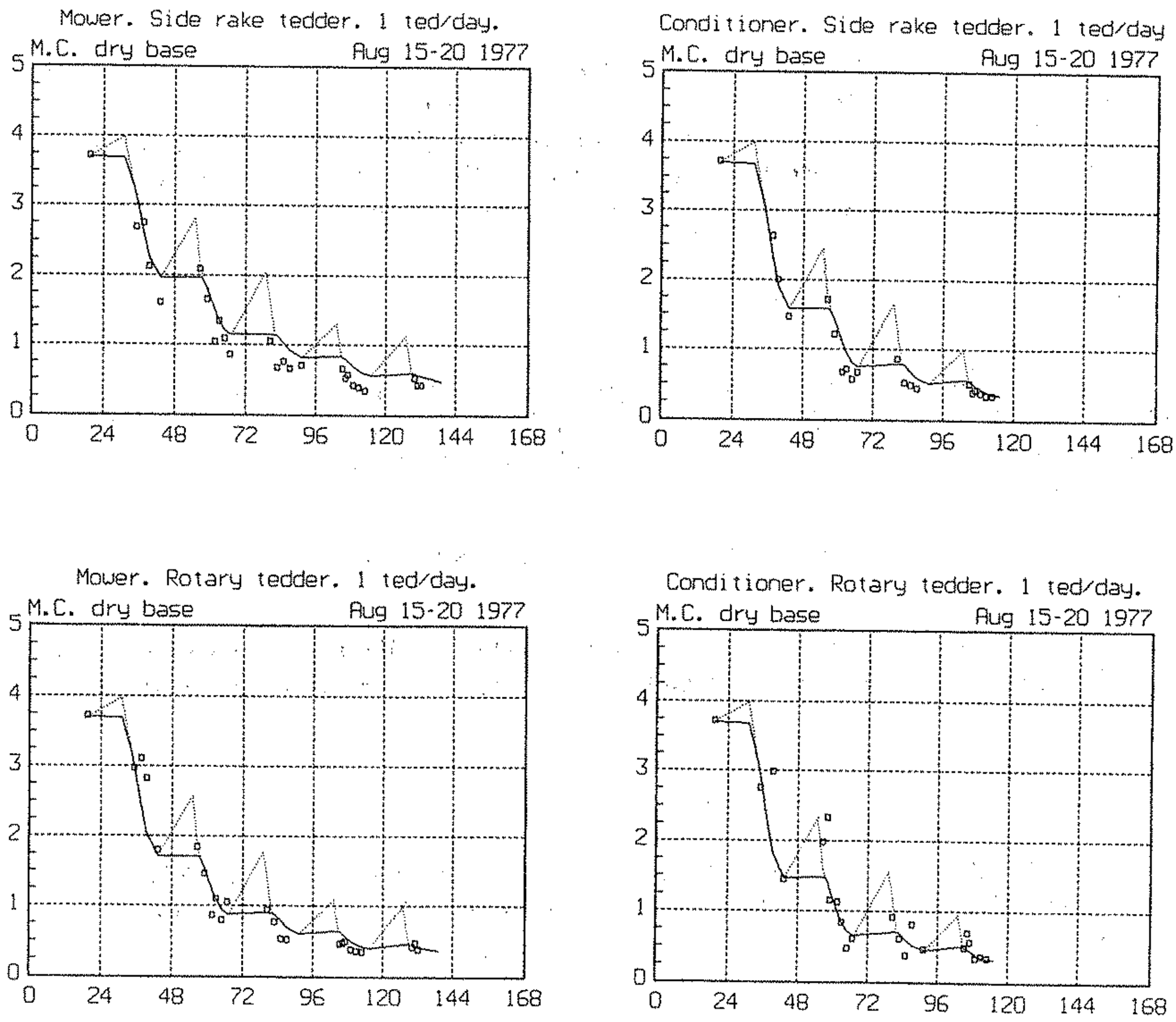

Figure 20. The measured and simulated drying curves with different combinations of mower type and tedder type for the second-cut experiment 1977, using the estimated initial moisture content. Legend: Observations ▢, simulated _____, simulated incl. re-wetting by rain or dew ..... .

The conclusion from the re-run of experiment 4 is that the probable reason for the deviation between experimental and simulated data is some error in the initial moisture content, and/or in the stomatal closure moisture content. It might be that the latter should not be expressed as a fraction of the former, but rather as a fixed moisture content figure. The experimental data is however insufficient to confirm or reject this hypothesis.

From the results of experiment 2, 3, and the rerun experiment 4, no systematic deviations or trends could be found. Therefore, it was not regarded worthwhile to try to fine-adjust any of the parameters m, t, h, P and Q any further, since many other parameter values used was considered uncertain. Instead these rather informally extracted parameter values was considered appropriate to use in the validation.

6.2 Validation of the field drying model

The validation of the field drying model was performed using the experiments 1, 5 and 6, using the same values of the parameters m, t, h, P and Q as in the calibration. Since the initial moisture content was unknown for all these experiments, the estimated values shown in table 3 were used.

The drying curves are shown in the same way as in the calibration chapter, i.e. only the 1 tedding/day ones are shown.

The fit of the drying curves of experiment 1 (figure 21) is excellent, just as was the case with the first-cut experiments used for calibration. Obviously, both the criteria set up for the validation,

- good prediction,
- similar dynamic behaviour to the model

are fulfilled to a high degree for the first cut. The deviations are so small, so they are not worth discussing. It would not be possible to distinguish the natural variation from moisture content measurement errors or model errors.

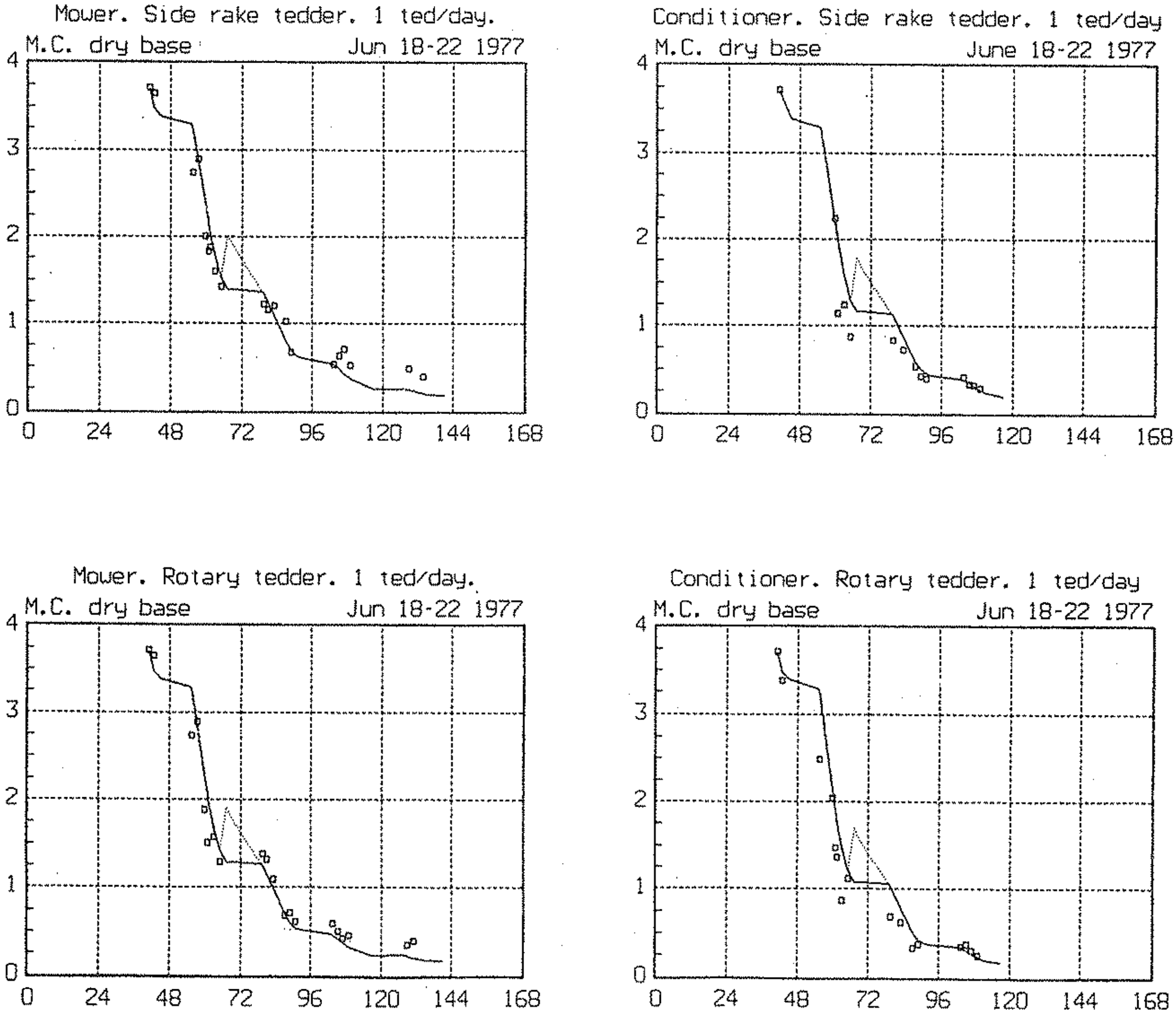

Figure 21. The measured and simulated drying curves with different combinations of mower type and tedder type for the first-cut experiment 1977. Legend: Observations ▢, simulated _____, simulated incl. rewetting by rain or dew ..... .

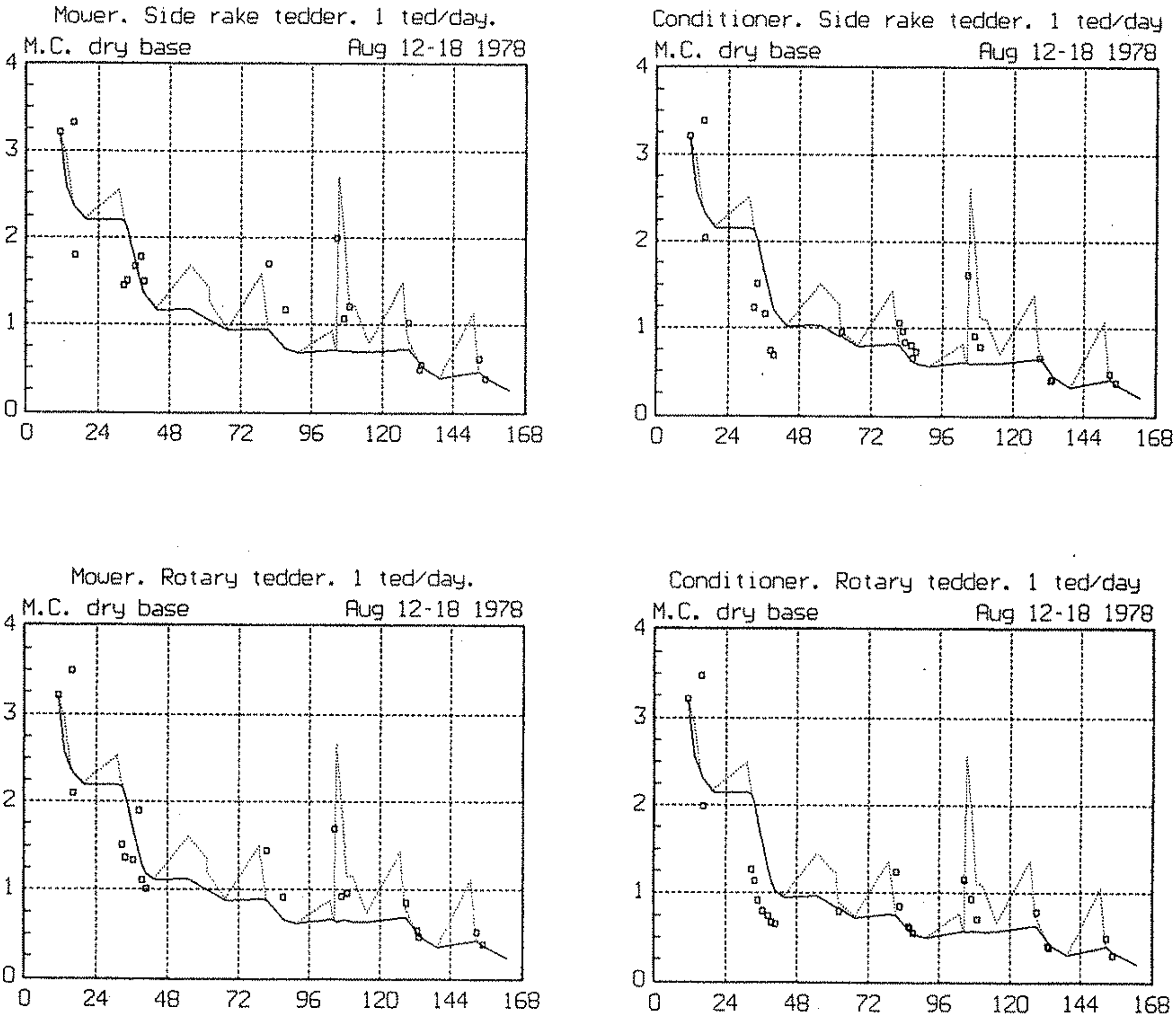

Figure 22. The measured and simulated drying curves with different combinations of mower type and tedder type for the second-cut experiment 1978. Legend: Observations ▢, simulated _____, simulated incl. rewetting by rain or dew ..... .

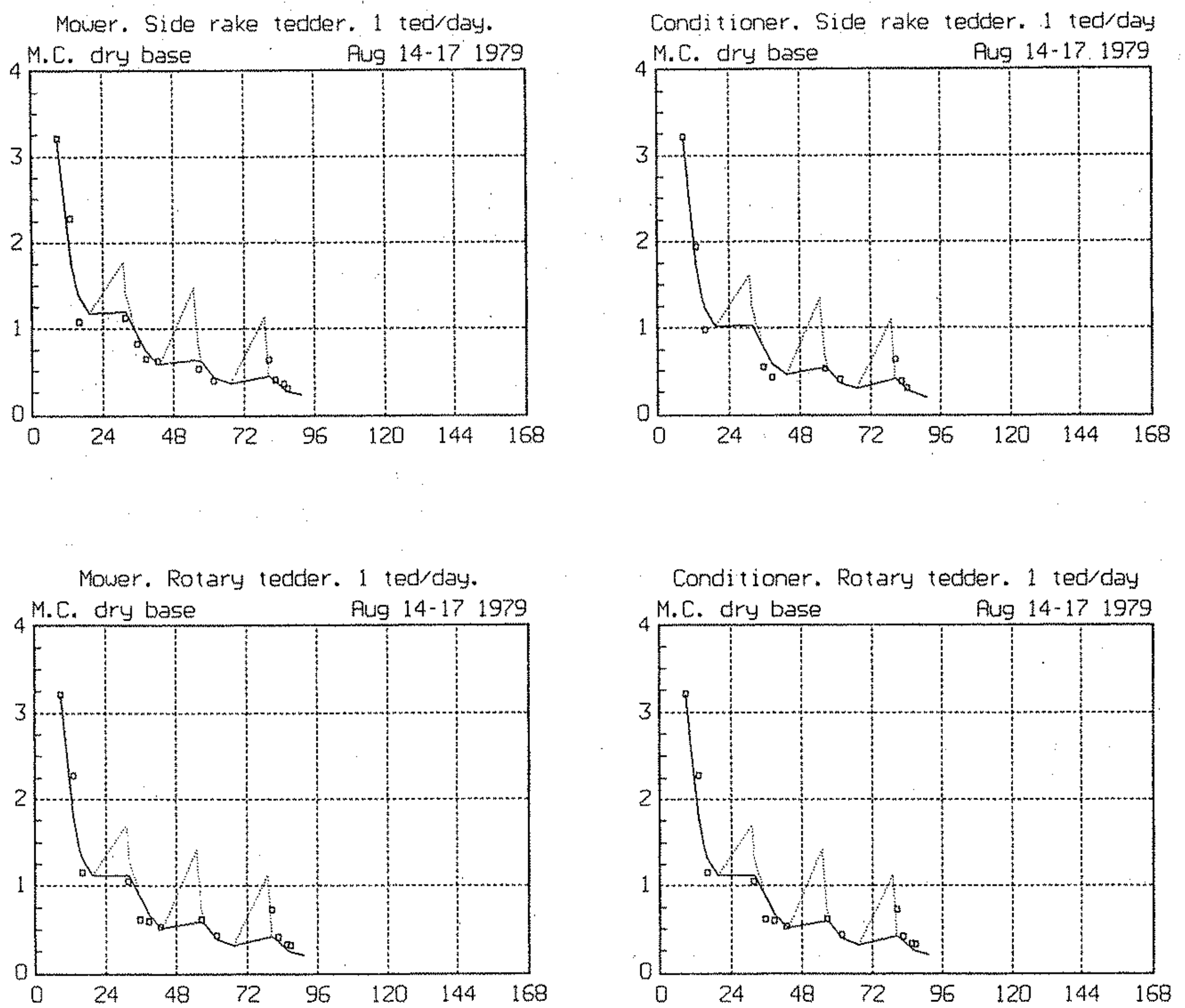

Figure 23. The measured and simulated drying curves with different combinations of mower type and tedder type for the second-cut experiment 1979. Legend: Observations ▢, simulated _____, simulated incl. rewetting by rain or dew ..... .

The two second-cut experiments (5 and 6) show different pictures. The latter one is obviously performed under good drying condition, but with dew during the night hours. Just as the first-cut experiments, the model follows the experimental curve very closely, and so the criteria are fulfilled.

The results of experiment 5 are more difficult to interpret. The period is characterized by a higher precipitation than the other ones, with rain occurring day 1, 3 and 5. The model reports occurrence of dew during all nights, but this is not confirmed by meteorological data.

The model seems to underestimate the drying rate from mowing until the mid of day 2. It is possible that the mowing, performed between 0900 and 1200 according to archive material, has in average been performed before 1030, the mowing time assumed. Some drying seem to have occurred during the first night, but since the moisture content was not registered between 1610 and 0840, most of the decay is probably due to drying during the evening. Another possible reason could be errors caused by interrupting the drying of the samples too early, resulting in too low calculated moisture content values.

The rest of the drying period consists mainly of drying of precipitated moisture. Here the model follows the experimental data fairly well. What may in the diagrams look like deviations are to some extent a difference in resolution, since the model reports the moisture content at every rain start and rain stop, while the measurements of moisture content have been sparse during rainy weather.

6.3 Validation of the field loss models

The experimental field losses were compared with the simulated ones by plotting the simulated data against the experimental ones. The result is displayed in figure 24.

A good agreement betwen the points and the diagonal line indicates a good correspondence between simulated and experimental values. If the points are offset, but the slope is correct, the model is still probably good. The offset may be a result of the error sources mentioned. An inappropriate slope however tells that the model is wrong.

Ranking the experiments, the Aug-78 and Aug-79 has a good fit. The Jun-78 one is a bit worse, followed by the Aug-77 and Jun-77 experiments. The Jun-79 experiment shows that the model underestimates the loss by a factor 2 or 3!

The ranking of the experiments can be seen to be negatively correlated to the percentage of clover. It is obvious that at least the shatter loss model is not valid for clover leys, while it seems to be fairly appropriate for grass leys. It should be noted that Jónasson (1983) did emphasize that the shatter loss model applies only to grass leys, due to lack of data for clover.

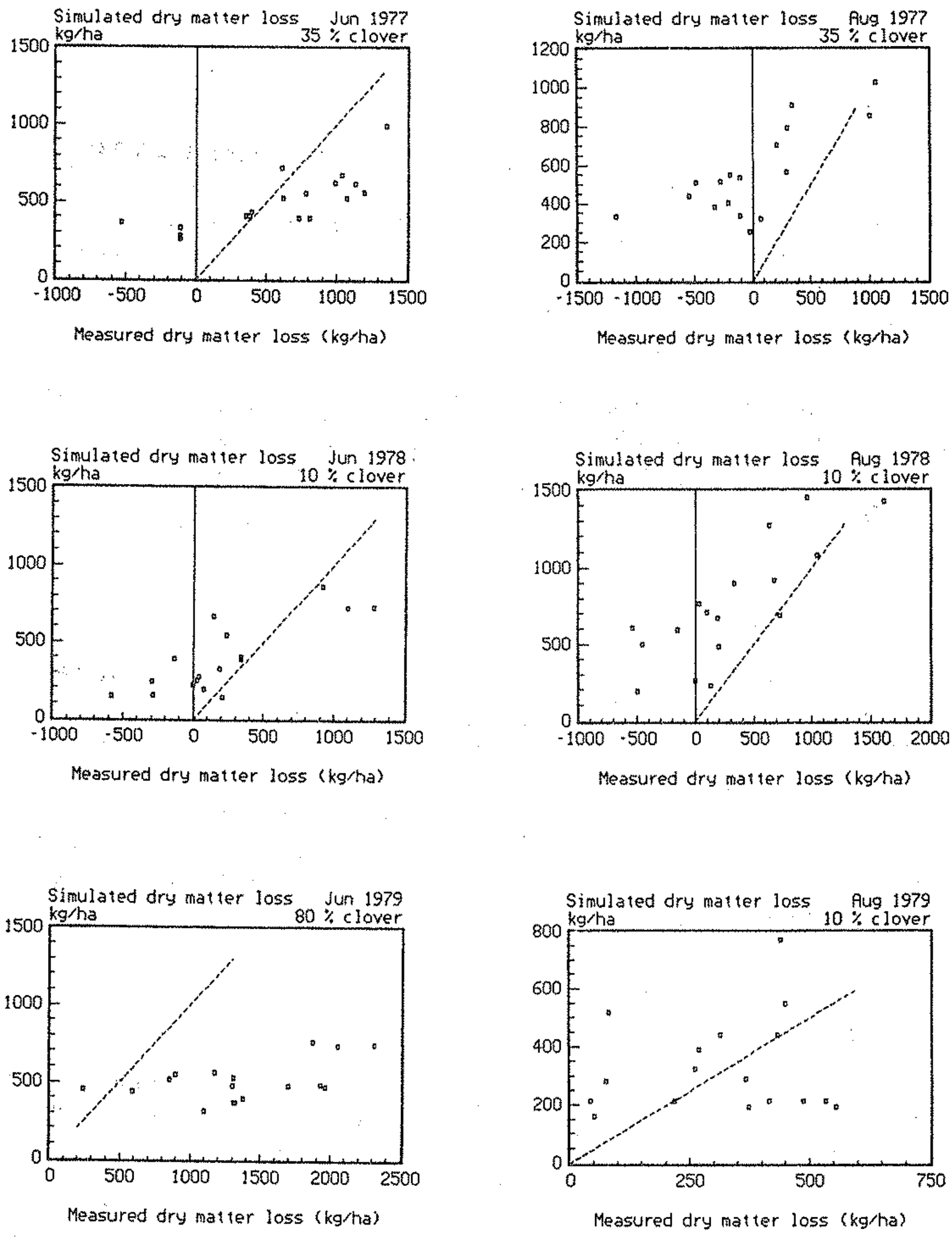

Figure 24. The simulated total field losses (excl. stubble losses) versus the estimated ones for each of the 6 experiments. The dotted line indicates the 1:1 relationship. The shatter losses occuring at windrowing and baling are not included in the simulated figures.

6.4 Validation of the integrated model

6.4.1 The growth model

The average net yield of the first cut 1981 was 5900 kg of dry matter per ha. This is reported to be 10-20% above the average for that geographical region (Arnesson et al, 1986), in spite of the moderate fertilizer levels used. It is also substantially higher than the biological yield estimated by the growth model, 3800 to 4300 kg d.m./ha. Obviously the favourable local conditions have not been appropriately considered in the indata to the model.

The metabolizable protein and energy levels in the dried hay were 63 g/kg and 9.0 MJ, respectively. The estimates by the model for a growing crop were between 60 and 100 g, and between 10.0 and 11.1 MJ. Since the energy levels of the hay have been reduced due to leaching of sugar in connection with rainfall, the energy estimates are probably fairly good.

6.4.2 The field operations model

The events of the real harvest, and those simulated by the model, are listed in appendices 1 and 2. A comparison between the two ones show that the model has been able to simulate the real harvesting work very close. One cause of deviations is that the capacity in reality varies due to the shape and size of the field etc. Furthermore, the farmer often interrupted the mowing, windrowing or carting before the field was finished. Unfortunately the acreage that was finished was generally not noted. Therefore this has been estimated from the time consumption of the operation in question on the two halves.

6.4.3 The field drying model

Since the moisture content was measured only at carting, only the final moisture contents will be compared here. As seen in table 6, the estimated carting moisture content varied between 0.17 and 0.84 dry base (15 to 46% wet base).

The simulated and measured final moisture contents are compared in figure 25. The figure shows that the correspondence between measured and simulated values are good at low moisture contents, but worse at higher moisture contents. The error however seem to be quite random.

Table 6. The mowing date, carting date, simulated and measured moisture content at carting, and acreage of the fields.

FIELD_ID	Mow date	time	Cart date	time	MCDB sim.	MCDB expr	ha
Field_4a 1	81-06-17	16:15	81-06-23	11:46	0.84	0.45	0.2
Field_4a 2	81-06-18	13:30	81-06-24	13:39	0.45	0.84	0.9
Field_4a 3	81-06-17	16:15	81-06-23	13:35	0.72	0.45	0.3
Field_4b 1	81-06-22	13:10	81-06-28	16:36	0.56	0.67	0.4
Field_4b 2	81-06-22	13:10	81-07-02	12:22	0.62	0.67	1.0
Field_6a 1	81-06-22	18:50	81-07-02	16:24	0.55	0.56	0.7
Field_6a 2	81-06-22	18:50	81-07-03	13:20	0.40	0.44	0.3
Field_6a 3	81-06-22	18:50	81-07-03	10:50	0.47	0.44	0.4
Field_6b 1	81-06-24	09:10	81-07-05	11:34	0.55	0.33	0.3
Field_6b 2	81-06-24	09:10	81-07-05	17:13	0.42	0.33	0.2
Field_6b 3	81-06-24	09:10	81-07-05	13:45	0.49	0.33	0.9
Field_5 1	81-07-04	11:28	81-07-08	11:09	0.43	0.46	0.4
Field_5 2	81-07-04	13:40	81-07-08	14:52	0.36	0.29	0.6
Field_5 3	81-07-04	15:46	81-07-09	12:10	0.28	0.25	0.8
Field_5 4	81-07-04	11:28	81-07-08	13:30	0.37	0.46	0.3
Field_5 5	81-07-04	13:40	81-07-08	19:00	0.32	0.29	0.6
Field_A1a 1	81-07-06	10:31	81-07-10	09:49	0.32	0.24	0.4
Field_A1a 2	81-07-06	13:51	81-07-10	16:29	0.19	0.24	0.3
Field_A1a 3	81-07-06	10:31	81-07-10	11:21	0.27	0.24	0.3
Field_A1a 4	81-07-06	10:31	81-07-10	12:50	0.24	0.24	0.6
Field_A1a 5	81-07-06	13:51	81-07-10	19:54	0.17	0.24	0.4
Field_A1a 6	81-07-06	13:51	81-07-11	09:00	0.23	0.25	0.6

One error source is that the simulated moisture content was recorded at the beginning of the simulated carting operation. The measured values are however average values from the entire carting operation, so this factor causes too high simulated m.c.values.

Another error source is that the simulations were performed using the simulated yields, which were too low. This factor offsets the other one, which may be the reason to the seemingly randomly distributed error.

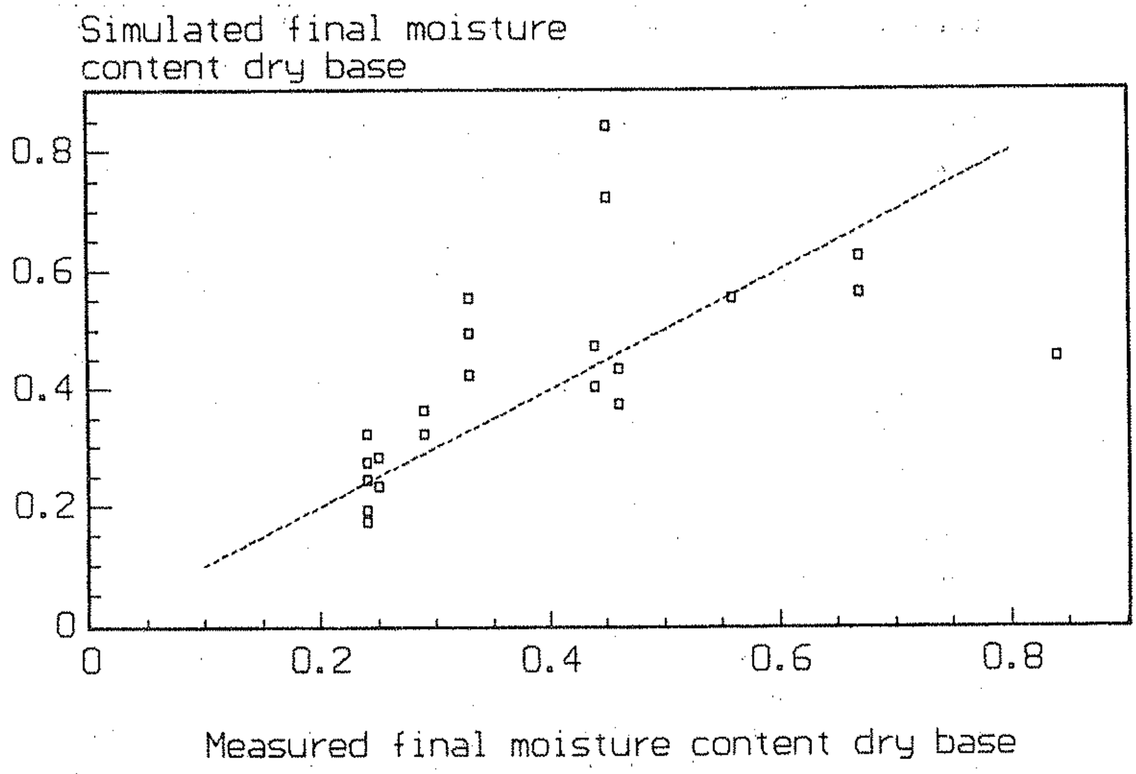

Figure 25. The simulated carted moisture content plotted against the experimental one. The dotted line represents the ideal 1:1 relationship.

6.4.4 The field loss models

Since the yield has not been registered at mowing, there is no means of performing a validation of the field loss models. Therefore the results can be discussed only from a reason point of view. The simulated loss figures are shown in table 7.

If the loss models are correct they have underestimated the losses in kg/ha, since apparently the growth model have underestimated the yield, and the losses are calculated as a fraction of the yield in most cases.

The leachage loss figures are very high in some cases. It is questionable if the model really is valid for the huge amounts of rain which has fallen on field 6a and 6b.

Table 7. The number of teddings (including spreading but not windrowing), mm of precipitation received, and estimated evaporation losses, shatter losses and leachage losses (kg dry matter per ha).

FIELD_ID	No of teddings	mm of rain	evap losses	shatter losses	leach. losses	total losses
Field_4a 1	5	13.9	279	221	553	1053
Field_4a 2	5	13.3	263	185	535	983
Field_4a 3	5	13.9	282	221	553	1056
Field_4b 1	7	17.7	197	471	739	1407
Field_4b 2	7	29.2	232	742	1044	2018
Field_6a 1	7	29.2	262	554	1048	1864
Field_6a 2	7	29.2	272	554	1048	1874
Field_6a 3	7	29.2	270	554	1048	1872
Field_6b 1	10	38.4	394	673	1063	2130
Field_6b 2	10	38.4	397	673	1063	2133
Field_6b 3	10	38.4	395	673	1063	2131
Field_5 1	4	4.0	218	299	173	690
Field_5 2	4	4.0	222	286	173	681
Field_5 3	5	4.0	228	398	173	799
Field_5 4	4	4.0	219	299	173	691
Field_5 5	4	4.0	223	286	173	682
Field_A1a 1	4	0.0	232	347	0	579
Field_A1a 2	4	0.0	269	305	0	574
Field_A1a 3	4	0.0	233	347	0	580
Field_A1a 4	4	0.0	234	347	0	581
Field_A1a 5	4	0.0	269	305	0	574
Field_A1a 6	4	0.0	275	305	0	580

6.4.5 The management model

The simulation has demonstrated that the logic of the procedure DetermineAction described in figure 12 above has been appropriate to permit the simulation of all combinations and sequences of events occurring at the farm of Storegården. Since only one gang is started or stopped at a time, there is no risk that a gang is started if the men and machinery, and a field in the right state, is not available. Thus the risk of "deadlock error", i.e. the different actors lock each other in their struggle for resources, is completely eliminated.

6.4.6 The barn drying model

The simulated yields after field losses were found to be significantly lower than the experimental values. It was therefore judged not to use the simulated values as input data into the barn drying model, but rather to use the experimental data.

In order to simplify the input of the storing procedure, all of the hay on one field was treated as one batch, divided into two parts and put into the two dryers at one moment.

The result of the barn-drying simulations is showed in table 8. Detailed reports from the two dryers are found in the appendices 3 and 4.

Table 8. Comparison between simulated and actual barn drying results.

Dryer	carted hay, kg dry matter	Energy consumption kWh	Storage losses %	Final m.c.w.b. %
Dryer 217 m^2 (sim.)	41406	3042	0.5	19.56
Dryer 71 m^2 (sim.)	22836	2561	0.3	18.96
Both (measured)	64272	6187	(5)	(<20)
Difference	30	-584	-	-

The difference in carted hay is probably due to some minor indata error. The difference in energy consumption, 9.4%, is however probably due to some error in the model. A possible error source is however that the dryer fan schedule for the large dryer has been assumed to be valid also for the small one, since the schedule for the latter was missing.

The storage losses could of course not be measured, but was estimated to 5%. This includes losses due to microbial activity, whereas only the respiration losses were simulated. The final moisture content was measured, but was reported only as showed in the table.

6.4.7 The model as a whole

The data material available did not allow a formal validation to be performed. The simulation run performed against data from Storegården is actually just a demonstration of that the model works as expected, not only its different parts, but also that they work together.

As the results from the validation of the individual sub-models indicate, the connection between the growth model and the harvesting model does work perfectly well. Since the barn drying model is a separate program because of computer primary memory limitations, the data between the two models had to be transmitted manually. All data needed was produced by the harvesting model, except for the development stage, which is not estimated by the growth model.

The simulation of the Storegården hay harvest 1981 took about 12 hours on a 12 MHz AT with a numerical co-processor, of which the field drying model is responsible for at least 95%. One reason for the long time is that the farmer is a very cautious man who generally cuts just a minor part of the acreage at a time, resulting in a large number of fields to be simulated. Another reason is of course the adverse weather conditions this particular year, resulting in long drying periods.

7 DISCUSSION

7.1 Validity and limitations of the present model

7.1.1 The growth model

The growth and quality model by Torssell et al (1982) does generate most of the data needed by the rest of the integrated model. The only data missing is some parameter describing the stage of phenological development. Such a parameter is required by the barn-drying model, since it has some influence upon the resistance to air flow through the hay bin. This lack of information is however not considered to be very serious.

Other advantages of this growth model are its simplicity, compactness and computational speed, and above all the fact that the model is validated (Torssell & Kornher, 1983). For these reasons, it was the natural growth model of choice for the integrated model.

The growth and quality model however has some major limitations. For one thing, it has been validated exclusively against Swedish experimental data. The question must be put whether it is applicable also in other countries.

It is somewhat surprising that no nutrient budgets are included in the model. Potassium, Magnesia, Calcium and Phosphorus are not considered at all, and the nitrogen fertilizer rate is considered only with respect to the annual yield. This makes the model useless for simulation experiments on fertilizer management. It also introduces an error source into the model, since the distribution of nitrogen between the 1st and 2nd cuts may indeed affect the yield.

The most suspect detail in the growth model is that the yield and quality of one harvest are affected by the planned number of harvests, assuming that the yield and quality are affected by future actions. Such inversely causal relationships have little to do with System Dynamics.

7.1.2 The field drying model

The validation on the component level was amazingly successful. The deficit between the experimental and simulated values were smaller then the author had considered possible to achieve, considering the uncertainty of much of the indata, the scarcity of weather records etc.

An even more important result than the small deficit is the fact that it dynamically reacts very much in the same way as the experiments. This result is in fact enough to draw the conclusion that the model has good predictive properties.

The main weakness in the validation lies in the choice of validation data. Since all the experiments are performed under similar geographical conditions, the model can not a priori be considered to work well under other conditions. This is particularly valid for the choice of soil. The heavy clay in Uppsala causes no problem with capillary water transport from the ground water. On a silt soil however, this transport may be a major error source of the model.

The main part of the model is doubtlessly general, since it consists of physical laws. The biological part consists of just a few equations, which makes it possible to calibrate the model for different biological materials although the entire model is large and complicated.

The computing effort required is indeed a problem. Simulating the drying of one field during 5 days takes 1 to 1 ½ hour of computing time using a 12 MHz IBM AT equipped with a numeric co-processor, if 9 iterations per 30 min time step are performed. By using certain results as initial values in the next time step, and introducing a convergence criterion, this time has been reduced by about 50%. Further reductions are not possible to achieve without changing the equation system solution routine, either by re-coding it into assembly language or by replacing the algorithm with a faster one.

7.1.3 The harvesting and conservation model

The general structure of the harvesting and conservation model is object-oriented. This property has enabled a clear description of the different sub-models as well as the interactions between them.

Since the interfaces between the different sub-models are well-defined, it is also possible to make adjustments to or even replace a submodel without disturbing the rest of the model as long as the interfaces are unchanged. This will simplify further development of the model significantly.

The field operations sub-model (FIELD_OP) acquires labour, machinery and fields in a realistic manner. The validity and usefulness of the model in general is discussed in Axenbom (1988). Its major limitation is that the field capacity is calculated using a static model. The strengths are that the model permits the inclusion of biological sub-models, updating the state of the fields. Particularly in hay-making models, this is a great advantage. The limitations mentioned are not very severe, because the interrelations between the fields, the machinery and the weather when hay-making are more important to study.

Since the field on which the operation is performed is "occupied" by the gang, two operations can not be performed simultaneously on one field. This restriction is however easily eliminated by permitting a combination of gangs to occupy the field instead, see van Elderen (1977). In FIELD_OP this is accomplished by defining a gang effectively consisting of the gangs required to be able to work simultaneously on one field.

Since the field work rate is calculated statically, it does not consider variations in capacity due to the shape and topography of the different fields. Works by Elinder (1984) and Jonsen (1984) prove that the driving pattern on the field can be simulated detailedly within reasonable computing effort.

The concept of FIELD_OP does not permit simulation of the driving pattern on the field. Nevertheless, the resolution of the capacity calculations could be improved by using a more sophisticated empirical capacity calculation model, such as Axenbom (1988).

The field drying sub-model simulates the drying of an evenly spread hay swath very detailedly. It alas do not cover the situation of windrowed hay. The drying model by Smith (1985), covering both cases, should be further investigated to see if it would add something to the harvesting and conservation model.

The barn drying sub-model is not as detailed as the field drying one. The resolution is however considered good enough for this purpose. Since it is largely based upon the laws of thermodynamics, its potentially weak parts are the estimation of the utilized fraction of the air, and the losses.

The validation indicated that the drying behaviour of the model corresponded to the actual one, but the data available was not sufficient to confirm this. The loss model concerns itself only with the plant respiration, and not with the microbial activity. Under conditions as in 1981, when the hay could not be dryed below 20% for a long period of time due to very damp air, it is likely that a significant microbial activity takes place. The model did warn for risk for moulding long before the hay was dried, but no mouldy hay has been reported. Obviously the mould model is not appropriate under these conditions. Moreover, a nearly 10% difference between simulated and measured energy consumption of the fans was found. The conclusion is that the barn drying model should be validated more thoroughly.

The weather sub-model, making historical weather data available to the rest of the model, is restricted to the data actually available. Knowing the latitude and longitude of the site and the day of the year, also the sun height for any time of the day and consequently also the sunrise time and sunset time can be calculated.

No attempts have been made to simulate weather data, since it is known to be very difficult to develop such a model of acceptable quality, and because historical data are needed anyway in order to validate the model.

The management model gives many possibilities to, and should be an object of further development. The present version which is completely "operator-driven" (interactive) is useful to observe and compare the strategies of real-world farmers. It should however be complemented with different heuristic and optimizing algorithms to be useful for other problems. Thanks to the well-defined interface between the management model and the field operations model, such a supplementing is relatively easy to perform.

7.1.4 The hay-to-milk conversion model

The technique used in the hay-to-milk conversion model, linear programming (LP), is widely accepted for diet composition problems. Thanks to the simplifications of the model, namely omitting all mineral balance restrictions and whole-number type feeding strategy restrictions, the model has remained small enough to run in a personal computer.

The LP matrix generation routine is designed so as to enable a flexible degree of resolution of the model. Thus, it is possible to make tradeoffs between precision on one hand, and computer speed and memory requirement on the other.

Unfortunately the model has not been updated and validated against recent feeding experiments. It is however the author's belief that the basic concept of the model is well suited as a part of the integrated model, as well as for a multitude of other applications.

7.1.5 The integrated model as a whole

The validation of the integrated model has proved that it may be used to simulate the growth and harvesting processes in one run, still retaining a high resolution of the model.

The limitations are dependent of the applications, where the requirements on the specific sub-models may be different for different problems. For example, when analyzing a silage-making system the field drying process may not be critical. But the model of field operations perhaps must simulate the movements of the machinery on the field in detail to produce appropriate results.

7.2 Potential use of the model

As mentioned before, the integrated model is aimed as a tool for investigating a number of problems rather than directed towards a specific problem. This is the reason why the model does not output "THE solution of THE problem". Now when the problem of integrating growth, harvesting and utilization have been solved, this opens a field of applications.

In order to find the optimal machinery system for an individual farm using a simulation model, a great number of simulations should be done, using historical weather data for different years. One or many predetermined strategies may be used.

The results will have the form of probability distributions. The difference between the distributions of the output variables between different sets of machinery is then used to select the "optimal" one. The ranking should be performed using some model for decision-making under uncertainty, for example stochastic dominance or maximum expected utility.

An interesting application would be to determine the optimal harvesting dates, in general and for the current year, according to the yield forecast.

Decision support in daily management is another subject where the integrated model should be useful. Since the model is quite detailed, it could help estimating the current state and predicting its future changes. As a part of a decision support system, the model would calculate the expected value of different strategies under certain weather outcomes.

In the future, similar projects concerning spring harrowing and sowing, ensiling, or combine harvesting may be started. The general FIELD_OP model is useful also for such models. Also some of the biological sub-models and the management model are expected to be reusable in different applications.

The present integrated model could be further developed into a strategic game within reasonable effort. The main problem is that nobody have time to wait for the time the computer needs to make its calculations.

The field drying model could be useful in extending the increasingly popular local weather forecasts for farmers with special field drying forecasts. Instead of just giving general meteorological data, the moisture content could be predicted for the days ahead under certain assumptions concerning mowing time, yield, teddings etc.

7.3 Suggested improvements of the model

There are two improvements to be done within the harvesting and conservation model:

- include a sub-model of field drying in windrows,
- include some heuristic strategies into the management sub-model.

The first one of these is important, but should not be exaggerated, since the common practice is to windrow only shortly before carting. The other one would indeed simplify the task of developing an application built upon the base model. Unfortunately, none of these have been possible to realize within the project boundaries.

7.4 Need for further research

An aim of the project was to achieve a resolution as high as possible in the sub-models. Although the best models found have been used, there is still more to do.

The growth model is simple and handy, but it does seem to have difficulties in predicting the growth very detailedly. Perhaps is the concept too simple? Maybe a compartment model, using a higher-degree differential equation, is needed?

The field drying model has proved to be extremely precise. The obvious further development would be to fine-tune the presently roughly calibrated parameters. This should however be preceded by a thorough sensitivity analysis of all input variables to the model. It is likely that the model is more or less insensitive to some of them, which makes it useless to perform experiments for their fine-tuning.

The field loss models should be subject to a review, preferably in a joint project with both biologists and agricultural engineers. Particularly the mechanisms behind the leaching loss should be further examined.

The field operations model has proved appropriate for the present project. Applications demanding a higher resolution, for example cyclic transport systems, may however require a different concept.

The barn drying model is also appropriate for the present project. The resolution has been improved and is now satisfactory. The most urgent improvement would be to develop a dynamic model of the microbial growth in the moist hay, eventually leading to moulding if the drying rate is not fast enough.

The hay-to-milk conversion model, must be updated in conjunction to the present feeding recommendations and consumption restrictions. This should of course be done in cooperation with researchers on animal husbandry.

An urgent improvement on the integrated model would be to really include the barn drying model and the hay-to-milk conversion model in the integrated simulation program. This should be possible within a reasonable time, since the PC Simula compiler is continuously being improved on.

8 CONCLUSIONS

An integrated model of the entire hay production and utilization system has been successfully developed. The validation shows that the model is essentially appropriate. The growth model underestimated the growth significantly, but this may depend on the inability to adjust for the high nitrogen mineralization rate. The models of field losses and conservation losses should be further validated to determine whether more research is needed.

The model is not oriented toward one specific problem. The discussion however demonstrated that a large class of problems influencing the entire hay production and utilization system could be thoroughly analyzed using the integrated model.

Since the system that was modelled is complicated, and the model had to be detailed, it became complicated too. In particular, it does require quite a lot of input data of different kinds. In many cases it is expected that some programming is required, too. Therefore, this model can not be considered an advisory tool, but rather a research one. It is however believed that it will be useful also in the development of simple programs for advisory purposes.

This report shows that it is possible to build detailed simulation models of large biological and technical systems without falling into programming problems if an appropriate programming technique is used. The object-oriented programming concept of Simula and the tools for discrete event handling in DEMOS have shown to be highly appropriate for this type of project.

The inclusion of models from different disciplines into an integrated model has caused some difficulties, but the main impression of the author is that the work with connecting these different models has created an improved climate for future cooperation within inter-disciplinary projects.

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APPENDIX 1: The events of the hay harvest at Storegården 1981

Date	Working time	Operation	Field	Ha	Comments
81-06-17	16:15 - 17:05	mowing	4a	1.5	part 1
81-06-18	13:30 - 14:55	mowing	4a	1.5	part 2
	14:15 - 15:00	tedding	4a	1.5	
81-06-19	10:20 - 11:15	tedding	4a	1.5	
	15:20 - 16:00	tedding	4a	1.5	
81-06-21	18:50 - 19:25	tedding	4a	1.5	
81-06-22	13:10 - 15:20	mowing	4b	1.5	
	13:50 - 14:30	tedding	4a	1.5	
	14:30 - 15:25	tedding	4b	1.5	contemp. w. mowing
	18:50 - 20:50	mowing	6a	1.5	
81-06-23	10:20 - 11:35	wrowing	4a	1.5	part 1
	10:30 - 11:10	tedding	6a	1.5	
	11:15 - 11:55	tedding	4b	1.5	
	11:45 - 12:30	carting	4a	1.5	part 1
	13:35 - 17:15	carting	4a	1.5	part 1 cont.
	15:20 - 16:00	tedding	4b	1.5	
81-06-24	09:10 - 11:55	mowing	6b	1.5	
	10:30 - 11:15	tedding	4b	1.5	
	11:20 - 12:00	tedding	6a	1.5	
	12:00 - 12:55	tedding	6b	1.5	
	14:00 - 14:15	wrowing	4a	1.5	part 2
	14:10 - 14:55	carting	4a	1.5	part 2
81-06-26	18:50 - 19:30	tedding	4b	1.5	
81-06-27	11:45 - 12:20	tedding	6a	1.5	
	12:20 - 12:50	tedding	6b	1.5	
	19:00 - 19:35	tedding	4b	1.5	
81-06-28	11:40 - 12:20	tedding	6a	1.5	
	11:45 - 12:10	tedding	4b	1.5	
	12:20 - 12:55	tedding	6b	1.5	
	15:20 - 15:40	wrowing	4b	1.5	part 1
	16:35 - 17:40	carting	4b	1.5	part 1
81-06-30	10:30 - 11:05	tedding	6a	1.5	
	10:30 - 11:05	tedding	4b	1.5	part 2
	11:05 - 11:40	tedding	6b	1.5	
81-07-01	09:20 - 09:45	tedding	4b	1.5	part 2
	10:15 - 11:15	tedding	6a	1.5	
	11:15 - 11:45	tedding	6b	1.5	
	16:15 - 16:35	tedding	4b	1.5	part 2
	18:45 - 19:25	tedding	6a	1.5	
	19:25 - 20:00	tedding	6b	1.5	

Date	Working time	Operation	Field	Ha	Comments
81-07-02	11:30 - 12:00	wrowing	4b	1.5	part 2
	12:10 - 12:50	carting	4b	1.5	part 2
	13:40 - 14:40	carting	4b	1.5	part 2 cont.
	14:00 - 14:55	wrowing	6a	1.5	part 1
	14:55 - 19:15	carting	6a	1.5	part 1a
	18:05 - 18:50	tedding	6b	1.5	
81-07-03	10:50 - 11:15	carting	6a	1.5	part 1b
	11:50 - 12:05	wrowing	6a	1.5	part 2
	13:20 - 14:15	carting	6a	1.5	part 2
81-07-04	10:40 - 11:10	tedding	6b	1.5	
	11:35 - 12:40	mowing	5	2.7	
	13:30 - 15:30	mowing	5	2.7	cont.
	14:05 - 14:35	tedding	6b	1.5	
	15:45 - 16:30	mowing	5	2.7	
	16:30 - 17:50	tedding	5	2.7	
81-07-05	10:35 - 11:45	wrowing	6b	1.5	
	11:35 - 12:45	carting	6b	1.5	
	13:45 - 16:35	carting	6b	1.5	cont.
	17:15 - 18:45	tedding	5	2.7	
81-07-06	10:30 - 12:30	mowing	A1a	2.5	part 1
	13:50 - 15:55	mowing	A1a	2.5	part 2
	14:40 - 16:00	tedding	A1a	2.5	
	16:15 - 17:25	tedding	5	2.7	
81-07-07	10:45 - 12:00	tedding	5	2.7	
	16:25 - 17:35	tedding	A1a	2.5	
81-07-08	09:20 - 09:50	tedding	5	2.7	part 3
	09:35 - 10:50	wrowing	5	2.7	part 1
	10:45 - 12:30	carting	5	2.7	part 1
	13:30 - 17:30	carting	5	2.7	part 1 cont.
	15:30 - 15:50	wrowing	5	2.7	part 2
	17:05 - 18:15	tedding	A1a	2.5	
	19:00 - 21:00	carting	5	2.7	part 2
81-07-09	16:15 - 17:10	tedding	A1a	2.5	
81-07-10	09:30 - 11:05	wrowing	A1a	2.5	part 1
	09:50 - 12:20	carting	A1a	2.5	part 1
	12:50 - 17:50	carting	A1a	2.5	part 1 cont.
	19:55 - 21:40	carting	A1a	2.5	part 1 cont.
81-07-11	09:10 - 10:05	wrowing	A1a	2.5	part 2
	09:45 - 12:20	carting	A1a	2.5	part 2
	13:10 - 15:40	carting	A1a	2.5	part 2 cont.

APPENDIX 2: The simulated events of the Storegården hay harvest

DATE	WORKING TIME	GANG	OPERATION	FIELD
81-06-17	16:15 - 17:05	mow-gang	mowing	Field_4a 1
81-06-18	13:30 - 14:54	mow-gang	mowing	Field_4a 2
	14:15 - 14:33	spr-gang	spreading	Field_4a 1
	14:54 - 15:24	spr-gang	spreading	Field_4a 2
81-06-19	10:20 - 10:37	ted-gang	tedding	Field_4a 1
	10:37 - 11:07	ted-gang	tedding	Field_4a 2
	15:20 - 15:38	ted-gang	tedding	Field_4a 1
	15:38 - 16:08	ted-gang	tedding	Field_4a 2
81-06-21	18:50 - 19:07	ted-gang	tedding	Field_4a 1
	19:07 - 19:37	ted-gang	tedding	Field_4a 2
81-06-22	13:10 - 15:24	mow-gang	mowing	Field_4b 1
	13:50 - 14:08	ted-gang	tedding	Field_4a 1
	14:08 - 14:38	ted-gang	tedding	Field_4a 2
	15:24 - 16:12	spr-gang	spreading	Field_4b 1
	18:50 - 21:05	mow-gang	mowing	Field_6a 1
81-06-23	10:20 - 10:46	Windr-gang	windrowin	Field_4a 1
	10:30 - 11:17	spr-gang	spreading	Field_6a 1
	11:17 - 12:05	ted-gang	tedding	Field_4b 1
	11:46 - 12:30	Cart-gang	carting	Field_4a 1
	13:35 - 14:56	Cart-gang	carting	Field_4a 3
	15:20 - 16:07	ted-gang	tedding	Field_4b 1
81-06-24	09:10 - 11:24	mow-gang	mowing	Field_6b 1
	10:30 - 11:17	ted-gang	tedding	Field_4b 1
	11:17 - 12:05	ted-gang	tedding	Field_6a 1
	12:05 - 12:53	spr-gang	spreading	Field_6b 1
	12:53 - 13:39	Windr-gang	windrowin	Field_4a 2
	13:39 - 17:09	Cart-gang	carting	Field_4a 2
81-06-26	18:50 - 19:38	ted-gang	tedding	Field_4b 1
81-06-27	11:45 - 12:52	ted-gang	tedding	Field_6a 1
	12:32 - 13:20	ted-gang	tedding	Field_6b 1
	20:00 - 20:48	ted-gang	tedding	Field_4b 1
81-06-28	11:40 - 12:28	ted-gang	tedding	Field_6a 1
	12:28 - 13:15	ted-gang	tedding	Field_4b 1
	13:15 - 14:03	ted-gang	tedding	Field_6b 1
	15:20 - 15:40	Windr-gang	windrowin	Field_4b 1
	16:36 - 18:09	Cart-gang	carting	Field_4b 1
81-06-30	10:15 - 11:02	ted-gang	tedding	Field_6a 1
	11:02 - 11:37	ted-gang	tedding	Field_4b 2
	11:37 - 12:25	ted-gang	tedding	Field_6b 1
81-07-01	09:20 - 09:54	ted-gang	tedding	Field_4b 2
	09:54 - 10:42	ted-gang	tedding	Field_6a 1
	10:42 - 11:30	ted-gang	tedding	Field_6b 1
	16:15 - 16:49	ted-gang	tedding	Field_4b 2
	18:39 - 19:27	ted-gang	tedding	Field_6a 1
	19:27 - 20:15	ted-gang	tedding	Field_6b 1

DATE	WORKING TIME	GANG	OPERATION	FIELD
81-07-02	11:30 - 12:22	Windr-gang	windrowin	Field_4b 2
	12:22 - 16:24	Cart-gang	carting	Field_4b 2
	14:00 - 14:55	Windr-gang	windrowin	Field_6a 1
	16:24 - 19:17	Cart-gang	carting	Field_6a 1
	18:05 - 18:53	ted-gang	tedding	Field_6b 1
81-07-03	10:50 - 12:14	Cart-gang	carting	Field_6a 3
	11:50 - 12:07	Windr-gang	windrowin	Field_6a 2
	13:20 - 14:39	Cart-gang	carting	Field_6a 2
81-07-04	10:40 - 11:28	ted-gang	tedding	Field_6b 1
	11:28 - 12:33	mow-gang	mowing	Field_5 1
	13:40 - 15:40	mow-gang	mowing	Field_5 2
	14:04 - 14:52	ted-gang	tedding	Field_6b 1
	15:46 - 17:00	mow-gang	mowing	Field_5 3
	16:30 - 16:53	spr-gang	spreading	Field_5 1
	16:53 - 17:36	spr-gang	spreading	Field_5 2
	17:36 - 18:02	spr-gang	spreading	Field_5 3
	18:02 - 18:50	ted-gang	tedding	Field_6b 1
81-07-05	10:34 - 11:34	Windr-gang	windrowin	Field_6b 1
	11:34 - 11:47	Windr-gang	windrowin	Field_6b 2
	11:34 - 12:45	Cart-gang	carting	Field_6b 1
	13:45 - 17:13	Cart-gang	carting	Field_6b 3
	17:13 - 18:10	Cart-gang	carting	Field_6b 2
	17:13 - 17:37	ted-gang	tedding	Field_5 1
	17:37 - 18:19	ted-gang	tedding	Field_5 2
	18:19 - 18:46	ted-gang	tedding	Field_5 3
81-07-06	10:31 - 12:31	mow-gang	mowing	Field_A1a 1
	13:51 - 16:00	mow-gang	mowing	Field_A1a 2
	14:40 - 15:23	spr-gang	spreading	Field_A1a 1
	16:00 - 16:46	spr-gang	spreading	Field_A1a 2
	16:46 - 17:09	ted-gang	tedding	Field_5 1
	17:09 - 17:52	ted-gang	tedding	Field_5 2
	17:52 - 18:19	ted-gang	tedding	Field_5 3
81-07-07	10:45 - 11:08	ted-gang	tedding	Field_5 1
	11:08 - 11:50	ted-gang	tedding	Field_5 2
	11:50 - 12:17	ted-gang	tedding	Field_5 3
	16:25 - 17:07	ted-gang	tedding	Field_A1a 1
	17:07 - 17:54	ted-gang	tedding	Field_A1a 2
81-07-08	10:19 - 10:46	ted-gang	tedding	Field_5 3
	10:34 - 11:09	Windr-gang	windrowin	Field_5 1
	11:09 - 12:30	Cart-gang	carting	Field_5 1
	13:30 - 14:52	Cart-gang	carting	Field_5 4
	13:30 - 14:35	Windr-gang	windrowin	Field_5 2
	14:52 - 17:29	Cart-gang	carting	Field_5 2
	17:05 - 17:48	ted-gang	tedding	Field_A1a 1
	17:48 - 18:34	ted-gang	tedding	Field_A1a 2
	19:00 - 21:22	Cart-gang	carting	Field_5 5
81-07-09	09:00 - 09:40	Windr-gang	windrowin	Field_5 3
	12:10 - 15:16	Cart-gang	carting	Field_5 3
	16:15 - 16:58	ted-gang	tedding	Field_A1a 1
	16:58 - 17:44	ted-gang	tedding	Field_A1a 2

DATE	WORKING TIME	GANG	OPERATION	FIELD
81-07-10	09:30 - 19:49	Windr-gang	windrowin	Field_A1a 1
	09:49 - 11:21	Cart-gang	carting	Field_A1a 1
	09:49 - 10:34	Windr-gang	windrowin	Field_A1a 3
	11:21 - 12:20	Cart-gang	carting	Field_A1a 3
	12:50 - 15:19	Cart-gang	carting	Field_A1a 4
	15:19 - 16:29	Windr-gang	windrowin	Field_A1a 2
	16:29 - 17:49	Cart-gang	carting	Field_A1a 2
	19:54 - 21:42	Cart-gang	carting	Field_A1a 5
81-07-11	09:00 - 11:16	Cart-gang	carting	Field_A1a 6

APPENDIX 3: Report from the 217 m^2 barn dryer

Date	Hay kg dm	loss kg	mcwb %	Height m	Airflow m3/h	Fan el. kWh	kWh/ kg H2O
81-06-23 15:54	5252	0	31.10	0.76	0	0.0	-
81-06-23 16:00	5252	0	31.10	0.76	0	0.0	-
81-06-24 00:00	5250	2	29.28	0.76	48471	47.1	0.239
81-06-24 13:38	6447	5	31.94	0.82	48471	127.5	0.358
81-06-25 00:00	6443	9	27.85	0.82	48408	188.6	0.211
81-06-26 00:00	6441	11	25.88	0.82	48409	330.4	0.292
81-06-27 00:00	6439	13	29.28	0.82	48409	472.1	0.661
81-06-27 19:30	6433	19	30.92	0.82	48409	587.3	1.172
81-06-28 00:00	6431	21	30.93	0.82	0	587.3	1.174
81-06-28 07:35	6428	25	30.96	0.82	0	587.3	1.180
81-06-28 13:09	8231	27	32.60	0.95	48409	620.3	1.010
81-06-28 22:00	8224	34	31.51	0.95	48322	672.8	0.830
81-06-29 00:00	8223	35	31.52	0.95	0	672.8	0.830
81-06-29 08:20	8215	43	31.57	0.95	0	672.8	0.835
81-06-29 22:05	8207	51	29.76	0.95	48323	754.4	0.675
81-06-30 00:00	8206	52	29.77	0.95	0	754.4	0.676
81-06-30 07:05	8203	55	29.79	0.95	0	754.4	0.677
81-06-30 21:45	8197	61	28.99	0.95	48323	841.4	0.674
81-07-01 00:00	8196	62	29.00	0.95	0	841.4	0.674
81-07-01 06:50	8194	64	29.01	0.95	0	841.4	0.675
81-07-02 00:00	8190	68	29.14	0.95	48324	943.3	0.769
81-07-02 12:22	10178	71	31.71	1.14	48324	1016.7	0.787
81-07-02 16:23	15598	74	32.96	1.54	48238	1040.8	0.710
81-07-03 00:00	15589	83	32.49	1.54	47953	1086.8	0.665
81-07-03 13:20	17075	97	31.29	1.68	47954	1167.6	0.579
81-07-04 00:00	17063	109	30.06	1.68	47887	1232.4	0.502
81-07-05 00:00	17039	133	29.81	1.68	47888	1378.2	0.539
81-07-05 17:13	21025	147	27.93	2.06	47889	1482.9	0.503
81-07-06 00:00	21021	151	27.78	2.06	47715	1524.5	0.506
81-07-06 18:30	21013	160	26.82	2.06	47716	1637.9	0.482
81-07-06 21:15	21011	161	26.82	2.06	0	1637.9	0.482
81-07-07 00:00	21010	162	26.73	2.06	47716	1654.8	0.482
81-07-08 00:00	21001	171	25.77	2.06	47716	1802.0	0.474
81-07-08 13:30	24282	174	26.51	2.37	47717	1884.8	0.492
81-07-08 19:00	26594	176	25.77	2.56	47576	1918.7	0.475
81-07-09 00:00	26593	177	25.66	2.56	47461	1949.8	0.477
81-07-09 12:09	29422	180	25.10	2.80	47461	2025.4	0.493
81-07-10 00:00	29419	183	24.33	2.80	47323	2099.4	0.466
81-07-10 12:50	35837	185	23.11	3.32	47323	2179.7	0.460
81-07-10 19:00	37620	186	22.28	3.46	47003	2218.9	0.430
81-07-10 22:00	37620	186	22.14	3.46	46913	2238.1	0.427
81-07-11 00:00	37620	186	22.14	3.46	0	2238.1	0.427
81-07-11 06:50	37620	187	22.14	3.46	0	2238.1	0.427
81-07-11 15:00	41219	187	21.32	3.74	46913	2290.2	0.404
81-07-11 22:09	41219	187	20.80	3.74	46728	2336.4	0.388
81-07-12 00:00	41219	187	20.80	3.74	0	2336.4	0.388
81-07-12 07:05	41219	187	20.80	3.74	0	2336.4	0.388
81-07-12 21:50	41219	187	19.77	3.74	46728	2431.4	0.364

81-07-13 00:00	41219	187	19.77	3.74	0	2431.4	0.364
81-07-13 07:00	41219	187	19.77	3.74	0	2431.4	0.364
81-07-13 20:09	41219	187	19.57	3.74	46728	2516.2	0.369
81-07-14 00:00	41219	187	19.57	3.74	0	2516.2	0.369
81-07-14 08:15	41219	187	19.57	3.74	0	2516.2	0.369
81-07-14 18:39	41219	187	19.52	3.74	46728	2583.2	0.378
81-07-15 00:00	41219	187	19.52	3.74	0	2583.2	0.378
81-07-15 10:30	41219	187	19.52	3.74	0	2583.2	0.378
81-07-15 18:45	41219	187	19.56	3.74	46728	2636.4	0.387
81-07-16 00:00	41219	187	19.56	3.74	0	2636.4	0.387
81-07-16 08:00	41219	187	19.56	3.74	0	2636.4	0.387
81-07-16 18:54	41219	187	19.82	3.74	46728	2706.7	0.407
81-07-17 00:00	41219	187	19.82	3.74	0	2706.7	0.407
81-07-18 00:00	41219	187	19.82	3.74	0	2706.7	0.407
81-07-18 12:35	41219	187	19.82	3.74	0	2706.7	0.407
81-07-18 15:05	41219	187	19.91	3.74	46728	2722.8	0.413
81-07-19 00:00	41219	187	19.91	3.74	0	2722.8	0.413
81-07-19 11:00	41219	187	19.91	3.74	0	2722.8	0.413
81-07-19 17:15	41219	187	20.04	3.74	46728	2763.0	0.424
81-07-20 00:00	41219	187	20.04	3.74	0	2763.0	0.424
81-07-20 12:15	41219	187	20.04	3.74	0	2763.0	0.424
81-07-20 20:30	41219	187	20.08	3.74	46728	2816.2	0.434
81-07-21 00:00	41219	187	20.08	3.74	0	2816.2	0.434
81-07-21 12:00	41219	187	20.08	3.74	0	2816.2	0.434
81-07-21 19:00	41219	187	19.69	3.74	46728	2861.3	0.425
81-07-22 00:00	41219	187	19.69	3.74	0	2861.3	0.425
81-07-22 10:00	41219	187	19.69	3.74	0	2861.3	0.425
81-07-22 18:45	41219	187	19.23	3.74	46728	2917.6	0.415
81-07-23 00:00	41219	187	19.23	3.74	0	2917.6	0.415
81-07-23 10:50	41219	187	19.23	3.74	0	2917.6	0.415
81-07-23 17:39	41219	187	18.99	3.74	46728	2961.6	0.413
81-07-24 00:00	41219	187	18.99	3.74	0	2961.6	0.413
81-07-24 15:00	41219	187	18.99	3.74	0	2961.6	0.413
81-07-24 18:24	41219	187	18.97	3.74	46728	2983.6	0.415
81-07-25 00:00	41219	187	18.97	3.74	0	2983.6	0.415
81-07-26 00:00	41219	187	18.97	3.74	0	2983.6	0.415
81-07-27 00:00	41219	187	18.97	3.74	0	2983.6	0.415
81-07-27 10:00	41219	187	18.97	3.74	0	2983.6	0.415
81-07-27 12:05	41219	187	19.02	3.74	46728	2997.0	0.418
81-07-28 00:00	41219	187	19.02	3.74	0	2997.0	0.418
81-07-29 00:00	41219	187	19.02	3.74	0	2997.0	0.418
81-07-30 00:00	41219	187	19.02	3.74	0	2997.0	0.418
81-07-30 10:00	41219	187	19.02	3.74	0	2997.0	0.418
81-07-30 17:00	41219	187	19.33	3.74	46728	3042.1	0.437

APPENDIX 4: Report from the 71 m^2 barndryer

Date	Hay kg dm	loss kg	mcwb %	Height m	Airflow m3/h	Fan el. kWh	kWh/ kg H2O
81-06-23 15:54	3502	0	31.10	1.20	0	0.0	-
81-06-23 16:00	3502	0	31.10	1.20	0	0.0	-
81-06-24 00:00	3501	2	29.11	1.20	36010	33.9	0.237
81-06-24 13:38	4205	3	31.32	1.30	36011	91.8	0.357
81-06-25 00:00	4203	5	26.67	1.30	35608	137.0	0.212
81-06-26 00:00	4202	6	25.56	1.30	35610	241.7	0.330
81-06-27 00:00	4201	7	29.54	1.30	35610	346.5	0.837
81-06-27 19:30	4196	12	31.24	1.30	35611	431.6	1.607
81-06-28 00:00	4195	13	31.25	1.30	0	431.6	1.612
81-06-28 07:35	4192	16	31.29	1.30	0	431.6	1.622
81-06-28 13:09	5094	18	32.26	1.48	35615	455.9	1.281
81-06-28 22:00	5090	21	31.01	1.48	35156	495.7	1.003
81-06-29 00:00	5089	22	31.02	1.48	0	495.7	1.003
81-06-29 08:20	5085	26	31.06	1.48	0	495.7	1.009
81-06-29 22:05	5081	30	29.11	1.48	35161	557.5	0.801
81-06-30 00:00	5080	31	29.11	1.48	0	557.5	0.802
81-06-30 07:05	5079	32	29.13	1.48	0	557.5	0.803
81-06-30 21:45	5076	35	28.51	1.48	35164	623.5	0.823
81-07-01 00:00	5076	35	28.51	1.48	0	623.5	0.823
81-07-01 06:50	5075	36	28.52	1.48	0	623.5	0.823
81-07-02 00:00	5073	38	29.00	1.48	35166	700.7	0.987
81-07-02 12:22	6071	40	31.17	1.75	35167	756.3	1.012
81-07-02 16:23	8474	41	31.47	2.25	34760	774.9	0.889
81-07-03 00:00	8470	45	30.93	2.25	33568	812.4	0.837
81-07-03 13:20	9589	50	29.62	2.52	33570	878.2	0.721
81-07-04 00:00	9584	55	28.06	2.51	33092	932.2	0.615
81-07-05 00:00	9576	63	27.88	2.51	33094	1053.6	0.678
81-07-05 17:13	12600	66	26.18	3.27	33098	1140.6	0.643
81-07-06 00:00	12600	66	26.01	3.27	31898	1176.8	0.649
81-07-06 18:30	12600	67	25.00	3.27	31898	1275.6	0.624
81-07-06 21:15	12599	67	25.00	3.27	0	1275.6	0.624
81-07-07 00:00	12599	67	24.93	3.27	31898	1290.3	0.627
81-07-08 00:00	12599	67	24.12	3.27	31898	1418.4	0.634
81-07-08 13:30	14241	67	25.13	3.71	31898	1490.5	0.674
81-07-08 19:00	15441	67	24.44	3.98	31334	1520.5	0.648
81-07-09 00:00	15440	68	24.30	3.98	30847	1548.3	0.650
81-07-09 12:09	16856	68	23.85	4.30	30847	1616.0	0.671
81-07-10 00:00	16856	68	22.91	4.30	30293	1683.0	0.628
81-07-10 12:50	20076	68	21.86	5.01	30293	1755.7	0.617
81-07-10 19:00	20968	68	20.99	5.20	29078	1792.0	0.576
81-07-10 22:00	20968	68	20.82	5.20	28752	1809.8	0.571
81-07-11 00:00	20968	68	20.82	5.20	0	1809.8	0.571
81-07-11 06:50	20968	68	20.82	5.20	0	1809.8	0.571
81-07-11 15:00	22768	68	19.99	5.59	28752	1858.2	0.540
81-07-11 22:09	22768	68	19.36	5.59	28103	1901.3	0.519
81-07-12 00:00	22768	68	19.36	5.59	0	1901.3	0.519
81-07-12 07:05	22768	68	19.36	5.59	0	1901.3	0.519
81-07-12 21:50	22768	68	18.11	5.59	28104	1990.1	0.486

Date	Hay kg dm	loss kg	mcwb %	Height m	Airflow m3/h	Fan el. kWh	kWh/ kg H2O
81-07-13 00:00	22768	68	18.11	5.59	0	1990.1	0.486
81-07-13 07:00	22768	68	18.11	5.59	0	1990.1	0.486
81-07-13 20:09	22768	68	17.82	5.59	28104	2069.4	0.494
81-07-14 00:00	22768	68	17.82	5.59	0	2069.4	0.494
81-07-14 08:15	22768	68	17.82	5.59	0	2069.4	0.494
81-07-14 18:39	22768	68	17.74	5.59	28104	2132.2	0.505
81-07-15 00:00	22768	68	17.74	5.59	0	2132.2	0.505
81-07-15 10:30	22768	68	17.74	5.59	0	2132.2	0.505
81-07-15 18:45	22768	68	17.77	5.59	28104	2181.8	0.518
81-07-16 00:00	22768	68	17.77	5.59	0	2181.8	0.518
81-07-16 08:00	22768	68	17.77	5.59	0	2181.8	0.518
81-07-16 18:54	22768	68	18.07	5.59	28104	2247.6	0.547
81-07-17 00:00	22768	68	18.07	5.59	0	2247.6	0.547
81-07-18 00:00	22768	68	18.07	5.59	0	2247.6	0.547
81-07-18 12:35	22768	68	18.07	5.59	0	2247.6	0.547
81-07-18 15:05	22768	68	18.19	5.59	28104	2262.6	0.556
81-07-19 00:00	22768	68	18.19	5.59	0	2262.6	0.556
81-07-19 11:00	22768	68	18.19	5.59	0	2262.6	0.556
81-07-19 17:15	22768	68	18.40	5.59	28104	2300.3	0.576
81-07-20 00:00	22768	68	18.40	5.59	0	2300.3	0.576
81-07-20 12:15	22768	68	18.40	5.59	0	2300.3	0.576
81-07-20 20:30	22768	68	18.63	5.59	28104	2349.9	0.600
81-07-21 00:00	22768	68	18.63	5.59	0	2349.9	0.600
81-07-21 12:00	22768	68	18.63	5.59	0	2349.9	0.600
81-07-21 19:00	22768	68	18.44	5.59	28104	2392.1	0.601
81-07-22 00:00	22768	68	18.44	5.59	0	2392.1	0.601
81-07-22 10:00	22768	68	18.44	5.59	0	2392.1	0.601
81-07-22 18:45	22768	68	18.29	5.59	28104	2444.8	0.606
81-07-23 00:00	22768	68	18.29	5.59	0	2444.8	0.606
81-07-23 10:50	22768	68	18.29	5.59	0	2444.8	0.606
81-07-23 17:39	22768	68	18.29	5.59	28104	2485.9	0.616
81-07-24 00:00	22768	68	18.29	5.59	0	2485.9	0.616
81-07-24 15:00	22768	68	18.29	5.59	0	2485.9	0.616
81-07-24 18:24	22768	68	18.37	5.59	28104	2506.5	0.626
81-07-25 00:00	22768	68	18.37	5.59	0	2506.5	0.626
81-07-26 00:00	22768	68	18.37	5.59	0	2506.5	0.626
81-07-27 00:00	22768	68	18.37	5.59	0	2506.5	0.626
81-07-27 10:00	22768	68	18.37	5.59	0	2506.5	0.626
81-07-27 12:05	22768	68	18.48	5.59	28104	2519.1	0.635
81-07-28 00:00	22768	68	18.48	5.59	0	2519.1	0.635
81-07-29 00:00	22768	68	18.48	5.59	0	2519.1	0.635
81-07-30 00:00	22768	68	18.48	5.59	0	2519.1	0.635
81-07-30 10:00	22768	68	18.48	5.59	0	2519.1	0.635
81-07-30 17:00	22768	68	18.96	5.59	28104	2561.2	0.673