Scheduling models in farm management:
a new approach

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Proefschrift

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Abstract

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Three operational planning models to calculate schedules for an arable farm are examined. These models are a linear programming model, a dynamic programming model and a simulation model. They are examined at different levels of aggregation and relaxation in a retrospective way. Also a probabilistic dynamic programming model is examined. A new algorithm is developed for scheduling farm operations. This algorithm which is heuristic (and comes from the field of Artificial Intelligence), is far more efficient and only a little less effective than the three mentioned models. The new model, called FLOS (= Farm Labour and Operations Scheduling), is probabilistic and makes use of the weather forecast and soil moisture and grain moisture models to calculate future workability. With this new model, several tests are executed including a practical test on an arable farm of the RIJP (Lake IJssel polders Development Authority). Around the heuristic FLOS, a Decision Support System called SCHEMA (= SCHEduling Multiple Activities) is developed.

Free descriptors: farm operations scheduling, timeliness, workability, linear programming, dynamic programming, simulation, aggregation, relaxation, heuristic, artificial intelligence, weather forecast, soil moisture, grain moisture, certainty equivalence, decision support system.

STELLINGEN

I

Ten behoeve van de operationele planning op een akkerbouwbedrijf is een adequaat meteorologisch advies onontbeerlijk. Daarom moeten het meteorologisch onderzoek en de daarbij behorende voorlichting zich vooral richten op die aspecten die voor het goed functioneren van beslissingsmodellen van wezenlijk belang zijn. De aspecten die van belang zijn moeten door de modellen worden aangegeven.

II

Het streven naar een kwalitatief goed model op een gedetailleerd niveau is pas relevant, indien men de invoer voor dit model, met een gegarandeerde kwaliteit, eveneens op het bijbehorende niveau kan krijgen.

III

Ondanks het feit dat een weerbericht slechts voor zeventig procent betrouwbaar is, is het bij de operationele planning beter hiervan gebruik te maken dan van een reeks van historische, meteorologische gegevens.

Dit proefschrift.

IV

Aan de practische betekenis van werkindelingsmodellen met planningsperioden langer dan een dag dient te worden getwijfeld.

Dit proefschrift.

V

Het inbrengen in een planningsmodel van ervaringsaspecten van de boer zoals zijn manier van reageren op veranderingen betreffende grond, gewas en weer, is voor de acceptatie van de modeluitkomst door de boer van wezenlijke betekenis.

VI

Vanuit praktisch oogpunt is het opportuun resultaten en inzichten uit de kunstmatige intelligentie verder te integreren in de operationele research.

VII

Het verdient aanbeveling om zowel statische, geografische structuren zoals kustlijnen, bergen en rivieren met ogenschijnlijk geen logische structuur, als dynamische, chaotische systemen zoals klimaat, te simuleren met behulp van fractals.

> Fournier, A., P. Fussell and L. Carpenter (1982). Computer rendering of stochastic models. Communications of the ACM, Vol. 25, No. 6, 371-384.

VIII

Wie zuivere wiskunde te abstract, saai en slaapverwekkend vindt, zou zich meer bezig moeten houden met computer-animatie.

> Peitgen, H.-O. and P.H. Richter (1987). The beauty of fractals. Springer Verlag, München.

IX

De bosbrandpreventie in Nederland door middel van brandgangen is in de loop der tijd verwaarloosd. Er moet een nieuw brandgangenstelsel komen in de nederlandse bossen met daaraan gekoppeld een forse verlaging van de premie van de brandverzekering.

X

Als men het over vooruitgang heeft dan moet daaronder in sommige gevallen vooruitgang in de achteruitgang worden verstaan.

Peter J.M. Wijngaard
Scheduling models in farm management: a new approach
Wageningen, 2 september 1988

My father could not complain about the weather because the Lord made the weather. Uncle Jim, a neighbour, complained about the weather; therefore, he should not have been a farmer...

Liberty Hyde Bailey

To my parents
To Inge

PREFACE

This dissertation is concerned with operational planning models in farm management. Operational planning models are used to schedule, in time, several different operations; operations like harvesting, sowing, cultivating, and so on. The time variable can be of different lengths, i.e. the operations can be scheduled from hour to hour, but also from month to month. During such a period, the sequence of operations is unknown.

The operations should be scheduled in such a way that current and future costs like timeliness cost, overtime cost and additional costs (e.g. cost caused by the employment of an agricultural contractor) are minimized.

Several operational planning models, or scheduling models, using different techniques of Operations Research have been developed. Most of them are deterministic.

In this dissertation, several scheduling models of the above kind, are analysed. Comment is made about the usefulness of these models. Based on these ideas and to fill gaps identified by this investigation, a scheduling model with a new approach is developed. This approach is based on a combination of techniques from the field of Operations Research and Artificial Intelligence. The new scheduling model uses information from the future (forecasting) and it can be used to improve effectivity and efficiency of planning operations. Using this model, it is possible to decrease farming costs like timeliness, investment in new machinery, storage, and so on.

The research is carried out at the Department of Agricultural Engineering and at the Department of Mathematics, Section Operations Research, both of the Agricultural University, Wageningen and at the Institute of Agricultural Engineering, Wageningen, The Netherlands.

This dissertation is intended for research workers in the combined field of Operations Research, scheduling and planning, and agriculture. The new model described in this thesis could be used by research workers and advisory services.

The new approach of this model is also based on using micro-computers since the micro-computer is becoming more and more important on the farm. Therefore, the model could be used directly by the farmer to improve farm management.

The dissertation is divided in two main parts. Part one, containing Chapters 1 to 5, describes scheduling in agriculture in general and a few, commonly used, scheduling models in particular. A comment on the usefulness of these models is given. The second part, Chapters 6 to 9, contains the description of the scheduling model with the new approach, several test cases including one in a real environment, together with the description of the software package build for the new model.

Many of the ideas in this thesis originated during work with others. I would like to acknowledge my debt to them here.

First of all, I wish to express many thanks to Dr. Ir. E. van Elderen for his encouragement and constructive contribution. Especially his moral support and his patience were of great value.

I wish to thank Prof. Dr. P. van Beek for giving me the opportunity to write this dissertation and for his broad interest.

PREFACE

Special thanks to Ir. H.W. Vos, Prof. Dr. Ir. L. Speelman and Prof. Dr. h.c. Ir. A. Moens of the Department of Agricultural Engineering of the Agricultural University for their valuable contribution, support and interest.

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Thanks to Ir. H.A. Arendse of „COVAM-Advies Wageningen" for giving me the opportunity to use their laserprinter. Without him, this dissertation would not look so nice.

Special thanks to my friend, Ir. M.P. Reinders, for giving me, again and again, the strength to succeed.

And you, Inge, only I know how invaluable your support was.

Peter J.M. Wijngaard

Wageningen
September 1988

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Chapter 1

SCHEDULING MODELS

1.1. INTRODUCTION

The manager in agricultural systems contributes either directly or indirectly to the production and distribution of food, feed, fibre and other products (ASAE, 1987b) by using renewable and other resources. This transformation of resources into products which people want, and for which they are prepared to pay, is not an automatic process. It has to be managed. Those who are working in agriculture have to take into account the three classic questions posed by the theory of production, namely, what to produce, how much to produce and how to produce it.

Managers have to make decisions about the quantities of different goods and services produced or traded. For example they can change their production systems in order to increase the quantities of higher value products, whilst the requirements of consumers can be satisfied by improvements in the product quality and by changes in the timeliness, ease of availability of delivery of these products. The development and adoption of new methods can improve the inherent technical efficiency of production and enable more expensive inputs to be replaced by less expensive ones.

The challenge for management is to find a combination of enterprises, methods and resources together (a system) which can be operated in such a way that the resulting benefits are maximized in relation to the implementation costs. Strategic, tactical and operational decisions alike have to be made within a changing environment and their consequences accepted over time (Conway et al., 1967; Holt et al., 1960; Theil, 1966; Heyman and Sobel, 1984).

If this combination is desired, and to assist in making the right strategic, tactical or operational decisions, a model which simulates the system can be used.

There exists a large number of decision models that potentially can be used to improve the farm management. There are decision type models on investment, labour-budgeting, logistics, all kind of simulations, and scheduling. In agriculture, the scheduling models group is a large group and is commonly used.

> Definition 1.1
> A *scheduling model* is a decision model which gives, for each planning period within the planning horizon, the (amount of) work that must be performed. In a planning period, the sequence of operations is unknown. Availability of time, labour supply, job priorities, and crop requirements influence the solution of the scheduling model.

Scheduling models are commonly very large in size and contain many decision variables. The large number of variables gives rise to the problem of high complexity which is typically caused by the repetition of the same group of variables for each period. If the number of periods increases, then the model will also grow in size. To arrive at a detailed schedule (e.g. a schedule for every hour), more periods per planning horizon have to be considered, each period will be smaller and the model will become larger. Therefore, the length of one planning period will often be aggregated (and therefore the planning horizon will be divided into fewer periods) to keep the models manageable (Audsley, 1984; Hayhoe, 1980; Oving, 1977).

> Definition 1.2
> *Aggregation* means the extension of the length of the planning period. As a result, there will be less planning periods to consider. For example, the solution of the model will contain a schedule for half a month or a whole month instead of a schedule for an hour or half a day.

A schedule for a whole month which gives, for example, the number of hours to harvest, to bale and to gather in this month, may be difficult for the manager, i.e. the farmer, to use. He has to obtain his own detailed schedule for this large planning period, while the model only provides information on what to do but not when to do it within that month.

For practical purposes, the models will often be kept simple, the models will be relaxed.

> Definition 1.3
> *Relaxation* is a method of simplifying decision variables, in this research, it means the division of combinations (represented by the decision variables, see Chapter 2) into gangs and the division of gangs into individual elements of machinery or men (for definition of combination, gang and element, see Section 1.2.1). The purposes are to decrease the size of the model and to decrease the computing time.

The definitions of aggregation and relaxation are commonly used in another meaning.

These models might be smaller in size, smaller than a non-relaxed model, because the number of constraints is decreased (Audsley, 1979; Fokkens and Puylaert, 1981; Kok, 1981). However the question remains: are the solutions derived from the aggregated and relaxed models, although feasible within the simplified model, also feasible in practice?

A scheduling model can also be used as a decision model at the strategic level. Such a model should be used to evaluate decisions on investment in new machinery, decisions about cropping plans, and so on. To use a scheduling model as a model for strategic planning, it is necessary to deal with a lot of different situations (e.g. for a decision on investment in a new combine harvester, the model has to be developed to derive a schedule for several different grain harvests, different in area, workability constraints, machinery, and so on). The average of the results of all these situations can be used for evaluation of decisions at the strategic level. The scheduling models described in this dissertation should be treated in the same way.

The different levels of decisionmaking can be described using Anthony's framework in which the levels are (1) strategic planning, (2) management control (tactical planning) and (3) operations control (Hax and Candea, 1984).

Decision models at strategic and tactical level will not be discussed in this dissertation, attention will be mainly put on the operational aspects of the scheduling models.

Five questions require comment:

1. As there are a lot of available models and techniques (e.g. linear programming, dynamic programming, discrete simulation), which gives the best, i.e. the most reliable, results? In other words, which model will be of most benefit to the farmer?

2. Which length of planning period has to be used to still give a manageable schedule, i.e. which level of aggregation will be most suitable? The different levels of aggregations are used to find the differences between low and high levels of aggregations. A lot of scheduling models are based on a period of half a month (two weeks), and their results are often accepted without any doubt (due to lack of better models). The different solutions from models with different levels of aggregation are compared to test the hypothesis that the applicability of a model developed with a two-week (or higher) level of aggregation is questionable.

3. Are the solutions derived from relaxed models, although feasible within the simplified model, also feasible in practice? And therefore, how relaxed can the models be? Can the individual separate elements (e.g. machinery, men) be used, or gangs or even combinations of gangs?

4. Is it possible to develop a new model and a new algorithm performing better in practice?

5. What kind of effect has a new model on the decision process of the farmer? Will it increase effectivity and efficiency of this decision process?

There are several authors who did made an attempt to answer these questions. Van Elderen (1980) and Kok (1981) have compared several scheduling models in a quantitative and a qualitative way. Very recently, Glen (1987) did a thorough research to mathematical models in farm planning. Glen described (1) crop production models: for cropping policy, harvesting operations, capital investment for crop production, pest and disease control and (2) livestock production models: diet formulation, ration formulation, feeding policy for intensive livestock production, livestock production on pasture, livestock breeding and replacement, waste disposal, planning in a livestock production unit. Scheduling models are mainly described under harvesting operations.

The research described in this dissertation is partly based on the work of Kok (1981) and Van Elderen (1980). Kok did only compare linear programming models and Van Elderen compared linear programming models with a dynamic programming model whereby the latter is solved with a heuristic scheduling procedure. But, the conclusions made by Kok and Van Elderen are not completely satisfactory for use in practice, e.g. the models are not compared for different levels of aggregation and a model, which can be used in practice, is not available and has therefore to be developed. In this dissertation, a continuation of the research: comparison of scheduling models, is described in the following way.

The first part of this research, which has resulted in Chapters 2 to 5 of this dissertation, attempts to answer the first three problems. In the second part of the research, the development of a new model using new techniques is performed (Chapters 6, 7 and 9) and a description of a real test case, i.e. a harvest on an arable farm (Chapter 8), are given to answer questions 4 and 5.

1.2. THE ELEMENTS OF THE SCHEDULING MODEL

There are four elements which are important to the scheduling model. These elements are:

1. the availability of labour, equipment, and correspondingly, the gangs or combinations of gangs;
2. the timeliness of materials, and correspondingly, the timeliness of operations;
3. the weather, i.e. the subsequent intervals of wet or dry conditions;
4. the workability of materials, influenced by the weather, and in line with this the moisture content of materials (e.g. grain, straw, soil).

These elements will be mentioned first separately before the structure of the scheduling model is discussed (in Chapter 2).

1.2.1. LABOUR, EQUIPMENT, MATERIALS AND GANGS

Definition 1.4
Labour availability means that one or more operators are present to operate the machinery complement in question.

Definition 1.5
Machinery availability means that the machinery required for an activity has not been allocated elsewhere and is not in need of repairs (Russell et al., 1983).

Definition 1.6
An *element of machinery and men* is the smallest possible part of the available machinery or men. It cannot be divided anymore in smaller parts. Examples are a tractor, a baler, one man, and so on.

Definition 1.7
An operation requires a set of elements from the available men and machinery. Such a set of elements is called a *gang*. A *set of gangs* is called a *combination*, which performs simultaneously a set of operations and is a feasible composition of elements of machinery and men (Oving, 1971; Van Elderen, 1977; Van Elderen, 1980; Van Elderen, 1981).

A model can use these combinations as decision variables. The current selected combination can be used until the next decision moment. It transforms the quantities of materials according to the work capacity of each gang in the combination. With gangs as decision variables, the situation is simplified by deleting the simultaneous use of two or more gangs as given in the combinations (Van Elderen, 1981).

One can consider different types of labour, i.e. regular time and overtime. The data needed for these types are the hours available to be worked in each period (Audsley, 1981).

Definition 1.8
Labour costs are costs which depend on human impact. They include costs of regular time worked and costs of overtime worked.

Machinery operations can be scheduled by partitioning the production process into a number of activities. All activities can be reviewed as potential candidates for scheduling as determined by a priority parameter (an activity number). As many activities as allowed by labour and machinery availability can be scheduled each day (Russell et al., 1983).

Definition 1.9
Machinery costs contain operating costs and fixed costs. *Operating costs* are costs which directly depend on the amount of machine use. *Fixed costs* are costs which do not depend on the amount of machine use, such as depreciation, interest on investment, taxes, insurance and storage. Fixed costs must be charged regardless of machine productivity (ASAE, 1987a).

1.2.2. TIMELINESS

Definition 1.10
A *timeliness function* represents the economic effect of timeliness, namely the effect of reduction in crop value due to losses in yield and quality (Figures 1.1.a and 1.1.b).

The crop yield will vary depending on the time of harvesting the crop. The optimum timeliness effect varies with the system of cropping, harvesting, storage, processing and marketing (Audsley et al., 1978).

The losses depend on physical and physiological properties of the crops and meteorological factors, but usually not on relatively rare phenomena like storms or hail (Van Elderen, 1977; Rotz et al., 1983). Timeliness functions for several materials are not available yet and therefore, still strongly needed (Van Elderen, 1981).

The costs of field losses are the costs having the greatest influence on the harvesting sequence. Expected field losses can be computed as follows. Via a relation between the decline of the yield and quality, and some factors (wind, rain), representing the weather conditions since the ripening time of the crop, this can be computed by using multiple regression analysis (Fokkens and Puylaert, 1981);

However in reality there are a lot of differences in expected field losses between different fields. Crops, lying down, blighted, or germinating in the ear, will have higher field losses than healthy, upright crops. This means that the crops have to be subdivided into a number of groups. Crops with a substantial probability of high losses must be harvested first. For each field, estimates of the field losses on that field in comparison with normal crops can be made (Fokkens and Puylaert, 1981).

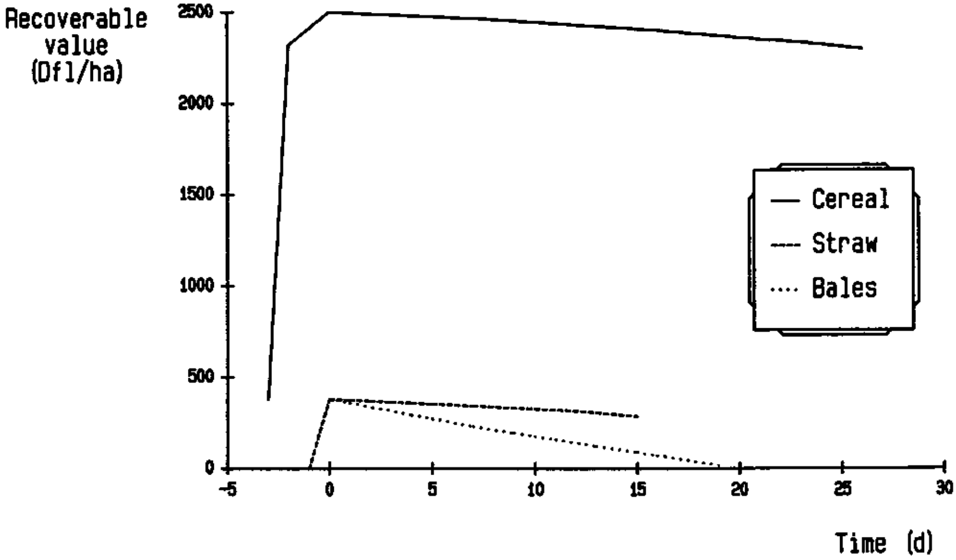


Figure 1.1.a. The recoverable value of the materials grain, straw and bales for thirty days ($f \cdot ha^{-1}$). At t=0, the value reaches its optimum.

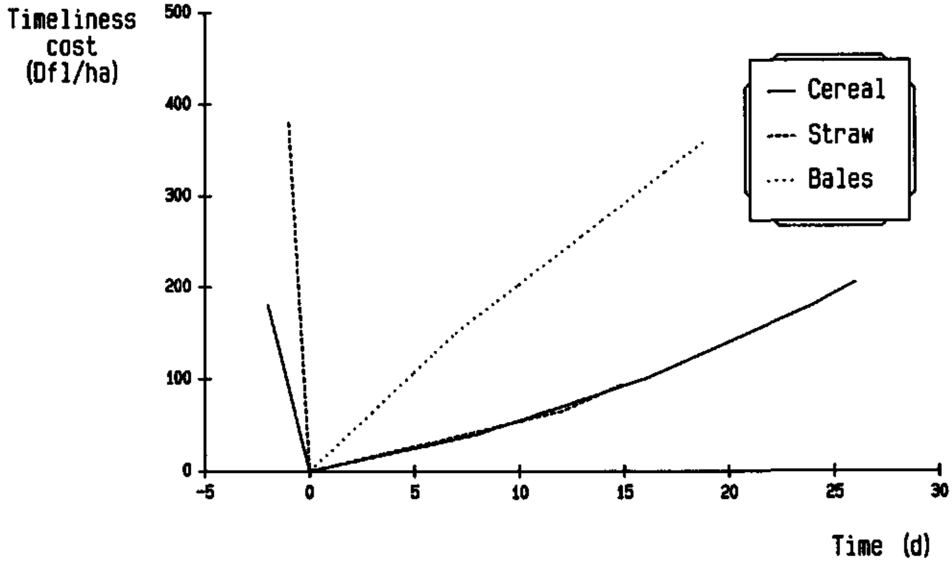


Figure 1.1.b. The timeliness cost of the materials grain, straw and bales for thirty days ($f \cdot ha^{-1}$). At t=0, timelinesss costs are minimum (equal to zero)

Timeliness of operations also varies with the size of machinery and the latter is largely determined by capacity requirements during the peak work season.

Timeliness also varies, for a given crop rotation and tillage system, with the farm size (Singh and Holtman, 1979).

Variation in timeliness costs is often a main source of variation in total costs. The total costs considered often are a sum of machinery costs (fixed costs and operating costs), labour costs and timeliness costs.

1.2.3. THE WEATHER

Weather is an important part of the whole agricultural system. It affects the yields, the field operations, the workable hours, the machinery operating and timeliness costs, and so on.

A harvesting schedule must be established by considering the climatic conditions during the harvesting season period. This uncontrollable factor in the harvesting process can be considered by deriving the probability of workable field conditions for each day during the harvesting season (Miyake et al., 1979).

For each day, there can be changes in crop and weather conditions which require adaptations to the harvesting plan. The probability of extensive field losses will increase as the period between ripening and harvesting becomes longer, and depends on the weather conditions during that period (Fokkens and Puylaert, 1981).

Weather risk is an important variable to include in a decision model. Only a few studies illustrate the interaction between weather risk, machinery complement selection and crop mixes in order to maximize returns to the firm. Weather risk often is directly incorporated into the model via the available field time in a critical period.

The random variable weather, can be introduced into a model (and consequently the analysis) by using historical weather data to simulate actual weather conditions (Russell et al., 1983).

To reduce risks associated with weather, farm managers often use more machine capacity in order to have an „insurance" for completing required field operations in time (Whitson et al., 1981). Because weather is variable, farmers are most likely to choose a set of machinery that performs well under a wide range of weather conditions (Danok et al., 1980).

Weather (especially rainfall and evaporation) also has an approximate relation to moisture content. This is an important factor in models, e.g. the moisture content of grain, straw, soil, and so on, in grain harvesting models. In this case, it determines the starting date of harvesting. Models for properties of crop and soil (moisture content) are needed to create „historical" series of properties from historical weather data (Van Elderen, 1981).

1.2.4. WORKABILITY

For efficient machinery management, a farmer needs information on the number of field working days available in order to assess the balance between the timeliness costs of an inadequate system and the inflated capital costs of over-investment in machinery (Hayhoe, 1980). Organization of work, once established, is expected to be maintained for a prolonged period with only minor changes (Gekle, 1981).

> Definition 1.11
> *Workability or readiness* is an attribute of a material (crop, soil) and refers to properties or conditions of the material and of the weather such that the operation can be performed (Van Elderen, 1981).

Workability is best represented in a detailed model by a chronological sequence of weather data and properties of materials. Relaxing the original sequence of workability leads to ununderbroken durations of workable time (e.g. all those hours in a week within regular time and workable for wheat and straw, but not for soil, are put together and summarized as a number, Van Elderen, 1980).

However, the detailed data are often not available. The number of suitable field days which is available during different periods of the year is a random variable. Regardless of the method used to estimate the probability distribution of suitable field days, nearly all machinery selection models have then converted this distribution into a single-valued expectation, of suitable field days, for each calendar period under study (Edwards and Boehlje, 1980).

The data are often aggregated over a period and the workable duration is nested: the smaller number is contained in the larger number. If this nesting occurs, then the connection between workability of several operations has been lost completely (Van Elderen, 1981; Van Elderen, 1984).

Most techniques for farm and machinery planning use the concept that a certain number of hours will be available for a task. This is a simplification which is necessary to make the calculations feasible, but neglects two factors:

1. the number of workable hours available each year ranges from a few to many for different years (see also Chapter 5). The penalty for not completing the task is frequently high and obvious (e.g. field not subsequently planted on time) but the penalty for completing the task too quickly, which means having too much machinery or using too much energy, is less obvious. Between the extremes there is an optimum level of mechanization (strategic problem of machinery selection);

2. the condition of the soil ranges over the season from definitely workable to definitely not workable. Working on wet soil may cause compaction and subsequent loss of yield. The farmer has to decide whether to pay this penalty or to wait. If he waits and conditions improve, he was „right to wait". If conditions deteriorate further, he has to pay the higher cost of not completing the task at all (operational problem of scheduling, Audsley, 1984).

The latter, the operational problem of scheduling, is the problem mainly examined in this dissertation.

Completion dates of harvesting are calculated with the aid of workable hours. They are estimated by calculating the total number of field hours needed to complete a machine operation (or set of operations) over a given number of hectares, and dividing by the number of field hours available per day to obtain the number of required field days (Edwards and Boehlje, 1980).

Although the manager uses standards, machinery (capacity) selection would be a less difficult task if he could be certain of the available number of days or hours to perform a particular farm operation.

The summing up of the four elements, i.e. (1) labour, equipment, materials and gangs, (2) timeliness, (3) the weather and (4) workability (Sections 1.2.1 to 1.2.4), and some of their effects on a schedule ends this chapter and is sufficient enough to start the next chapter with the integration within models.

Chapter 2

THE DESCRIPTION OF THE MODELS

The first element in a general decision model is the objective to be met in making the decision. Having chosen the objective, the next need is to identify the alternative decisions. The effectiveness with which each of the alternative decisions meets the objective is dependent upon future events. Now that the alternative decisions and the events have been specified, a means of measuring the outcome or „payoff" must be selected. A decision criterion for choosing one of the alternatives must be selected.

> Definition 2.1
> A *decision criterion* is a logical or rational method of choosing the alternative decisions which best meets the objective. The choice of the decision variables depends on the degree to which the actual event that will occur in the future can be predicted (Dannenbring and Starr, 1981).

Since there are a lot of decision models this study is restricted to scheduling models (for a few examples, see Kok, 1981). Comparison of all different kinds of scheduling models would take considerable time and the results from this investigation might become obsolete before new models made their appearance. It is better to compare the common models used to build specific scheduling models. Then, the differences discovered are assumed to be indicative for each model using the definitions of these general models. There are three main general models considered:

1. a dynamic programming model;
2. a linear programming model;
3. a simulation model.

These are the commonly used models in operational research (Hillier and Lieberman, 1987; Wagner, 1977). Linear programming is especially used in operational research and a lot of economical solutions are based on this type of model. Simulation is very common in operational research and its area of application is still growing (Zeigler, 1976). Dynamic programming is the least used type of method especially due to the so-called curse of dimensionality.

Scheduling models are commonly of a probabilistic nature because it is not known with certainty how much and which of the events will affect the result. But probabilistic models have some disadvantages in this research, as mentioned below, concerning the comparison of scheduling models. Therefore, the research is based on deterministic models with the decision making under certainty, because:

1. The probabilistic structure of a model affects the behaviour and the results of the model. Exceptional effects of weather, the effect of exceptional years (e.g. years with an extremely high rate or an extremely low rate of workability) disappear by taking an average or calculating ranges of workability with some probability from the years examined. The effects of these peculiar years, e.g. the effect of a year with an extremely low rate of workability on the solution of the model, remains unknown in such a probabilistic model. This situation will also be discussed in Chapter 5;

2. The models, especially the linear programming and the simulation models, have a deterministic structure as a base. The probabilistic structure is an extension of the model. This is clearly shown by the Chance-Constrained approach of linear programming. The behavior of the model will be determined by the deterministic structure;

3. In this investigation, the multi-stage formulation of linear programming is used. While the deterministic linear programming model will contain about T times M constraints (T is the total number of periods and M is the number of constraints per period), the probabilistic linear programming model (using the multi-stage formulation), with five levels of probability, which are mutually independent from stage to stage, will contain about:

   $$\{ \sum_{i=1}^{T} (5^{i}) \} \cdot M^{\dagger}$$

   constraints (Wagner, 1977). The probabilistic linear programming model would become too large and therefore hardly manageable. Therefore, the probabilistic dynamic programming model will be considered (in Chapter 5);

4. In agricultural practice, scheduling models using a deterministic structure are still being used. This research is also performed to consider the questionable usefulness of these models.

The models are developed for the grain harvest in the Netherlands for the season August 1 to September 4 (five weeks in a season), for twelve years, 1957 to 1968 (weather data from De-Bilt). They have to calculate a schedule for the harvest of cereal, straw and bales for a farm with two men (the farmer with one labourer). The grain harvest is chosen because a sufficient amount of data about the mentioned materials are available. Before describing the different models in detail, the following elements:

1. level of aggregation;

(†) The sign · is a multiplication sign (according to the American system).

2. combinations of gangs;
3. weather;
4. workability.

of the system which determine the models, are described.

2.1. THE LEVELS OF AGGREGATION

Each of the three models are developed for five levels of aggregation. These are levels with time as the aggregation dimension. The models give the quantity of work that must be done in a certain period as the result. The length of a period depends on the level of aggregation.

The levels of aggregations are, from low to high (expressed in the length of period):

1-hour-level: five weeks, 105 periods per week:

for each day (Monday till Friday):
5 periods of 1 h regular (morning)
1 period of 1 h overtime (morning, lunch time)
5 periods of 1 h regular (afternoon)
4 periods of 1 h overtime (evening)

for each day (Saturday and Sunday):
15 periods of 1 h overtime (morning, afternoon and evening)

5-hour-level: five weeks, 21 periods per week:

for each day (Monday till Friday):
1 period of 5 h regular (morning)
1 period of 5 h regular (afternoon)
1 period of 5 h overtime (evening) 1)

for each day (Saturday and Sunday):
3 periods of 5 h overtime (morning, afternoon and evening)

1) Including 1 h overtime in de morning (see 1-hour-level)

day-level: five weeks, 12 periods per week:

for each day (Monday till Friday):
1 period of 10 h regular (morning and afternoon)
1 period of 5 h overtime (evening)

for each day (Saturday and Sunday):
1 period of 15 h overtime (morning, afternoon and evening)

week-level: five weeks, 3 periods per week:
1 period of 50 h regular
1 period of 40 h overtime (including Saturday)
1 period of 15 h overtime (Sunday)

month-level: 3 periods per season
1 period of 250 h regular
1 period of 200 h overtime (including Saturdays)
1 period of 75 h overtime (all Sundays)

The reason that Sunday overtime hours are separated from the other overtime hours is that the overtime work on Sunday is assumed to be more expensive than overtime work on the other days.

At a low level of aggregation, the models result in the amount of work for every hour. At the highest level of aggregation, the models give the total amount of work for a whole month as the result. It can be seen that models at 1-hour-level give much more detailed solutions for scheduling than the models at higher levels of aggregation.

As stated in Chapter 1, the different levels of aggregations are used to find the differences between low and high levels of aggregations. A lot of scheduling models are based on a period of half a month (two weeks), and their results are often accepted without any doubt (due to lack of better models, Audsly, 1979; Audsley, 1981; Kok, 1981; Cevaal and Oving, 1979). The different solutions from models with different levels of aggregation are compared to test the hypothesis that the applicability of a model developed with a two-week (or higher) level of aggregation is questionable.

2.2. THE COMBINATIONS OF GANGS

A schedule for the grain harvest can be derived by solving the model on the specific level of aggregation. To fulfill the operation grain harvest, the farm contains the following equipment: two tractors, a combine-harvester, a baler, a bale-loader, a plough, several trailers, and a grain-

dryer. Two men represent the available labour. Higher quantities (three and four men, with three and four tractors respectively) are also examined (see Chapter 4).
Gangs are built using the equipment and labour. The following gangs can be constructed:

- harvesting with one man;
- harvesting with two men (one man is harvesting, the second man is transporting the grain);
- baling;
- bale gathering (is loading and transporting formed bales), and
- ploughing.

These gangs are combined in sets under restrictions of the quantity of equipment and labour. The models make use of combinations as decision variables instead of gangs or equipment units because:

1. our dynamic programming model can only give one set of operations per period (Hillier and Lieberman, 1987). When the model uses gangs as decision variables, the model will give a sequence of operations performed by the gangs separately and not by combinations of gangs which perform some operations simultaneously (see also Section 1.2.1),

2. models which use individual units of machinery or gangs as decision variables (or as constraints), give solutions which sometimes cannot be used in practice. The solutions contain contradictions, for example; two gangs operate at the same time and the quantity of equipment does not allow this. This problem will be further analysed in Chapter 4,

3. the set of combinations (including the null or empty combination, i.e. the combination „Do nothing") represents each possible decision variable and for a given period, only one combination is preferred.

2.3. THE WEATHER

Here models are developed for the grain harvest. To calculate the workability of the operations: harvesting, baling, bale-gathering and ploughing (see next section), hourly weather-data from the years 1957 to 1968 are used. For every year, five weeks of data are used, from August 1 to September 4. These weather-data contain the following hourly records:

• air temperature	(°C)
• relative humidity	(fraction)
• cloud amount	(fraction)
• rain duration	$(\mathrm{min \cdot h^{-1}})$
• quantity of rain	$(\mathrm{mm \cdot h^{-1}})$
• global radiation	$(\mathrm{cal \cdot (h \cdot cm^2)^{-1}})$

$(1\ \mathrm{cal \cdot (h \cdot cm^2)^{-1}} = 42\ \mathrm{kJ \cdot (h \cdot m^2)^{-1}})$

- mean wind speed $(m \cdot s^{-1})$

The workability is calculated using these hourly weather-data in a model developed by Van Elderen and Van Hoven (1973). Twelve years of weather-data contain too less information for a thorough statistical analysis. Nevertheless, only twelve years are used because:

1. in this research, an attempt is made to find out the differences between the models with different levels of aggregation and relaxation. Near-equality of results from the different levels is accepted when the difference in results is below a certain error-level (using a reference-model; in this case the dynamic programming model). If statistical equality is required, the difference in results must be small enough. The error made by rounding off workability (see next section) is already more significant than this difference;

2. the twelve years with weather data measured may represent thirty years with weather data (the standard climatological period). It is assumed that the results of models using thirty years of weather-data will give the same conclusions as the results of models using twelve years of weather-data. This is taken into account during the explanation of the results of the models in Chapter 3. To find out the equality in weather-data between the twelve year period and the thirty year period, the weather parameters most closely linked to workability; i.e. rainfall, quantity of dry days (where the daysum of rainfall is lower than 0.1 mm), and radiation, have to be investigated. Radiation data are not available for all of the years 1930 to 1985, therefore only rainfall and the quantity of dry days are examined.

   The average of rainfall (Table 2.1.a) and the average of the number of dry days (Table 2.1.b) in the thirty year period is approximately the same as the average in twelve years. This only counts for the thirty year period 1941—1970. The years before 1941 and after 1970 seem to be drier because the averages of rainfall (dry days) of 1941—1970 are in general higher (lower) than those of 1932—1985, 1932—1970, 1941—1985 and 1951—1980, especially for the first four decades;

2.4. THE WORKABILITY

The moisture content (m.c.) influences the workability and the workability itself influences the decision to operate or not. For the grain harvest model, the decision to operate depends on the following moisture contents:

To harvest cereal (without drying)	grain m.c.	≤ 19% wet base
To harvest cereal (with drying)	grain m.c.	19—23% wet base
Impossible to harvest cereal	grain m.c.	> 23% wet base
To bale straw	straw m.c.	≤ 25% wet base
To plough soil	soil m.c.	≤ 47% wet base

The workability (discussed in Chapter 1) is strongly dependent on the levels of aggregation. There are two methods used of formulating the number of workable hours for the different levels of aggregation.

Table 2.1.a. The amount of rainfall (mm) for the decades of August and September for different groups of years (ave is average, std is standard deviation, data derived from weather station De Bilt, The Netherlands).

			August			September	
years		I	II	III	I	II	III
32—85	ave	26.69	28.80	24.08	20.31	25.80	23.24
	std	20.97	21.74	24.18	18.00	23.24	21.29
32—70	ave	31.00	33.01	27.06	21.11	27.01	23.82
	std	22.03	22.78	26.77	17.60	23.09	20.68
41—85	ave	28.25	29.41	25.28	19.75	24.32	21.92
	std	21.28	22.79	25.97	18.03	23.80	22.10
51—80	ave	25.66	31.55	30.71	21.24	22.49	21.63
	std	16.65	24.20	28.42	18.77	22.69	23.68
41—70	ave	31.46	38.46	30.82	26.51	25.14	21.72
	std	21.99	24.23	29.61	17.61	24.01	21.79
57—68	ave	29.62	40.37	31.59	28.69	26.13	23.76
	std	13.59	25.34	26.30	20.56	29.39	28.87

Table 2.1.b. The number of dry days for the decades of August and September for different groups of years (ave is average, std is standard deviation, data derived from weather station De Bilt, The Netherlands).

			August			September	
years		I	II	III	I	II	III
32—85	ave	4.26	3.68	4.51	3.96	3.51	3.11
	std	2.42	2.53	2.72	2.68	2.43	2.56
32—70	ave	4.13	3.11	3.97	3.79	3.13	2.66
	std	2.45	2.42	2.69	2.72	2.18	2.31
41—85	ave	4.05	3.57	4.41	3.89	3.39	3.14
	std	2.26	2.64	2.91	2.75	2.54	2.71
51—80	ave	4.14	3.55	4.28	4.00	3.55	2.97
	std	2.42	2.75	3.10	2.87	2.73	2.90
41—70	ave	3.76	2.76	3.66	3.62	2.83	2.55
	std	2.18	2.49	2.91	2.82	2.24	2.47
57—68	ave	3.08	2.50	3.17	3.25	3.08	2.25
	std	1.88	2.58	3.16	2.90	2.68	2.38

Rounding off workability.

The hours of workability are rounded off for the length of a period, the model only deals with a number of workable hours equal to zero or equal to the length of a period. The whole period is workable or it is not workable. This is shown by two examples:

1. A 5-hour period:
   number of workable hours ≤ 2 → period is not workable at all,
   zero workable hours and workability is false,
   number of workable hours ≥ 3 → period is workable,
   five workable hours and workability is true.

2. For a week, a period of 50 hours:
   number of workable hours ≤ 24 → period is not workable at all,
   zero workable hours and workability is false,
   number of workable hours ≥ 25 → period is workable,
   fifty workable hours and workability is true.

It is possible that a large error is introduced, especially for the models at week-level or more aggregated levels. However rounding off workability is necessary because it is very difficult to treat workable hours as a continuous variable instead of a discrete variable for periods which are used in the dynamic programming model. It causes the existence of new decision moments which can be situated after every hour in one period. These additional stages complicates the problem. The need to use uniform periods in the dynamic programming model is the only reason for rounding. More details are given when discussing the development of the dynamic programming model (Section 2.5).

To get a better view on practice, models using real workability are also developed.

Real workability.

With real workability, the real total number of workable hours per period is considered. For example there are zero to five workable hours possible in a 5-hour period.

A solution based on real workability is more reliable in practice because this definition of workability presents reality in a better way.

The developed models are a dynamic programming model, a linear programming model and a simulation model. The first two are developed by the author, the latter model is developed by Van Elderen (1987). These models will be described in the following sections (see also Wijngaard, 1986a).

2.5. THE DETERMINISTIC DYNAMIC PROGRAMMING MODEL

Even though dynamic programming cannot often be implemented easily, it will be discussed first. A large part of one of the linear programming models is based on the formulation used in the dynamic programming model (Section 2.6). The formulation of the models is analogous; the dynamic programming model was considered as a reference model for the two other models, linear programming and simulation. The dynamic programming model is a reference model because it is assumed that the dynamic programming model is the best representation of reality while it is formulated such that the model can only schedule one combination of gangs per period (just as in practice) and the solution technique guarantees an optimal solution. For comparison reasons, the linear programming model must have almost the same set of variables as the dynamic programming model.

The basic features which characterize dynamic programming problems are presented below (Hillier and Lieberman, 1987).

1. The problem can be divided into so-called decision stages, with a decision required at each stage.
2. Each stage has a number of states associated with it. The states are the various possible conditions in which a system might exist at that stage of the problem. The number of states may be either finite or infinite.
3. The effect of the decision at each stage is to transform the current state into a state associated with the next stage.
4. Given the current state, an optimal decision for the remaining stages is independent of the decision adopted in previous stages.
5. The solution procedure begins by finding the optimal decision for each state of the last stage (backward recursion).
6. A recursive relationship (Bellman's relation) that identifies the optimal decision for each state at stage t–1, given the optimal decision for each state at stage t is available.
7. Using this recursive relationship, the solution procedure moves backward (in the deterministic problems in this research, forward) stage by stage, each time finding the optimal decision for each state of that stage, until it finds the optimal decision when starting (or ending) at the initial stage (or the final stage).

The technique was developed by Bellman in 1957 (Hillier and Lieberman, 1987). This technique calculates the shortest, or cheapest path, in a directed network (for a definition of a directed network, see also Hillier and Lieberman, 1987: page 216). In the present description of the model, this path can represent a schedule.

The dynamic programming formulation contains the following vectors and functions (it is assumed that the reader is familiar with the notations, see also Figure 2.1).

A. The statevector x_t contains the amounts of material (ha): cereal (CE), straw (ST), bales (BA), stubble (SF) and wet grain (WE) for every stage t. The statevector x_t is represented as follows:

$$x_t' = (x_t^1, x_t^2, x_t^3, x_t^4, x_t^5) = (x_t^j) \qquad \begin{array}{r} j = 1, \ldots, 5 \\ t = 1, \ldots, T \end{array}$$

where

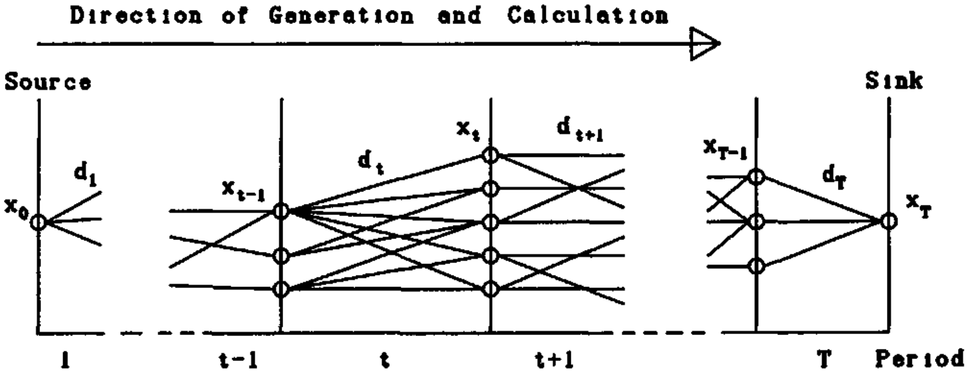


Figure 2.1. A representation of a directed network as used by the deterministic dynamic programming model. The solution procedure moves forward.

$x_t^1 = CE_t$, $x_t^2 = ST_t$, $x_t^3 = BA_t$, $x_t^4 = SF_t$ and $x_t^5 = WE_t$

j = number of the material
t = number of the stage

The highest amount of a material is twenty hectares, the lowest zero hectare. The decrease or increase is a multiple of five hectares (including zero hectare). So, one material can have five states in a stage (0, 5, 10, 15 or 20). This counts for all the five materials. Therefore the statespace can contain a maximum of 5^5 is 3125 components (some states are logically impossible, e.g. twenty hectares for all five materials).

B. The vector of decision variables $\mathbf{d}_t$ at stage t (further identified as decisionvector) contains twenty-four 0-1 variables. It involves the following decision; which operations and which combination (set of gangs) must operate. The decisionvector $\mathbf{d}_t$ is as follows:

$$d_t' = (d_t^1, d_t^2, \ldots, d_t^{24}) = (d_t^k) \qquad k = 1, \ldots, 24$$

where

d_t^1 = grain harvesting (wet and dry) with two men in period t
d_t^2 = grain harvesting (wet and dry) with one man in period t
d_t^3 = baling with one man in period t
d_t^4 = bale gathering with one man in period t
d_t^5 = ploughing with one man in period t
d_t^6 = grain harvesting (one man, wet and dry) and baling in period t

$d_t^7 =$ grain harvesting (one man, wet and dry) and gathering in period t
$d_t^8 =$ grain harvesting (one man, wet and dry) and ploughing in period t
$d_t^9 =$ baling and bale gathering in period t
$d_t^{10} =$ baling and ploughing in period t
$d_t^{11} =$ bale gathering and ploughing in period t
$d_t^{12} =$ do nothing in period t

(d_t^{13} to d_t^{24} have the same meaning as d_t^1 to d_t^{12} except that drying wet grain is also involved)

and

$$\sum_{k=1}^{24} d_t^k = 1 \qquad \text{for all } t$$

k = number of the combination
t = number of stage

C. The transformation function T_t (from stage t–1 to stage t) expresses the decrease or increase in amounts (ha) of the materials.

$$\mathbf{x}_t : \mathbf{x}_t = T_t(\mathbf{x}_{t-1}, \mathbf{d}_t)$$

and this means in our case:

$$\mathbf{x}_t = (\mathbf{x}_{t-1} - \mathbf{CP}_t' \cdot \mathbf{d}_t + \mathbf{CL}_t' \cdot \mathbf{d}_t)^+ \qquad (\mathbf{x}^+ \overset{df}{=} \max(\mathbf{0},\mathbf{x}))$$

where

$$x_t^j = (x_{t-1}^j - \mathbf{d}_t' \cdot \mathbf{cp}_t^j + \mathbf{d}_t' \cdot \mathbf{cl}_t^j)^+ \qquad j = 1,\ldots,5; \qquad (x^+ \overset{df}{=} \max(0,x))$$

and

$$\mathrm{CP}_t = \begin{pmatrix} cp_t^1(1) & \ldots & cp_t^5(1) \\ \vdots & cp_t^j(k) & \vdots \\ cp_t^1(24) & \ldots & cp_t^5(24) \end{pmatrix} \qquad \mathrm{CL}_t = \begin{pmatrix} cl_t^1(1) & \ldots & cl_t^5(1) \\ \vdots & cl_t^j(k) & \vdots \\ cl_t^1(24) & \ldots & cl_t^5(24) \end{pmatrix}$$

$\mathrm{CP}_t =$ matrix with the processing capacities (i.e. the working rate of combination k processing material j) for combination k and material j in period t ($\text{ha} \cdot \text{period}^{-1}$)

CL_t = matrix with delivery capacities (i.e. the working rate of the combination k delivering the material j) for combination k and material j in period t (ha · period^{-1})

If the workability for material j is false (e.g. when the material is too wet, there are no workable hours) in period t, then $cp_t^j(k)$ has the value zero (for all k). If the operation k is not scheduled in period t, d_t^k has the value 0 and there will be no increase or decrease of material. If the combination k is scheduled in period t, the workability is true for combination k in period t and the area of material j is unequal to 0, then d_t^k will have the value 1 and the change in amount of material j is equal to the capacity of the dependent operation ($cp_t^j(k)$)

The operation k determines the increase or decrease of material. For example:

- The operation grain harvesting and baling means:
  - a decrease of the amount of cereal (j=1, cereal is processed),
  - an increase of the amount of straw (j=2, straw is delivered) and simultaneously,
  - a decrease of the amount of straw (j=2, straw is processed),
  - an increase of the amount of bales (j=3, bales are delivered).
- The operation is ploughing only, this only has as result a decrease of stubble (j=4, stubble is processed).

D. The costfunction G_t depends on the statevector $\mathbf{x}_{t-1}$ and the decisionvector $\mathbf{d}_t$.

$G_t : G_t(\mathbf{x}_{t-1}, \mathbf{d}_t)$

$$G_t(\mathbf{x}_{t-1},\mathbf{d}_t) = \begin{cases} \infty & \text{if } \mathbf{CP}_t' \cdot \mathbf{d}_t = \mathbf{0} \text{ and } d_t^{12} = 0 \\ \mathbf{dr}_t' \cdot \mathbf{d}_t + TM_t + \mathbf{ov}_t' \cdot \mathbf{d}_t{}^{\dagger} & \text{otherwise} \end{cases}$$

with the drying cost: $\mathbf{dr}_t = (dr_t^k)$

$$dr_t^k = \begin{cases} \dfrac{x_{t-1}^5 + \mathbf{d}_t' \cdot \mathbf{cl}_t^5 - x_t^5}{\mathbf{d}_t' \cdot \mathbf{cp}_t^5} \cdot DC & \text{if } \mathbf{d}_t' \cdot \mathbf{cp}_t^5 \neq 0 \\ 0 & \text{otherwise} \end{cases}$$

DC = the drying cost per period (f·period^{-1})

(†) The multiplication of vector $\mathbf{ov}_t$ with vector $\mathbf{d}_t$ is equal to the inner product of both vectors. This is true for the multiplication of all the vectors (vectors are printed bold).

the timeliness cost: TM_t

$$TM_t = \mathbf{x}_t' \cdot \mathbf{tc}_t$$

$\mathbf{tc}_t = (tc_t^j)$ vector with the fixed timeliness cost for period t and material j (ƒ·(period · ha)$^{-1}$)

and the overtime cost: $\mathbf{ov}_t = (ov_t^k)$

$$ov_t^k = \begin{cases} \sum\limits_{j=1}^{4} oc_t^j(k) \cdot \dfrac{x_{t-1}^j + \mathbf{d}_t' \cdot \mathbf{cl}_t^j - x_t^j}{\mathbf{d}_t' \cdot \mathbf{cp}_t^j} & \text{if } \mathbf{d}_t' \cdot \mathbf{cp}_t^j \neq 0 \\ 0 & \text{otherwise} \end{cases}$$

$OC_t = (oc_t^j(k))$ the matrix with overtime cost per period for period t when material j is processed with combination k (ƒ·period^{-1})

Drying costs are stated on ƒ30.00 per hour.

The condition of the material j for period t is the start condition of this material for period t. The delivery date of the materials straw, bales, stubble and wet grain is unknown. Therefore, the time when the recoverable value of this material is maximum or when the timeliness cost of this material is minimum is unknown. Timeliness costs are now calculated as follows. Instead of calculating the difference in timeliness cost between the delivery date and the processing date, the timeliness costs are now a sum of timeliness cost per period for each period that a material is not processed. For example, if a material is delivered at t=0 and processed at t=5, then the timeliness cost is the sum of the fixed timeliness cost at t=0, 1, 2, 3, 4 and 5 (instead of the difference in timeliness cost at t=0 and at t=5). Therefore, the timeliness costs for these materials are fixed per period. This is legal because the timeliness cost is assumed to be linear. For simplicity reasons, the timeliness cost of cereal is treated in the same way. The timeliness costs are as follows (example for a model with a planning period of a day, ƒ·(ha·d)$^{-1}$):

cereal	5.00
straw	5.40
bales	21.10
stubble	2.50
wet grain	1.20

The delivery date of cereal is well known (equal to the first stage), for this material is used the timeliness function itself (Figure 2.2). For cereal, the difference between the timeliness costs at harvesting date and the timeliness cost at delivery date (the beginning of the season) is calculated. The timeliness costs for the other materials are the cumulative sum of all the timeliness penalties at the end of the periods (if material exists).

If the period has no overtime hours, there will be no penalty charged. If the period has overtime hours, ƒ10.00 overtime cost per hour and per person will be charged. If the period contains ex-

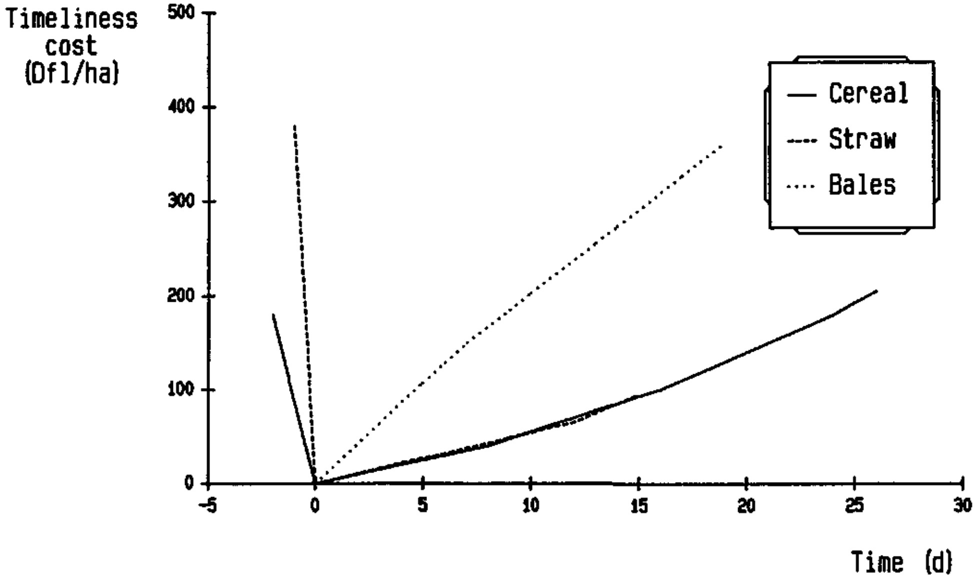


Figure 2.2. The timeliness cost of the materials grain, straw and bales ($f \cdot ha^{-1}$). At t=0, the timeliness costs are minimum (equal to zero).

traordinary overtime hours (as Sunday does), *f*15.00 overtime cost per hour will be charged. Overtime costs will only be charged when materials decrease in amount.

E. The value function V_t gives the value for a certain state at a certain stage t after calculating the whole dependent network preceding stage t (remember that the solution procedure moves forward).

$$V_t(\mathbf{x}_t) = \min_{\mathbf{d}_t \in D_t(\mathbf{x}_t)} \{ G_t(\mathbf{x}_{t-1}, \mathbf{d}_t) + V_{t-1}(\mathbf{x}_{t-1}) \}$$

$D_t(\mathbf{x}_t)$ = the set of all possible decisionvectors $\mathbf{d}_t$ for given state $\mathbf{x}_t$

The initial amount of cereal is twenty hectares. This value is so low while the quantity of states per stage will otherwise grow enormously. The maximal quantity of states per stage is now 3125 components and is defining the statespace. For an amount of sixty hectares (an amount also used in linear programming and simulation) the state space would have 13^5 is 371293 components (for five materials, the amounts 0, 5, 10, ..., 55, 60, this creates 371293 possible states). This is too much and far beyond the possibilities of the computer.

The number of stages depends on the level of aggregation (see Section 2.1), a stage represents a period. The number of stages per level of aggregation is for the

1-hour-level: 525 stages,
5-hour-level: 105 stages,
day-level: 60 stages,
week-level: 15 stages,
month-level: 3 stages.

In addition there are the first stage (the origin or the source) and the final stage (the destination or the sink).

2.5.1. SHORT DESCRIPTION OF THE PROCEDURE

At the beginning of the planning horizon (t=0), twenty hectares of cereal and zero hectare of the other materials do exist. The program determines the possible operations (depending on workability and the amount of materials) and constructs the states of the first stage. At this first stage, the program determines, for every state, the decisions (the operations), and generates and calculates the states for the second stage. It also looks for so-called corresponding states (i.e. the states at the second stage where the statevector $\mathbf{x}_t$ has the same values for the state variables but another link to the first stage) at the second stage. If there is any, the program calculates immediately the minimum of cost of the already existent state at t and the same new state at t using the value function.

The algorithm handles every stage. Finally, the program calculates, for the destination stage or the sink, the final state. For this state, the amount of all the materials is stated at zero. The optimal strategy will be found by finding the minimal path through the network by going back from destination to origin.

The program has been written in SIMULA 67. The input is the same as the input of the linear programming model and will be described in Section 2.6.

The problems and the results of the dynamic programming model will be described in Chapter 3.

2.6. THE LINEAR PROGRAMMING MODEL

Two linear programming models are developed, one using rounded workability and one using real workability (see also Section 2.4).

The linear programming model using rounded workability is based on the same set of decision variables as used in the dynamic programming model (see Section 2.5). The workability is constant for the whole planning period. The decision variables of the linear programming model are continuous with an upper boundary of 1 (the whole planning period) instead of 0-1 (the variables can be 0-1 if the Branch-and-Bound technique is used, but the computing time will increase enormously). Therefore, more than one decision (and therefore more than one combination) can be made per planning period. Summarized, the solution gives for each planning period a set of decisions and for each decision, the fraction of the used time in this planning period is given. The linear programming model using rounded workability is for comparison with the dynamic programming model.

The linear programming model using real workability is used to describe a real system. The decisions variables are continuous, but the upper boundary is not 1 but equal to the number of workable hours per planning period. The set of decision variables is slightly different: drying is treated as an individual gang instead of combined with other gangs (the decisions variables 13 to 24 in the dynamic programming model). Also the processing of grain is different. Instead of having one combination which can process dry *and* wet grain, there are now two combinations: one for the processing of dry grain and one for the processing of wet grain. For the model with rounded workability , if wet grain was delivered or not, that was taken care by the delivery matrix (CL_t). In this matrix, the workability of grain is also present (i.e. if the workability is zero, there is no wet grain, then the delivery capacity of wet grain is also zero, if the workability is one, i.e. the whole planning period is workable for wet grain, then the delivery capacity is equal to the working rate of the combination grain harvesting). For real workability, a planning period can have a different number of workable hours, therefore, this approach of using the delivery matrix to present the workability of wet grain is not possible. Two different combinations are therefore used.

The model with rounded workability.

This model is primarily for comparison with the dynamic programming model. Therefore, the same variables (but continuous instead of 0-1) and size of farm (twenty hectares) is used. This is a low amount. To meet problems of finishing work in time, or a schedule which does not fit in the season of five weeks, the linear programming model is also calculated with a larger initial amount of cereal, sixty hectares.

The model is divided into four submodels, one for each level of aggregation except for the 1-hour-level. The model at 1-hour-level is the same as the model at 1-hour-level with real workability and will be discussed there. The linear programming formulation is as follows:

Minimize Z

$$Z = \sum_{t=1}^{T} \{ \sum_{j=1}^{5} (tc_t^j \cdot x_t^j) \quad +$$

$$\sum_{j=1}^{5} \sum_{k=1}^{23} d_t^k \cdot oc_t^j(k) \quad +$$

$$\sum_{k=13}^{24} d_t^k \cdot DC \; \}$$

subject to the restrictions

$$x_0^j = A_j \qquad \text{for } j=1, \ldots, 5$$

$$x^j_{t-1} + \sum_{k=1}^{24} \{-cp^j_t(k)\cdot d^k_t + cl^j_t(k)\cdot d^k_t\} - x^j_t = 0 \qquad \text{for } t=1, \ldots, T, j=1, \ldots, 5$$

$$\sum_{k=1}^{24} d^k_t = 1 \qquad \text{for } t=1, \ldots, T$$

and

$$x^j_t \geq 0, 0 \leq d^k_t \leq 1 \qquad \text{for } t=1, \ldots, T, j=1, \ldots, 5, k=1, \ldots, 24$$

Aj =	the initial amount of material j (ha)
DC =	the drying cost per period ($f\cdot$period^{-1})
T	the total number of periods in the planning horizon (depends on the level of aggregation)

If the workability for material j is false (there are no workable hours) in period t, than $cp^j_t(k)$ has the value zero (for all k).

The linear programming model calculates costs in the same way as the dynamic programming model. The delivery date of straw, bales, stubble and wet grain is unknown, so the model also works with fixed timeliness cost per period for the materials. The costs are calculated at the end of each period. The linear programming model uses the same periods (or intervals) as the dynamic programming model.

The software package used to solve the linear programming models is LINDO (1981). It can handle problems with 800 constraints and 5000 variables. The 5-hour model (the largest model with rounded workability) has 635 constraints and about 2625 variables. The solver can handle this problem. The matrix generator for LINDO and this particular problem has been written by the author in SIMULA 67.

The model with real workability.

This model cannot be used to compare with the dynamic programming model because the initial amount is sixty hectares only. The operations in this model have for every period their own number of workable hours. A workability constraint is needed for every operation and not only for the combination (which can deal with more than one operation). This constraint restricts the quantity of work in the period according to the limits of workable hours. The matrix contains more constraints than the matrix of the model which uses rounded workability. But there are fewer variables while drying is taken as a separate operation. The linear programming formulation is as follows:

Minimize Z

$$Z = \sum_{t=1}^{T} [\sum_{j=1}^{5} \{tc^j_t /2.0 \cdot x^j_t\} \qquad +$$

$$\sum_{j=1}^{5} \{ \sum_{k=1}^{11} d_t^k \cdot oc_t^j(k) + \sum_{k=25}^{29} d_t^k \cdot oc_t^j(k) \} \qquad +$$

$$d_t^{24} \cdot DC \ ]$$

subject to the restrictions

$$x_0^j = A_j \qquad \text{for } j=1, \ldots, 5$$

$$x_{t-1}^j + \sum_{k=1}^{12} \{-cp_t^j(k) \cdot d_t^k + cl_t^j(k) \cdot d_t^k\} +$$

$$\sum_{k=24}^{29} \{-cp_t^j(k) \cdot d_t^k + cl_t^j(k) \cdot d_t^k\} - x_t^j = 0 \qquad \text{for } t=1, \ldots, T, j=1, \ldots, 5$$

$$\sum_{k=1}^{12} d_t^k + \sum_{k=25}^{29} d_t^k = PL_t \qquad \text{for } t=1, \ldots, T$$

$$0 \le d_t^{24} \le PL_t \qquad \text{for } t=1, \ldots, T$$

$$0 \le d_t^k \le WK_t^j(k) \le PL_t \qquad \text{for } t=1, \ldots, T, j=1, \ldots, 5, k=1, \ldots, 12,25, \ldots, 29$$

and

$$x_t^j \ge 0 \qquad \text{for } t=1, \ldots, T, j=1, \ldots, 5$$

A_j = the initial amount of material j (ha)
DC = the drying cost per period (ƒ·period^{-1})
PL_t = the length of the period t (h)
$WK_t^j(k)$ = the number of workable hours for material j processed by combination k in period t

Additional variables are (for the different treatment of grain, see the introduction of this section):

d_t^{25} = harvesting wet grain with two men in period t
d_t^{26} = harvesting wet grain with one man in period t
d_t^{27} = harvesting wet grain (one man) and baling period t
d_t^{28} = harvesting wet grain (one man) and bale gathering in period t
d_t^{29} = harvesting wet grain (one man) and ploughing in period t

The calculation of timeliness costs is different. The model takes the average of the timeliness costs for every period. It takes the fixed timeliness costs for each period and divides it by two. This gives a better representation of reality. According to the timeliness cost, the linear programming model and the dynamic programming model behave different from the simulation model, i.e. the simulation model divides the timeliness cost by two only when material is processed and not each period (as the linear and the dynamic programming models do).

The software package used to solve the linear programming models with real workability is SCICONIC (1983), a powerful linear programming solver. The size of the matrix for the model is:

level	rows	columns	non-zero elements
1-hour	11225	2795	67542
5-hour	2317	2421	13632
day	1327	1386	7532
week	337	351	1912
month	73	75	392

The model at 1-hour-level was too large for SCICONIC, (in 1986 SCICONIC supports a maximum of 4097 rows) , therefore, for the model at 1-hour-level the matrix of the model with rounded workability was taken and this gave the same solution as the model with real workability. The size is now:

level	rows	columns	non-zero elements
1-hour	3682	12081	30400

The matrix is formulated with a matrix generator and the results are operated by a report writer for proper output (see Appendix A, Table A.1). These programs have been written in FORTRAN IV by the author.

Both the linear programming model and the dynamic programming model have two inputfiles; a costfile and a weather datafile. The costfile is the same for both and it contains:

- the timeliness costs of the materials wheat, straw, bales, stubble and wet grain;
- the overtime costs, *f*10.00 per hour for overtime (Monday till Saturday) and *f*15.00 per hour for overtime (Sundays);
- drying costs (drying of wet grain), *f*30.00 per hour;
- initial amount of cereal, sixty or twenty hectares;
- rate of operation of the gangs per hour ($ha \cdot h^{-1}$):

grain harvesting, with two men:	2
grain harvesting, with one man:	1
baling:	2
bale gathering:	2
ploughing:	1
drying:	1

The rate of operation is given in an integer format. This keeps the number of states of the dynamic programming model limited.

The weather file for rounded workability is the same for both models. It contains the following elements:

- date: month, day, type of the day (1 = Monday, 2 = Tuesday, ..., 7 = Sunday);
- part of the day; normal hours, overtime hours or Sundays;
- length of a part of the day in hours;
- number of the day (from one to thirty-five in the season of five weeks);
- workability properties (five variables), for dry grain harvesting, for wet grain harvesting, for baling, for bale gathering and for ploughing. These properties have the value 0 (workability is false) or 1 (workability is true) and concern the whole period.

The weather file for the model with real workability (only used by the linear programming model) has the same data except for the workability properties. For every period, the total of workable hours is given for every combination of gangs (in variable $WK_t^j(k)$).

The data for the model with rounded workability as well as the data for the model with real workability are derived from hourly weather-data and moisture content data (with use of transformation programs which have been written in SIMULA 67).

2.7. THE SIMULATION MODEL

Simulation is also used for problems with rounded workability (with an initial amount of cereal of twenty and of sixty hectares) and for problems with real workability (sixty hectares only). The simulation model is fully described in Van Elderen (1987). This section contains a short description of the model.

The simulation model makes use of a heuristic strategy. This strategy in the scheduling problem evaluates the current state of the system and its expected development at each decision date. The basic concept is that a certain urgency of an operation is related to the expected timeliness loss of materials. This can only be prevented by processing the material without delay. The urgency of processing a material is based on the timeliness of operation which is represented by the timeliness function. From such functions, the urgency and lack of urgency (dis-urgency) of materials are derived. The urgency of materials are assigned to the gangs and to the combinations by distributing the urgency of materials among the gangs processing that material relative to their capacities. Such an urgency of a gang is corrected by subtracting the variable costs of, for example, overtime. The urgency of a combination is the sum of the urgency of those gangs which have a positive corrected urgency and can operate in the combination. Whether a gang is applied depends on equipment, weather, material properties (moisture content), available material for processing and available storage for the materials delivered. After selecting the preferred combination (with maximum urgency), the next decision dates determined by the end of operation, filling the storage, start of overtime or pause or no-work time, change of weather expectation or properties of materials, machine failure or by finish of repair or service.

The heuristic works with expected workability (as a long-range expectation) and not as the linear and dynamic programming models, with knowledge of the future workability (the workability of the twelve years; 1957—1968). Therefore, the heuristic is myopic and not able to produce an optimal strategy. For the same reason is the simulation model not deterministic in the sense as the linear and dynamic programming models are called deterministic.

The decision process takes place at discrete moments in time. For instance at a decision point of time, a set of gangs is selected to execute operations for some time. Executing operations results in continuous change of amounts of materials processed or delivered. For the scheduling of operations, it is not necessary to know the state of the system at each moment of time; it suffices to consider the events when one or more structural properties of the system are changed. In the decision process events occur when an operation starts or ends (the so-called event-step incrementation, see Wagner, 1977).

The weather information is given at equidistant points of time, for example hourly records. Events also occur when the weather synopsis in the past changes, or when a material changes from being ready to unready for processing because of its moisture content. More details of this model will be described in the input-files of the simulation program (see below).

Two models have been developed (Van Elderen, 1987); a simplified version, which can be used for common scheduling problems, and a more extensive one which has been special developed for the grain harvest. However, in this investigation, the simplified version is used because:

1. the weather-files of the more extensive version contain too much information and are difficult to change. The weather-files used to specify workability are an important function of aggregation and have to be changed for every level of aggregation;

2. in the extensive version the moisture content of straw influences the capacity of grain harvesting. This capacity must be fixed for comparison with the other models.

The simplified version can be used for all kinds of activities. It has six input-files (see also Van Elderen, 1987):

A. An experiment file (a list of files with input data);

B. A file with field properties;

C. A file with sets of the man-machine system;

D. The material file;

E. The environment file.

Only the weather-file needs more explanation. There are two kinds of weather-files, one for rounded workability and one for real workability.

1. Rounded workability, the weather file contains the following data:

   - date, month, day, hour and type of the day (1 = Monday, ..., 7 = Sunday);
   - rainfall in mm;
   - moisture content of grain (a minus stands for wheat remaining moist, the cereal cannot be processed when moisture remains);
   - moisture content of straw;
   - moisture content of soil.

   The steps in time between the successive dates are determined by the level of aggregation. The material properties are derived from the input-data used by the linear programming model and the dynamic programming model (see Table 2.2).

2. Real workability. The data and the steps in time are the same as in the weather-file for the simulation model with rounded workability. However a period (with length equal

Table 2.2. The conversion of linear programming (LP) and dynamic programming (DP) workability input to simulation workability input.

LP/DP	workab.	Simulation	material properties
dry grain	1	m.c. grain	≤ 19 %
wet grain	1	m.c. grain	> 19 and ≤ 23 %
straw	1	m.c. straw	≤ 25 %
bales	1	rainfall	≤ 1 mm
stubble	1	m.c. stubble and rainfall	≤ 1 mm and ≤ 47 %
dry grain	0	m.c. grain	> 19 %
wet grain	0	m.c. grain	≤ 19 or > 23 %
straw	0	m.c. straw	> 25 %
bales	0	rainfall	> 1 mm
stubble	0	m.c. stubble and rainfall	> 1 mm or > 47 %

Table 2.3. The different characteristics of the groups of hours (+ = property in an hour agrees with the characteristics, – = characteristic is not met by the property in an hour, from Van Elderen, 1977, Table 21).

Groups of hours	m.c. grain <19%	m.c. grain 19—23%	m.c. straw < 25%	mm rain < 1 mm	m.c. stubble < 47%
1	+	–	+	+	+
2	+	–	+	+	–
3	+	–	–	+	+
4	+	–	–	+	–
5	–	+	+	+	+
6	–	+	+	+	–
7	–	+	–	+	+
8	–	+	–	+	–
9	–	–	+	+	+
10	–	–	+	+	–
11	–	–	–	+	+
12	–	–	–	+	–
13	–	–	–	–	–

to the length of one step) is divided into groups of hours with similar characteristics. The groups of hours are ordered (Table 2.3) such that workable hours precede unworkable hours. First are groups with dry grain harvesting, then those with wet grain harvesting, followed by hours not available for wheat harvesting and so on for processing straw, bales and stubble, ending with the hours of rain. Such a sequence approximates to the expected use of workable hours in the linear programming model where, within a period, the sequence is discarded (Van Elderen, 1977). Moreover, all the hours are placed before the overtime hours and within each group, the ordering of Table 2.3 is used

The data are derived from the input-data of the linear programming model with use of transformation programs written in SIMULA 67.

The simulation program has also been written in SIMULA 67. The results of the execution of the models and the discovered problems will be discussed in Chapter 3.

Chapter 3

RESULTS AND COMPARISON OF THE MODELS

The results of the models, the differences between them and, the difference between the levels of aggregation within each model will be discussed in this chapter (see also Wijngaard, 1986a). All the models examined in this dissertation are given in Table 3.1.

The chapter is divided into three parts, the first part (Section 3.1) for the models with rounded workability and an initial amount of cereal of twenty hectares (the dynamic programming, the linear programming and the simulation model); the second part (Section 3.2) for the models with rounded workability and an initial amount of cereal of sixty hectares (the linear programming and the simulation model), and a third part (Section 3.3) for the models with real workability and an initial amount of cereal of sixty hectares (the linear programming and the simulation model). For each part, the results will be presented using graphs. The quantitative results are stated in Appendix B. The following costs are involved: timeliness cost of cereal, straw and bales; the overtime cost; the drying cost and two kinds of total cost (i.e. the total cost which is the sum of the timeliness costs of all the materials, the overtime cost and the drying cost, and the total cost minus the timeliness cost of bales). Total cost is reduced by the timeliness cost of bales, because the timeliness cost of bales occurs arbitrarily (i.e. the simulation model does not take full account of the timeliness costs of bales), especially in the simulation model (further explained in Section 3.1).

3.1. ROUNDED WORKABILITY WITH AN INITIAL AMOUNT OF TWENTY HECTARES

From hereon the term ROUN20 will be used to indicate the models discussed in this section. The results are presented in Tables B.1 to B.9. The models are, the linear programming model, the simulation model and the dynamic programming model. These models are aggregated models. The solution of the aggregated models is disaggregated, and treated as input of the reference model. For example, if there are two models: model A and model B and both are aggregated. Then a solution is derived by executing these models. These solutions are dis-aggregated and given as input of the reference model C. The reference model is executed and the solutions are compared. In scheme, this is as follows:

Table 3.1. The examined models (marked with #, DP is dynamic programming, Sim is simulation, LP is linear programming) and the aggregation levels.

Aggregation level	ha	DP roun	DP real	DP prob. 1)	Sim roun	Sim real	LP roun	LP real	LP relax.
1-h	20								
	60				# 4)	# 4)	# 5)	# 5)	
5-h	20	#		# 2)	#		#		
	60				#	#	#	#	
day	20	#			#		#		
	60				#	#	#	#	# 3)
week	20	#			#		#		
	60				#	#	#	#	
month	20	#			#		#		
	60				#	#	#	#	

1) Probabilistic, all the other models are deterministic.
2) For difference of effect of unknown and known future (Chapter 5).
3) Relaxed model for a farm with two, three or four men (Chapter 4).
4) These models are the same.
5) These models are the same.

Way of comparison: within the row, the elements with each other (models), and within the column, the elements with each other (aggregation).

$$\left.\begin{array}{lll} \text{aggregated model A} & \rightarrow & \text{dis-aggregated in reference model C} \\ \text{aggregated model B} & \rightarrow & \text{dis-aggregated in reference model C} \end{array}\right\} \text{compared}$$

The dis-aggregation takes place as follows. Firstly, a solution is derived from an aggregated model. This solution gives for the planning horizon the optimal set of decisions. For example, if the length of a planning period is equal to a week, then the solution predicts decisions for the whole week at once. The decision indicates the amount of work that has to be done by a certain gang, for example gang 1, in a planning period, say week A. The solution will be dis-aggregated. This means that gang 1 has to be scheduled again in the same week, i.e. week A. But week A is not taken as a whole (as in the aggregated model), but it is partitioned in smaller planning periods (with a minimum length, e.g. an hour or five hours). Therefore, the amount of work that has to be done by gang 1 has to be scheduled for the planning periods in week A.

For example:
    aggregated model:
        model at week-level:
            gang 1 scheduled in the week A for forty hours (as a whole);

    reference model:
        model at 1-hour-level:
            gang 1 also has to work for forty hours in the first week.

When the workability is rounded, then it is possible that the complete week (forty hours) in the aggregated model (at week-level) is workable. But, in the reference model (at 1-hour-level), complete hours are workable. The sum of workable hours for a whole week in the reference model does not have to be equal to a complete week workable (as in the aggregated model). Therefore, it is possible that gang 1 cannot be scheduled completely in week A. If this is not possible and there is still material left at the end of the week (which was processed by the aggregated model) then this material will become an additional penalty equal to the timeliness cost of this material at the end of the season (at the end of five weeks). It is assumed that this material will be lost to prevent the same problem (i.e. with scheduling and not processing a material completely) in the next week.

Note: the assumption of lost material is made to prevent difficulties with scheduling of the aggregated schedule for use by the reference model (as mentioned above). This can be critical in practice, but the dis-aggregated schedule does not have to be used especially in practice. Dis-aggregation does only take place to calculate, in a correct way, the differences between lower and higher levels of aggregation.

For example:

aggregated model:			
	week 1:	initial amount:	20 ha
		processed:	10 ha
	week 2	initial amount:	10 ha
		processed:	10 ha
	week 3	initial amount:	0 ha
reference model:			
	week 1:	initial amount:	20 ha
		processed:	8 ha
	week 2	initial amount:	10 ha
		processed:	10 ha
	week 3	initial amount:	0 ha

In week 1, two hectares of the material cannot be processed (due to scheduling problems). Nevertheless, week 2 starts with ten hectares of the material (instead of twelve hectares). The two hectares will be charged with an additional penalty and it is assumed that it will be lost to prevent problems with scheduling in week 2.

It is also possible that a combination of gangs has to be assigned to a certain planning period (in the reference model) where the workability is false for a material processed by one of the gangs. For example, for the combination grain harvesting and straw baling, it is possible that there are no workable hours for either cereal or straw in the planning period. Therefore, there are two possibilities: cereal is not workable or straw is not workable. How to handle is described below.

1 Cereal is not workable in the planning period (in the reference model). Cereal is treated as the main material, i.e. one has to process cereal first before one can process straw (which is delivered during the processing of cereal). Therefore, if cereal cannot be processed, then straw cannot be delivered and there is no reason to assign the combination to the planning period. The whole combination will be shifted to a later period

in the planning horizon (until cereal is workable again) and another combination can possibly be assigned to the planning period.

2 Straw is not workable in the planning period (in the reference model). Cereal is still workable. If this occurs then the combination will be divided and only processing of cereal takes place. Straw will be processed as a separate operation later in time (but as soon as possible to decrease timeliness cost of straw).

The other combinations are treated in the same way. The dis-aggregation is carried out by hand, the reference model is only executed to obtain the different cost catagories.

The reference model is for ROUN20 the model at 5-hour-level. For the other models (see Sections 3.2 and 3.3), the models at 1-hour-level are used as reference model.

The different models are compared by cost. First costs such as timeliness cost of the cereal material, straw and bales, the drying cost and the overtime cost will be discussed, then total cost and total cost minus the timeliness cost of bales. These costs are an average of the cost per year over twelve years. Total cost is also reduced by the timeliness cost of bales, because the timeliness cost of bales occurs arbitrarily, especially in the simulation model. The simulation model does not assign a high urgency to the operation of bale-gathering because it considers bale-gathering as a less important operation (the grain harvesting itself is more important, Van Elderen, 1987), and therefore, does not process bales timely (what was expected considering the timeliness cost which is *ƒ*21.10 per day). The linear programming and the dynamic programming models do assign a high urgency (they take the timeliness cost of bales into account), and therefore process bales in a fast way (or prevent to have bales at the end of a period). The three models can only be compared using total cost minus the timeliness cost of bales).

The discussion of each cost factor will contain all or parts of the following points:

- the differences between the models and the levels of aggregation shown by figures with the slopes described quantitatively. A slope is a linear interpolation between the results at different levels of aggregation. In the figures represents the x-axis the levels of aggregation (expressed in length of the planning period in hours) and the y-axis the different cost catagories. Figures are a better way to present the differences than quantitative values because they immediately make clear the ratio between models and levels of aggregation. All the figures are given at the end of each section;

- the relation between cost and the workability data; to examine the effect of less or more workable hours on the result of the models;

- trying to explain the differences using the slopes of the graphs, the workability data, and the average and the sample standard deviation of the cost.

The results of the models at month-level deserves special attention. Rounding off the number of the workable hours implies that the number of workable hours for cereal is zero at month-level for all the periods of every year. Processing of cereal is not possible, therefore the timeliness costs of cereal are maximum. For a harvesting period of five weeks, it is assumed that the penalty will be *ƒ*325.00 per hectare. With an amount of twenty hectares, the total timeliness cost of cereal will be twenty times *ƒ*325.00 which is *ƒ*6500.00. The other costs are zero (there is no processing of straw, bales and stubble). Therefore, the total cost will be *ƒ*6500.00.

The timeliness cost of cereal

The results of the different models are shown in Figure 3.1.a (note that the x-axis is logarithmic). The cost-functions have almost the same shape. The difference in cost for each model between the 5-hour-level and the day-level is approximately negligible. The average slope of the three cost-functions between 5-hour-level and day-level is $-1.18\ f{\cdot}h^{-1}$, a slight decrease in cost. The costs increase from the day-level to the week-level, the average slope here is $11.46\ f{\cdot}h^{-1}$. The increase from week-level to month-level is almost the same, the average slope being $12.47\ f{\cdot}h^{-1}$.

An attempt is now made to explain the differences using workability percentages.

> Definition 3.1
> A *workability percentage* is calculated making use of the average over twelve years of the sum of (1) workable hours for dry grain from a total of five weeks (is the length of the planning horizon) and of (2) workable hours for wet grain from a total of five weeks. This average is divided by the total number of hours it is possible for men to work. This is five weeks of 105 hours which is 525 hours.

The workability percentages (of the workability of cereal) are:

1-hour-level:	235 hours workable =	45%.
5-hour-level:	235 hours workable =	45%,
day-level:	223 hours workable =	42%,
week-level:	112 hours workable =	21%,
month-level:	0 hours workable =	0%.

The decrease in workable hours is caused by rounding off.

The increase of timeliness cost is due to a decrease in the workable hours. The decrease in workable hours causes a shift of finishing the grain harvest to a later point in time, this means a delay of the completion of the harvest. This is true for all the models.

Dealing with the linear programming and the dynamic programming results, the following explanation can be given. The length of a planning period in the models at day-level, is larger than the length of a planning period at the 5-hour-level. The costs are calculated at the end of a planning period. This is also done if cereal is completely processed at an earlier point in time *during this period*, but the finishing point of the operation is the same as the end of the planning period. This gives an error which becomes larger according to the level of aggregation and becomes greater while the difference in time between the harvest finishing point and the end of a planning period increases. This error must be introduced while the exact point in time of finishing the grain harvest (or a depending action) is unknown.

With linear programming, there can also occur more decisions in one period; the occurrence of non-equality of finishing point of operation and end of period can occur more frequently. Therefore the error may become larger.

This error does not occur with simulation. The timeliness cost of cereal is calculated at the exact point in time, when the grain harvest is stopped (the total harvest or parts of it).

The timeliness cost of straw

The costs are shown in Figure 3.1.b. The cost at month-level is zero because there is no delivery of straw.

The cost-function lines of the different models show about the same slope, only the cost-function of the simulation model is different at week-level. The average workability percentages per level of aggregation (of the workability of straw) are:

1-hour-level: 289 hours workable = 55%.
5-hour-level: 299 hours workable = 57%,
day-level: 342 hours workable = 65%,
week-level: 335 hours workable = 64%,
month-level: 373 hours workable = 71%, (no relevance).

The linear programming solution shows a fast processing of the straw material and bales because the fixed timeliness cost of these materials per period is high. The processing of straw (and bales) is often in the same period as the processing of cereal. Therefore, there will hardly be any straw left at the end of the period and no calculation of timeliness cost of straw will be possible since the timeliness cost of straw is only calculated if there is material left at the end of a period. The simulation model calculates the timeliness losses at moments when an operation stops, so losses can occur within a period; this is the main reason why the week-level results in higher timeliness cost for the simulation model than for the linear and the dynamic programming models.

The dynamic programming solution implies higher costs than the linear programming solution because the dynamic programming strategy is forced temporarily to lay aside some of the materials. It can only take one operation per period, contrary to linear programming. This set aside of materials becomes larger at higher levels of aggregation.

The timeliness cost of bales

The costs are shown in Figure 3.1.c. The solution of the linear programming model shows very low cost, the transportation of a number of bales across a boundary of a period rarely happens. The processing of bales often takes place at the same time as the processing of straw. This is due to high initial timeliness cost of bales per period. The model tries to avoid the transportation of material across the boundary of the period because timeliness cost is only calculated if and only if transportation across a boundary of a period occurs (some amount of material exists at the end of a planning period).

The dynamic programming model often gives a solution where the processing of bales and straw takes place in the same period. This is true for the model at week-level. If transportation of bales across a boundary of a period at week-level occurs then there are extremely high timeliness costs because the fixed timeliness costs of bales per period are very high at week-level.

For the simulation model, the expectation is that the total timeliness cost of bales is low, due to the high penalty of the initial timeliness cost of bales (i.e. the model tries to process bales as quick as possible). However, this is not the case. The high timeliness costs of bales for simulation occur due to the myopic strategy which does not know the future workability of bale gathering. The explanation can be found in Van Elderen (1987). Therefore, the total cost must be reduced by the timeliness cost of bales for a balanced interpretation of the results of the models.

The average workability percentages (of the workability of bales) are:

1-hour-level: 503 hours workable = 96%.
5-hour-level: 518 hours workable = 99%,
day-level: 523 hours workable = 100%,
week-level: 525 hours workable = 100%,
month-level: 525 hours workable = 100%, (no relevance).

The workability almost is 100% in all cases, therefore, it is not a restrictive, cost determining factor.

The drying cost

The drying costs (Figure 3.1.d) are calculated for the duration of processing, contrary to the timeliness costs of materials which are always calculated for the whole period (even if the duration of processing is not equal to the length of a period). The simulation solution gives high drying cost because the processing of cereal is done immediately, irrespective of whether the grain is dry or wet. The linear programming and the dynamic programming models try to delay the processing of cereal until the sum (over the entire season) of timeliness costs of cereal and the drying costs are at a minimum (the storage capacity of the drier is assumed unlimited).

The overtime cost

The overtime costs (Figure 3.1.e) are also calculated for the duration of processing. However the solution of the simulation model hardly shows any increase in costs. The simulation model uses more overtime hours because the strategy is myopic and unable to optimize over the entire season. For the simulation model at week-level, the use of overtime hours however is lower due to the predicted ordering of workability (Table 2.3) and of regular time before overtime (within a week).

The linear programming solution shows a decrease in costs from the 5-hour-level to day-level and uses some hours of overtime for processing cereal only.

The dynamic programming model uses overtime hours more sparingly than the linear programming model. Dynamic programming uses whole periods whilst the linear programming model may only use a part of a period (i.e. an overtime period). Because the overtime cost is calculated by the hour, the linear programming model can decide to use a part of a period which will give lower cost overall. The dynamic programming model can only decide to use a whole period and so well charge for it. Therefore, the dynamic programming model will not choose to use overtime hours readily.

The length of a planning period is longer at higher levels of aggregation, therefore it takes more time to process a material completely when the models make use of the normal periods only (i.e. the periods with regular hours). The model has to skip large periods with overtime hours, this will lead to higher timeliness costs. The dynamic programming and the linear programming models will decide to choose a period with overtime hours more frequently at higher levels of aggregation instead of skipping such periods which have associated timeliness costs.

The total costs

The total costs (Figure 3.1.f) are the sum of the different cost catagories. The timeliness costs of cereal have the largest influence on the total cost. The function of total cost has almost the same slope as the function of timeliness cost of cereal (Figure 3.1.a).

The total costs of the solution of the simulation model are much higher (up to two times) than the total costs of solution of the dynamic programming model (due to the myopic strategy of the simulation model). The latter are slightly higher than the total costs of the solution of the linear programming model. The linear programming and the dynamic programming models both give optimal solutions over the complete season with regard to the models themselves. However the linear programming model gives lower costs because the periods are used in a better way, i.e. more sets of operations are scheduled per period. The dynamic programming model can only schedule one set of operations per period.

In some cases, the linear programming model gives a solution with higher cost than the solution of the dynamic programming model. For example, the years 1961 and 1968 for the models at 5-hour-level. The reason is that in those years the dynamic programming model, which determines a schedule for only one week (for the model at 5-hour-level), cannot process all the materials in one week (contrary, the linear programming model has a planning horizon of five weeks). Therefore, a solution is chosen where stubble (i.e. the less important material) is not processed and all the other materials are completely processed. The linear programming model takes account of the processing of stubble and can put processing of stubble in the first week at the cost of processing other materials later involving higher cost (only the timeliness cost of the other materials is taken into account, not the timeliness cost of stubble). Therefore, the solution of the linear programming model contains higher cost. The same reason is true for other levels of aggregation.

The simulation model cannot give an optimal solution because the strategy is myopic (and the algorithm is heuristic).

The cost are increasing (as predicted by the reference model) according as the level of aggregation becomes higher. But, for the linear and the dynamic programming models, the cost are slightly decreasing between 5-hour-level and day-level. This has to do with the way of calculation of timeliness cost. The timeliness cost is only calculated at the end of the planning period. At higher levels of aggregation, the fixed timeliness cost per planning period increases. Therefore, the model can decide to let rest as less as possible of a certain material at the end of a planning period to avoid calculation of timeliness cost. At higher levels of aggregation, this behaviour takes even more place. At a low level of aggregation, the fixed timeliness cost is lower, and therefore, it occurs more often that a material passes the planning period boundary, i.e. the model will process it later. At higher levels of aggregation, processing takes place in a faster way. So, after dis-aggregation, this will give lower cost for the dis-aggregated model.

But, after day-level, cost are increasing again. This occurs through less workability at higher levels of aggregation, which diminish the effect of the timeliness cost.

Another possible reason of decreasing costs is the way of dis-aggregation. The dis-aggregation is carried out by hand and therefore errors can arise during this dis-aggregation.

Because of the arbitrary occurrence of the timeliness cost of bales, the total cost minus the timeliness cost of bales is also considered. This is shown in Figure 3.1.g. With rounded workability and an initial amount of twenty hectares, the difference between Figure 3.1.g and Figure 3.1.f is hardly relevant.

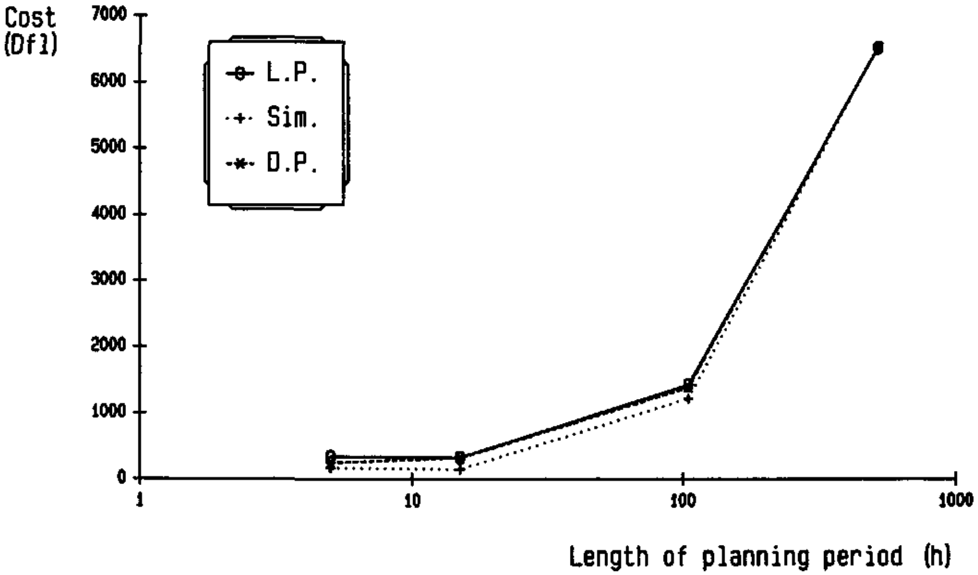


Figure 3.1.a. The timeliness costs of cereal (*f*) against the level of aggregation (in length of planning period, h) for ROUN20. L.P. is linear programming, Sim. is simulation and D.P. is dynamic programming.

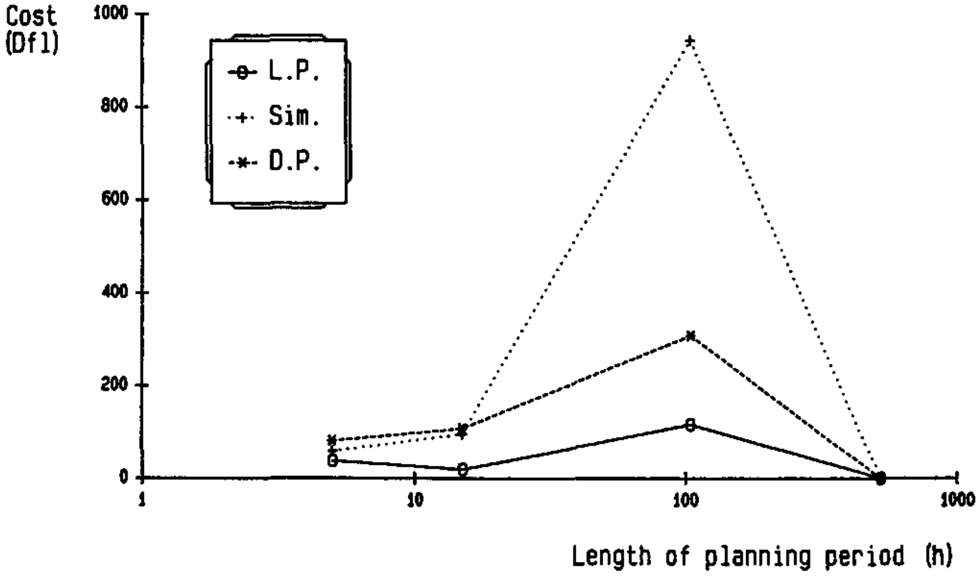


Figure 3.1.b. The timeliness costs of straw (*f*) against the level of aggregation (in length of planning period, h) for ROUN20. L.P. is linear programming, Sim. is simulation and D.P. is dynamic programming.

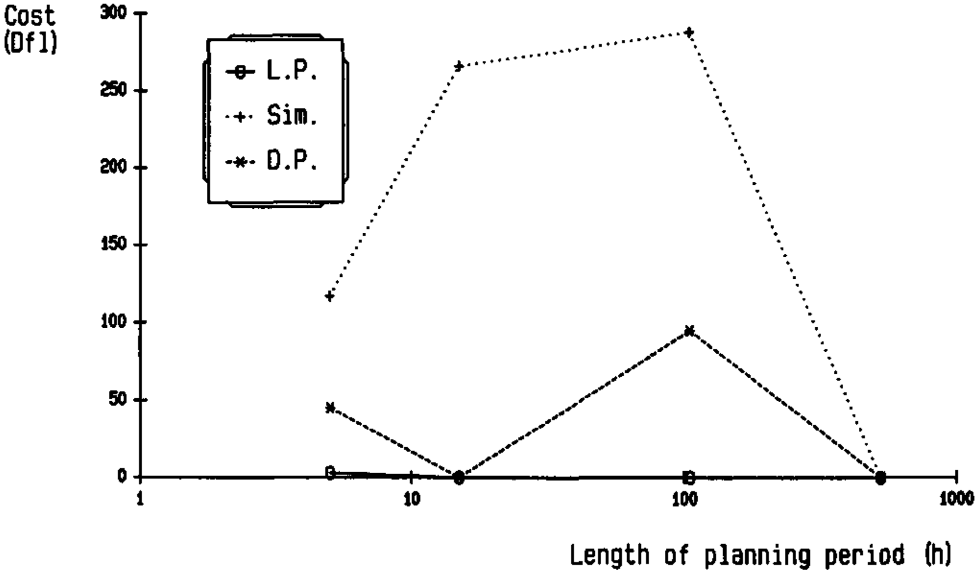


Figure 3.1.c. The timeliness costs of bales (*f*) against the level of aggregation (in length of planning period, h) for ROUN20. L.P. is linear programming, Sim. is simulation and D.P. is dynamic programming.

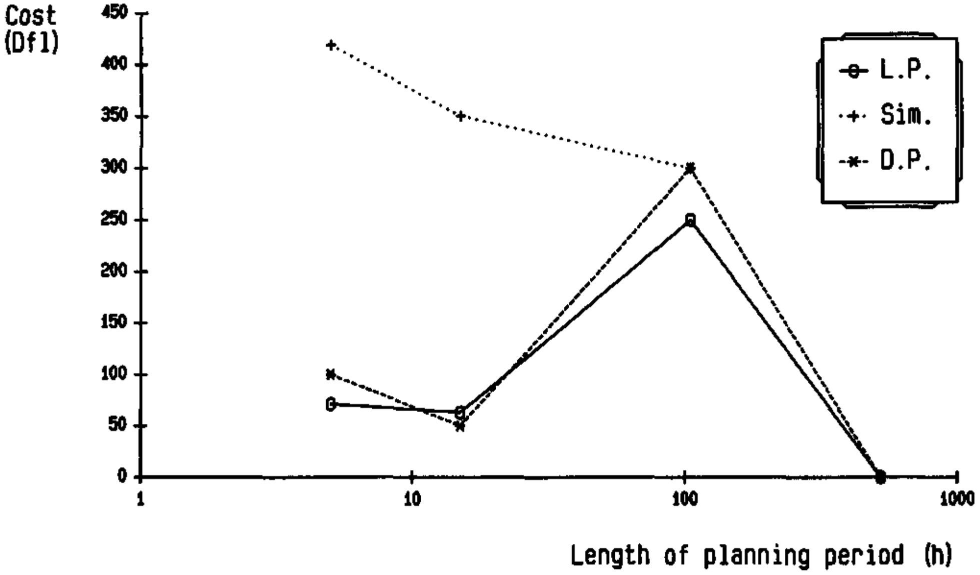


Figure 3.1.d. The drying costs (*f*) against the level of aggregation (in length of planning period, h) for ROUN20. L.P. is linear programming, Sim. is simulation and D.P. is dynamic programming.

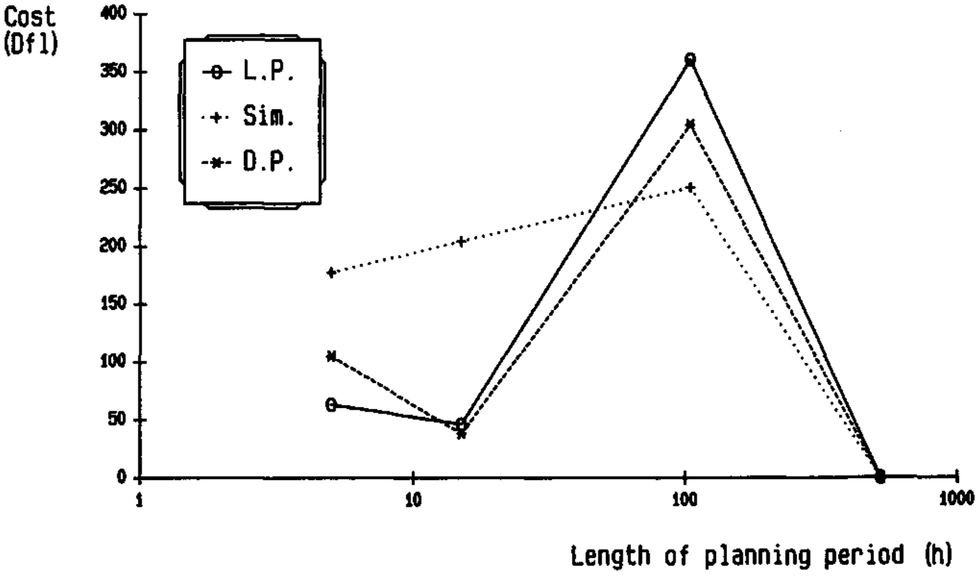


Figure 3.1.e. The overtime costs (*f*) against the level of aggregation (in length of planning period, h) for ROUN20. L.P. is linear programming, Sim. is simulation and D.P. is dynamic programming.

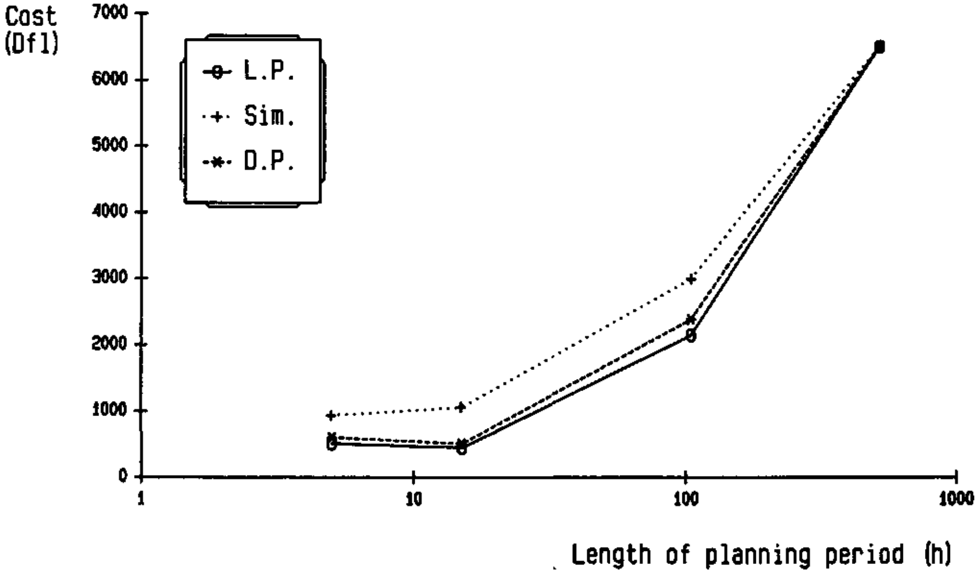


Figure 3.1.f. The total costs (*f*) against the level of aggregation (in length of planning period, h) for ROUN20. L.P. is linear programming, Sim. is simulation and D.P. is dynamic programming.

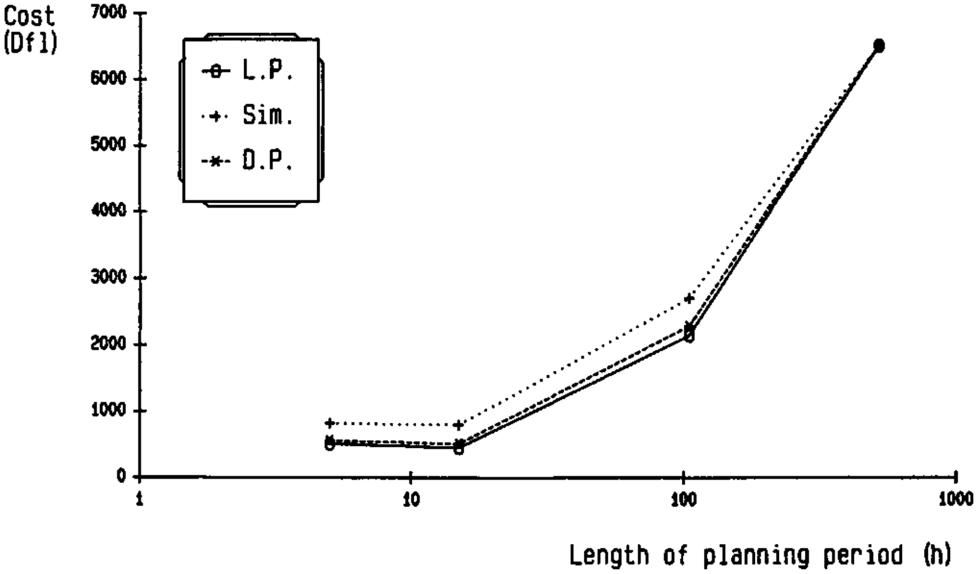


Figure 3.1.g. The total costs reduced by the timeliness costs of bales (*f*) against the level of aggregation (in length of planning period, h) for ROUN20. L.P. is linear programming, Sim. is simulation and D.P. is dynamic programming.

3.2. ROUNDED WORKABILITY WITH AN INITIAL AMOUNT OF SIXTY HECTARES

The term ROUN60 is used to indicate the models mentioned in this section. The results are given in Tables B.10 to B.17. The models are the linear programming model and the simulation model. The dynamic programming model is not used because the initial amount of cereal is too large. ROUN60 has the same conditions as ROUN20 except the initial amount of cereal. The discussion will also contain the differences between ROUN20 and ROUN60.

The number of workable hours for processing cereal is again zero for the models at the month-level. The timeliness costs of cereal are *f*6500.00 (initial amount of twenty hectares) or *f*19500.00 (initial amount of sixty hectares). The total costs are equal to the timeliness costs because the other costs are zero. Therefore, the models at month-level will not be discussed.

Only the remarkable differences will be analysed. It is possible to use 1-hour-level for the simulation and the linear programming models (with an initial amount of sixty hectares). The models at 1-hour-level will be used as a reference because they give the most detailed information. Solutions of the aggregated models will be disaggregated and evaluated again by substituting this disaggregated solution into the reference model.

The timeliness cost of cereal

The graph for ROUN20 (Figure 3.1.a) and for ROUN60 (Figure 3.2.a) show the same picture.

The timeliness cost of straw

The graphs (Figure 3.1.b for ROUN20 and Figure 3.2.b for ROUN60) again show the same picture.

The timeliness cost of bales

The results are shown in Figure 3.2.c. The results of the linear programming model with sixty hectares give higher costs at week-level than with twenty hectares. This is because the probability of passing through a period boundary with a fixed number of bales is larger for the model with sixty hectares than for the model with twenty hectares because there is more material to process with the same machinery capacity (and timeliness cost of bales is only calculated if there is any number of bales available at the end of a planning period). This also leads to higher costs for the model with sixty hectares (compared with twenty hectares).

The slopes of the cost-function of the results of the simulation model are presented in Table 3.2.

The rest of the graphs (the timeliness cost of bales given by the linear and the dynamic programming model) almost show the same picture (ROUN20 compared with ROUN60).

Table 3.2. The slopes of the cost-function of the timeliness costs of bales for the simulation model ($f\cdot h^{-1}$).

	total area	
slope	20 ha	60 ha
hour → 5-hour		30.25
5-hour → day[1]	14.90	19.92
day → week[2]	0.24	7.47

[1] There is a relative small difference between the results of the model with twenty hectares and the model with sixty hectares.

[2] There is a relative large difference. There is more cereal to process for an initial area of sixty hectares, this gives a lower priority for processing bales and the bales will remain longer on the field. The length of a period also becomes larger. These two factors cause relatively higher cost.

The drying cost

The results of ROUN60 (Figure 3.2.d) again show the same pattern as the results of ROUN20.

With an initial area of sixty hectares, there is more cereal to process, but the number of workable hours of processing wet and dry grain in the season remain the same for ROUN60 as for ROUN20. It is more difficult to process dry grain alone due to the lack of time and the model has to decide to process also wet grain. This is true for linear programming. The simulation model follows exactly the sequence of workable hours of 1-hour-level, 5-hour-level and day-level (see Chapter 2) and the strategy is unable to look ahead in the future to prevent the harvesting of wet grain. At higher levels of aggregation there are less workable hours of processing wet grain than of processing dry grain due to rounding off (to relatively lower levels). Therefore, there is less use of the workable hours for processing wet grain. The drying costs are lower. Another reason for lower drying cost is the ordering of workability with dry grain harvesting hours ordered before wet grain harvesting hours (Table 2.3).

The overtime cost

The results (Figure 3.2.e) show the same pattern as the results of ROUN20.

The increase from day-level to week-level is almost the same, for both models, for models with twenty hectares as with sixty hectares (i.e. in the linear programming and the simulation models). The explanation is the same as for ROUN20.

The total cost

The results (Figure 3.2.f) show about the same picture as the ROUN20 results. The timeliness costs of cereal possess the largest influence for both initial amounts of cereal. The shape of the cost-function of the models with sixty hectares is almost the same as those for the models with twenty hectares. This is true for linear programming as well as for simulation.

The results of the models at week-level are higher due to the higher timeliness costs of cereal and straw at week-level as can be expected with a higher amount.

The slope of the cost-function of the linear programming model between 1-hour-level and day-level is almost zero. The differences between 1-hour-level and day-level are very small; the total costs at 1-hour-level are 99% of those at day-level and the total costs at the 5-hour-level are 106% of those at the day-level. The total costs at the 1-hour-level are 94% of those at the 5-hour-level.

The differences for the simulation model are: the total costs at the 1-hour-level are 98% of those at the 5-hour-level and 98% of those at the day-level, the total costs at the 5-hour-level are 101% of those at the day-level.

For ROUN60, the cost are slightly decreasing between 5-hour-level and day-level (as for ROUN20). The explanation is the same as for ROUN20 (see Section 3.1, the total costs) and has to do with the way of calculation of timeliness cost.

The conclusion for both models is that if these slight differences are accepted, the models at day-level can be used instead of models at 1-hour-level since they give almost the same costs, while calculation of a model at day-level saves a lot of time. The models at week-level and at month-level should not be used because the difference in cost with the model at day-level is very significant. The conclusion is the same for the models with an initial amount of cereal of twenty hectares.

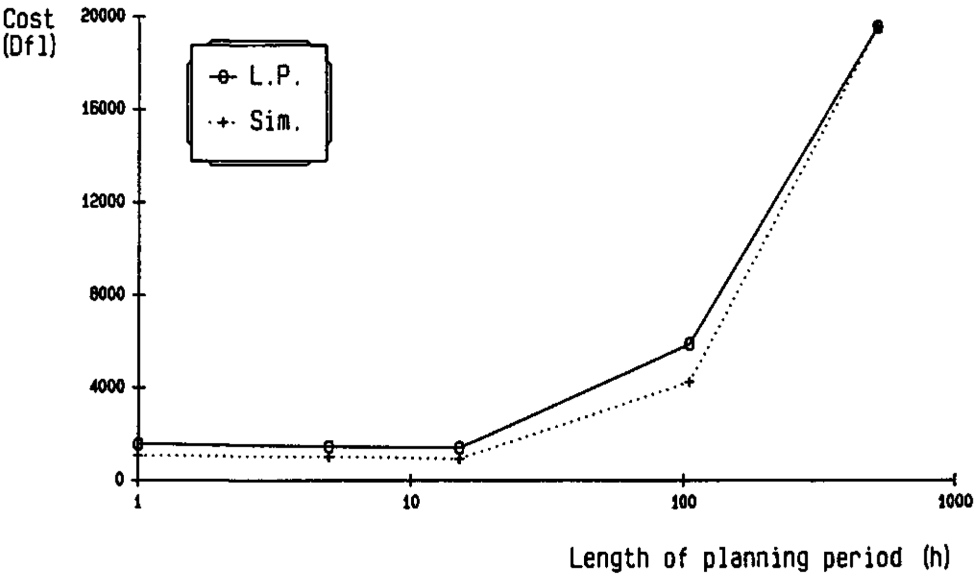


Figure 3.2.a. The timeliness costs of cereal (*f*) against the level of aggregation (in length of planning period, h) for ROUN60. L.P. is linear programming and Sim. is simulation.

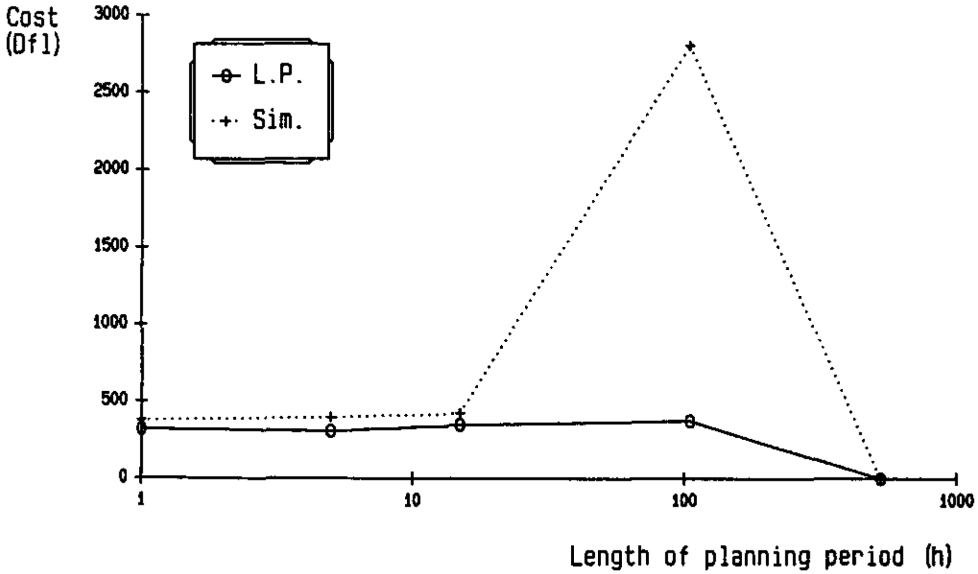


Figure 3.2.b. The timeliness costs of straw (*f*) against the level of aggregation (in length of planning period, h) for ROUN60. L.P. is linear programming and Sim. is simulation.

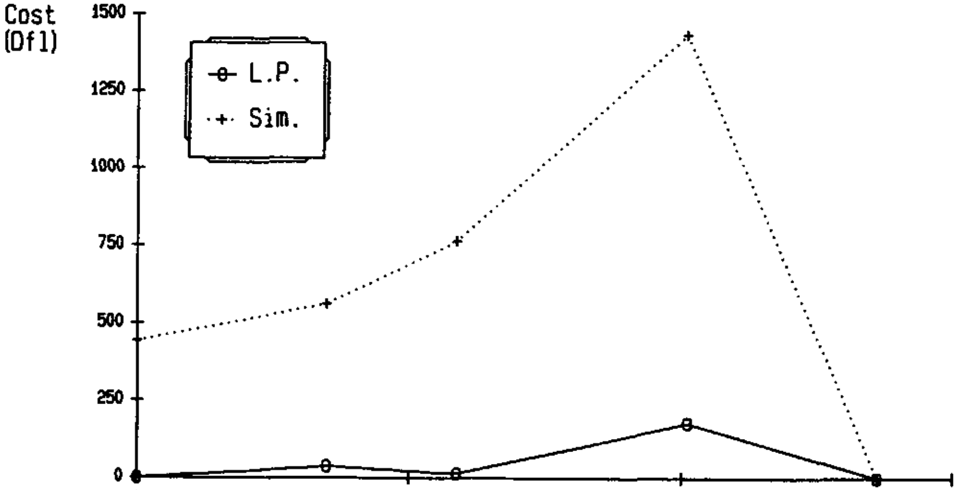


Figure 3.2.c. The timeliness costs of bales (*f*) against the level of aggregation (in length of planning period, h) for ROUN60. L.P. is linear programming and Sim. is simulation.

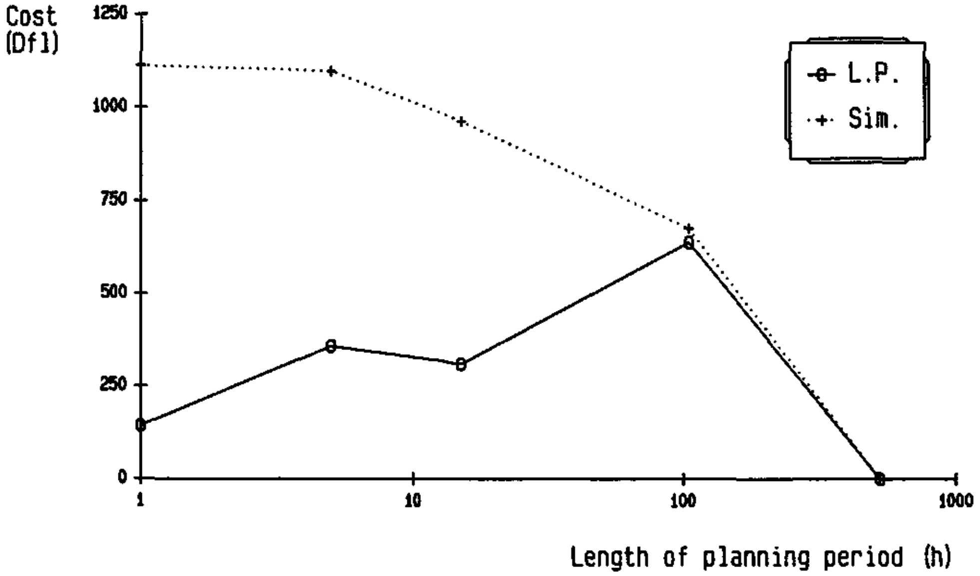


Figure 3.2.d. The drying costs (*f*) against the level of aggregation (in length of planning period, h) for ROUN60. L.P. is linear programming and Sim. is simulation.

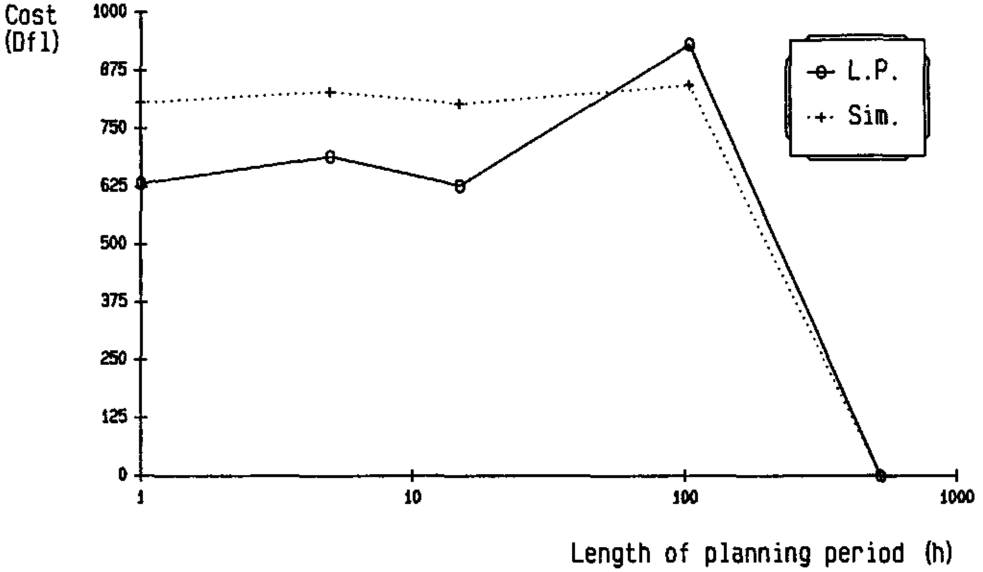


Figure 3.2.e. The overtime costs (*f*) against the level of aggregation (in length of planning period, h) for ROUN60. L.P. is linear programming and Sim. is simulation.

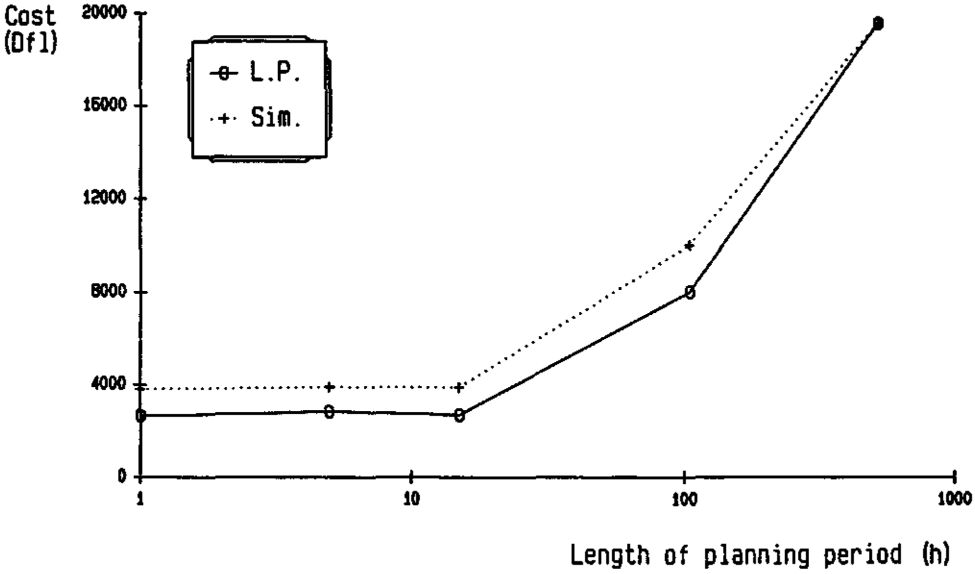


Figure 3.2.f. The total costs (*f*) against the level of aggregation (in length of planning period, h) for ROUN60. L.P. is linear programming and Sim. is simulation.

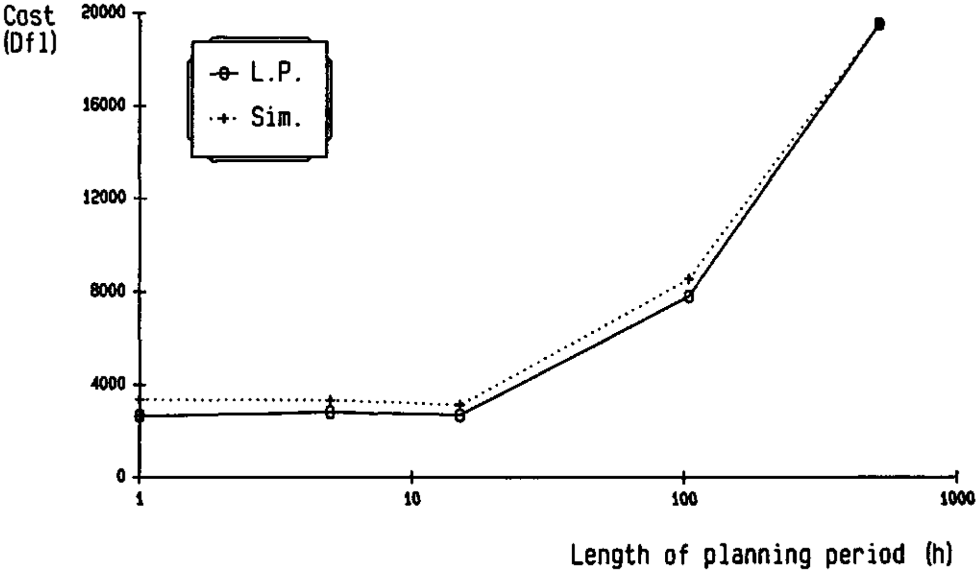


Figure 3.2.g. The total costs reduced by the timeliness costs of bales (*f*) against the level of aggregation (in length of planning period, h) for ROUN60. L.P. is linear programming and Sim. is simulation.

3.3. REAL WORKABILITY WITH AN INITIAL AMOUNT OF SIXTY HECTARES

This title is expressed as REAL60, the results are in Tables B.10, B.11 and B.18 to B.25. The models used are the linear programming model and the simulation model. The dynamic programming model is not used because firstly, new decision moments which can be situated after every hour within a planning period, for the model with real workability (described in Chapter 2), enlarge the problem enormously and secondly, the initial amount of cereal is too large (implying a very large number of states).

The models at month-level have the same number of workable hours as the models at 1-hour-level, 5-hour-level, day-level and week-level. Therefore, the models at month-level also play an important role in the comparison.

Concerning the timeliness costs, the models with real workability take the average of the timeliness cost per period, contrary to the models with rounded workability. The difference between the models with real and the models with rounded workability is there because an investigation of the effect of taking the average on the outcome of the models is required.

The timeliness cost of cereal

The results are shown in Figure 3.3.a. The slope of the cost-function is negative between 1-hour-level and week-level for both models. The explanation is that the number of workable hours remains the same from 1-hour-level to week-level. The ordering of hours is better for week-level and becomes even better as the level of aggregation increases. This is especially true for the simulation model, where the ordering of workable hours approximates the expected use of workability hours in the linear programming model, within a period where the sequence is disregarded. The best hours for workability are situated at the beginning of each period (see Section 2.7). There also are workable hours in almost every period, contrary to the models with rounded workability, where complete periods may have been dropped because the period has no workable hours at all (due to the rounding off). The penalty for models with rounded workability is therefore higher, especially at higher levels of aggregation.

For REAL60, every period has workable hours and these are all situated at the beginning of each period. This is contrary to ROUN60, which also gets fewer workable hours as the level of aggregation increases (due to rounding off).

An exception is the month-level of the linear programming model. The error (discussed in Section 3.1.1), becomes extremely high due to the timeliness costs of cereal which are only calculated at the end of each period. If the period is very large, then the timeliness costs are high even though the material is processed at the very beginning of a period. The results of the models at month-level are therefore unreliable and cannot be used in practice.

The decrease in costs between the 1-hour-level and the 5-hour-level is due to the existence of the overtime hour; 12.00—13.00 at the 1-hour-level. By preference the linear programming model will not use this hour. This means a delay in harvesting cereal giving higher timeliness costs for the models at the 1-hour-level. This hour is placed in the evening period (17.00—22.00) for the models at 5-hour- and day-level.

The timeliness cost of straw

The costs (Figure 3.3.b) which result from REAL60 are lower than those from ROUN60. The increase for ROUN60, between 1-hour-level and 5-hour-level, is less than the increase for REAL60, due to more workable hours at the 5-hour-level for ROUN60. There is again a larger increase for the ROUN60 simulation model than for the REAL60 simulation model between day-level and week-level. The explanation is stated in the preceding section.

For the linear programming model, the decrease in cost between 1-hour-level and 5-hour-level is larger for REAL60 than for ROUN60. This large decrease in cost is due to a better distribution of workable hours for REAL60 (almost every period has workable hours contrary to the periods for ROUN60). This is especially true as the level of aggregation becomes higher.

The timeliness cost of bales

The results (Figure 3.3.c) show almost no difference between REAL60 and ROUN60; the number of workable hours is equal for both (for each level of aggregation).

The timeliness costs for simulation at week-level are higher for REAL60 than for ROUN60. This is due to the arbitrary occurrence of processing bales (the myopic strategy of the simulation model).

The drying cost

The results are shown in Figure 3.3.d. The differences between ROUN60 and REAL60 are minimal. Only the results of the linear programming model at week-level contain higher costs for ROUN60. The total number of workable hours for processing dry grain is the same for the REAL60 week-level as for the REAL60 day-level, but, for ROUN60, the total number of workable hours of processing *dry* grain will be less at week-level than at day-level. This also gives higher drying cost for ROUN60 at week-level.

The simulation model, which has no optimization strategy, does not make use of the advantage of delaying the harvest operation, consequently the drying costs are not significantly lower for REAL60.

At month-level, all the workable hours for processing dry grain are placed at the beginning of the period (see Section 2.7). This number is large enough for processing sixty hectares of cereal (with dry grain). This is true for simulation. The linear programming model will also place all the workable hours at the beginning of a period. This gives extremely low drying cost at month-level for both models because dry grain only is processed.

The positive slope of the cost-function of the linear programming model, between 1-hour-level and 5-hour-level has the value 53.50 $f \cdot h^{-1}$ for REAL60 and 53.75 $f \cdot h^{-1}$ for ROUN60. The large difference between 1-hour-level and 5-hour-level occurs due to the better distribution of workable hours for processing dry grain at 1-hour-level. The operator would choose to wait a few hours and incurs a very low penalty of timeliness cost of cereal compared with not waiting and obtaining a very large penalty of drying costs. This difference in penalties becomes smaller as the level of aggregation increases. The model will choose to precede for drying instead of waiting.

The overtime cost

The simulation results (Figure 3.3.e) show a decrease in costs at higher levels of aggregation. This is due to the use of overtime hours. This situation occurs more often at the end of the season as the level of aggregation increases. All the normal hours are situated at the beginning of the season. Therefore, there is no reason to make use of the overtime hours (at higher level of aggregation). This is also true for the results of the linear programming model.

The total cost

The total costs results (Figure 3.3.f) show the sum of results of the different cost catagories. The most important factor in the total cost of linear programming is the timeliness cost of cereal. After this, the overtime costs are the most important. The slope of the cost-function of the timeliness cost of cereal also determines the slope of the cost-function of the total costs.

The cost are now decreasing (as predicted by the reference model) according as the level of aggregation becomes higher. The effect of the timeliness cost (as described in Section 3.1, the total costs) is here not diminished by less workability. Therefore, the cost will decrease from 1-hour-level to month-level.

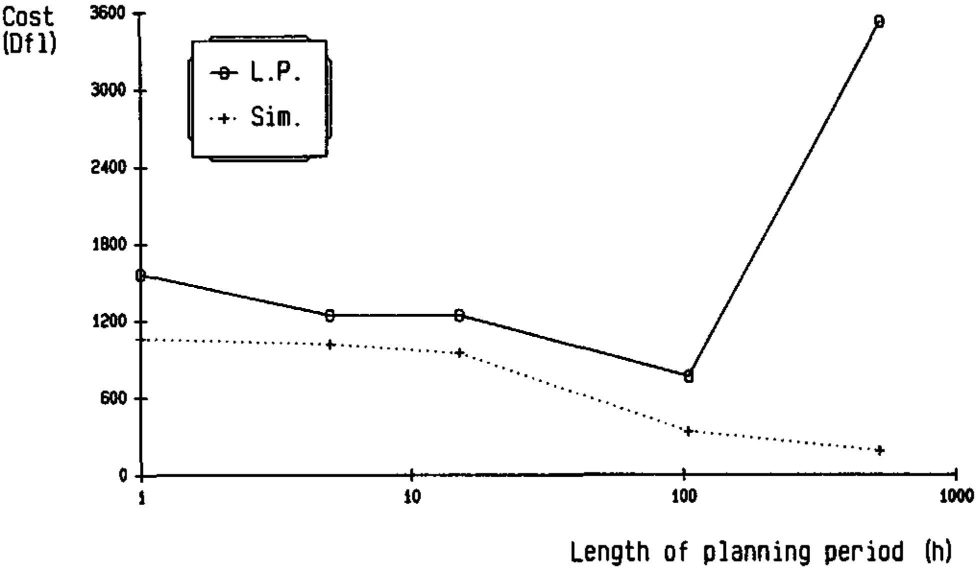


Figure 3.3.a. The timeliness costs of cereal (*f*) against the level of aggregation (in length of planning period, h) for REAL60. L.P. is linear programming and Sim. is simulation.

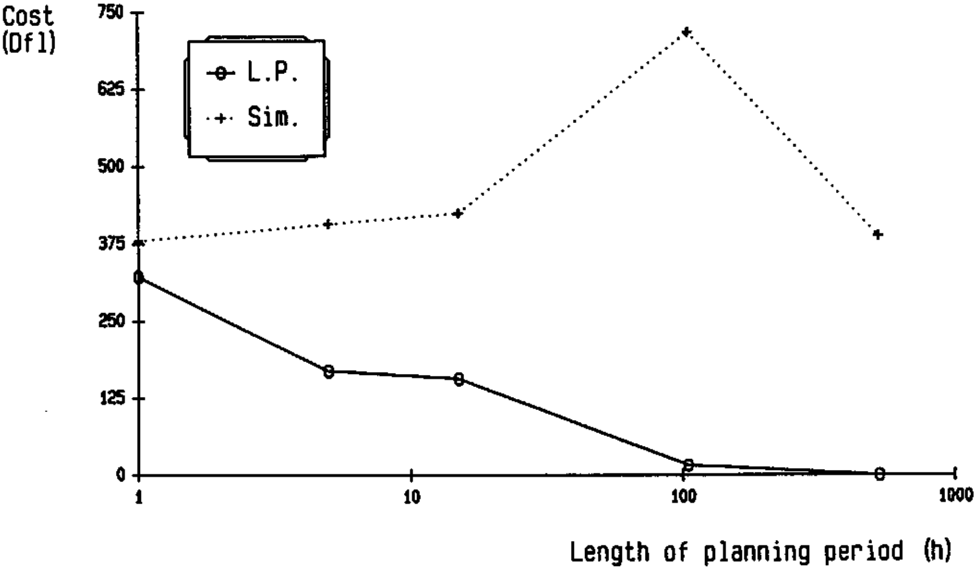


Figure 3.3.b. The timeliness costs of straw (*f*) against the level of aggregation (in length of planning period, h) for REAL60. L.P. is linear programming and Sim. is simulation.

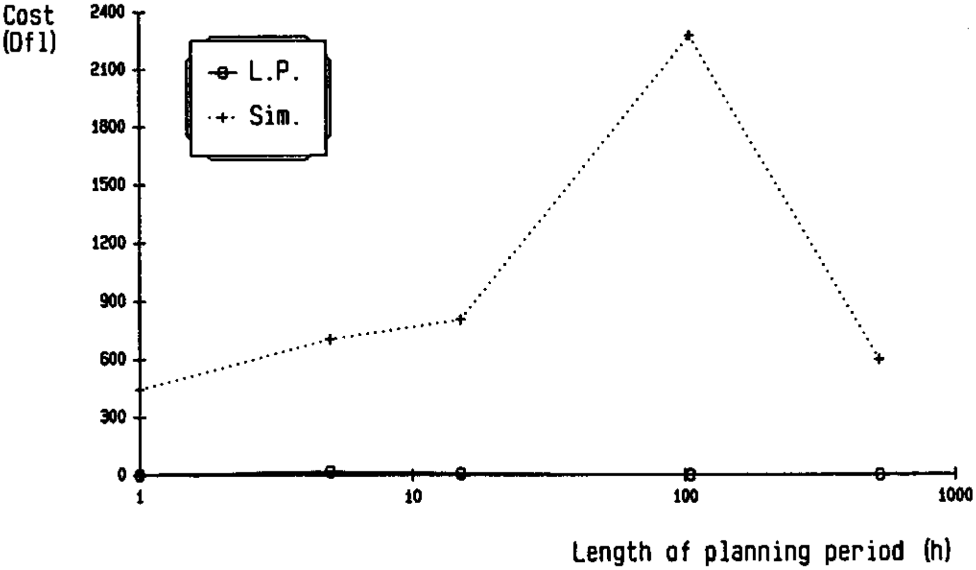


Figure 3.3.c. The timeliness costs of bales (*f*) against the level of aggregation (in length of planning period, h) for REAL60. L.P. is linear programming and Sim. is simulation.

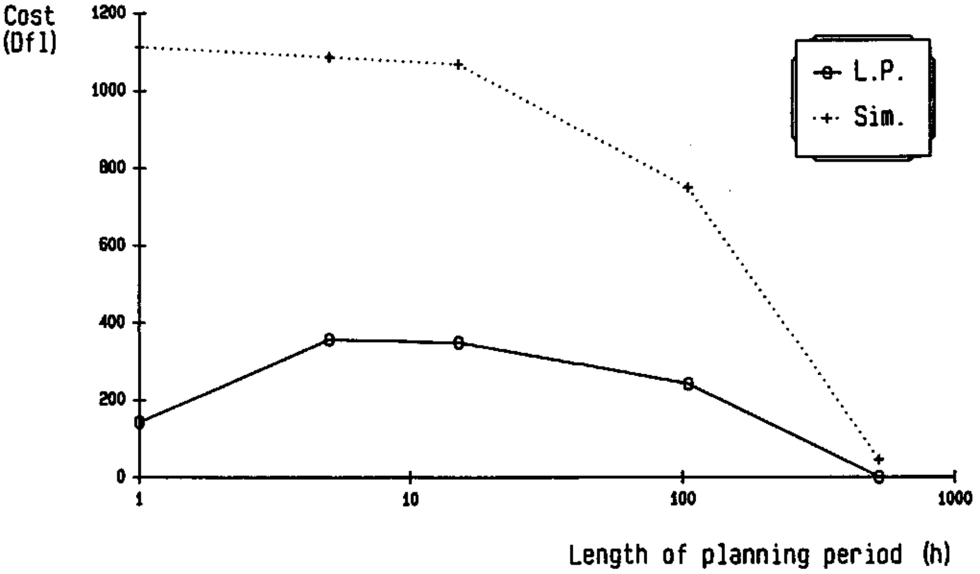


Figure 3.3.d. The drying costs (*f*) against the level of aggregation (in length of planning period, h) for REAL60. L.P. is linear programming and Sim. is simulation.

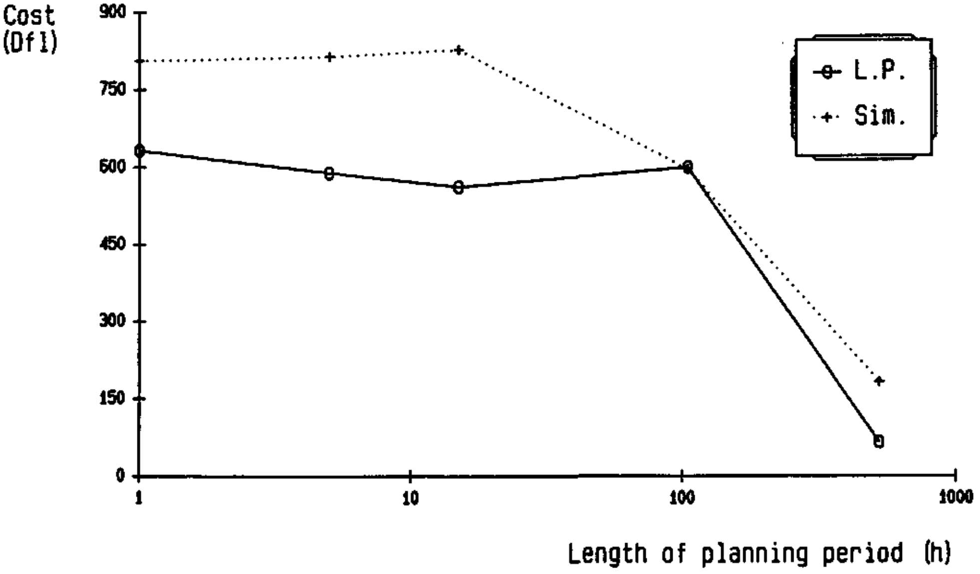


Figure 3.3.e. The overtime costs (*f*) against the level of aggregation (in length of planning period, h) for REAL60. L.P. is linear programming and Sim. is simulation.

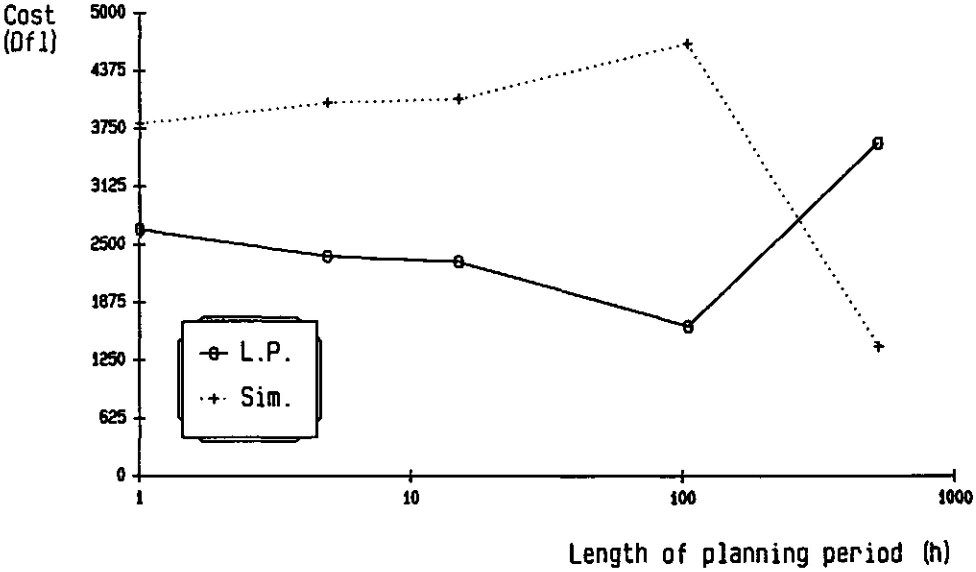


Figure 3.3.f. The total costs (*f*) against the level of aggregation (in length of planning period, h) for REAL60. L.P. is linear programming and Sim. is simulation.

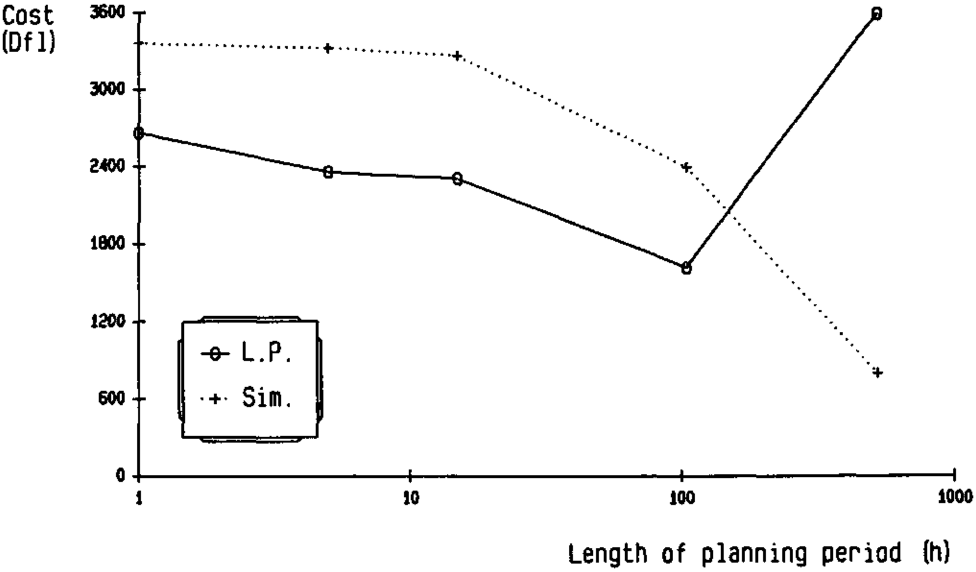


Figure 3.3.g. The total costs reduced by the timeliness costs of bales (*f*) against the level of aggregation (in length of planning period, h) for REAL60. L.P. is linear programming and Sim. is simulation.

3.4. CONCLUSIONS AND DISCUSSION

Using the description stated in Chapter 2 and the results given in this chapter, the following advantages and disadvantages of each model become clear (see also Van Elderen, 1987 and Wijngaard, 1986a).

The simulation model:

Advantages:

- the model is a very concise description of reality;
- the sequence of the operations in each period is correct, the simulation model can only choose one set of operations per period, therefore, it will always put the operations in the proper sequence;
- the computing time is short.

Disadvantages:

- the solution is not optimal due to the myopic strategy of the simulation model (and the algorithm is heuristic);
- the information on future workability is imperfect in this model (i.e. it is not being used, see also Chapter 5).

The dynamic programming model:

Advantages:

- the solution is optimal with regard to the model itself;
- the model is a very concise description of reality;
- the formulation is simple (for both deterministic and probabilistic problems, see also Chapter 5);
- the sequence of the operations is correct for each period, the dynamic programming model can only choose one set of operations per period, therefore, it will always put the operations in the proper sequence.

Disadvantages:

- the computing time is very substantial;
- the size of the model is very large and must be limited, otherwise it cannot be run on the computer due to lack of memory;
- the initial amount of the material must be limited otherwise the size of the model would become too large (the curse of dimensionality);
- in a deterministic case, it has complete knowledge on future workability of the entire season (this is beyond the possibilities of a farmer).

The linear programming model:

Advantages:

- the solution is optimal with regard to the model itself (it uses the Simplex algorithm);
- the computing time is acceptable;

- the formulation is simple (for deterministic problems, but not for probabilistic problems, e.g. the Chance-Constrained approach in models with the multi-stage formulation, see also Chapter 5);
- standard software is available (like LINDO, SCICONIC, MPSX or APEX).

Disadvantages:

- the linear programming matrices are very large, they contain a repetition of the same set of constraints for each period, i.e. the more periods, the more constraints;
- the sequence of operations in each period is unknown, the linear programming model can choose for more sets of operations per period and the user of the model has to place these operations in a proper sequence by himself. This creates an additional problem for the user;
- there is a loss of the correct sequence of operations in each period;
- the size of the model must be limited otherwise it will be too large to be calculated by computer and by many linear programming packages;
- in the deterministic case the model has perfect knowledge of the future workability and therefore is too optimistic about the information the farmer can gather.

The choice of the model

The user of the models may desire an optimal solution or a sub-optimal solution. If he needs an only slightly sub-optimal solution then using the simulation model is sufficient enough. The simulation model is the best model except that it gives generally non-optimal solutions, it has the shortest computing time and the process is close to reality (i.e. practice).

Also close to reality is the dynamic programming model, this model also offers an optimal solution (with regard to the model itself), but the computing time can be extremely long (an execution with two hours CPU time and twenty-four to forty-eight hours run time is not extraordinary, on a VAX 8600 computer with VMS operating system). For that reason, it cannot be used in practice. The dynamic programming model has the advantage that it can adapt a strategy (using the solution) immediately if changes occur in the environment.

The results of the linear programming model are optimal (with regard to the model itself) but the sequence of the operations is disturbed in each period. The large problem of building a probabilistic linear programming model is also a disadvantage (see Chapter 5). The computing time is short (relative to the dynamic programming model), from about half a second CPU time at month-level to about half an hour CPU time at 1-hour-level using SCICONIC (LINDO is two or three times slower, VAX 8600/VMS).

The choice of the level of aggregation

The results at the 1-hour-level, the 5-hour-level and the day-level are not very different from each other, for all the models (for both ROUN60 and REAL60). Only the results at week-level and at month-level are different. The models at week-level and at month-level can only be used if the results are interpreted properly. This is very difficult. If the minor differences between 1-hour-level, 5-hour-level and day-level are acceptable then day-level can be the appropriate level of aggregation for the scheduling models (Wijngaard, 1986a).

Advice into practice

The commonly used models are, in practice, the linear programming model with fourteen days, half a month or a month as period lengths. The results and the value of reality of such models are examined in this chapter. The advantage of linear programming is the available standard software which makes it easy to develop these models. But scheduling models are large and cannot always fit in the maximum available matrix size (which is predefined by the linear programming software packages). Therefore, these models have often to be aggregated. It is better to spend more effort to develop new models and new algorithms with which a detailed scheduling model can be executed within reasonable time (see also Chapter 4).

Choice for further research

The model with the most promising results is the dynamic programming model, except that it has the disadvantage of a long computing time. Suitable future research would develop a model with the same structure as the dynamic programming model, with a different, i.e. a faster algorithm, to find a path with minimum length in a network. This model has to be developed with a level of aggregation which is not higher than day-level. This is legal while the differences between 1-hour-level and day-level are small. The model must have a well-balanced ratio between the computing time (efficiency) and the difference between its solution and the optimal solution (effectivity, see also Wijngaard, 1986a).

Chapter 4

THE RELAXATION OF THE LINEAR PROGRAMMING MODEL

Another way to simplify models, besides aggregation, is relaxation.

> Definition 4.1
> *Relaxation* is a method of simplifying decision variables, in this research, it means the division of combinations into gangs and the division of gangs into individual units. A unit represents a gang in which the number of labourers has a maximum of one. Examples are gang 1: one man harvesting, gang 2: one man baling, gang 3: another man harvesting, and so on.

The definition of relaxation is different from the definition commonly given in mathematical programming literature.

The constraints containing combinations of gangs as decision variables are relaxed and the objective function is minimized subject only to the remaining constraints. The minimum value of the objective function in the relaxed problem is a lower bound for the minimum value of the objective function in the original problem (Murty, 1976).

Relaxation reduces the number of decision variables and the number of constraints. The number of decision variables is reduced because combinations are partitioned into gangs and there are less gangs than combinations. The number of constraints are reduced because there are less workability constraints. In the non-relaxed model, each combination has his own workability constraint presenting the total number of possible workable hours for this combination. In the relaxed model, only the gangs have a workability constraint. There are less gangs than combinations and therefore less constraints. Due to the reducing of constraints, the solution space increases (Van Elderen, 1977). Relaxation is still commonly used in several planning models (Audsley, 1979; Fokkens and Puylaert, 1981; Kok, 1981). However, the solution of a relaxed model is not always reliable; the solution needs not always be feasible in practice. For example the solution may contain contradictions regarding to the use of men and machinery. These contradictions will be discussed in this chapter.

In Chapters 2 and 3, three models have been discussed, i.e. a dynamic and a linear programming model, and a simulation model. In this chapter, the relaxation of these models will be described.

The relaxation of the dynamic programming model is not possible because it can only schedule one combination or one gang per period. This means that for a relaxed dynamic programming model, one unit (e.g. one man harvesting or one man baling in one period) per period has to be used. But, a common relaxed model should give a decision to use more units simultaneously in the same period if the model has to present the system (the environment) in a more realistic way. In practice, this is possible only for the simulation and the linear programming model (it is in fact possible for the dynamic programming model but with a lot of complications).

The simulation model does not provide optimal solutions. Therefore, only the relaxation of the linear programming model will be discussed.

4.1. THE STRUCTURE OF A RELAXED LINEAR PROGRAMMING MODEL

The differences between a relaxed model (a model with units), and a model with combinations will be examined with models which are developed for a farm with two men. To compare the differences for larger farms, models which are developed for farms with three and four men will also be dealt with. The effect of relaxation only is examined. A model at day-level which uses an initial area for cereal of sixty hectares is developed.

Furthermore, the following terminology is used; model U-i: a model which uses individual units and is developed for a farm with i men (i = 2, 3, 4), and model C-i: a model which uses combinations and is developed for a farm with i men (i = 2, 3, 4).

The decision variables (representing the decision to use unit k, k = 30,...,37) of model U-2 are (the first twenty-nine decision variables are stated in Chapter 2, they are not used here):

d_t^{30} = dry grain harvesting with one man in period t
d_t^{31} = wet grain harvesting with one man in period t
d_t^{32} = dry grain harvesting with the second man in period t
d_t^{33} = wet grain harvesting with the second man in period t
d_t^{34} = baling with one man in period t
d_t^{35} = bale gathering with one man in period t
d_t^{36} = ploughing with one man in period t
d_t^{37} = drying of wet grain in period t

Note: if units 30 and 32 are working together, than one man is harvesting and the other man is transporting the grain.

The linear programming formulation for the model U-2 is as follows:

Minimize Z

$$Z = \sum_{t=1}^{T} \Big[\sum_{j=1}^{5} \{tc_t^j/2.0 \cdot x_t^j\} \; + \; \sum_{j=1}^{5} \sum_{k=30}^{36} d_t^k \cdot oc_t^j(k) \; + \; d_t^{37} \cdot DC \Big]$$

subject to the restrictions

$$x_0^j = A_j \qquad \text{for } j=1, \ldots, 5$$

$$x_{t-1}^j + \sum_{k=30}^{37} \{-cp_t^j(k) \cdot d_t^k + cl_t^j(k) \cdot d_t^k\} - x_t^j = 0 \qquad \text{for } t=1, \ldots T, j=1, \ldots 5$$

$$\sum_{k=30}^{36} d_t^k = PLM_t \qquad \text{for } t=1, \ldots, T$$

$$d_t^{37} \leq PL_t \qquad \text{for } t=1, \ldots, T$$

$$0 \leq d_t^k \leq WK_t^j(k) \leq PLM_t \qquad \text{for } t=1, \ldots, T, j=1, \ldots, 5, k=30, \ldots, 36$$

and

$$x_t^j \geq 0 \qquad \text{for } t=1, \ldots, T, j=1, \ldots, 5$$

where

$j =$ number of the material
$k =$ number of the unit
$t =$ number of the period
$DC =$ the drying cost per period ($f \cdot \text{period}^{-1)}$
$A_j =$ the initial amount of material j (ha)
$PL_t =$ the length of the period t (h)
$PLM_t =$ the length of the period t multiplied with the number of men (h)
$cp_t^j(k) =$ processing capacity for unit k and material j in period t ($\text{ha} \cdot \text{period}^{-1}$)
$cl_t^j(k) =$ delivery capacity for unit k and material j in period t ($\text{ha} \cdot \text{period}^{-1}$)
$tc_t^j =$ the fixed timeliness cost for material j for period t ($f \cdot (\text{period} \cdot \text{ha})^{-1}$)
$oc_t^j(k) =$ the overtime cost for unit k, material j and period t ($f \cdot \text{period}^{-1}$)
$WK_t^j(k) =$ the number of workable hours for material j processed by unit k in period t
$x_t^j =$ the amount of material j at the end of period t (ha)

Model U-3 has two additional decision variables:

d_t^{38} = dry grain harvesting with the third man in period t
d_t^{39} = wet grain harvesting with the third man in period t

and model U-4 has four additional decision variables:

d_t^{38} = dry grain harvesting with the third man in period t
d_t^{39} = wet grain harvesting with the third man in period t
d_t^{40} = dry grain harvesting with the fourth man in period t
d_t^{41} = wet grain harvesting with the fourth man in period t

The linear programming formulation of model C-2 (real workability) is described in Section 2.6. Models C-3 and C-4 are extensions of model C-2.

4.2. THE RESULTS

The models are developed at day-level with REAL60 (real workability with an initial area of sixty hectares for cereal, see Chapter 3). The models are applied with the workability data for the years 1957 to 1968. The results, the values of the objective function are stated in Tables 4.1.a, 4.1.b and 4.1.c for the two, three and four men farms respectively.

The average of the values of the objective function of the model U-2 is lower than of the model C-2. This is due to the larger solution space of the model U-2. But the enlargement of the solution space also causes a less reliable solution containing contradictions and overestimation of the use of men and machinery. It may be impossible to use the schedule in practice. This will be explained with use of the following examples.

A solution of the model U-2 can have the following schedule for the first period:

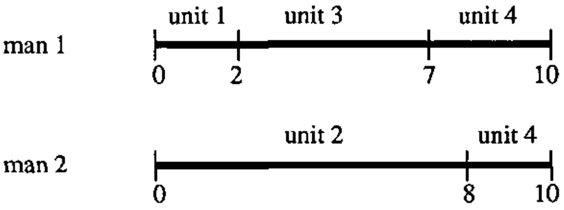
• the first man has to harvest dry grain (unit 1) for	2 hours
• the second man has to harvest dry grain (unit 2) for	8 hours
• one man is baling (unit 3) for	5 hours
• one man is gathering bales (unit 4) for	5 hours

The number of workable hours in this period is for

• harvesting dry grain	8 hours
• baling	10 hours
• gathering bales	10 hours

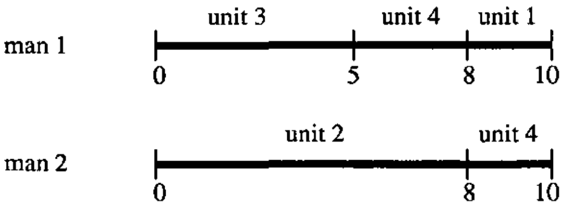
The total length of the first period is 10 hours

The solution of the model U-2 comes up to meet the requirements of the constraints (see formulation of the linear programming model U-2). A schedule could be:



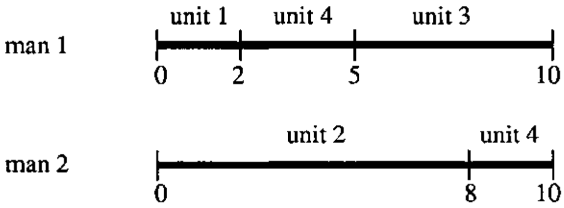
This is not feasible as indicated by the last two hours. It is not possible to gather bales with two men at the same time because only one bale-loader is available (see Chapter 2).

Another schedule could be:



This is not feasible too because the total number of workable hours needed for cereal harvesting is ten hours whilst only eight hours exist.

Another schedule could be:



Constraints on equipment would not prevent this but the farmer must load bales before baling. It is possible that bales are not available. This also is an impractical solution.

Another example (for period 1):

• the total length of the period is (there are two man, therefore PLM_1 is 20)	10 hours
• the workable hours of harvesting dry grain ($WK_1^1(30)$)	5 hours
• the workable hours of ploughing (processing stubble, j=5, $WK_1^5(36)$)	10 hours

A part of the constraints of the model is as follows:

Table 4.1.a. Values of the objective function of the linear programming models for a farm with two men (ave is the average).

	Models which use		
	individual units	combinations	Difference
year	U-2	C-2	C-2 – U-2
1957	1560	1625	65
1958	2229	2351	122
1959	3356	3360	4
1960	2505	2599	94
1961	2343	2434	91
1962	3047	3100	53
1963	2052	2294	242
1964	2322	2337	15
1965	2150	2195	45
1966	5124	5140	16
1967	2061	2138	77
1968	2210	2256	46
ave	2578	2652	73

Table 4.1.b. Values of the objective function of the linear programming models for a farm with three men (ave is the average).

	Models which use		
	individual units	combinations	Difference
year	U-3	C-3	C-3 – U-3
1957	1202	1207	5
1958	1781	1797	16
1959	3092	3099	7
1960	2128	2132	4
1961	1790	1794	4
1962	2374	2384	10
1963	1461	1461	0
1964	1847	1847	0
1965	1682	1687	5
1966	4866	4868	2
1967	1513	1513	0
1968	1651	1655	4
ave	2115	2120	5

$$\sum_{k=30}^{36} d_1^k \leq 20$$

$$0 \leq d_1^{30} \leq 5$$

$$0 \leq d_1^{36} \leq 10$$

It is possible to harvest with two men for five hours. According to the first constraint, it is possible to plough for ten hours, but there are only five hours left to work (after harvesting) during the period. If the LP-solver decides to plough for ten hours, then the total length of working time would be fifteen hours (five hours harvesting and ten hours ploughing). This is five hours too

Table 4.1.c. Values of the objective function of the linear programming models for a farm with four men (ave is the average).

year	Models which use individual units U-4	combinations C-4	Difference C-4 – U-4
1957	971	1018	47
1958	1479	1504	25
1959	2896	2954	58
1960	1902	1983	81
1961	1491	1556	65
1962	2006	2037	31
1963	1204	1292	88
1964	1633	1682	49
1965	1445	1528	73
1966	4727	4727	0
1967	1188	1272	84
1968	1312	1403	91
ave	1854	1913	58

Table 4.2. The timeliness costs of stubble (iv is individual units, comb is combinations, ave is the average, std is the standard deviation).

	2-men iv	2-men comb	3-men iv	3-men comb	4-men iv	4-men comb
ave	256	337	183	178	148	159
std	89	131	96	92	98	104

much (length of the period is ten hours). Therefore, the linear programming model can give feasible solutions which cannot be executed in practice.

It is possible to restrict this occurrence, but the additional number of constraints is large. The model U-2 must have additional constraints for each workability constraint to restrict simultaneous use of the same unit. Such an extended model will not differ much in size from the model C-2.

The results in Table 4.1 (i.e. the objective function values for all the years) show a decrease in cost of approximately three percent for the models U-2 and U-4 compared with the models C-2 and C-4, but the decrease for a model which uses a farm with three men (U-3 compared with C-3) is almost zero. This has the following explanation. The model U-3 can combine his units to almost the same combinations as used by model C-3. This is particularly important for the operations other than cereal harvesting, namely; baling, gathering and ploughing. The model U-3 can give the following combination as solution: one man baling, one man gathering and one man ploughing in the same period. This is feasible. The equality in solution space results in equality of the values of the objective function. The same is expected for the models U-4 and C-4, but the solution space here is larger. The model U-4 can give the following combination as solution: one man baling, one man gathering and two men ploughing in one period. This is not a feasible solution for a farm with one plough and therefore not present as combination in model C-4.

The extra degree of freedom of choice for the model U-4 counts only for the operations of baling, gathering and ploughing. The timeliness cost of stubble is a good example of results of the extra degree of freedom (Table 4.2). There is a decrease in the average of timeliness costs between the solution of the model U-3 and the solution of the model C-3 (instead of the increase between U-2 and C-2, and between U-4 and C-4).

4.3. CONCLUSIONS

There are many scheduling models (still commonly used) which give, as solution, the number of hours for each unit (e.g. the number of tractor hours, the number of man hours, and so on) per period (Audsley, 1979; Fokkens and Puylaert, 1981; Kok, 1981). This period may have the length of a week, fourteen days or even longer. Such models do not give the manner in which the different combinations of these units are scheduled. This problem is for the farmer to solve. The farmer must attempt to schedule his operations within the limits of the solution of the relaxed model whilst believing that this solution is optimum. As a result the schedule can become non-executable or, if he forces it into practice schedule costs rise. These costs are higher than the costs which the solution of a model with combinations offers.

Relaxed models are useful for investment decisions (at the strategic level) (Audsley, 1979; Audsley, 1981; Edwards and Boehlje, 1980). Examples are the decision to invest capital in new equipment, in additional storage space, and so on, or the decision to remove old equipment. The solution has to be approached with care. It may contain an overestimate of possibilities according to the use of man or machine hours (due to the impractical schedule). This may cause the wrong decision for a new investment to be made.

The final conclusion is that models at operational level which use combinations are preferred to models which use individual units. When it is impossible to execute a model with combinations, the rate of overestimation of possibilities has to be assessed, i.e. the difference between the solution of the relaxed model and the solution which can be used in practice. The idea is that a relaxed model is solved, then the solution per period for each period is scheduled and then the imperfections (i.e. the problems with scheduling) are quantified. The imperfections must be taken into account.

The relaxation of models is not always necessary. It is possible, with the solvers which now exist, to solve very large problems in an acceptable time. It is recommended that solving a model with combinations is tried first, even though the whole process takes more time (and is therefore more expensive), before relaxing the model to find an optimal solution with a schedule that perhaps cannot be used in practice.

Chapter 5

THE PROBABILISTIC DYNAMIC PROGRAMMING MODEL

As has been described in Chapter 2, a decision criterion is a logical or rational method of choosing the decision that best meets the objective. The choice of decision variable depends on the state and on the degree to which an uncontrollable event that may occur in the future can be predicted. If the uncontrollable event can be identified with certainty then the decision problem would be classified as one of decision making under certainty. If it is not known with certainty which of the uncontrollable events will result, but if probabilities can be attached to each event, than the decision problem can be classified as decision making under risk. In some cases it may not be possible to provide such probabilities. Although the uncontrollable events can be identified, the future may be so uncertain that it is impossible to estimate, with any confidence, the probability of the uncontrollable events occurring. Such decision situations are referred to as decision making under uncertainty (Dannenbring and Starr, 1981).

Within decision models for decision making under risk, the value of perfect information can be calculated.

> Definition 5.1
> The *value of perfect information* is the return of a system with perfect information minus the expected costs of the same system without perfect information.

In reality, in a situation of decision making under risk, it is not often that perfect information is available. Nonetheless, the ability to calculate the value of perfect information in a risk situation can be quite important. Although perfect information may not be available, frequently it is possible to obtain additional information that will increase confidence in the probability measures associated with the various uncontrollable events.

To calculate the value of perfect information and to obtain the difference between the effect of a well-known future and the effect of a vague future on the results of models, a probabilistic model can be developed in addition to the deterministic models (as described in Chapters 2 and 3). The model can be a linear programming model, a simulation model or a dynamic programming model.

A probabilistic multi-stage (multi-period) linear programming model will become too large. Each constraint will be quintupled (using the transition matrix in Table 5.1), and the quintupled constraints must be quintupled in the next stage, and so on (Wagner, 1977). The deterministic linear programming model will contain about T times M constraints (T is the total number of periods and M is the number of constraints per period). If T is 105 (a model at 5-hour-level) and M is 21 (see Section 2.6), then the matrix will contain 2205 constraints. The probabilistic linear programming model (using the multi-stage formulation) with five evels of probability which are mutually independent from stage to stage, will contain about:

$$\{\sum_{i=1}^{104} (5^i)\} \cdot 21$$

which is about $2.6 \cdot 10^{73}$ constraints. Therefore, the probabilistic linear programming approach is not feasible.

The simulation model being used does not provide facilities which accept probabilities whilst the simulation model also gives a solution which is not optimal.

A probabilistic dynamic programming model will also become very large in size, but nevertheless it is possible to obtain a solution. A dynamic programming solution also gives a schedule which is quite realistic. Therefore, it was finally decided to choose and to develop a probabilistic dynamic programming model as a model for decision making under risk.

Table 5.1.a. The probability transition matrix (from the morning, 7.00—12.00 h to the afternoon, 13.00—17.00 h, Q_t is the state of workability in period t and t = 1 + 3i where i=1,2,...,34).

			Q_t		
Q_{t-1}	1	2	3	4	5
1	0.96	0.00	0.00	0.03	0.01
2	0.59	0.35	0.03	0.03	0.00
3	0.10	0.52	0.12	0.26	0.00
4	0.04	0.23	0.29	0.43	0.01
5	0.00	0.00	0.00	0.99	0.01

Table 5.1.b. The probability transition matrix (from the afternoon, 13.00—17.00 h to the evening, 18.00—22.00 h, Q_t is the state of workability in period t and t = 2 + 3i where i=1,2,...,34).

			Q_t		
Q_{t-1}	1	2	3	4	5
1	0.87	0.00	0.00	0.13	0.00
2	0.21	0.47	0.05	0.26	0.01
3	0.01	0.28	0.43	0.28	0.00
4	0.00	0.05	0.15	0.78	0.02
5	0.00	0.00	0.00	0.99	0.01

Table 5.1.c. The probability transition matrix (from the evening, 18.00—22.00 h to the morning, 7.00—12.00 h, the next day, Q_t is the state of workability in period t and t = 3 + 3i where i=1,2,...,34).

			Q_t		
Q_{t-1}	1	2	3	4	5
1	0.33	0.13	0.05	0.48	0.01
2	0.08	0.27	0.05	0.58	0.02
3	0.08	0.16	0.19	0.56	0.01
4	0.08	0.17	0.07	0.66	0.02
5	0.00	0.20	0.00	0.80	0.00

5.1. THE STRUCTURE OF THE MODEL

The dynamic programming formulation contains the following vectors and functions (it is assumed that the reader is familiar with the notations). Note that the description is based on a backward recursion procedure. A forward recursion procedure will give a wrong solution for a probabilistic model (Schneeweiß, 1977).

A. The statevector $\mathbf{x}_t$ contains the amount of materials, cereal (CE), straw (ST), bales (BA), and wet grain (WE) for every stage t (ha). The material stubble is excluded from the statevector, otherwise the probabilistic dynamic programming model would become too large. The weather variable Q_t will be treated as the fifth component of $\mathbf{x}_t$. The statevector $\mathbf{x}_t$ is now:

$$\mathbf{x}_t' = (x_t^1, x_t^2, x_t^3, x_t^4, x_t^5) = (x_t^j) \qquad j = 1, \ldots, 5 \quad t = 1, \ldots, 105$$

where

$x_t^1 = CE_t$, $x_t^2 = ST_t$, $x_t^3 = BA_t$, $x_t^4 = WE_t$ and $x_t^5 = Q_t$

j = number of the material
t = number of the stage

Q_t has have five values, i.e. five cumulative, mutually exclusive, workability conditions (the possible operations):

$Q_t = 1$: harvesting dry grain, baling and gathering in period t,
$Q_t = 2$: harvesting wet grain, baling and gathering in period t,
$Q_t = 3$: only baling and gathering in period t,
$Q_t = 4$: only gathering in period t,
$Q_t = 5$: no operation is possible in period t.

The probability transition matrices are given in Table 5.1 and are derived from twelve years (i.e. the years 1957 to 1968) with workability data.

B. The decisionvector $\mathbf{d}_t$, this vector contains sixteen 0-1 variables and is as follows:

$$\mathbf{d}_t' = (d_t^1, d_t^2, \ldots, d_t^{16}) = (d_t^k) \qquad k = 1, \ldots, 16$$

where

$d_t^1 =$ grain harvesting (wet and dry) with two men in period t,
$d_t^2 =$ grain harvesting (wet and dry) with one man in period t,
$d_t^3 =$ baling with one man in period t,
$d_t^4 =$ bale gathering with one man in period t,
$d_t^5 =$ grain harvesting (one man, wet and dry) and baling in period t,

$d_t^6 =$ grain harvesting (one man, wet and dry) and gathering in period t,
$d_t^7 =$ baling and bale gathering in period t,
$d_t^8 =$ do nothing in period t.

(d_t^9 to d_t^{16} have the same meaning as d_t^1 to d_t^8, except that drying of wet grain is also involved)

and

$$\sum_{k=1}^{16} d_t^k = 1 \qquad \text{for all } t$$

k = number of the combination
t = number of stage

C. The transformation function T_t (from stage t–1 to stage t). It expresses the decrease or increase in amount (ha) of the materials.

$$\mathbf{x}_t : \mathbf{x}_t = T_t(\mathbf{x}_{t-1}, \mathbf{d}_t, Q_t)$$

and

$$x_t^j = (x_{t-1}^j - \mathbf{d}_t' \cdot \mathbf{cp}_t^j + \mathbf{d}_t' \cdot \mathbf{cl}_t^j)^+ \qquad j = 1,\ldots,4; \qquad (x^+ \overset{\mathrm{df}}{=} \max(0,x))$$

where cp_t^j and cl_t^j are column vectors of CP_t and CL_t respectively and

$$CP_t = \begin{pmatrix} cp_t^1(1) & \ldots & cp_t^5(1) \\ \vdots & cp_t^j(k) & \vdots \\ cp_t^1(24) & \ldots & cp_t^5(24) \end{pmatrix} \qquad CL_t = \begin{pmatrix} cl_t^1(1) & \ldots & cl_t^5(1) \\ \vdots & cl_t^j(k) & \vdots \\ cl_t^1(24) & \ldots & cl_t^5(24) \end{pmatrix}$$

$CP_t =$ matrix with the processing capacities for combination k and material j in period t (ha·period^{-1})
$CL_t =$ matrix with delivery capacities for combination k and material j in period t (ha·period^{-1})

D. The costfunction G_t depends on the statevector $\mathbf{x}_{t-1}$ and the decisionvector $\mathbf{d}_t$.

$$G_t : G_t(\mathbf{x}_{t-1}, \mathbf{d}_t, Q_t)$$

$$G_t(\mathbf{x}_{t-1},\mathbf{d}_t,Q_t) = \begin{cases} \infty & \text{if } CP_t' \cdot \mathbf{d}_t = \mathbf{0} \text{ and } d_t^8 = 0 \\ \mathbf{dr}_t' \cdot \mathbf{d}_t + TM_t + \mathbf{ov}_t' \cdot \mathbf{d}_t & \text{otherwise} \end{cases}$$

fore, the weekend with the according overtime cost, takes place sooner or later. To diminish the reflection error made by this effect, two kinds of schedules are calculated using the probabilistic solution:

1. a schedule for a season which begins on August 1 and where August 1 has the correct type of day. This type of day can be different for each year. The effect of the weekend with the related overtime cost is different for each year;

2. a schedule for a season which begins on August 1 and where the type of day for all the years is assumed to be Thursday. Therefore, this type of day is the same for each year. The probabilistic dynamic programming model also uses a season which begins with a Thursday. The effect of the weekend with the related overtime cost is the same for each year.

The solution of the deterministic dynamic programming model is the average of the solutions (representing total cost, which is the sum of timeliness cost of cereal, straw and bales, overtime cost and drying cost) over twelve years (1957—1968).

The average of twelve years of the total costs of the deterministic solution, of solution 1 and solution 2, and the values of perfect information are:

	Dynamic programming			value of	
	determ. sol.	prob. sol.		perfect information	
		1	2	1	2
mean:	602	559	544	–43	–58

1: type of the day, August 1 is the correct type of the day
2: type of the day, August 1 is Thursday

The results of the probabilistic model contain lower costs than the results of the deterministic model. This is not what was expected because a probabilistic model should give higher costs as a result than the deterministic model due to lack of information of the future. The value of perfect information must be positive. This is explained below.

The deterministic dynamic programming model offers higher costs due to the reflection errors as explained above, but mainly due to the effect, on the average of twelve years of the total costs, of the results of two years, i.e. 1959 and 1966. In these years, it was not possible to harvest completely the total amount of cereal in the first week of August. The effect of the results of these two bad years (at least, bad weather in the first week of August) will be smoothed for the probabilistic model (using averages of workable time), but not for the deterministic model (using the real value of workable time, see also Chapter 2). Therefore, the average solution (including 1959 and 1966) of the deterministic dynamic programming model is not suitable for comparison. When the results of the two years 1959 and 1966 are removed from the average, the following results are obtained:

	Dynamic programming determ. sol.	prob. sol. 1	 2	value of perfect information 1	 2
mean:	416	478	461	+62	+45

1: type of the day, August 1 is the correct type of the day
2: type of the day, August 1 is Thursday

Now, the results of the probabilistic model contain higher costs than the results of the deterministic model. The value of perfect information is positive. The probabilistic model is a model for decision making under risk whereas the deterministic model is for decision making under certainty. The information for the deterministic model is perfect, the future is well-known, a better look into the future would provide lower cost and therefore better results.

5.3. CONCLUSIONS

In this chapter, a probabilistic version of the dynamic programming model is discussed. The probabilistic model is based on the probability of state transitions of workability. The probability of state transitions is based on workability data from the past.

The deterministic dynamic programming model offers higher costs due to the effect, on the average of twelve years of the total costs, of the results of two years, i.e. 1959 and 1966. In these years, it was not possible to harvest completely the total amount of cereal. The effect of the results of these two bad years will be smoothed for the probabilistic model (using averages of workable time), but not for the deterministic model (using the real value of workable time).

Therefore, the effect of extraordinary years (e.g. years with an extremely high rate of rainfall and therefore with a minimum of workable hours) will be smoothed, due to the use of the probability of state transition. Using averages of workable time (as used by the probabilistic programming model) can give in some cases an infeasible solution related to practice. It is better to use a more practical estimate to derive workability data, e.g. the weather forecast instead of workability data from the past.

Another disadvantage of the probabilistic dynamic programming model is the so-called „curse of dimensionality".

But, a probabilistic model as described in this chapter has the advantage that it gives a solution in which already a lot of different workability situations are present. Therefore, if changes occur in the workability situation, then the model has not to be executed again to derive a new solution.

Chapter 6

SCHEDULING REVISITED

Scheduling can be carried out in many different ways. In this chapter, a new way of looking at the scheduling problem is presented. In Chapter 2, the problem was dealt with according to the linear and the dynamic programming approaches. The method in this chapter is more common and is associated with the theory of machine scheduling in an industrial setting (Rinnooy Kan, 1976). The reason for this new approach is the search for a new algorithm which will calculate schedules more quickly. This algorithm is based on a network structure, in the same way as the deterministic dynamic programming model, because the results of a model which uses the network approach, is of more value in practice (as stated in Chapter 3).

6.1. MACHINE SCHEDULING PROBLEMS

Scheduling problems are very common occurrences. They exist whenever a number of tasks has to be ordered. A problem can involve: jobs in a manufacturing plant, aircraft waiting for landing clearance or jobs on a farm.

Scheduling problems are problems which are mostly NP-hard (for a full definition of NP-hard, see Rinnooy Kan, 1976), it may be difficult to obtain an optimal solution within a reasonable time for large problem instances. Research in this field can be divided into: firstly, research on the occurrence of scheduling problems; secondly, research on the definition of similar problems and thirdly, research to find suitable algorithms to solve scheduling problems (Rinnooy Kan, 1976; Conway et al., 1967).

A scheduling problem classification has the following format:

$$\alpha/\beta/\gamma/\delta$$

where:

α represents the number of jobs; α will be assumed an integer variable;

β represents the number of machines; β is an integer variable;

γ indicates the type of ordering of machines for each job;

δ indicates the optimization criterion, e.g. the minimization of cost or the minimization of flow time.

The better known methods that have been used to solve scheduling problems will be discussed now (Rinnooy Kan, 1976; Conway et al., 1967). An optimal schedule can be found in principle by *complete enumeration* of all possible schedules, or of a subset containing an optimal schedule. However the number of elements is far too large for this method to be suitable for any but the smallest problems.

Hence, the search for an optimal schedule has to be conducted in a more efficient manner, by exploiting characteristic features of the problem under consideration. Methods of *combinatorial analysis* often turn out to be useful in this context. Scheduling problems frequently involve a close examination of the effect of a minor change in a particular schedule (notably the interchange of two, possible adjacent, jobs).

The evident approach to scheduling problems is through *mixed integer programming* methods. Several formulations of a scheduling problem as a 0-1 model turn out to be possible. Although the formulations are elegant and multi-applicable, the generality of these models has a predictably negative influence on their computational efficiency and more specific methods are necessary.

Many algorithms developed with the latter purpose are of a more „global" nature: by successively partitioning the set of possible schedules into smaller and smaller subsets each schedule is either explicitly or implicitly considered.

Methods of branch-and-bound fall within the description of partitioning the set of possible schedules, they are among the most widely used solution methods for combinatorial programming problems. They were developed and first used in the context of mixed integer programming and the travelling salesman problem, but soon their wide applicability was perceived. The main reason for their present popularity seems to be the simplicity of the basic principles, combined with easy implementation and often surprising computational efficiency.

Methods of dynamic programming (see also Chapter 2 and 5) have been used to solve a number of scheduling problems. This method interprets scheduling and other combinatorial optimization problems as multistage decision problems.

Efficient algorithms are difficult to be found for many types of machine scheduling problems. *Heuristic methods*, producing suboptimal solutions, are therefore unavoidable in many practical situations. But they also possesses favorable properties, e.g. they are usually quite fast, easy to apply and may be the only way of obtaining a solution (Dannenbring and Starr, 1981). In actual practice it seems possible to exploit known optimal algorithms to produce a good heuristic approach.

In the next section of this chapter, the above mentioned scheduling problem classification will be used to describe the problem, the scheduling of farm operations, in a new way.

6.2. THE PROBLEM DEFINITION

The underlying problem is the problem of scheduling farm operations. The scheduling of farm operations deals with the scheduling of jobs. A job stands for the processing of a material and can be grain harvesting, straw baling, ploughing, and so on. The scheduling involves the assignment of men and machinery to the jobs and the assignment of the jobs to periods in time. The goal is minimization of the total cost c (the minimization of total cost c, which is the sum of timeliness cost, overtime cost and any additional cost of special jobs like contract work or grain drying, can result in a fast processing of all the available materials like crops or soil). The assignment and minimization takes place under the restriction of the number of jobs, the available equipment (machines) and men, and the properties of the materials. The properties of the materials are related to the weather.

The problem is defined as a general n/m job-shop problem with the identification n/m/G/c, where m is the number of machines or groups of machinery and men (e.g. a worker, a straw baler, a tractor) which must be assigned to n jobs (e.g. harvesting, sowing, ploughing). G will be used to indicate the general job-shop problem where the processing order may be different for each job, and c is the cost (i.e. the total costs, which are the sum of timeliness cost, overtime cost, and additional cost of special jobs like contract work and drying of wet grain). Each job i is given as a unique sequential set of P(i) operations. Each operation has three identifiers, i, e and u: i, the job number to which the operation belongs; e, the sequence number of the operation (1,2,...,P(i)); and u, the number of the machine or group of machinery and men required to perform the operation. In this case, each job i has exactly one operation (e=P(i)=1), so, by definition, a job is equal to an operation. The assignment of the job i to a machine (or group of machinery and men) u will result in a gang. Gangs working parallel (i.e. parallel jobs) are represented by a combination of gangs (see Chapters 1 and 2). A combination of gangs (executing one or more jobs simultaneously) has the identifier k (Chapter 2). The decision to assign combination k to period t is represented by the decision variable d_t^k which is a 0-1 variable (Chapter 2).

The planning horizon has a predetermined length (e.g. five weeks or more), or until all the available material is processed. This planning horizon is divided into periods with a fixed length of one day, and each day is divided into:

1. a morning period:	07:00 — 12:00 h	(is regular time*))
2. an afternoon period:	12:00 — 17:00 h	(is regular time*))
3. an evening period:	17:00 — 22:00 h	(is overtime)
4. a night period:	22:00 — 07:00 h	(is overtime)

*) On Saturdays and Sundays, the usual regular time is overtime.

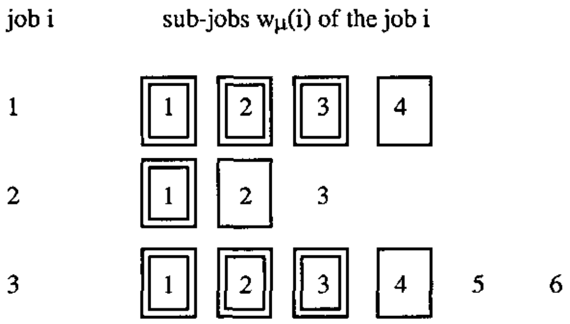
The results of the tests described in Chapter 3 show that the length of the periods has an upper boundary of a day (for a static environment, i.e. where the input is not changing after every planning period). But five hours is used as the length of a period here. This will enlarge the size of the problem. Therefore, problems with computer memory capacity can be determined. These problems will not occur if the length of a period is a whole day.

The use of predetermined lengths of the planning periods will result in a model (discrete in time) which is contrary to the common scheduling problems, where the length of a period equals the processing-time required to perform an operation. The processing-time can be different for each operation. This creates the following problem for our model.

Every combination of gangs k must be assigned to a period t. But, dependent on the working rate ($ha \cdot h^{-1}$) of a gang executing job i (when job i is one of the jobs executed by combination k) and the amount of the material which have to be processed by this gang, a job i cannot be assigned to one period as a whole. For example, if the combination contains only one gang and the working rate of this gang is two ($ha \cdot h^{-1}$), the amount of material is twenty-five hectares, and the fixed length of a period is five hours, then the processing of the material will last for two and a half periods. Therefore, a job i has to be divided into smaller sub-jobs $w_\mu(i)$ ($\mu=1,2,\ldots,Q_{i,u}$, $Q_{i,u}$ is the total number of sub-jobs of job i). Each sub-job $w_\mu(i)$ will be assigned to one period. By definition, the processing-time of $w_\mu(i)$ equals the length of period t, therefore, only *one* sub-job $w_\mu(i)$ will be assigned to a period. Only the processing-time of the last sub-job $w_\mu(i)$ (for $\mu=Q_{i,u}$) might not equal the length of period t while the amount of the material processed in this period can be smaller. After assigning $w_\mu(i)$ to t, $w_\tau(j)$ can be assigned to the period t+1. The following values are possible for τ:

$$\tau = \theta(i) = \mu + 1 \qquad \text{if } j = i$$
$$\tau = \theta(j) \qquad \text{if } j \neq i$$

$w_\theta(j)$ is the first sub-job of job j which is free, i.e. it is not yet scheduled. If $j = i$ and $\mu = Q_{i,u}$, then the assignment of $w_\tau(j)$ is not possible, $\theta(j)$ is then undefined. This concept will be further clarified in the following example: the assignment of four sub-jobs. The sub-jobs in the double-lined boxes are already scheduled in the past. The sub-jobs in the single-lined boxes can be scheduled. The remaining sub-jobs are not considered for scheduling.



If $w_3(1)$ is assigned to period t, then the assignment for t+1 can be $w_4(1)$ ($\mu=3$ and $j=i=1$, therefore, $\tau = \mu+1 = 3+1 = 4$ which gives $w_4(1)$), $w_2(2)$ or $w_4(3)$ (and not $w_3(2)$, $w_5(3)$ and $w_6(3)$). Therefore, all sub-jobs $w_\mu(i)$ of the same job i do not have to be scheduled behind each other, i.e. after $w_3(1)$, it is not necessary to schedule only $w_4(1)$.

The following costs affect the assignment of $w_\mu(i)$ to period t:

- the timeliness cost of the material ($f \cdot ha^{-1}$). Delaying the assignment of the combination k (and therefore the assignment of $w_\mu(i)$) will result in higher timeliness cost.

- the overtime cost ($f \cdot h^{-1}$), a period t can be a period with regular hours or a period with overtime hours (hours in the evening, at night or in the weekends). An assignment of $w_{\mu}(i)$ to a period with overtime hours will result in higher cost.

The number $Q_{i,u}$ of sub-jobs depends on the length of period t, the work-rate of the gang executing job i, and the amount of the material processed by the gang. In the example in this section, if the number of periods required is two and a half, then $Q_{i,u}$ equals three (the smallest integer greater than or equal to the number of periods required). If $Q_{i,u}$ has a high value, then the set of feasible assignments (the assignment of i to t) will also be large.

The assignment of a machine (or group of machinery and men) u is restricted to a job i. For example, a plough can only be assigned to the job ploughing, but a man can be assigned to any job (if his experience is adequate). Also, certain assignments may only be applicable to certain periods, e.g. the harvest of winter wheat only takes place in August or September (in the northern part of the world). This will reduce the set of feasible assignments and, therefore, will reduce the size of the problem.

Nevertheless, the size of the problem is large. A problem with more than ten jobs, more than ten machines and more than hundred periods is not rare in agricultural practice (see the description of the models in Chapter 2).

The discrete model is structured as a network (compare the dynamic programming approach in Chapter 2). In this network, a statevector x_{t-1} represents a vector of the amount of different materials, available at the field at the beginning of period t (ha). The decisionvector $\mathbf{d}_t$ contains the decisions d_t^k to process at least a part of some material available in state x_{t-1} or doing nothing. The number of the decisions for a period depends on which materials are available, the amount of these materials in state x_{t-1}, and the workability of these materials in period t.

Each decision d_t^k represents the selection of a combination of gangs (executing one or more jobs simultaneously) for period t (k indicates the number of the combination and k=1, 2, ..., K, K is the total number of combinations, this depends on the problem). The combination processes an amount of material available in state x_{t-1}. A combination of gangs is operational for period t if all the materials processed by the combination are workable for period t. Taking the decision d_t^k

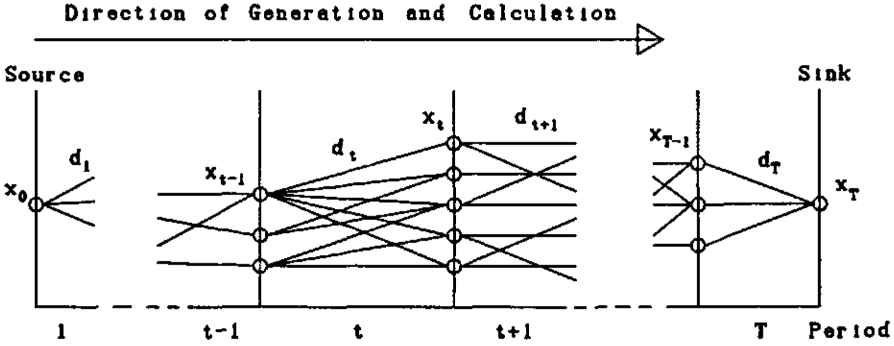


Figure 6.1. The schematic representation of the network and the direction of generation of nodes and calculation of the path with minimum cost (the solution procedure moves forward).

involves costs: timeliness cost (i.e. the difference in cost between the value of the material at optimum date of processing, and the value of the material at time t), the overtime cost, and the additional cost (i.e. the cost of scheduling additional jobs). The goal is to find a path in this network with minimum cost. This path represents a sequence of decisions (Figure 6.1).

The dynamic programming technique is often used as a solution method for this decision model (Audsley, 1979; Audsley, 1984; Morey et al., 1971). It is possible to find a solution for small problem instances, but the disadvantage of dynamic programming is the large computing time and the storage requirements due to the „curse of dimensionality".

6.3. HEURISTICS, INTELLIGENT SEARCH STRATEGIES

Because of the already mentioned „curse of dimensionality" of the dynamic programming technique, it is necessary to find a more efficient algorithm to solve the dynamic programming model. This algorithm has to perform a search through the network described in Section 6.2 but, it has to be far more efficient than the dynamic programming approach. Fast search techniques can be found in the field of artificial intelligence. These search strategies can, but do not have to, obtain an optimal solution. Search strategies will be described in this section.

> Definition 6.1
> *Heuristics* deal with criteria, methods or principles for deciding which among several decision alternatives promises to be the most effective in order to achieve the goal. They represent compromises between two requirements: the need to make such criteria simple and, at the same time, the desire to see them discriminate correctly between good and bad choices (Pearl, 1984).

A heuristic may be a rule of thumb that is used to guide one's actions. For example, a popular method for choosing ripe cantaloupe involves pressing the spot on the candidate cantaloupe where it was attached to plant, and then smelling the spot. If the spot smells like the inside of a cantaloupe, it is most probably ripe. This rule of thumb does not guarantee choosing only ripe cantaloupe, nor does it guarantee recognizing each ripe cantaloupe judged, but it is effective most of the time.

The field of heuristics is very large. Only a few basic notations and a few basic techniques which are used to scan networks (Pearl, 1984) will be dealt with here. The notations are as follows.

> Definition 6.2
> A *graph* (or a *network*) consists of a set of *nodes* (or *vertices*). A node has the identifier s. Certain pairs of nodes are connected by *arcs* (or *links*), which represent the decisions which can be made.

> Definition 6.3
> If an arc is directed from node s to node s′, node s′ is said to be a *successor* (or a *child* or an *offspring*) of s and node s is said to be a *parent* (or a *father*) of s′.

Definition 6.4
The most elementary step of graph searching is *node generation*, that is, computing the representation code of a node from that of its parent. The new successor is then said to be *generated* and its parent is said to be *explored.* A coarser computational step of great importance is node expansion, which consists of generating all successors of a given parent node. The parent is then said to be *expanded.*

Definition 6.5
A *search procedure*, a *policy*, or a *strategy* is a prescription for determining the order in which nodes are to be generated.

A few basic techniques which are used to scan networks are hill-climbing, backtracking and best-first search (Pearl, 1984).

Hill-Climbing, a strategy based on local optimizations, is a simple and the most popular strategy. It is called hill-climbing because, like a climber who wishes to reach the mountain peak quickly, it chooses the direction of steepest ascent from its current position. This type of procedure is sometimes called the „greedy" heuristic. Greedy heuristics are so called because they take what appears to be the best immediate option (Dannenbring and Starr, 1981)

The hill-climbing strategy amounts to repeatedly expanding a node, inspecting its newly generated successors, and choosing and expanding the best among these successors, while retaining no further reference to the predecessors. Obviously, the computational simplicity of this strategy is not without shortcomings. Unless the evaluation function used is extremely informative, there may be a risk of violating the first principle of systematic search, i.e. examine all possibilities. Moreover, as soon as a local optimum (a node more valuable than any of its successors) is reached, no further improvement is possible and the process must terminate with a local solution. This strategy is called irrevocable, because the process does not permit to shift attention back to previously discarded alternatives, even though they may have offered a greater promise than the alternatives used. Hill-climbing is a useful strategy when there is a highly informative guiding function to avoid local optima, ridges, and plateaus and which leads the procedure quickly toward an optimal solution (Wheeling, 1968).

Backtracking. In backtracking, priority is given to nodes at deeper levels of the graph. The finest computational step in backtracking is node expansion, i.e. each node chosen for exploration gets all its successors generated before another node is explored.

After each node expansion, one of the newly generated children is again selected for expansion and this forward exploration is pursued until, for some reason, progress is blocked. If blocking occurs, the process resumes from the deepest of all nodes left behind, namely, from the nearest decision point with unexplored alternatives. This policy works well when solutions are plentiful and equally desirable, or when there are reliable early warning signals to indicate an incorrect candidate direction (Pearl, 1984).

More sophisticated backtracking strategies also use a technique called „backmarking" with which, after meeting a dead-end condition, they may back up several levels at once. This is done by submitting the dead-end condition to a critical analysis to see if that condition can be attributed to one of the earlier ancestors along the path.

Best-First search. This technique is using heuristic information to evaluate certain directions of search which are more promising than others. The most natural stage for using heuristic information is in deciding which node to expand next. What sets „best-first" apart from other search strategies is the commitment to selecting the best from among all the nodes encountered so far, no matter where it is in the partially developed tree. The promise of a node s is estimated by a heuristic evaluation function f(s) which, in general, may depend on the description of s, the description of the goal, information gathered by the search up to that point, and most important, on any extra knowledge about the problem domain. The heuristic evaluation function f(s) often is a sum of two functions; the function g(s), which provides information gathered by the search up to node s, and the function h(s), which provides information gathered by the search from node s, information of the future.

The difference with hill-climbing is that hill-climbing only evaluates one stage at a time while the best-first search technique evaluates more than one stage at a time (using the function h(s)).

There exists a risk that since techniques like backtracking and best-first search scan the whole network (as the dynamic programming technique does), they will take a long time to find a solution. Therefore, the hill-climbing technique has been chosen as a base strategy for a heuristic that has to calculate schedules at operational level. The hill-climbing technique needs a strong, effective heuristic evaluation function to avoid local optima so far as possible. The heuristic with its evaluation function will be described in Chapter 7.

Chapter 7

A NEW ALGORITHM FOR SCHEDULING FARM OPERATIONS: FLOS

In this chapter, a new algorithm (a modified dynamic programming algorithm) which can be used to calculate schedules for a farm will be described (see also Wijngaard, 1987b). The chapter is divided into three parts:

1. the description of the algorithm and how it was developed;
2. the deterministic version of the model with the results of several validation tests;
3. the probabilistic version of the model, including:
    - weather forecast,
    - soil and grain moisture models,
    - certainty equivalence,
    - calculation of workability,
    - validation tests.

7.1. THE DESCRIPTION OF THE ALGORITHM

As shown in Chapter 6, the algorithm relies upon techniques from the field of artificial intelligence. The techniques hill-climbing, backtracking and best-first search have been described shortly. If techniques like backtracking and best-first search are used to scan the whole network (as the dynamic programming technique does), in that case, it will take too long to reach a solution. Therefore, the hill-climbing technique is chosen. This is a simple technique, but it will be combined with a strong heuristic evaluation function to avoid local optima as much as possible (for description of the used variables, see Chapters 2 and 6).

The heuristic which has been developed is based on the principle of hill-climbing (this heuristic will be further named as the heuristic FLOS which stands for Farm Labour and Operations

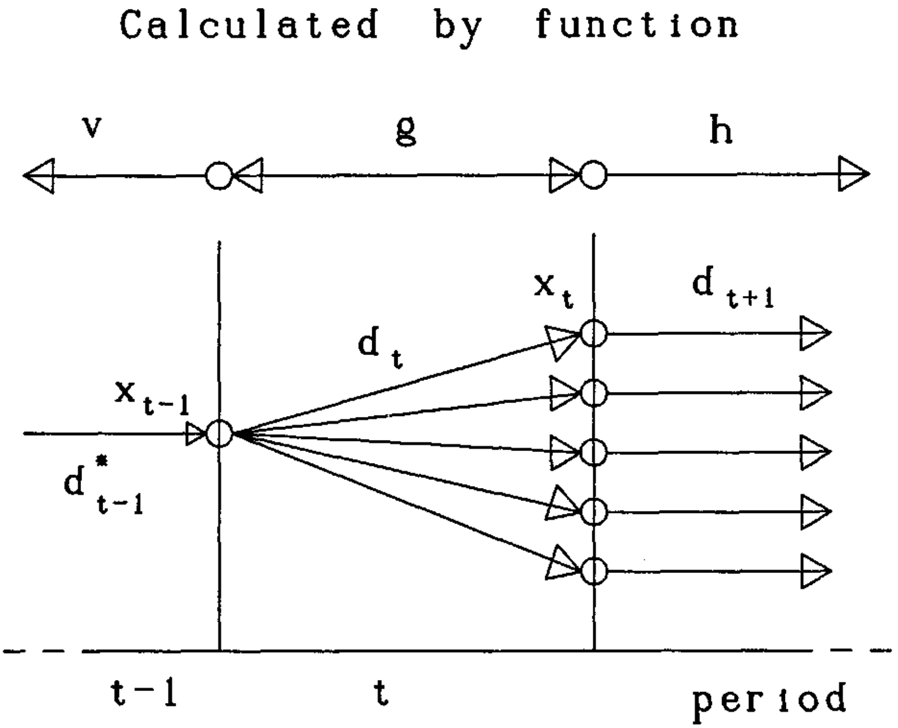


Figure 7.1. The schematic representation of the network as calculated by the heuristic FLOS.

Scheduling). The technique of hill-climbing uses a network (Figure 7.1). The structure of this network is the same as described in the Chapters 2 and 6. The value of a certain state (i.e. the calculated cost) is estimated by a heuristic evaluation function f_t (Pearl, 1984). This function is a composition of three functions: the function v_{t-1}, which provides information (i.e. the calculated cost) gathered by the search up to time t–1 (at the beginning of period t); the function g_t, which provides information on the decision in period t, it calculates the cost made in period t (g is used in the usual hill-climbing technique); and the function h_t, which provides information (i.e. the expected cost) gathered by the search from time t, it gives information about the future. The function h_t must be seen as a guiding function to achieve a solution which is as good as possible (Figure 7.1).

The procedure of the heuristic FLOS is as follows. Beginning at state $\mathbf{x}_{t-1}$, the decisionvector $\mathbf{d}_t$ is examined. Each decision d_t^k represents the assignment of sub-job $w_\mu(i)$ (see Chapter 6) to period t and therefore, the selection of a gang (or a combination of gangs). The combinations of gangs processes an amount of material available at state $\mathbf{x}_{t-1}$. The processing of $\mathbf{x}_{t-1}$ is done according to the transformation function T_t. The transformation function T_t (from stage t–1 to stage t) expresses the decrease or increase in amounts (ha) of the materials.

$$\mathbf{x}_t : \mathbf{x}_t = T_t(\mathbf{x}_{t-1}, \mathbf{d}_t)$$

and this means in our case:

$$\mathbf{x}_t = \mathbf{x}_{t-1} - \mathrm{CP}_t' \cdot \mathbf{d}_t + \mathrm{CL}_t' \cdot \mathbf{d}_t$$

and

$$x_t^j = (x_{t-1}^j - \mathbf{d}_t' \cdot \mathbf{cp}_t^j + \mathbf{d}_t' \cdot \mathbf{cl}_t^j)^+ \qquad j = 1,\ldots,J; \qquad (x^+ \overset{df}{=} \max(0,x))$$

and

CP_t = matrix with the processing capacities (i.e. the working rate of combination k processing material j) for combination k and material j in period t (ha · period^{-1})

CL_t = matrix with delivery capacities (i.e. the working rate of the combination k delivering the material j) for combination k and material j in period t (ha · period^{-1})

J = the total number of materials

For the decisionvector $\mathbf{d}_t$, the value of the function g_t will be calculated. This is done by simulating the processing of the materials. The value of the g-function represents the total costs in period t. The total costs are the sum of the timeliness cost of all the materials processed in period t (TM), the possible overtime cost (OV) for all the gangs, and the possible additional cost (EC, e.g. the drying cost). The timeliness cost is calculated for all the materials present in state $\mathbf{x}_t$. The overtime cost is only considered when the period is an overtime period (i.e. periods 3 and 4, and Saturdays and Sundays, see Chapter 6).

The value of the function h_t will be calculated. This value represents the expected cost which is needed to process the amount of material which is left in state $\mathbf{x}_t$.

The value of the function v_{t-1} is known for state $\mathbf{x}_{t-1}$. The function v_{t-1} is a kind of accountancy function, it is independent of the decisionvector $\mathbf{d}_t$ and has therefore no influence on the choice of the „best" decision.

For the decisionvector $\mathbf{d}_t$, the value of the heuristic evaluation function f_t is:

$$f_t(\mathbf{x}_{t-1},\mathbf{d}_t) = v_{t-1}(\mathbf{x}_{t-1}) + g_t(\mathbf{x}_{t-1},\mathbf{d}_t) + h_t(\mathbf{x}_t)$$

The best decisionvector $\mathbf{d}_t^*$ will be selected as follows:

$$\mathbf{d}_t^*: \min_{\mathbf{d}_t \in D_t(\mathbf{x}_{t-1})} \{ g_t(\mathbf{x}_{t-1},\mathbf{d}_t) + h_t(\mathbf{x}_t) \}$$

with:

$$\mathbf{x}_t = T_t(\mathbf{x}_{t-1}, \mathbf{d}_t)$$

$D_t(\mathbf{x}_{t-1})$ = the set of all possible decisionvectors $\mathbf{d}_t$ given state $\mathbf{x}_{t-1}$

The best decisionvector $\mathbf{d}_t^*$ involves the choice of only one combination k in period t because:

$$\mathbf{d}_t = (d_t^k),$$

d_t^k is a 0-1 variable and

$$\sum_{k=1}^{K} d_t^k = 1$$

K = total number of combinations

If the workability is zero, i.e. there are no workable hours, in period t, then d_t^k has the value zero. If the complete period is workable , then d_t^k can have the value one or zero (according to the chosen combination).

The combination k which matches the best decisionvector $\mathbf{d}_t^*$ will be assigned to period t. Then, for the state $\mathbf{x}_t$, the decisionvector $\mathbf{d}_{t+1}$ will be examined. The procedure will continue until the planning horizon is reached or until all the available material is processed.

The advantages of this procedure are:

1. The exclusion of a great number of nodes, it is unnecessary to build the complete network;

2. When all the materials are processed, then the algorithm is finished, this is contrary to the unmodified dynamic programming approach which must calculate the whole planning horizon (the structure of the network used by dynamic programming is pre-defined);

3. Interim decision moments can easily be created. The structure of the network is not fixed. During execution of the procedure, it is possible to include additional stages (for example, when a man gets sick or in case of machine failure);

4. Due to above facts, one and two, the expectation is that this algorithm is faster than the unmodified dynamic programming algorithm (Bellman's);

5. Also, due to facts one and two, the expectation is that the algorithm uses less computer memory;

6. The user can have a strong interactive influence on the algorithm (e.g. the influence on which decision is made; gangs can already be scheduled before calculation, by the algorithm, begins, see also Chapter 9).

The description of the functions is as follows. The v-function has the same meaning as the value-function of the forward dynamic programming technique (Wagner, 1977). It calculates the value of the total cost made in the past (up to the beginning of period t). At time zero, only possible timeliness costs are calculated. The v-function is in the formula:

$$v_{t-1}(\mathbf{x}_{t-1}) = \sum_{\tau=1}^{t-1} g_{\tau}(\mathbf{x}_{\tau-1},\mathbf{d}_{\tau}^{*})$$

The v-function is only used to calculate the cost incurred in the past. It is independent of the decisionvector $\mathbf{d}_t$, it has no influence on the choice of the „best" decision in period t.

The value of the g-function is defined as the total cost for the decisionvector $\mathbf{d}_t$ for period t. In formula (see also Chapters 2 and 5):

$$g_t(\mathbf{x}_{t-1},\mathbf{d}_t) = \mathbf{ec}_t' \cdot \mathbf{d}_t + TM_t + \mathbf{ov}_t' \cdot \mathbf{d}_t$$

where

$\mathbf{ec}_t$ = the vector with additional cost ($f\cdot$period^{-1}) incurred in period t (e.g. the drying cost, the description can be found in Chapter 2)

TM_t = the timeliness cost at the end of period t ($f\cdot$period^{-1}), calculated as follows:

$$TM_t = \mathbf{x}_t' \cdot \mathbf{tc}_t$$

$\mathbf{tc}_t = (tc_t^j)$ vector with the fixed timeliness cost for period t ($f \cdot (\text{period} \cdot \text{ha})^{-1}$)

$\mathbf{ov}_t = (ov_t^k)$ the vector with the possible overtime cost ($f\cdot$period^{-1}), calculated as follows:

$$ov_t^k = \begin{cases} \sum_{j=1}^{J} oc_t^j(k) \cdot \dfrac{x_{t-1}^j + \mathbf{d}_t' \cdot \mathbf{cl}_t^j - x_t^j}{\mathbf{d}_t' \cdot \mathbf{cp}_t^j} & \text{if } \mathbf{d}_t' \cdot \mathbf{cp}_t^j \neq 0 \\ 0 & \text{otherwise} \end{cases}$$

$CL_t = (cl_t^j(k))$ matrix with delivery capacities for combination k and material j in period t (ha·period^{-1}, see also Chapter 2)

$CP_t = (cp_t^j(k))$ matrix with the processing capacities for combination k and material j in period t (ha·period^{-1}, see also Chapter 2)

J = total number of materials

$OC_t = (oc_t^j(k))$ the matrix with overtime cost per period for period t ($f\cdot$period^{-1})

The h-function estimates the expected total cost of the schedule for period t+1 up to and including period T (is the total number of periods). The formulation of the function h_t which calculates the expected total cost (based on optimal decisions) is as follows:

$$h_t(\mathbf{x}_t) = \min_{\mathbf{d}_{t+1},\ldots,\mathbf{d}_T} \left\{ \sum_{\tau=t+1}^{T} g_{\tau}(\mathbf{x}_{\tau-1},\mathbf{d}_{\tau}) \right\}$$

The h-function is equal to the value function (see Chapter 2) in the unmodified dynamic programming model where the solution procedure moves backward. The h-function can give an optimal value. This can be calculated using the unmodified dynamic programming algorithm (Bellman's) which is very time consuming. Therefore, the value of h-function is estimated using a heuristic algorithm which is far more efficient. This algorithm will be described in the next section.

7.1.1. THE H-FUNCTION

The computation of the value of the h-function, or the guiding function, has been done using an algorithm. This algorithm is very important, it determines the both efficiency and effectivity of the heuristic FLOS. Therefore, a more detailed description of this algorithm will follow. The h-function evaluates the materials available in state x_t. These materials have to be processed in the future. The function h_t will calculate the cost incurred by the complete processing of all the materials available. The processing of the materials available by the algorithm has to be performed by a number of different gangs. These gangs have to be scheduled. Two basic assumptions have been made:

1. A material will be processed by a gang. This material has to be processed completely (until amount of this material equals zero) before another gang starts processing another material. The calculation of the value of the h-function stops when all the materials have been processed;

2. The processing of a material by a gang takes place constantly (only interrupted by non-workability of this material). No other assignments of gangs to other operations are possible (even when the material currently processed is not workable).

These assumptions have been made to increase the efficiency of the heuristic. The advantage of this procedure is that gangs have only to be scheduled in a sequence. The sequence of the gangs influences the value of the h-function and has therefore to be determined such that total cost is minimum. This sequence will be obtained by the properties of the materials processed by the gangs, i.e. the timeliness cost and the workability. These properties and their effects on the sequence of gangs are as follows.

The timeliness cost of the materials.

The timeliness function represents as has already been remarked the economic effect of timeliness, namely the effect of reduction in value of the crop due to losses in yield and quality when the operation is untimely.

For example, if the following input is given:

	amount (ha)	processed by	working rate (ha·period^{-1})	timeliness cost (f·(ha·period)$^{-1}$)
material A	10	gang 1	2	3
material B	10	gang 2	2	2

It will take five periods to process material A and five to process material B. It is assumed that these materials cannot be processed simultaneously. During the processing of material A, material B still contributes to the total timeliness cost. Material A and material B are workable in all the periods. The timeliness cost is calculated as follows:

If material A is processed completely before material B, at t=5 (after five periods), material A is processed completely and at t=10, material B is processed completely. The timeliness cost at end of each period and the total timeliness costs are:

	periods										total
	1	2	3	4	5	6	7	8	9	10	
material A	24	18	12	6	0	0	0	0	0	0	60
material B	20	20	20	20	20	16	12	8	4	0	140
											+
											200

(At the end of period 1, 2 ha of material A has been processed, 8 ha remains, the timeliness cost is 8 · 3 (= fixed timeliness cost) = 24)

But, if material B is processed completely before material A (at t=5, material B is processed completely, and at t=10, material A is processed completely):

	periods										total
	1	2	3	4	5	6	7	8	9	10	
material A	30	30	30	30	30	24	16	12	6	0	210
material B	16	12	8	4	0	0	0	0	0	0	40
											+
											250

Therefore, to reduce timeliness cost, material A has to be processed before material B. Gang 1 has to be scheduled before gang 2. The same calculation can be done for more than two gangs.

But, the calculation of the expected timeliness cost is also influenced by workability. Therefore, the sequence of gangs is determined by a combination of effects of timeliness cost and workability.

The workability.

The sequence of gangs will be prescribed by the total number of workable and non-workable periods for each gang (a non-workable period for a gang means that this gang cannot be operational in this period), and also by the corresponding fixed timeliness cost ($f\cdot(\text{ha}\cdot\text{period})^{-1}$) of the materials processed by each gang.

For example, the following input is given:

	amount (ha)	processed by	working rate ($\text{ha}\cdot\text{period}^{-1}$)	timeliness cost ($f\cdot(\text{ha}\cdot\text{period})^{-1}$)
material A	10	gang 1	2	2
material B	10	gang 2	2	2

Normally, it will take five periods to process material A and five to process material B. It is assumed that the materials cannot be processed simultaneously. Material A cannot be processed in 16.7% of the periods, these periods are non workable. Therefore, it will take one extra period to process material A (one period is 16.7% of six periods and six periods is the sum of five periods workable and one period not). Material B cannot be processed in 37.5% of the periods, these periods are also non workable, and it will take three extra periods to process this material (three periods is 37.5% of eight periods and eight periods is the sum of five periods workable and three not). It is assumed that the non workable periods come first and the extra periods are workable. If material A is processed before B, then material A is not workable in period 1 and material B is not workable in periods 7, 8 and 9. If material B is processed before material A, then material A is not workable in period 9 and material B is not workable in periods 1, 2 and 3.

If material A is processed completely before material B, at t=6, material A is processed completely and at t=14, material B is processed completely. The timeliness cost at end of each period and the total timeliness cost are:

	periods														total
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	
material A	20	16	12	8	4	0	0	0	0	0	0	0	0	0	60
material B	20	20	20	20	20	20	20	20	20	16	12	8	4	0	220
															+
															280

(the first period is not workable for material A, there are still 10 ha of this material available at the end of period 1, the periods 7, 8 and 9 are not workable for material B, there are still 10 ha of this material available at the end of period 9)

But if material B is processed completely before material A (at t=8, material B is processed completely, and at t=14, material A is processed completely):

	periods														total
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	
material A	20	20	20	20	20	20	20	20	20	16	12	8	4	0	220
material B	20	20	20	16	12	8	4	0	0	0	0	0	0	0	100
															+
															320

(the ninth period is not workable for material A and the periods 1, 2 and 3 are not workable for material B)

Even though the total duration is the same for both cases, the timeliness cost is different. The conclusion is that material A has to be processed before material B and therefore, gang 1 has to be scheduled before gang 2, to obtain minimum timeliness cost.

The clustering of gangs.

Gangs will also be clustered to a special kind of combination. There are three ways to cluster the gangs. They are as follows:

I. Gangs working simultaneously in practice. The sequence is also influenced by the knowledge or the experience of the user. All the materials which, *in practice*, are processed simultaneously, will also be processed „simultaneously" by the algorithm. The user must give, as inputs to the model, the materials which must be processed simultaneously. All the gangs processing these materials are treated as one combination of gangs processing *all* the materials simultaneously. This combination is not equal to combinations of gangs used by the g-function. The program will calculate an average working rate (see also Chapter 9).

For example, grain harvesting, straw baling and bale gathering occur simultaneously. In this case, cereal is the main material. If this is processed completely, then the processing of straw and bales will also stop. If the following working rates do exist:

• grain harvesting:	$2.35\ \text{ha}\cdot\text{h}^{-1}$,
• straw baling:	$1.41\ \text{ha}\cdot\text{h}^{-1}$,
• bale gathering:	$2.74\ \text{ha}\cdot\text{h}^{-1}$.

The working rate W_{rate} per hour for processing cereal, straw and bales simultaneously will be calculated as follows:

$$\frac{1}{2.35}\cdot W_{rate}+\frac{1}{1.41}\cdot W_{rate}+\frac{1}{2.74}\cdot W_{rate}= \quad 1 \qquad (= 1\ \text{ha})$$

$$0.43\cdot W_{rate}+0.71\cdot W_{rate}+0.36\cdot W_{rate}= \quad 1 \qquad (= 1\ \text{ha})$$

$$1.50\cdot W_{rate}= \quad 1 \qquad (= 1\ \text{ha})$$

$$W_{rate}= \quad 0.67 \qquad (\text{ha}\cdot\text{h}^{-1})$$

If sixty hectares of grain is available (and zero hectare of straw and bales), then it will take approximately 89.6 hours to process grain, straw and bales simultaneously. Only straw and bales delivered by this sixty hectares of grain will be processed. If there was already straw or bales available, then it will not be processed by this combination of gangs but later by another gang or cluster of gangs (which has straw or bales as main material).

II. Gangs processing the same material. When there are two or more gangs which process the *same* material, then one gang with the working rate as calculated above (W_{rate}) will be assumed.

III. Delivered materials will be processed simultaneously. The gangs must not only take care of their own material, they also have to arrange the processing of all the materials resulting from processing their own material. This is necessary because it is possible that the delivered materials will not be processed anymore. For example, if the following sequence with main gangs has been determined (with minimum timeliness cost and only the material cereal, straw and bales):

• Baling of straw	gang 2
• Harvesting of grain	gang 1
• Loading of bales	gang 3

Harvesting of grain (by gang 1) results in the delivery of straw. Baling of straw (by gang 2) takes place *before* harvesting of grain (by gang 1), therefore, straw (delivered by the grain harvest by gang 1) will never be processed. To prevent this, harvesting of grain will be clustered with a supplement gang: baling of straw (and with the supplement gang: loading of bales). These supplement gangs will work simultaneously with the initial gang (harvesting of grain) with the working rate W_{rate} (as calculated above). The supplement gang straw baling (working simultaneously with gang 1: harvesting of grain) has therefore another working rate than the initial gang straw baling, i.e. gang 2.

Momentary, the user of the model must give the number and order of these supplement gangs (see Chapter 9, file GAN_SEC.GEG). For example, the set of gangs can be extended with the following supplement gangs:

Initial gangs	Supplement gangs
• Baling of straw	Loading of bales
• Harvesting of grain	Baling of straw and loading of bales
• Loading of bales	

then the sequence of gangs will become as follows:

- Baling of straw and loading of bales simultaneously
- Harvesting of grain, baling of straw and loading of bales simultaneously
- Loading of bales

Clustering gangs improve the algorithm. Which order of supplement gangs is connected to each gang depends on the decision of the user of the model. The best order is the one used in practice (e.g. loading bales after straw baling and not straw baling after loading bales).

The three aspects, i.e. timeliness, workability and clustering, will create the sequence of gangs for use by the h-function. This will be done as follows.

Firstly, all the gangs are examined. The gangs processing the same material are clustered and the gangs processing different materials simultaneously are clustered and W_{rate} for these gangs is calculated. A set of gangs with single gangs (materials processed alone) and clustered gangs (materials processed simultaneously) has now been created.

For each gang, the materials processed by the gang are examined. If the gang is a clustered gang, then only *the first material* is examined (the first to be processed before other materials can be processed, in the previous example cereal). The fixed timeliness cost per day, from these materials, is used.

Then, for each gang (single or clustered), the workability percentage (percentage of periods in which material is workable) is calculated.

For each gang, a so-called order value ($ORDV_{i,j,u}$) is calculated as follows:

$$ORDV_{i,j,u} = (x_0^j / W_{rate} + 1.0) \cdot |TC_0^j| \cdot PWH_{i,j,u}$$

where

x_0^j = the amount of material j or of the first material j processed by a gang (single or clustered) at time zero (ha)

W_{rate} = the working rate for clustered gangs ($ha \cdot h^{-1}$), see the third aspect, i.e. the clustering of gangs

TC_0^j = the fixed timeliness cost of material j or of the first material j processed by gang (single or clustered) at time zero ($f \cdot (ha \cdot d)^{-1}$), see the first aspect, i.e. timeliness cost of materials

$PWH_{i,j,u}$ = the percentage workable hours in the planning horizon (%) of the gang (single or clustered, identified by job i and machine-set u) which processes material j, see the second aspect, i.e. the workability

The factor 1.0 is introduced to incorporate those gangs where there is no related material.

The gangs will be chained with ascending order of order values. Gangs which have a workability percentage (i.e. the percentage workable hours) equal to hundred will be placed at the tail of the sequence with descending order of timeliness cost. If all the gangs have the *same* workability percentage then they will also be ordered with descending order of timeliness cost. This formulation will be tested in Section 7.2.2.

Using this sequence, which in fact estimates $h_t(x_t)$ for each period, the timeliness cost, overtime cost and possible additional cost can be calculated. This is done by simulating the processing of the materials by the gangs in the order found. The value of the h-function is the sum of the above mentioned costs.

7.1.2. A SHORT EXAMPLE OF THE H-FUNCTION PROCEDURE

The procedure of the h-function is illustrated with a short example with two gangs. These gangs are gang 1: grain harvesting and gang 2: straw baling. The heuristic FLOS has to schedule both gangs and the combination of these gangs, i.e. the combination grain harvesting and straw baling. The heuristic starts (at t=0) with an initial amount of cereal of thirty hectares and of straw of zero hectare. FLOS calculates the values of the v-, the g- and the h-function at each moment (for each planning period) and chooses the „best" decision using the formulae stated in Section 7.1. A short example of the calculation of the value of the h-function is given at t=5.

Assume that the heuristic is deriving the „best" decision for period 5. It has already calculated the values of the v- and the g-function and it has to calculate the value of the h-function. This is done as follows.

First of all, the sequence of gangs for the h-function has to be derived. The first step in ordering the gangs is a possible clustering of gangs. In the preceding section, it is stated that delivered material must be processed simultaneously. During the processing of cereal, straw is delivered. Therefore, cereal must be processed with the delivered straw (which is not the straw already present on the field), and therefore, grain harvesting will be clustered with straw baling.

Note: during the processing of straw, bales will be delivered. But, no clustering takes place because the operation bales loading is not taken into account.

The working rate W_{rate} has to be calculated for the clusters. Using the working rate of straw baling (gang 2) and the W_{rate} of the cluster grain harvesting — straw baling (gang 1) and the information given below, the ordering values are calculated using the formula in the preceding section and the sequence of gangs is derived (for definition of the parameters and the dimensions, see Section 7.1.1).

	TC_0^j	x_0^j	working rate	W_{rate}	$PWH_{i,j,u}$	$ORDV_{i,j,u}$
gang 1 (cluster)	5.00	30.00	4.00	1.54	46.00	4710.00
gang 2	5.40	0.00	2.50	2.50	54.00	292.00

The sequence will be ordered with ascending order values and is now: (1) the gang straw baling and (2) the cluster grain harvesting — straw baling.

At t=5, ten hectares of cereal and five hectares of straw are still available. The h-function simulates the processing of these materials. It starts with the processing of straw according to the derived sequence. The working rate of the gang straw baling is 2.5 $ha{\cdot}period^{-1}$, so, the processing of straw will take two periods, i.e. period 6 and period 7. But, straw is not workable in period 7, therefore, the h-function waits and continues processing of straw in period 8. At the end of period 8, the straw is completely processed. The amount of the materials cereal and straw (ha) and the timeliness cost (f) at the end of each period is as follows:

amount of material at end of period (ha)

	5	6	7	8
cereal	10.00	10.00	10.00	10.00
straw	5.00	2.50	2.50	0.00
			⇑ 1)	

1) Straw is not workable in period 7.

timeliness cost at end of period (f)

	6	7	8	total	
cereal	50.00	50.00	50.00	150.00	
straw	13.50	13.50	0.00	27.00	+
				177.00	

At the beginning of period 9 (at t=8), the processing of cereal takes place. There is ten hectares of cereal and, if cereal is completely processed, ten hectares of straw will be delivered. It is assumed that the ten hectares of cereal and the delivered ten hectares of straw will be processed simultaneously starting at t=8. The working rate W_{rate} is 1.54 ha·period^{-1} and therefore, it will take approximately seven periods to process straw and cereal simultaneously. But, cereal is not workable in period 10, therefore the processing of cereal temporarily stops and will continue in period 11. The processing of straw will still continue, also in period 10. Straw is not workable in period 14, the processing of straw will temporarily stop but the processing of cereal still continues. The amount of materials (ha) and the timeliness costs (f) at the end of each period are as follows:

amount of material at end of period (ha)

	8	9	10	11	12	13	14	15	16
cereal	10.00	8.46	8.46	6.92	5.38	3.84	2.30	0.76	0.00
straw 1)	10.00	8.46	6.92	5.38	3.84	2.30	2.30	0.76	0.00
			⇑ 2)				⇑ 3)		

1) This straw is delivered only during the processing of the ten hectares of cereal.
2) Cereal is not workable in period 10.
3) Straw is not workable in period 14.

	timeliness cost at end of period (ƒ)								
	9	10	11	12	13	14	15	16	total
cereal	42.30	42.30	34.60	26.90	19.20	11.50	3.80	0.00	180.60
straw	45.68	37.37	29.05	20.74	12.42	12.42	4.10	0.00	161.78 +
									342.38

The total timeliness costs are now ƒ177.00 plus ƒ342.38 which is ƒ519.38 and this is also the value of the h-function (no overtime or extra costs are charged).

A deterministic and a probabilistic version of this algorithm has been developed. For the deterministic model, the future workability is perfectly known for the entire planning horizon. For the probabilistic model, the workability is derived using a weather forecast which is changing every day. The probabilistic model makes use of so-called „rolling horizon" concept. The structure of these two versions, with the results of several tests will be successively described in Section 7.2 and Section 7.3.

7.2. THE DETERMINISTIC VERSION OF THE HEURISTIC FLOS

For the deterministic version, the same workability data as input for the linear programming, the dynamic programming and the simulation model have been used. Twelve years of workability data: 1957 till 1968 have been used. This means that the h-function is calculated for a future workability which is perfectly known for the entire planning horizon. This has been done to compare the first results of the heuristic FLOS with the results of the other models (which are examined in Chapter 3).

First of all, the heuristic will be compared with the models which give optimum results. With this comparison, the performance of the heuristic will be analysed. Aspects which have influence on the outcome of the heuristic are the hill-climbing algorithm (looking only one stage ahead), the ordering of gangs for the h-function and the workability data in the future. These aspects have to be analysed and therefore the following tests were setup:

1. Four different evaluation functions were compared; with each other and with the results of the linear programming, the dynamic programming and the simulation models. In addition to the costs, the calculated schedule has been examined. The latter only for comparison with the dynamic programming model (stated as the reference model, see Chapter 2). The tests will be discussed in Section 7.2.1;

2. In Section 7.2.2, the effects of different sequences of gangs in the h-function will be discussed.

3. The effects of a single period or of a double period g-function will be discussed in Section 7.2.3. A single period g-function means that the value of the g-function is calcu-

lated for one period, considering each period one after another. For a double period g-function, the value of the g-function is calculated for two periods ahead, considering each period one after another;

4. The effects of knowing the workability data of a few periods ahead is given in Section 7.2.4.

7.2.1. THE FOUR DIFFERENT H-FUNCTIONS

In the first results, four heuristics have been tested and compared with the results of the outcome of the linear programming, together with the dynamic programming and the simulation models (for the models, see Chapter 2). Each heuristic has a different evaluation function, i.e. a different h-function. With the h-function, overtime periods may or may not (if not, it will jump to the next non-overtime period, a regular period) be used. The h-function may also incorporate jobs which are not essential. These jobs can accelerate the processing of materials, but they are also more expensive. Contract work and the drying of wet grain are jobs examples. The four heuristics are:

FLOS A:	with additional jobs and without overtime,
FLOS B:	without additional jobs and without overtime,
FLOS C:	with additional jobs and with overtime,
FLOS D:	without additional jobs and with overtime.

The assignment of gangs to $\mathbf{d}_t^*$ is not altered however; only the h-function is drawn up into a different way. The heuristics are calculated using climatological data for twelve years, from 1957 to 1968, and within these years, from August 1 to September 4. It determines a schedule for the grain harvest (see Chapter 2 and 3). It must process the materials cereal, straw, bales, stubble and perhaps wet grain. It uses the following gangs:

- harvesting of grain with one man
- harvesting of grain with two men
- baling of straw
- loading of bales
- ploughing stubble
- drying of wet grain

The sequence of processing materials (and therefore the clusters of gangs) for the h-function is predetermined and as follows:

1. baling of straw, loading of bales and ploughing stubble
2. loading of bales and ploughing stubble
3. harvesting grain, baling straw, loading bales, ploughing stubble
4. ploughing stubble
5. drying of wet grain

This sequence is based on the principles and the formulae stated in Section 7.1.1 (see also Section 7.2.2). The heuristics have a planning horizon of five weeks. Two sizes of farm are used: twenty and sixty hectares. The length of a period is five hours, therefore, the results can be compared with the ROUN20 and the ROUN60 models at the 5-hour level (Chapter 3). For every schedule, the timeliness, the overtime and the additional costs are calculated. The additional costs of the grain harvest are the drying costs of wet grain. The total costs are given in Tables 7.1 and 7.2 (the results of the dynamic programming model with sixty hectares does not exist due to the „curse of dimensionality", see Chapter 2), the differences between the heuristics and the other models (i.e. linear programming, dynamic programming and the simulation model) are given in Table 7.3. Only the differences between two groups of models (the group as a whole) are important. Group 1 is holding the simulation model, the linear and the dynamic programming models (fully described in Chapter 2, see also Van Elderen, 1987), and group 2 is holding the four heuristics. The differences between the models in group 1 (e.g. the differences between the linear programming model and the dynamic programming model) are not considered here.

Table 7.1. The total costs (*f*) for a farm with twenty hectares (DP is dynamic programming, LP is linear programming, Sim is simulation, ave is average, B1 to B3 are also given in Appendix B).

	FLOS				Min	DP	LP	Sim
year	A	B	C	D	(A,B,C,D)	(B3)	(B2)	(B1)
1957	316	316	462	462	316	168	152	306
1958	538	538	538	538	538	454	427	1137
1959	1222	1112	1168	1323	1112	1101	899	1360
1960	753	902	750	1101	750	749	532	1000
1961	391	443	391	731	391	357	361	799
1962	723	723	979	868	723	677	576	1049
1963	423	423	783	783	423	347	324	621
1964	618	584	1166	957	584	502	475	1111
1965	491	490	1374	1264	490	457	444	1059
1966	1545	1507	1673	2461	1507	1965	1339	1687
1967	282	282	217	677	217	202	194	577
1968	334	334	457	505	334	249	412	531
ave	636	638	830	973	615	602	511	936

Table 7.2. The total costs (*f*) for a farm with sixty hectares (LP is linear programming, Sim is simulation, ave is average, B12 and B13 are also given in Appendix B).

	FLOS				Min	LP	Sim
year	A	B	C	D	(A,B,C,D)	(B13)	(B12)
1957	1839	1602	1890	1998	1602	1418	2345
1958	2837	3081	2962	3097	2837	2599	3945
1959	3615	3756	3815	5918	3615	3277	4194
1960	3103	4335	3492	3400	3103	3081	4462
1961	3002	2750	3361	3048	2750	2522	3864
1962	3857	4303	4252	4530	3857	3622	3919
1963	1848	2384	2083	2258	1848	2435	2912
1964	2816	2873	3554	2536	2536	2462	3706
1965	2559	2446	4476	3236	2446	2373	3920
1966	5535	5450	5352	5601	5352	5333	6397
1967	2530	2692	2876	2402	2402	2340	3228
1968	2985	2874	3888	3423	2874	2706	3889
ave	3044	3212	3500	3454	2935	2847	3898

Table 7.3. The average difference in result (%) between the minimum of the heuristics and DP, LP, and simulation for a farm with twenty and sixty hectares.

farm size	Min (A,B,C,D)	DP	LP	Sim
20	0	–2.11	–16.91	+52.20
60	0		–3.00	+32.81

They are fully described in Chapter 3. Using the results of group 2, the best heuristic according to minimum cost will be chosen.

The heuristic is mainly compared with the linear programming and the dynamic programming model because the linear and dynamic programming models offer optimal results (with regard to the models themselves). The simulation model is of less importance because it offers non-optimal results (see Chapter 3). The heuristic is compared with the optimal results because the difference in cost between the results of the heuristic and the optimum has to be analysed. The smaller the difference, the better the performance of the heuristic.

The values of the results of the heuristics are not much higher than the outcome of the DP and LP (with 60 ha), but they are significantly lower than the outcome of the simulation model. The average differences between FLOS and the dynamic and linear programming models (except for LP with 20 ha) are small, about two to three percent.

However, the difference in computing time is large. The difference between the heuristic FLOS and the dynamic programming model is approximately a factor of 10,000 for a farm size of twenty hectares, and about a factor of 6,000 for a farm size of sixty hectares. The difference between FLOS and the linear programming model is about a factor of 100 for a farm size of twenty hectares, and about a factor of 65 for a farm size of sixty hectares (for CPU seconds, MicroVAX).

FLOS also is much smaller in size. The maximum number of states per stage is equal to the maximum number of combinations of gangs; in this example twenty-four. This is contrary to the dynamic programming model. The latter has a maximum number equal to the maximum number of states of the materials. For a farm of twenty hectares, this is equal to 5^5 (for five materials, the areas 0, 5, 10, 15 and 20, this gives 3125 states), and for a farm of sixty hectares 13^5 (for five materials, the areas 0, 5, 10,..., 55, 60, this gives 371293 states). FLOS uses less on memory and therefore, is within the possibilities of a micro-computer.

Within group 2, i.e. the four heuristics, the averages of the results of FLOS A and FLOS B contain the lowest cost (compared with FLOS C and FLOS D). FLOS A also incorporates the handling of extra jobs. Using FLOS B, the extra jobs which are important, will be lost. Therefore, FLOS A, i.e. with extra jobs and without overtime, is chosen to be the heuristic with which further research will be performed.

Schedules can also be compared with each other. The schedule of the dynamic programming model has been compared with the schedules of the heuristics FLOS A (with extra jobs and without overtime) and FLOS B (without extra jobs and without overtime) for a farm with twenty hectares. The following results were compared:

1. the number of periods with overtime hours used by the models;

2. the number of periods with drying of wet grain scheduled;

Table 7.4. The average number of periods with overtime hours, with drying of wet grain scheduled, until all the cereal is processed, and until all the materials are processed, for the heuristics FLOS A and FLOS B and the dynamic programming model (DP) for a farm of twenty hectares.

	average number of periods for			
model	overtime	drying	finish cereal	finish all mat.
DP	0.75	0.00	6.75	9.25
FLOS A	0.75	0.13	7.88	10.50
FLOS B	0.75	0.13	9.25	11.38

3. the number of periods until the grain is processed completely;
4. the number of periods until all the materials are processed completely.

The results are shown in Table 7.4. The differences are small. FLOS is a little slower in processing the materials and has to use more drying periods. It takes the decision to process cereal earlier as wet grain with the disadvantage of higher drying cost, but the advantage of lower timeliness cost. The dynamic programming model decides to delay the processing until the material is workable and does not decide to harvest wet grain.

Conclusions of this section are:

- the heuristic FLOS offers near-optimal results (the decrease of effectivity is small);
- the heuristic FLOS is very efficient (related to the solution of the unmodified dynamic programming model);
- the heuristic FLOS is small in size and is within the possibilities of a micro-computer;
- therefore, the heuristic improves the effectivity and the efficiency of the decision process;
- FLOS A is chosen as the heuristic with which further research will be performed

7.2.2. DIFFERENT SEQUENCES OF GANGS FOR THE H-FUNCTION

An approach to ordering the combination of gangs for the h-function was discussed in Section 7.1.1. In this section, the results of a test are given in which all possible sequences for the h-function are used.

A grain harvesting problem was chosen again. The gangs with their working rate (ha·h^{-1}) are as follows:

• harvesting of grain with one man	1.0
• harvesting of grain with two men	2.0
• baling of straw	2.0
• loading of bales	2.0
• drying of wet grain	1.0

Table 7.5. The timeliness cost (TC_0^j, $f\cdot(\text{ha}\cdot\text{d})^{-1}$), the initial amount ($x_0^j$, ha), the working rate (W_{rate}) and the percentage workable hours for each year ($PWH_{i,j,u}$, over 35 days, %) for each gang.

				$PWH_{i,j,u}$		
gang	TC_0^j	x_0^j	W_{rate}	1957	1959	1968
1	5.0	60.0	0.6	29.52	71.43	45.14
2	5.4	0.0	1.0	43.62	75.24	57.33
3	21.1	0.0	2.0	94.67	98.67	97.52
4	1.2	0.0	1.0	100.00	100.00	100.00

Ploughing is not involved. It is not supposed to be relevant for this problem.

These gangs are clustered as described in Section 7.1.1. The following clusters (combined or single gangs) with the working rate (W_{rate}, $\text{ha}\cdot\text{h}^{-1}$) do exist:

1.	harvesting grain[1], baling straw and loading bales	0.6
2.	baling straw and loading bales	1.0
3.	loading bales	2.0
4.	drying wet grain	1.0

[1] harvesting grain is a cluster of harvesting grain with one man and harvesting grain with two men. The W_{rate} of this cluster is 1.5 $\text{ha}\cdot\text{h}^{-1}$.

The four gangs are ordered in twenty-four different sequences. These different sequences are for use by the model only, because several sequences do not reflect reality. The sequences are taken as an input of the model. This model is calculated with workability data from the years 1957, 1959 and 1968. These years are chosen considering the results stated in the tables in Appendix B. 1957 always gives a solution with the lowest cost in the range 1957—1968 because the workability is almost not restrictive. 1959 gives a solution with the highest cost in the range 1957—1968. Only 1966 gives solutions with higher cost because the workability in 1966 is worse than in 1959. But 1959 is chosen because the workability in 1966 is *too* restrictive. 1968 offers a solution where the cost is almost equal to the average over twelve years (considering *all* the tables).

The heuristic calculates as FLOS A (with extra jobs and without overtime). The timeliness cost of the materials, the percentage of workable hours in the planning period for each gang per year, and the initial amount are presented in Table 7.5. The results are stated in Table 7.6.

In Section 7.1.1, a formula has been developed which helps to order the gangs for the h-function. This formula calculates an order value ($ORDV_{i,j,u}$) as follows:

$$ORDV_{i,j,u} = (x_0^j / W_{rate} + 1.0) \cdot |TC_0^j| \cdot PWH_{i,j,u}$$

where

x_0^j = the amount of material j or of the first material j processed by a gang (single or clustered) at time zero (ha)

W_{rate} = the working rate for clustered gangs ($\text{ha}\cdot\text{h}^{-1}$)

TC_0^j = the fixed timeliness cost of material j or of the first material j processed by gang (single or clustered) at time zero ($f\cdot(\text{ha}\cdot\text{d})^{-1}$)

Table 7.6. The results (total costs, *f*, minimum value is underlined), the difference with the minimum value for each year and the average (ave) for different sequences of gangs for the years 1957, 1959 and 1968 for a farm of sixty hectare.

				difference with minimum			
sequence	1957	1959	1968	1957	1959	1968	ave
1 2 3 4	1529	3643	2889	372	696	206	425
1 2 4 3	1529	3643	2889	372	696	206	425
1 3 2 4	1529	3643	2889	372	696	206	425
1 3 4 2	1529	2947	3388	372	0	705	359
1 4 2 3	1529	2947	3388	372	0	705	359
1 4 3 2	1529	2947	3388	372	0	705	359
2 1 3 4	1186	3266	2913	29	319	230	193
2 1 4 3	1186	3266	2913	29	319	230	193
2 3 1 4	1186	3266	2913	29	319	230	193
2 3 4 1	1186	3266	2913	29	319	230	193
2 4 1 3	1186	3266	2913	29	319	230	193
2 4 3 1	1186	3266	2913	29	319	230	193
3 1 2 4	1247	3401	2825	90	454	142	229
3 1 4 2	1247	3401	2825	90	454	142	229
3 2 1 4	1158	3273	3079	1	326	396	241
3 2 4 1	1158	3009	3371	1	62	688	751
3 4 1 2	1247	3437	2998	90	490	315	298
3 4 2 1	1157	2962	3418	0	15	735	250
4 1 2 3	1186	3081	2683	29	134	0	54
4 1 3 2	1186	3081	2683	29	134	0	54
4 2 1 3	1529	3043	2800	372	96	117	195
4 2 3 1	1529	3043	2800	372	96	117	195
4 3 1 2	1247	3093	2998	90	146	315	184
4 3 2 1	1158	3104	3419	1	157	736	298

$PWH_{i,j,u}$ = the percentage workable hours in the planning horizon (%) of the gang (single or clustered, identified by job i and machine-set u) which processes material j, see the second aspect, i.e. the workability

For 1957, 1959, and 1968, the order values are stated in Table 7.7 (for sixty hectare of cereal).

If the gangs are ordered according to ascending order values, for each year the sequence 4 — 2 — 3 — 1 is obtained. Gang 4 will be treated specially because the percentage workable hours is 100%. Gang 4 will be placed at the tail of the sequence. The sequence of gangs is now 2 — 3 — 1 — 4. This sequence gives almost the lowest cost (see the average in Table 7.6). Only the

Table 7.7. The order values of the gangs for the years 1957, 1959 and 1968.

gang	1957	1959	1968
1	14908	36072	22796
2	236	406	310
3	1998	2082	2058
4	120	120	120

sequences 4 — 1 — 2 — 3, 4 — 1 — 3 — 2 and 4 — 3 — 1 — 2 give better results. The ordering based on ordering values (calculated with the formula given above) gives not always the best results. Another ordering, e.g. by using an algorithm for solving the Travelling Salesman Problem, can give better results. But the principle of ordering values is chosen above a more sophisticated algorithm because it is assumed that the increase in efficiency is large (but effectivity decreases a little). More research is necessary to find a more reliable mathematical function for the h-function, more reliable than the ordering value function.

The conclusion is that the sequence of gangs is an important factor in viewing the future for the h-function. The formulation of this sequence will be used further to order gangs for the h-function. Gangs where workability is of no importance (i.e. material is *always* workable) will be placed, with descending order of timeliness cost, at the tail of the sequence.

7.2.3. SINGLE PERIOD OR DOUBLE PERIOD G-FUNCTION

FLOS is evaluated one period at a time. For each period, the value of the g-function and of the h-function is calculated for each possible decision. The outcomes of the possible decisions are compared, and the minimum is taken. This is done for one period at a time. But, it is also possible to calculate the g-function for two periods or more. If the g-function for T periods (T is the total number of periods) is calculated, the forward dynamic programming approach is obtained. In this section, the results of a model with a one-period g-function (the single period g-function) and a model with a two-period g-function (a double period g-function) are compared. The purpose is the analysis of the hill-climbing algorithm and a possible improvement of the effectivity of the heuristic FLOS (efficiency will probably decrease).

Again, the same four heuristics, i.e. FLOS A, FLOS B, FLOS C and FLOS D, described in Section 7.2.1 are used. These heuristics are calculated for two farm sizes, i.e. twenty and sixty hectares, with workability data from the years 1957 to 1968. The results, i.e. the average of the total costs (*f*), the time needed to calculate a solution (CPU seconds, MicroVAX) and the difference between the results of the single period and the double period g-function models (related to the single period g-function model, %) are stated in Table 7.8.

The heuristic FLOS is improved if the double period g-function is used, but the improvement is only one to two percent. However, the calculation time is strongly increased, by about a factor

Table 7.8. The average results over twelve years of a model with a single period and a model with a double period g-function (cost in *f* and CPU time in seconds) and the differences in results (in % of the single period g-function model).

	single period min (A,B,C,D)		double period min (A,B,C,D)		Difference in result	
farm size	cost	CPU	cost	CPU	cost	CPU
20	535.00	2.08	533.00	5.93	–0.44	+185.20
60	2688.00	3.28	2623.00	12.78	–2.42	+289.30

three to four. Due to the large decrease of efficiency and the little increase of effectivity, the double period g-function is not a preferred substitute for the present heuristic (using a single-period g-function).

The conclusion is that the enlarging of the number of periods calculated by the g-function will not improve the usefulness of the heuristic FLOS. Therefore, the present description of the g-function is maintained for the present and further research with this approach is continued.

7.2.4. AN INCOMPLETE LOOK AT THE FUTURE

The last test with the deterministic version of the model is the test with the incomplete look at the future. In this, the workability data are known as forecasted values for a selected sequence of periods only. The sequence with known workability data is followed by a sequence of periods without exact workability data. Therefore, for this test, this workability data have been assumed to be zero (i.e. the material is not workable in these periods). The workability is stated to be zero for examination of the behaviour of the h-function and the heuristic, when the numbers of periods, to which operations can be assigned, becomes small (if a material cannot be processed then timeliness cost is calculated at the *end* of the planning horizon). The effects of a lack of knowledge about the future is investigated in this test.

The heuristic FLOS A (Section 7.2.1) is tested for a farm with sixty hectares. Three years with workability data, i.e. 1957, 1959 and 1968 have been taken (for the same reason as stated in Section 7.2.2). The reference model is FLOS A with 105 periods with known workability. For the tested models, the number of periods with known workability data will decrease from thirty-five to one. The results of this test are visually presented in Figure 7.2.

When the number of periods with known workability decreases, at first the cost decreases and then increases, when the number falls below twenty. Also, in some cases, the cost is even lower than that of the reference model (FLOS A with known workability for 105 periods). A model offering optimal results will always show an increase in cost if knowledge of the future decreases. Therefore, during the decrease of cost, calculated by the heuristic, the difference between the results of the heuristic and the optimum becomes smaller. The performance of the heuristic becomes better. This will be explained below.

The effect of the h-function which is affected by the number of periods with known workability is the cause of the decrease of the cost. If the h-function has no information on a certain part of the future, high expected cost will result which forces the heuristic to assign all possible operations as soon as possible because the workability for the periods beyond the periods with known workability, is stated to be zero. Due to constraints on workability in the future, the h-function forces the heuristic to assign the operations to periods with well known workability.

Three conclusions can be made:

1. less information on the future does not imply higher cost, it is possible that FLOS produces a better solution (better than that of the reference model which knows the future

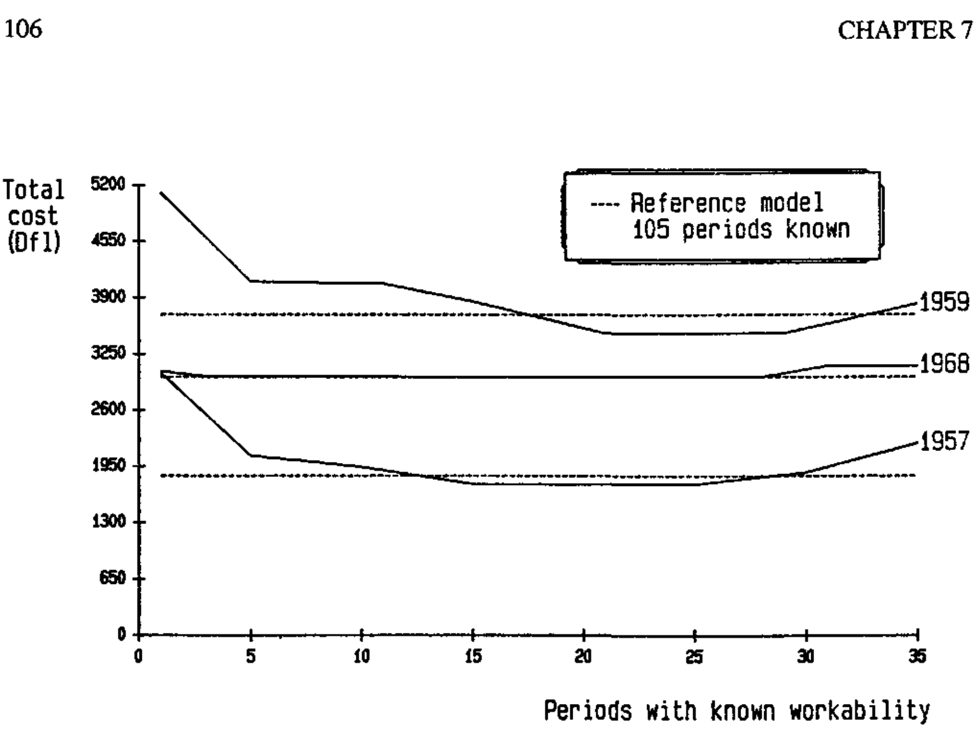


Figure 7.2. The results of the test on incomplete look at the future for the three years 1957, 1959 and 1968. The x-axis represents the number of periods with known workability. The line of the reference model (for each year) is the total cost resulting from FLOS with 105 periods with known workability (the whole planning horizon).

perfectly). This is contrary to a model which offers optimal results. For this model, less information of the future always implies higher cost. The heuristic FLOS performs better in situations with less information until a certain level of information is reached. The difference between the results of FLOS and the optimum becomes smaller. This conclusion is based on the results of three years;

2. applying more weight to the h-function by withholding information about the future (assuming future workability to be zero), or by decreasing the solution space can force FLOS to give better solutions;

3. the optimum range of known workability in this test is 15—30 periods or 5—10 days.

The main conclusion of Section 7.2 is that the deterministic version discussed in Section 7.1 performs well in several situations. Using this version, and in particular the heuristic FLOS A (the one with the use of additional jobs and without the use of periods with overtime hours in the h-function, see Section 7.2.1), a probabilistic version of the model will be developed. This version has the deterministic version as base structure. It will be described in the next sections.

7.3. THE PROBABILISTIC VERSION OF THE HEURISTIC FLOS

The probabilistic version of the heuristic FLOS will be described in this section. In fact, the probabilistic version has the same structure as the deterministic version. It uses the same network description, the same search algorithm and the same type of input. In a static environment, i.e. a situation where FLOS is calculated only once, the results of the tests of Section 7.2 and those described in Chapter 3 will be used. The results about the level of aggregation, i.e. the upper boundary on length of periods is a day, can be used too.

Summarizing, the model as described in Chapter 6 and Section 7.1 is used. The difference with the deterministic version of FLOS is the formulation of the input, i.e. the workability data. The workability data for the deterministic version of the model were known for all the periods (in advance). The data for the probabilistic version have to be calculated using a weather forecast, a soil moisture suction model, grain moisture content formulae and also climatological data.

This creates a dynamic environment because the weather forecast is changing from day to day, and with that, the sequence of workability data. The question now is: can the results from the test described in Chapter 3 and Section 7.1 still be used. The answer is given below.

In this section, the calculation of the workability data will be described using weather forecast, moisture models and climatological data (Section 7.3.1 and Appendix F). In Section 7.3.2, the results of the following tests will be given:

- the comparison of the probabilistic version with the results of the probabilistic dynamic programming model (Chapter 5);

- the effects of different weather forecast concerning:
  - different data, and
  - different lengths of forecast.

7.3.1. THE CALCULATION OF WORKABILITY DATA

The calculation of workability data uses:

- the weather forecast;

- the initial conditions of soil and grain, i.e. the soil moisture suction and the grain moisture content at time zero;

- a soil moisture suction model to calculate the soil moisture suction (for those periods for which a weather forecast is given);

- a grain moisture content model to calculate the grain moisture content (for those periods for which a weather forecast is given);

- files with sequences of soil moisture suction and grain moisture content calculated from climatological data (of about twenty-four years) by the same moisture models.

The weather forecast is given by the user of the model (as input), as are the initial conditions of soil and grain. The workability is only calculated for the crops winter wheat, barley, oats and colza. The workability of other materials comes from the soil workability data until moisture models for the other materials are available. The weather forecast has to contain:

1. the rainfall $(\mathrm{mm \cdot d^{-1}})$
2. the probability of rainfall (—)
3. the reference evaporation rate $(\mathrm{mm \cdot d^{-1}})$

If workability data are also desired for the crops wheat, barley, oats and colza, the weather forecast also has to contain:

4. the global radiation $(\mathrm{kJ \cdot (d \cdot cm^2)^{-1}})$

Some details on how a weather forecast is developed will be discussed in Appendix G.

The length of the weather forecast used by the heuristic FLOS is five days. For every day, the four data should be given. After the weather data have been given, FLOS will calculate a sequence of five days workability data using the moisture models. The workability data are calculated for soil and for the four mentioned crops (for other crops, momentary, no moisture model is available). The soil moisture suction model is described in Appendix F (Driessen, 1983). This model has a simple structure. There are a lot of better, more detailed models (Dyer and Baier, 1981; Witney et al., 1982; Jeevananda Reddy, 1983; Belmans et al., 1983; Martínez-Lozano et al., 1984), but these models need detailed data such as fraction of clouds, air and soil temperatures, information about soil layers and the flux between those layers. These data are today not completely supplied by weather forecast stations. Therefore, a simple soil moisture suction model has been used. The formulae used in this model are tested by Driessen (1983). They are also tested by Goense (1987) for a N-layer model (i.e. the top soil layer is divided in more than one layer) and this model is tested for several soils in Surinam. The model did perform well. If a better grain moisture model makes its appearance, then it can be easily take the place of the Van Kampen's formulae. The structure of the heuristic takes account of a possible new moisture model.

The same can be said of the grain moisture content models. A detailed model (Brück and Van Elderen, 1969) requires more detailed data than a weather forecast can give. For the grain moisture calculation, the formulae of Van Kampen (1969) are used. These formulae need only a limited number of data, they were tested by Van Kampen and did perform well for his situation. But, cultivars of cereal are changing and now they are different from those in 1969 which are used to verify the model. Still, these formulae are used until better grain moisture content models arise. The following formulae have been used here:

1. *for drying of grain under influence of radiation:*

$$\text{colza:} \quad MC_{new} = MC_{old} \cdot e^{(-0.00298 \cdot rad)}$$
$$\text{barley:} \quad MC_{new} = MC_{old} \cdot e^{(-0.00115 \cdot rad)}$$

oats: $MC_{new} = MC_{old} \cdot e^{(-0.00203 \cdot rad)}$

wheat: $MC_{new} = MC_{old} \cdot e^{(-0.00110 \cdot rad)}$

where:

MC_{old} = the moisture content at the beginning of the day (% wet basis)

rad = the radiation $(cal \cdot (d \cdot cm^2)^{-1})$ $(1\ cal \cdot (d \cdot cm^2)^{-1} = 42\ kJ \cdot (d \cdot m^2)^{-1})$

MC_{new} = the moisture content at the end of the day, this value is assumed to be the moisture content for the whole day (% wet basis)

2. the effect on moisture content by rainfall:

colza: $MC_{new} = 44 - (44 - MC_{old}) \cdot e^{(-0.01559 \cdot \sqrt{p})}$

barley: $MC_{new} = 34 - (34 - MC_{old}) \cdot e^{(-0.03050 \cdot \sqrt{p})}$

oats: $MC_{new} = 51 - (51 - MC_{old}) \cdot e^{(-0.01652 \cdot \sqrt{p})}$

wheat: $MC_{new} = 60 - (60 - MC_{old}) \cdot e^{(-0.00605 \cdot \sqrt{p})}$

where:

p = the rainfall $(mm \cdot d^{-1})$

The grain moisture content is calculated using a combination of the two functions. This combination is as follows. Firstly, DIF_RAD, the difference between MC_{new} and MC_{old} due to radiation, is calculated. Secondly, DIF_P, the difference between MC_{new} and MC_{old} due to rainfall, is calculated. The new moisture content, MC_{new}, is the sum of MC_{old}, DIF_RAD and DIF_P.

The moisture content is assumed to be fixed for the whole day and the formulae are used to calculate the changes in moisture content from day to day. This is not realistic but it is done while the weather forecast handles periods with a minimum length of a day. Only the morning period (7:00—12:00) has a different approach. If cereal is workable in the morning period, then the heuristic FLOS assumes that cereal can be processed only in the second half of the period (10:30—12:00). Cereal is not workable in the first half of the period due to too high moisture content which has been caused by dew.

Both the soil moisture suction and the grain moisture content model request the condition of the soil and the grain initially. This initial condition is given as an input, by the user of the model. But, it may be difficult for the user of the model to obtain a quantitative value. Therefore, he can choose a class of initial conditions. The classes of conditions for soil are derived from the work of Hokke and Tanis (1978). There are five conditions of the soil that can be chosen, i.e. very dry, dry, moist, wet and very wet.

The moisture model connects a quantitative value to the class of conditions (Table 7.9). Using the initial quantitative value, the moisture models and the weather forecast, a sequence of moisture contents is calculated. The heuristic FLOS uses this sequence of moisture suction (for soil) and moisture content (for grain) to obtain the workability (Table 7.10).

Now, a sequence of five days with workability data has been calculated. However the planning horizon can be longer than five days. The rest of the days are filled with workability data, calculated using climatological data. This occurs as follows.

Table 7.9. The classes of conditions with the related soil moisture suction (cm) and the grain moisture content (%).

class of condition	soil moisture suction (cm)	grain moisture content species 1 *)	species 2 *) (%)
very dry	1000	10	6
dry	500	15	8
moist	100	21	12
wet	65	30	15
very wet	35	35	20

*) species 1 is wheat, barley and oats (%), and species 2 is colza (%).

Table 7.10. The workability and non-workability with the boundary points (see also Chapter 2).

material	workable	workable with drying	not workable	
species 1 1)	≤ 19	19—23	> 23	(%)
species 2 1)	≤ 10	10—14	> 14	(%)
soil 2)	> 250	—	≤ 250	(cm)

1) The workability of grain is not depending on adherent moisture.
2) The boundary point for soil is the 90% value of the soil moisture content (%) at field capacity (pF = 2).

Firstly, with climatological weather data from 1963 to 1986 (momentary of DeBilt), sequences of moisture content were calculated in the same way as with the weather forecast. These sequences are specific for the user's situation, i.e. the soil data (Appendix F) are derived from the soil of the users farm. Not the whole year (of 1963 till 1986) needs to be used. Only parts of the year for which a planning is required by the farmer are used (1963—1986). The models again need an initial condition (Table 7.11).

After this calculation, for each year (1963 to 1986) five sequences of properties, moisture suction (for soil) and moisture content (for wheat, barley, oats and colza) are obtained. The sequence of moisture content has been taken instead of the sequence of climatological weather data because a sequence of moisture content is more stable in time due to the buffer function of the soil. A sequence of weather data fluctuates too much. Moisture suction data are also more easy to be interpret than weather data because moisture suction data only contain one datum, i.e. the moisture suction, while weather data contain more data, e.g. rainfall, evaporation and global radiation.

The following explanation is for the sequence of five days soil moisture suction data. The explanation above (i.e. using moisture content ranges instead of weather data ranges) also accounts

Table 7.11. The initial conditions for the workability calculation using climatological data.

material	initial condition	
species 1	19	(%)
species 2	10	(%)
soil	100	(cm)

Table 7.12. The classes with intervals (boundary values) for CD_{24} (for mapping of WD_5).

class	soil	grain
1	[1000,16000]	[30,80]
2	[500,1000)	[20,30)
3	[250,500)	[10,20)
4	[100,250)	[0,10)
5	[0,100)	

for the grain moisture content. A sequence of five days moisture suction or content (calculated using the weather forecast) is available. This sequence is given the identification WD_5. In addition 24 sequences (for each year one) of T days moisture suction data (T depends on the user and is at least equal to the size of the planning horizon) are used. These sequences have the identification CD_{24}. Using WD_5 and CD_{24}, a sequence of moisture suction or content for the whole planning horizon can be derived. This is done as follows. WD_5 is reflected onto CD_{24}, i.e. WD_5 without a break is sought in CD_{24}. The values of WD_5 do not have to exactly equal the values in CD_{24}, they have to fit in classes (otherwise WD_5 will never be found in CD_{24}). Momentary, five classes (Table 7.12) are assumed.

When the sequence WD_5 is found without a break in CD_{24}, the sequence of moisture data (in CD_{24}), with, as first point, the point in CD_{24} where WD_5 was found, will be remembered. This sequence, further named as FM_i ($i = 1,2,\ldots,n$), has a length less or equal to the length of the planning horizon (Figure 7.3). WD_5 can be found in CD_{24} more than once, not only in another year, but also in the same year of CD_{24}.

As result, there are n FM sequences. With this data, a probability distribution function can be created for each day in the sequence FM. But, the moisture suction or content per day is calculated as the average value of the n moisture data (also per day). The average is taken because:

1. The concept of certainty equivalence is used.

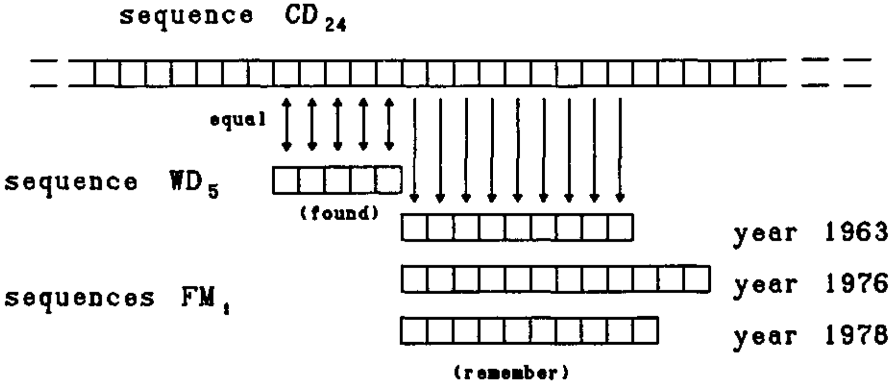


Figure 7.3. The procedure of finding WD_5 in CD_{24} and the remembering of FM_i. Each box stands for one day.

Definition 7.1
In finding an optimum of a decision problem under uncertainty, the knowledge of the probability distribution function is used. But, under certain assumptions given below, a point estimate allows the optimum to be found. This point estimate constitutes a *certainty equivalent* for complete knowledge of the probability distribution. The point estimate has been done using the expected value of the distribution function.

The concept of certainty equivalence is described by Holt et al (1960; see also Theil, 1957; Theil, 1966; Heyman and Sobel, 1984);

2. The probability distribution function of the n moisture data per day is assumed to be Normal. In fact, it is bimodal (Figure 7.4), but it is difficult to obtain the correct parameters for this function. Until there is a better approximation of the function comes, the Normal equivalent is used.

   Item: using the Normal equivalent gives a small error: the average soil moisture content is lower and therefore, more workable hours are calculated (see Figure 7.4);

3. The expected value of the Normal probability distribution is the average of the examined data.

The basic demands for the existence of certainty equivalence are (Heyman and Sobel, 1984):

1. Decisions are unconstrained by the state, this is not true for this model where the size of the decisionvector d_t is dependent on the statevector x_t;

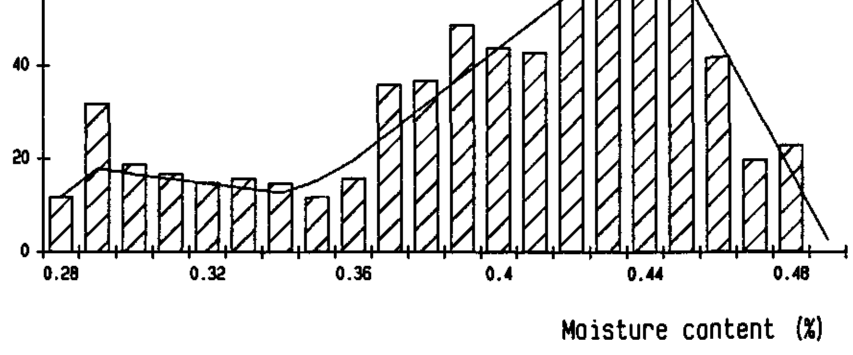


Figure 7.4. The frequency function of the soil moisture content for one day.

2. The transition function, i.e. the g-function, depends linearly on the state and the decision;

3. The single-stage reward function is the sum of quadratic functions of the state and decision. This is true in the current model but it also depends on the stage.

The concept of certainty equivalence is widely used in practice. Planning, using forecast, always depends on prognosis values.

The concept is not possible for our model, but, because of calculation efficiency, this concept is used instead of the whole probability distribution. Still, the quality of this approach is not certain. In the past, the twenty-percentile point is preferred to the expected value of the distribution function of the workable time per period. But even this may be an incorrect choice. Further research in this field is required.

The procedure will be continued for every day in the sequence FM_i ($i = 1,2,\ldots,n$). With the sequence WD_5 and the averages (per day) of FM_i, the sequence of moisture data for the whole planning horizon can be determined. From this sequence, the workability data can be derived using Table 7.10. The workability is uniform for the whole day. This is assumed because the weather forecast handles periods with a minimum length of one day. The use of rounded workability (workability stays equal for the whole day) is permitted, due to the results of the tests on levels of aggregation (the number of workable hours for rounded workability is almost the same as the number of workable hours for real workability, at least for a level of aggregation lower than day-level, see Chapter 3 and Section 7.3.2). Only the workability for grain, for the morning period is affected. Only half the period (10:30—12:00) is workable, because cereal is often not workable early in the morning owing to dew formation.

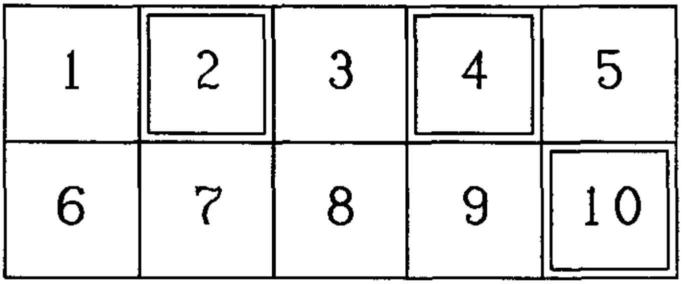
FLOS calculates a schedule using the workability data. This calculation takes place in the same way as described in Section 7.1 and Section 7.2. But, it is possible for FLOS to give more than one schedule. The difference between these schedules will depend upon the interpretation of the weather forecast. The weather forecast contains the rainfall ($mm \cdot d^{-1}$) and the probability of rainfall for a certain region. With these data, it is possible to suppose a probability distribution function for rainfall in that region.

The two extremes of this function are the minimum amount of rainfall, i.e. zero mm, and the maximum amount, that can fall in the region. For the maximum amount, the average rainfall of the part of the region *with* rainfall is taken (Wartena, 1987, personal communication) is taken.

Example: the expected amount of rainfall for the whole region is 2 mm
the probability of rainfall is 0.70

In thirty percent of the region, there is no rainfall. Two mm is an average for the whole region, with and without rainfall (Figure 7.5). Therefore, the average rainfall, P_w, for the region with rainfall is supposed to be:

$$0.30 \cdot 0 + 0.70 \cdot P_w = 2$$
$$P_w = 2.857 \qquad \text{(mm)}$$



Average rainfall is 2 mm

no rain in Region A (A=2,4,10)

Average: 0 mm

rain in Region B (B=1,3 and 5 to 9)

Average: 2,857 mm

Figure 7.5. The total area with Region A (without rain) and Region B (with rain).

The average, P_W, is taken as an upper boundary value for the amount of rainfall. It is most likely that more rain can fall than P_W predicts, but the prediction of this maximum is for only one day (the next day), and not for five days (Wartena, 1987, personal communication). Therefore, the value P_W has been assumed to be the maximum amount of rain. The following are extreme values of the distribution function:

minimum:	0 mm rain with a probability of 0.3, and
maximum:	2.857 mm rain with a probability of 0.7.

The heuristic FLOS can use both values to calculate a schedule. But, it can also use all the values of the distribution function. Only the minimum and the maximum, i.e. the best and the worst situation, are chosen for calculation (the results of a test on intermediate situations is given in the next section). The user can choose the schedule most appealing to him.

7.3.2. THE VALIDATION TESTS WITH THE PROBABILISTIC VERSION

The probabilistic version is mainly based on the data of the weather forecast. These data influence the workability and therefore, the outcome of the heuristic. Therefore, the weather forecast has to be analysed and especially the impact of the forecast on the results of the heuristic. Using the weather forecast as basis for several tests, the moisture models will also be analysed. Therefore, with the probabilistic version of the heuristic FLOS, the following validation tests have been made:

- the difference in results of models using different lengths of weather forecasts (Section 7.3.3);
- the effect of different weather forecasts (i.e. different data) on the outcome of FLOS (Section 7.3.4);
- the effects of the levels of aggregation (to prove the correct choice of the level of aggregation, Section 7.3.5).

It is possible that more tests are necessary, but momentary, only the weather forecast is analysed. All these tests are with imaginary data. A test in practice will be described in Chapter 8.

7.3.3. THE EFFECT OF DIFFERENT LENGTHS OF WEATHER FORECAST AND DIFFERENT AMOUNTS OF RAIN

Momentary, five days of weather forecast is used (is maximum possible). But, it is possible that less days of weather forecast can give better results (item: compare the effects of an incomplete look at the future, Section 7.2.4). Therefore, with this test, the effect of different lengths of a weather forecast on the outcome of FLOS is examined.

Again, there is the problem of the grain harvest. The model has to calculate a schedule for a farm which can have three sizes, i.e. twenty, forty and sixty hectares. The planning horizon has a length of five weeks. The weather forecast has five different lengths, i.e. one, two, three, four or five days. For each length of forecast, the forecast has the following data (hypothetical season):

- reference evaporation: 5.0 $(\mathrm{mm \cdot d^{-1}})$
- global radiation: 1.5 $(\mathrm{kJ \cdot (d \cdot cm^2)^{-1}})$
- probability of rainfall: 1.0 (—)

The amount of rainfall can have the following integer values:

- 0, 1, 2, 3, ..., 10 $(\mathrm{mm \cdot d^{-1}})$

The initial condition of soil and grain are dry.

For zero mm rainfall, the probability of rainfall is zero. If the amount of rainfall is zero mm, each day forecasted, an amount of zero mm rainfall is predicted. The same is true for the reference evaporation, the global radiation and the probability of rainfall. These variables are independent of the amount of rainfall. They are fixed while the effect of different amount of rainfall is examined besides the different lengths of a weather forecast. Rainfall is assumed to have the largest effect on the outcome of the heuristic FLOS.

The results are presented in Figures 7.6.a, 7.6.b and 7.6.c.

The results of FLOS remain almost equal for a weather forecast with a length of three, four and five days. Only the weather forecast with a length of one and two days provides different outcomes. For a rainfall of six mm and higher, the workability is zero from the first day (see the mark * in Figures 7.6.a, b and c). The conclusion of this test is that FLOS can allow a decrease in the length of the weather forecast to three days to obtain almost the same results using a weather forecast of five days. Therefore, diminishing the information does not always involve higher cost. This is a conclusion for the heuristic. For the probabilistic dynamic programming model, which offers optimal results, diminishing information always involves higher costs. It seems that the heuristic performs better when the amount of information not exceeds a certain level of information is reached. If the level of information further decreases then the heuristic will also offer solutions with higher cost (the same conclusion as found in Section 7.2.4).

This test gives little information about the effect of different weather forecasts (different lengths and amount of rain) on the outcome of FLOS due to the hypothetical season with a constant weather forecast (cannot be compared with practice). More information of the effect of the weather forecast is needed. A test with all kinds of different data for the weather forecast gives more information on the behaviour of FLOS (see following section).

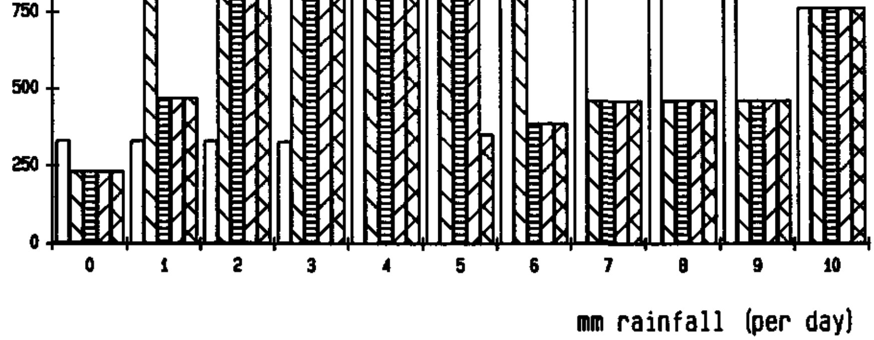


Figure 7.6.a. The total costs (*f*) againts the rainfall per day (mm) given by the weather forecast for five different lengths of weather forecast for a farm with 20 ha.

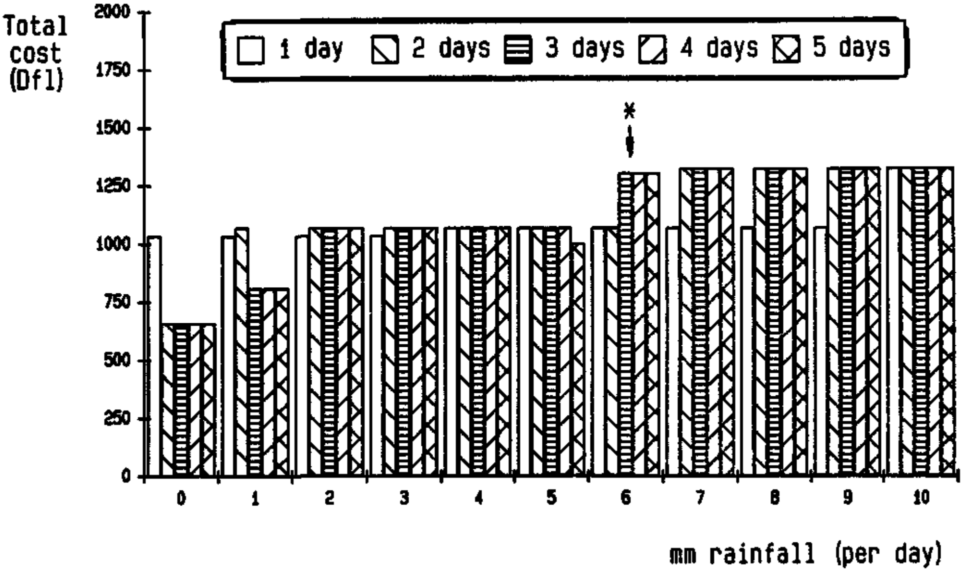


Figure 7.6.b. The total costs (*f*) againts the rainfall per day (mm) given by the weather forecast for five different lengths of weather forecast for a farm with 40 ha.

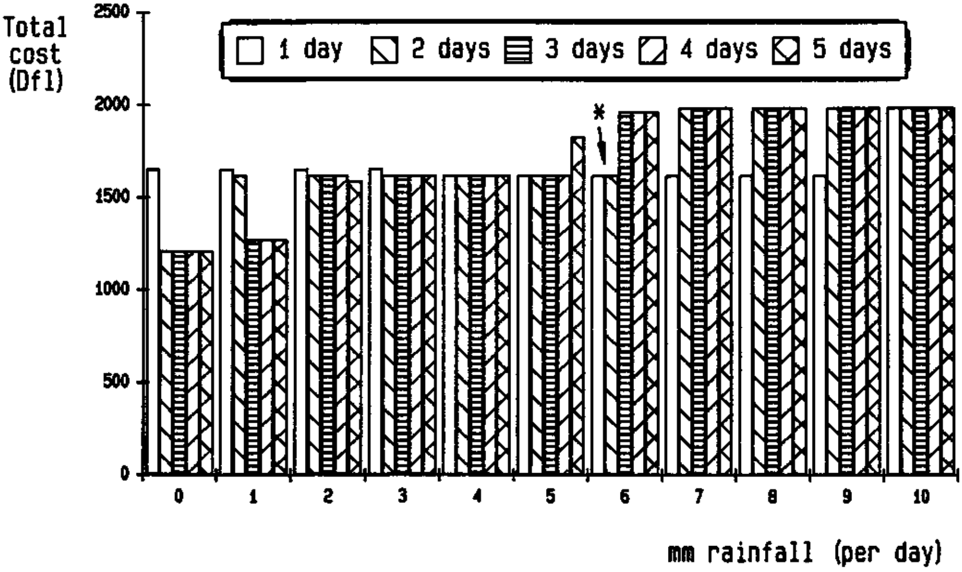


Figure 7.6.c. The total costs (*f*) againts the rainfall per day (mm) given by the weather forecast for five different lengths of weather forecast for a farm with 60 ha.

7.3.4. A TEST ON EVERY POSSIBLE WEATHER FORECAST

The weather forecast has an influence on material moisture content. The moisture can range from 0 to 16000 cm for soil (moisture suction) and from 0 to 80 % for grain (moisture content, wet basis). In this section, the effect of changing the moisture content on the results of FLOS is examined. The data of the moisture content is taken instead of the data of the weather forecast. This is because changing the weather forecast does not always involve a significant change of moisture content. To avoid repeating the calculation more than once, with the same moisture content, the moisture content itself is taken as input. For a complete test, all possible combinations of sequences of moisture contents, for five days of forecast, have to be taken as input. But, this will lead to an infinite number of tests.

Therefore, the intervals stated in Table 7.12 are used. For soil, there are five intervals; for grain, there are four. Of these intervals, an acceptable quantitative value is taken (Table 7.13). This concept gives, for soil the total number of 3125 combinations (is 5^5: five intervals and five days), and for grain 1024 combinations (is 4^5: four intervals and five days). But, not every combination is realistic. The most common combinations of moisture only are taken, i.e. the moisture of a material on the next day is only an element of the same class or of the one or two adjacent classes of moisture on this day. For example, on day t, the moisture suction for soil is an element of the interval [250,500). The possible classes for day t+1 (and day t–1) only are [100,250), [250,500) and [500,1000). This will decrease the number of possible combinations, for soil to 259 and for grain to 178.

With the combinations as input, the possible schedule for the grain harvest on a farm with twenty hectares can be calculated. The planning horizon has a length of five weeks. While testing the effect of different soil moisture suction, the grain moisture content is 15 %. During the grain moisture content test, the soil moisture suction is 500 cm. This test examines:

1. the results (the total cost) of FLOS for every moisture sequence;
2. the probability of finding the moisture sequence in the climatological files; 1963—1986 (i.e. the probability of finding WD_5 without a break in CD_{24});
3. how the expected value of the workability per day (for days in the sequence FM_i) is calculated, with:

Table 7.13. The quantitative value for each class (for soil and for grain).

	soil		grain	
class	interval	quant. value (cm)	interval	quant. value (%)
1	[1000,16000]	4000	[30,80]	40 1)
2	[500,1000)	750	[20,30)	22
3	[250,500)	375	[10,20)	15
4	[100,250)	175	[0,10)	5
5	[0,100)	60		

1) this value seems unrealistic. It is taken into account because the test has to be „complete".

- the number of samples found per day;
- the average of the moisture contents per day;
- the standard deviation per day.

This test is only for the situations where WD_5 is found in CD_{24}.

These tests will help provide more insight into the solutions which are bounded by the solutions giving the worst and the best weather forecasts.

The results of FLOS for every moisture sequence

The results of this test are in Table 7.14. In this table, the average total cost for the combinations with the same moisture content on the first day can be seen. All the combinations are ordered into groups where the moisture content on the first day is the same.

The results show that the worse the workability (i.e. the higher the grain moisture content and the lower the soil moisture suction), the higher the total cost. More important, is the conclusion that the grain moisture combinations give more stable results compared to the soil moisture combinations. The average coefficient of variation is lower for grain (i.e. 0.34) than for soil (i.e. 0.59). Therefore, changing the weather forecast has less influence for grain than for soil. When the data on the weather forecast are changed, then the grain moisture values switch less often from one interval to another compared to the soil moisture values.

Note: Only grain harvesting is depending on the workability of grain, all the other operations are depending on the workability of soil.

Table 7.14. The number of sequences, the average total cost (the sum of timeliness, overtime and drying cost, *f*), the standard deviation and the coefficient of variation.

moisture content first day		number of sequences	average total cost	standard deviation	coefficient of variation
grain [1]:	40	34	778	247	0.32
	22	55	565	245	0.43
	15	55	217	133	0.61
	5	34	144	0	0.00
soil [2]:	60	35	861	580	0.67
	175	60	551	574	1.04
	375	69	218	201	0.92
	750	60	139	31	0.22
	4000	35	140	17	0.12

[1] Soil moisture suction is 500 cm.

[2] Grain moisture content is 15 %.

Table 7.15. The number of sequences and the total times that WD_5 is found in CD_{24} with the related probability (prob.).

moisture content first day		number of sequences	number of sequences found in CD_{24} at least once	prob.
grain:	40	34	0	0.00
	22	55	0	0.00
	15	55	4	0.07
	5	34	5	0.14
soil:	60	35	19	0.54
	175	60	35	0.58
	375	69	39	0.57
	750	60	27	0.37
	4000	35	16	0.46

The probability of finding the moisture sequence in the files

More important, is the total times that WD_5 is found without a break in CD_{24}. The results are stated in Table 7.15.

The results of this test show that WD_5 is found in CD_{24} more times for soil than for grain. An explanation is that a moisture content higher than the range 20—30% seldom occurs in the climatological files. The calculation of the moisture content starts with an initial condition of 19%. Then, the moisture content only decreases due to the use of the formulae of Van Kampen. Therefore, combinations containing a grain moisture content of thirty percent or higher will seldom be found in CD_{24}.

Another explanation of the low probability of finding WD_5 in CD_{24} for grain, is that the interval length is too large. If grain moisture content for five days are elements of the same moisture content class, then WD_5 will be found in CD_{24} (except for thirty percent and higher). The decrease, or increase, of moisture content is too little. Therefore, a sequence, where the moisture contents are elements of different classes, seldom occurs. In practice, the decrease or increase is small enough, and WD_5 will be found in CD_{24} almost always.

The soil moisture suction behaves differently. The decrease or increase is sufficient. A sequence where the moisture suction are elements of different classes is possible. The average probability of finding WD_5 in CD_{24} is greater.

The conclusion is that the interval length for grain can be smaller. The length of the intervals for soil are sufficient. WD_5 does not occur in CD_{24} when the sequence of moisture of WD_5 is extraordinary, e.g. from 4000 cm to 60 cm in five days. This seldom occurs in practice. Therefore, the chosen boundary points for soil is sufficient.

The behaviour of the sequences of climatological data

The behaviour of the climatological data and the effect on the calculation of the expected value of moisture will be described. The results of the solutions where WD_5 is found in CD_{24} are examined. For each solution (for each run), the following results are presented:

- the number of occurrences of an FM_i per day for each day (i.e. the value of i for each day, i=1,2, ..., n, FM_i are the climatological data from CD_{24}, see Section 7.3.1). It is possible that for the last days of the planning horizon, no sample is available, i.e. i=0 (due to the end of the file). It is necessary to check how many times this will happen;
- of these samples, the coefficient of variation of moisture content or suction. With this coefficient, the stability of the sequence of moisture can be examined.

For grain, there are nine sequences where WD_5 maps onto CD_{24} (at least once), for soil, 131 are found (Table 7.15). The results are presented in Figure 7.7.

The average of total number that WD_5 is found in CD_{24} for grain, i.e. 28, seems promising, but the average is high because of the sequence 5 — 5 — 5 — 5 — 5 (%). This is found two hundred times. The average without this sequence has the value six. So eight sequences are found six times and one sequence is found two hundred times. The number of samples found per day decreases slightly while the coefficient of variation increases from day to day. But, the decrease and increase is small and the value of the coefficient of variation is low. Therefore, the CD_{24} sequence seems stable enough. Only the probability of finding WD_5 in CD_{24} is small.

The conclusion for grain is that the concept of taking the moisture content of grain for the sequence CD_{24} (instead of weather data) is sound because the sequence is more stable than the sequence of weather data, but, the length of the intervals can be smaller (see previous section).

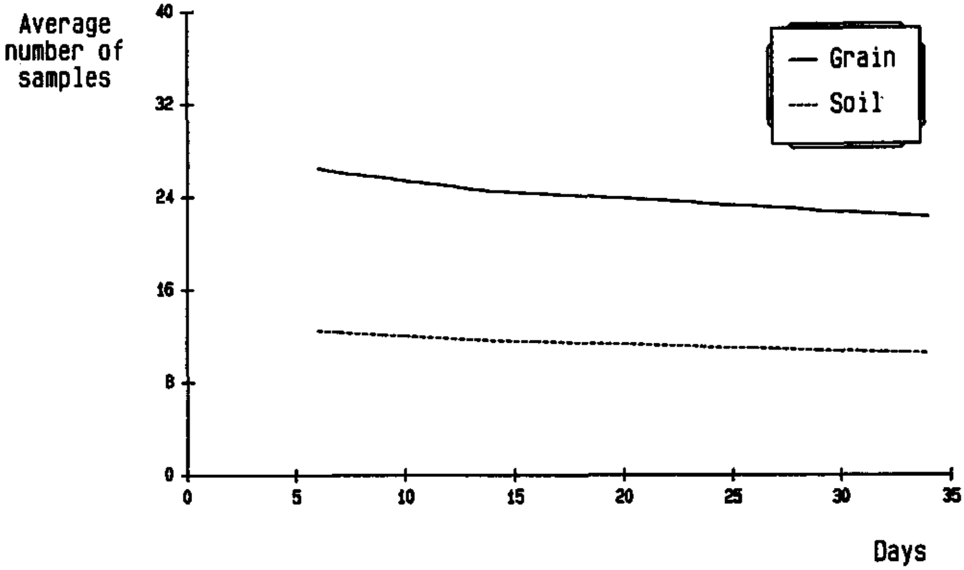


Figure 7.7.a. The average number of samples per day (the average value of i of FM_i) for day 6 to day 34 (the moisture content for day 1 to 5 are calculated using the weather forecast).

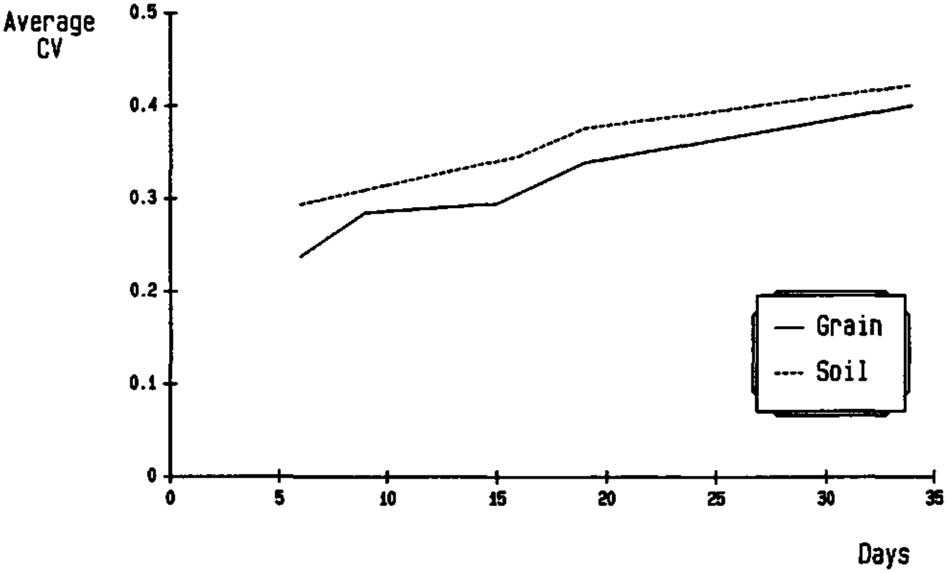


Figure 7.7.b. The average coefficient of variation of the moisture per day for day 6 to day 34 (the moisture content for day 1 to 5 are calculated using the weather forecast).

For soil, the average number of samples found is 12.5 per day. This value remains constant for the rest of the days. This value is very low thanks to the fact that WD_5 is found in CD_{24} only once or twice per run. This often happens. For a more reliable sequence of moisture suction (i.e. sequences arising more often in practice), e.g. a sequence where the moisture suction of each day are elements of the same class, finding WD_5 in CD_{24} occurs more often, e.g. one hundred to two hundred times per run. The coefficient of variation remains almost equal for each day. The conclusion is that for soil, the choice of using moisture suction instead of weather data (for the CD_{24} sequence) is good. Also the length of the classes are satisfactory.

7.3.5. THE LEVEL OF AGGREGATION

The last test described in this chapter is a test of the level of aggregation. The results given in Chapter 3, that day-level was an upper boundary for the length of a period, are known. But, this is for a static environment. For a dynamic environment, e.g. where every day the input (the weather data) can be modified and a new schedule can be calculated (the heuristic FLOS is appropriate for that), the feasibility of this upper boundary has to be checked.

The heuristic FLOS is calculated for the grain harvest with a planning horizon of five weeks. The farm can have three sizes: twenty, forty and sixty hectares. The weather forecast gives the following data (hypothetical season):

- reference evaporation: 5.0 (mm·d^{-1})
- global radiation: 1.5 (kJ·(d·cm^2)$^{-1}$)
- probability of rainfall: 1.0 (—)

The amount of rainfall can have the following integer values:

- 0, 1, 2, 3, 4, 5 (mm·d^{-1})

The initial condition of soil and grain are dry. For zero mm rainfall, the probability of rainfall is zero. The amount of rainfall is constant for five days of weather forecast.

FLOS has been developed for five levels of aggregation, i.e. 1-hour-, 5-hour-, day-, week- and month-level (see Chapter 2). After calculation of the schedule, the solution is disaggregated (described in Chapters 2 and 3) again and checked with the reference model, i.e. FLOS at 1-hour-level.

The results, the average of total costs over five different starting amounts of rain, are presented in Figure 7.8. This figure shows that day-level is a sufficient upper boundary. The results of the heuristic FLOS at hour-, at 5-hour-, and at day-level are slightly different, but close enough to justify the statement that the models, at these levels, can be interchanged. The results of the heuristic FLOS at week- and at month-level are extremely different from the results at day-level. Therefore, scheduling at the week- or month-level is unacceptable.

Modelling a heuristic with a level of aggregation lower than day-level is possible. Modelling at the 5-hour-level is chosen to shorten calculation time. A farmer is not aided by a schedule at 1-hour-level. This gives too much information while there is only one weather forecast per day.

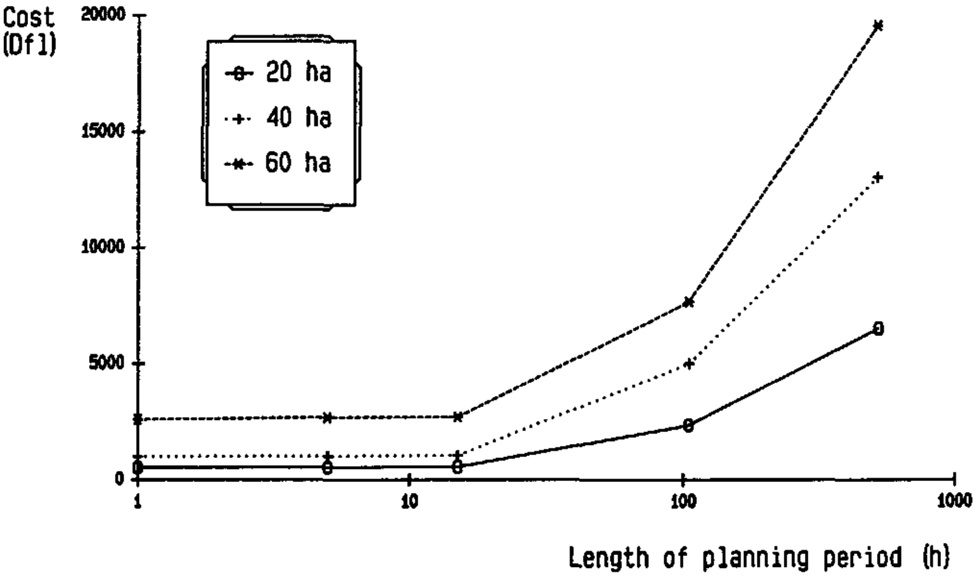


Figure 7.8. The total cost (*f*) against the level of aggregation (in length of planning period, h) for three sizes of farm, i.e. 20, 40 and 60 ha (the x-axis is logarithmic).

7.4. CONCLUSIONS

The following main conclusions are apparent from this chapter:

- the heuristic FLOS performs well in several test cases;
- it offers near-optimal results (the decrease of effectivity is small, see Table 7.1 and 7.2);
- it is fast (a large increase of efficiency);
- it fits on a micro-computer (a P.C., Personal Computer);
- the formulation to calculate the sequence of gangs for the h-function is appropriate;
- the chosen g-function (calculating only one period at a time instead of more at a time) is also satisfactory;
- the calculation of workability, in spite of the assumptions made, (e.g. simple soil and grain moisture models and using averages of moisture, based on the concept of certainty equivalence) is satisfactory;
- the concept of using files with sequences of moisture content (CD_{24}) instead of using climatological data, is appropriate;
- the choice of intervals (used by finding WD_5 in CD_{24}) is good, except for grain. For grain, if the length of interval will be shorter then more sequences FM will be found and the workability will be approached in a more reliable way (related to practice);
- the level of aggregation (5-hour periods) is correct.

The only remaining area to investigate is how the heuristic FLOS will behave in practice. In this chapter, invented test cases only are examined. In the next chapter, a real test case, i.e. the harvest on a large farm in the Lake IJssel Polders, is examined.

Chapter 8

THE TEST CASE: A HARVEST ON AN ARABLE FARM

The heuristic FLOS is described in Chapter 7. A deterministic and a probabilistic version of this heuristic are developed. Both versions are evaluated using several test cases. Using the results of these test cases, as described in Chapter 7, several conclusions about the performance of the heuristic were derived. But, all these test cases were imaginary and were not reflecting practice. For the heuristic, which is designed to solve operational planning problems in practice, at least a small practical test case is necessary. Therefore, for further evaluation and validation of the performance of the heuristic FLOS, a test case in a real environment is investigated.

In the first place, FLOS is designed to solve operational planning problems in the harvesting period. This is an important period to consider due to the large influence of timeliness. Therefore, the test case also took into consideration the harvesting period, from September to November 1987. The choice of the farm was based on connections of IMAG (Institute of Agricultural Engineering, Wageningen, The Netherlands) with the Lake IJssel Polders Development Authority and did result in the practical test on the arable farm A93. This farm has several advantages:

- it has a large area with several crops. The harvest of cereal, potatoes, sugarbeet and beans can be scheduled. The interaction between harvests and possible bottlenecks in the alternation of different harvests (e.g. the potato and the sugarbeet harvest) can be analysed;
- due to the large area, differences between good planning and bad planning will become more visible;
- all the data of the farm (e.g. number of machines, area, processing rates of several gangs, and so on) are already stored in IBIS („Intern Bedrijfs Informatie Systeem", a data-base management system, a project of the Institute of Agricultural Engineering, Wageningen, the Netherlands).

For the harvesting period, a schedule is calculated by the heuristic using a weather forecast (with meteorological data). Besides the schedule calculated by FLOS, a schedule given by the farmer is analysed. The farmer does not use mathematical models, planning is based on his experience. The results of FLOS are compared with the farmer's planning to analyse possible differences between them. Using the results of the comparison, there is an investigation into improving the

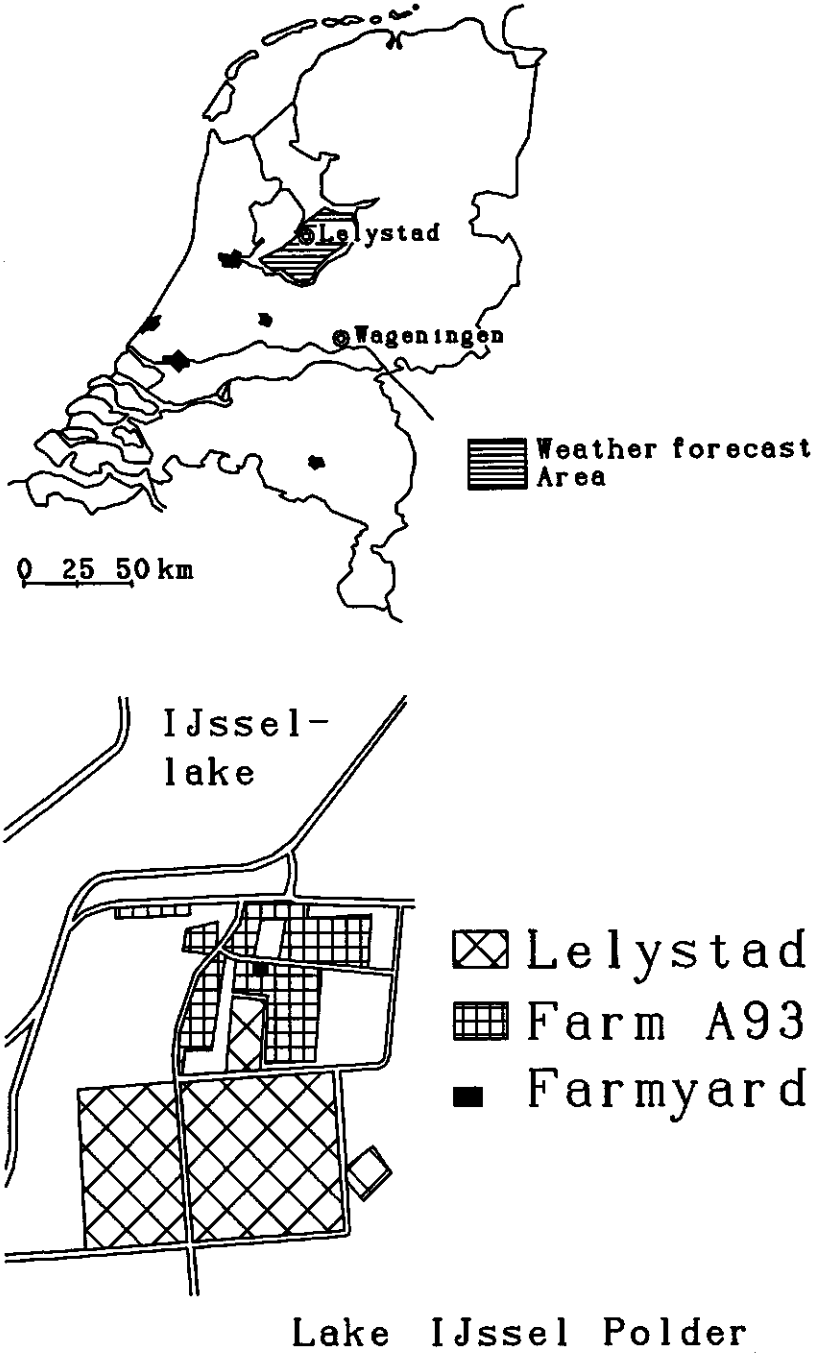


Figure 8.1. The location of farm A93 near Lelystad, The Netherlands.

effectivity and efficiency of the farmer's decision process. The actual schedule to analyse the difference between planning and practice is also given.

The heuristic uses a weather forecast. For validation of the weather forecast, a reference model is calculated. The reference model is the heuristic FLOS using actual recorded weather data. As a result, the following four cases are examined in this chapter:

1. a schedule calculated by FLOS using a weather forecast (the meteorological data), further stated as SCHEMA 1 or SCHEMA 2 (the schedules using a weather forecast with a maximum and a minimum amount of rainfall respectively (see also Section 7.3);
2. a schedule calculated by FLOS using actual (recorded) weather data, further stated as SCHEMA W;
3. a schedule given by the farmer (a planning based on the farmer's experience with knowledge of the weather forecast but without knowledge of the results of FLOS);
4. the actual schedule.

The test case is also used for the validation of the software package SCHEMA (described in Chapter 9 and the Appendices C, D and E). The arable farm A93 and the results of the four cases will be described in the following sections.

8.1. THE ARABLE FARM

The farm called A93 is situated in the Lake IJssel Polders above Lelystad (Figure 8.1). It is an arable farm of the Lake IJssel Polders Development Authority (RIJP). The size of the farm is about 277 ha. This area is spread over twenty united plots. The area of each plot ranges from seven to twenty-three hectares. The average distance from the farm yard to the fields is 1100 m.

For the soil moisture suction model (Appendix F), the following data are needed. The soil texture class is silty clay loam. The mean rooting depth is assumed to be 0.30 m. The initial ground water depth is 1.40 m. The drain depth is 1.50 cm, the drain spacing is 6 m, and the drain radius is 50 mm. These data have an effect on the results of the soil moisture suction model and therefore, influence the workability data. Changing these data will also change the workability data and therefore, the results of the heuristic FLOS.

The following crops are grown in 1987:

species	cultivar	amount
spring barley	„Grit”	78.00 ha
winter wheat	„Sarno”	43.90 ha
potatoes	„Bintje”	64.82 ha
field beans	„Alfred”	7.80 ha
string beans	„Belemi”	19.56 ha
sugarbeet	„Eva” and „Regina”	62.97 ha

The crops have to be harvested in the months August, September, October and November. After harvesting, the fields have to be ploughed and cultivated. The crops will be harvested after a starting date (given by the farmer, see material information below) by the farmer (and his labourer, a total of two men) or by an agricultural contractor. The processing of a material must be finished before a finishing date (given previously). If processing occurs after this date, then the timeliness cost will be multiplied by three to create an extra penalty. The finishing date is introduced because certain crops must be delivered at the factory in time (this is a demand of the factory, e.g. sugarbeets must be at the sugar factory in time).

For each crop, the harvesting process, the gangs needed and the connected materials are described.

Spring barley and winter wheat

Both crops are harvested by the farmer and his labourer. The harvest has to be transported to the grain dryers. The grain dryers are located on the farm yard.

material: spring barley
initial amount: 78.00 (ha)
starting date: August 10
finishing date: September 5
timeliness cost *): 5.40 $(f\cdot(\mathrm{ha}\cdot\mathrm{d})^{-1})$
connected materials: straw and bales
wet grain
stubble (uncultivated)
gang: 1: combine harvesting by one man and transport of the harvest to the farm yard by the second man
work rate: 1.20 $(\mathrm{ha}\cdot\mathrm{h}^{-1})$

*) The timeliness costs of all the materials are calculated using the formulae of Hunt (ASAE, 1987c). The values are not real, only in relation to the timeliness cost of other materials (mutual dependence).

material: winter wheat
initial amount: 43.90 (ha)
starting date: August 15
finishing date: September 12
timeliness cost: 5.40 $(f\cdot(\mathrm{ha}\cdot\mathrm{d})^{-1})$
connected materials: straw and bales
wet grain
stubble (uncultivated)
gang: 1: combine harvesting by one man and transport of the harvest to the farm yard by the second man
work rate: 1.30 $(\mathrm{ha}\cdot\mathrm{h}^{-1})$

Straw will be removed by the agricultural contractor. The work rate is 2 $\mathrm{ha}\cdot\mathrm{h}^{-1}$. The timeliness costs of straw and bales together are 17.50 $f\cdot(\mathrm{ha}\cdot\mathrm{d})^{-1}$. This is calculated using the timeliness cost of straw (5.4) and the timeliness cost of bales (21.1), with more weight on the timeliness cost of bales because bales lose their value more quickly than straw (after six days compared to sixteen days for straw). Grain is wet when the moisture content of grain rises above seventeen percent. The grain cannot be harvested (too wet material) when moisture content is higher than twenty-two percent (item: these values, i.e. 17 and 22%, are given by the farmer of A93, they are different to the assumed values used in Chapters 1 to 7). The wet grain will be dried day and night by grain dryers with a work rate of 0.80 $\text{ha}\cdot\text{h}^{-1}$ for spring barley and 0.85 $\text{ha}\cdot\text{h}^{-1}$ for winter wheat (average for different initial moisture contents). The timeliness cost of wet grain is 5.4 $f\cdot(\text{ha}\cdot\text{d})^{-1}$. It is assumed that there is no storage problem for wet grain. The storage capacity of the grain dryers is assumed to be sufficient.

Potatoes

Potatoes are harvested by the agricultural contractor. Firstly, haulm killing takes place. After this, the potatoes will be harvested and loaded onto trailers. The farmer and his labourer transport the harvest to Swifterbant, a little town, thirty kilometers distant. The potato storage firm of the RIJP is based in Swifterbant.

material:		potatoes	
initial amount:		64.82	(ha)
starting date:		September 28	
finishing date:		October 12	
timeliness cost:		6.00	($f\cdot(\text{ha}\cdot\text{d})^{-1}$)
connected materials:		haulm	
		potatoes on trailer	
gangs:	1:	haulm killing by agricultural contractor	
	work rate:	6.00	($\text{ha}\cdot\text{h}^{-1}$)
	2:	potato harvest by agricultural contractor	
	work rate:	0.33	($\text{ha}\cdot\text{h}^{-1}$)
	3:	transport of potatoes by farmer and labourer	
	work rate:	0.33	($\text{ha}\cdot\text{h}^{-1}$)

It is assumed that there are no problems with the storage capacity of the trailers. The fallow land, resulting from the potato harvest, will remain uncultivated.

Field beans and string beans

Field and string beans will be harvested by the RIJP (the holding, i.e. not the farmer of the arable farm) and by the agricultural contractor respectively.

material:		field beans	
initial amount:		7.80	(ha)
starting date:		September 25	
finishing date:		September 25	
timeliness cost:		7.60	($f\cdot(\text{ha}\cdot\text{d})^{-1}$)
connected materials:		stubble (uncultivated)	
gang:	1:	field beans harvested by the holding	

work rate: 1.50 $(\text{ha}\cdot\text{h}^{-1})$

material: string beans
initial amount: 19.56 (ha)
starting date: September 29
finishing date: September 30
timeliness cost: 7.60 $(f\cdot(\text{ha}\cdot\text{d})^{-1})$
connected materials: stubble (uncultivated)
gang: 1: string bean harvest by agricultural contractor
work rate: 1.50 $(\text{ha}\cdot\text{h}^{-1})$

The haulm will be cultivated into the soil.

Sugarbeet

Sugarbeets will be harvested by the agricultural contractor. The beets have to be transported to the farm yard by the farmer and his labourer. The sugarbeet harvest starts at September 24 and will be repeated four times with an intermediate period of three weeks due to a delivery contract.

material: sugarbeet
initial amount: 62.97 (ha)
starting date: September 24—October 15—November 5—November 19
finishing date: September 26—October 17—November 7—November 21
timeliness cost: 2.70 $(f\cdot(\text{ha}\cdot\text{d})^{-1})$
connected materials: sugarbeets on trailer
uncultivated field
gangs: 1: sugarbeet harvest by agricultural contractor
work rate: 0.67 $(\text{ha}\cdot\text{h}^{-1})$
2: transport by farmer and labourer
work rate: 0.67 $(\text{ha}\cdot\text{h}^{-1})$

The haulm will be mixed with the soil through cultivation.

Uncultivated land

Fallow land, resulting from harvest of cereal, beans and sugarbeet, will be cultivated and ploughed by the farmer and his labourer. The work rate of cultivation is 3 $\text{ha}\cdot\text{h}^{-1}$, of ploughing it is 1 $\text{ha}\cdot\text{h}^{-1}$ (the timeliness costs of uncultivated and unploughed land are 1.2 $f\cdot(\text{ha}\cdot\text{d})^{-1}$).

8.2. THE WEATHER

The weather forecast, as used by the heuristic FLOS, has to contain four variables:

- the amount of rainfall $(\mathrm{mm \cdot d^{-1}})$
- the probability of rainfall (—)
- the reference evaporation $(\mathrm{mm \cdot d^{-1}})$
- the global radiation $(\mathrm{kJ \cdot (d \cdot cm^2)^{-1}})$

These values are given for five days (each week starting on Tuesday). The values are given by a commercial meteorological business called Meteo-Consult (situated in Wageningen, the Netherlands). The weather forecast of Meteo-Consult is for an area of about 1500 $\mathrm{km^2}$ (see Figure 8.1.a). The test location (farm A93) is almost at the border of this area. For a planning horizon of twelve weeks, the values of the weather variables and how SCHEMA interprets them, are given in Table 8.1 (only those variables of the weather for those weeks discussed in Section 8.3 are given).

How a weather forecast is created will be discussed in Appendix G.

The initial condition of the soil and the grain (the moisture content) was corrected each week on Tuesday with a new value. They are stated in Table 8.2 (see also Section 7.3 and Table 7.9).

For a good evaluation of the value of the weather forecast and the possible influence on the outcome of FLOS, actual weather data are also required. The actual weather data about reference evaporation and global radiation are derived from a local weather station ten kilometers away. But, it was not possible to get the data for all the weeks due to computer problems on this station. Only the available weather data are given. The amount of rainfall is recorded on the arable farm A93 itself. All the values are also stated in Table 8.1.

Also the climatological data of the nearest main weather station, i.e. De Bilt, are given. In Table 8.3, the values of the decades and the value of the whole month with the deviation of the normal values are given. Each decade represents the sum of the values of ten days weather data. Decade I is for day one to day ten, decade II is for day eleven to day twenty, and decade III is for day twenty-one to the last day of the month. The month value (M) is the sum of the values of each day for the whole month. The normal values are average values for the period 1951—1980. The values are given for the months September, October and November.

The conclusions derived from the deviation values are as follows: there was significantly more rainfall in the months October and November and a little less in September (related to normal). In the months September and November, there was less global radiation, in October, there was more (also related to normal). The autumn of 1987 had, except for a few big rain showers, fine weather.

In the next section, the calculated schedules will be analyzed.

Table 8.1. The values of the weather forecast and of the actual weather (P is the amount of rainfall ($mm \cdot d^{-1}$), Prob is the probability of rainfall, E is the reference evaporation ($mm \cdot d^{-1}$) and Rad is the global radiation ($kJ \cdot (d \cdot cm^2)^{-1}$)).

date of first day	day	expected				actual		
		P	Prob	E	Rad	P	E	Rad
Sept. 1	1	1.0	0.05	2.5	1.7	0.0	2.5	1.7
	2	0.0	0.10	2.3	1.7	0.0	2.6	1.5
	3	0.0	0.10	3.0	2.1	0.0	2.0	1.0
	4	2.0	0.40	2.5	1.8	0.7	1.6	0.8
	5	0.5	0.20	1.9	1.5	1.9	2.1	1.1
Sept. 8	1	0.0	0.10	1.5	1.3	1.0	1.4	1.5
	2	0.0	0.10	1.5	1.3	1.2	1.3	1.2
	3	2.0	0.50	1.0	1.1	8.6	0.7	0.6
	4	0.5	0.35	1.5	1.3	1.1	2.8	1.6
	5	3.5	0.65	1.1	1.1	0.1	2.3	0.9
Sept. 22	1	1.5	0.20	1.5	0.6			
	2	4.5	0.80	1.2	0.5			
	3	3.5	0.70	1.6	1.2			
	4	1.5	0.60	1.4	1.0			
	5	1.0	0.40	1.4	1.0			
Oct. 6	1	5.0	0.50	1.0	0.6	5.4	1.0	0.4
	2	6.0	0.60	1.0	0.6	8.7	1.2	0.7
	3	6.5	0.90	1.0	0.6	16.2	1.0	0.5
	4	2.5	0.75	1.0	0.6	2.0	1.1	0.7
	5	1.5	0.60	1.0	0.6	0.2	1.2	0.7
Oct. 13	1	4.0	0.40	0.7	0.5	4.3	1.0	0.4
	2	3.0	0.50	0.7	0.5	6.2	1.0	0.7
	3	10.5	0.70	0.8	0.5	15.9	0.9	0.4
	4	4.5	0.95	0.5	0.4	1.0	0.9	0.6
	5	1.5	0.60	1.1	0.7	0.5	1.0	0.8
Oct. 20	1	2.5	0.20	1.0	0.7	0.0	0.9	0.6
	2	4.0	0.60	1.1	0.7	1.0	0.9	0.4
	3	1.0	0.40	1.0	0.7	3.5	0.8	0.8
	4	0.0	0.20	1.0	0.7	0.0	0.8	0.6
	5	0.5	0.30	0.6	0.5	0.0	0.7	0.6
Oct. 27	1	0.2	0.05	0.5	0.5			
	2	2.5	0.50	0.5	0.5			
	3	0.0	0.10	0.8	0.7			
	4	0.5	0.10	0.5	0.3			
	5	0.5	0.20	0.5	0.4			
Nov. 17	1	0.5	0.20	0.3	0.3	0.1	0.3	0.2
	2	0.5	0.20	0.0	0.3	0.0	0.2	0.2
	3	1.0	0.40	0.0	0.2	25.4	0.2	0.1
	4	4.5	0.70	0.0	0.3	5.6	0.0	0.3
	5	3.5	0.50	0.0	0.2	3.3	0.0	0.2

Table 8.2. The initial conditions of soil and grain on Tuesday (the first day).

date of		initial condition of		
first day	soil	value (cm)	grain	value (%)
Sept. 1	dry	500	moist	21
Sept. 8	dry	500	moist	21
Sept. 22	dry	500	moist	21
Oct. 6	moist	100	moist	21
Oct. 13	moist	100	moist	21
Oct. 20	moist	100	moist	21
Oct. 27	dry	500	moist	21
Nov. 17	dry	500	moist	21

Table 8.3.a. The decade values of rainfall (mm) recorded by De Bilt in 1987 (Dev is the deviation from normal values, < 0: lower than normal; > 0 higher than normal).

month	I	Dev	II	Dev	III	Dev	M	Dev
Sept.	5.3	–15.8	37.1	14.8	17.0	–4.4	59.4	–5.5
Oct.	43.1	21.1	30.7	2.7	22.7	–1.2	96.5	27.6
Nov.	2.2	–23.4	70.7	47.9	19.6	–6.6	92.5	17.8

Table 8.3.b. The decade values of the reference evaporation (mm) recorded by De Bilt (normal values are not available).

month	I	II	III	M
Sept.	17.8	16.0	15.3	49.1
Oct.	13.0	10.1	6.7	29.8
Nov.	4.2	3.3	1.5	9.0

Table 8.3.c. The decade values of global radiation ($kJ{\cdot}cm^{-2}$) recorded by De Bilt in 1987 (Dev is the deviation from normal values, < 0: lower than normal; > 0 higher than normal).

month	I	Dev	II	Dev	III	Dev	M	Dev
Sept.	10.566	–1.557	10.229	–0.407	9.926	1.097	30.721	–0.866
Oct.	8.462	0.955	6.679	0.416	4.831	–0.291	19.972	1.081
Nov.	2.953	–0.600	2.403	–0.284	1.277	–0.825	6.633	–1.709

8.3. THE NUMERICAL RESULTS AND DISCUSSION

The heuristic FLOS calculates schedules (by planning with expected data or simulation with recorded data) for the harvest period, i.e. September till November. The results of the following schedules are compared:

1. the schedules SCHEMA 1 and SCHEMA 2 (with meteorological weather data), the schedules using a weather forecast with a maximum and a minimum amount of rainfall respectively;
2. the schedule SCHEMA W (with actual recorded weather data);
3. a schedule given by the farmer (a planning based on the farmer's experience);
4. the actual schedule;

The first three schedules are determined by planning, the last one is the actual schedule of the week. The first two schedules are calculated by SCHEMA (the software package) with the option, „planning" (see Chapter 9). The last two are calculated by SCHEMA with the option, „simulation", to derive the costs incurred. For the first schedule, the minimum and maximum amount of rainfall is taken as an input, because the best and the worst situation according to rainfall will be considered. All the other possibilities of rainfall are assumed to be limited by these two extreme situations.

Three main harvests are analyzed, i.e. the cereal, the potato and the sugarbeet harvest. Also field operations like cultivating and ploughing will be analyzed. The harvests of field beans and string beans are of less importance because they only take one or two days. They will not be discussed. Of each schedule, the following costs are considered:

- regular time,
- overtime,
- machinery,
- timeliness, and
- total.

Also the progress of the processing will be analyzed. The weather forecast has a length of five days. To consider the effects of the weather forecast only (and not the effects of climatological data for the rest of the planning horizon, see Chapter 7) on the outcome of the heuristic FLOS, the planning horizon is stated to be a week. Each week, a new schedule is calculated using a new weather forecast and new initial amounts of material. This is done for the whole season containing twelve weeks. The weather forecast is used as an input. The forecast is determined on Tuesday (once a week), so the schedule also starts Tuesday. During the week, the weather forecast is not corrected. The results are given per week. A week has the identification Week_d-m where d is the day and m is the month. For example, Week_1-9 is the week with Tuesday September 1.

Firstly the main harvests will be discussed.

The grain harvest

The grain harvest was mainly in Week_1-9 and Week_8-9. On September 1, there still was a total amount of forty-nine hectares of cereal (spring barley and winter wheat together). The two cereals are discussed together because:

1. the processing of both materials was almost the same, e.g. the same working rate and the same timeliness cost;

2. therefore, the processing of spring barley alternates continuously with the processing of winter wheat (after each day).

The harvest of cereal was done totally by the farmer and his labourer. Two figures containing all the schedules are given, firstly a line diagram presenting the total amount of material per period and secondly a bar diagram presenting the different costs, i.e. the regular time, overtime, machine, timeliness and total cost (which is the sum of the first four costs).

Two versions of planning by SCHEMA are given: SCHEMA 1, the version with the maximum amount of rainfall possible as an input, and SCHEMA 2, the version with the minimum amount of rainfall (i.e. zero mm per day) as an input. These versions are chosen to represent the best and the worst situation related to workability (item: for a more realistic case, the average amount of rainfall may be chosen as an input). Besides SCHEMA 1 and SCHEMA 2, the planning of the farmer and the real situation are given. These two are calculated by SCHEMA by simulation, to obtain a correct comparison. For most cases, the planning of SCHEMA with real weather data, i.e. SCHEMA W is also given.

For the grain harvest the results are presented in Figures 8.2.a, b, c and d (note that each period stands for a period of five hours except for every fourth period which has a length of nine hours (the night), see Section 6.2). In Week_1-9 (Figures 8.2.a and b), the main part of cereal has been harvested. In Week_8-9 (Figures 8.1.c and d), only twelve hectares total amount is left and will all be harvested.

SCHEMA 1 offers the cheapest results in Week_1-9 because it only schedules a harvest of twelve hectares. The rest was not harvested due to workability constraints (the expected amount of rainfall is maximum).

In Week_8-9 the same picture exists. For SCHEMA 2, workability has no constraints, i.e. the expected amount of rainfall is zero mm per day, therefore, the harvest took place rapidly. A situation with zero mm rainfall per day is called the optimistic case, compared to a reference model. The reference model is SCHEMA using actual recorded weather data, i.e. SCHEMA W.

In the optimistic case, the schedule predicts a fast and complete processing of all the materials. There are never problems with the state of the weather, i.e workability has no constraints. In this case, the schedule predicts high cost (regular hours and machine cost are high, therefore total cost is high). This case is predicted by SCHEMA 2 (no rain).

Contrary to the optimistic case, there is a pessimistic case. In the pessimistic case, it is not possible to process all the materials due to workability constraints. The weather forecast always predicts a maximum amount of rainfall per day. In this case, the schedule gives low cost, but there is always material left (timeliness cost is high, but regular hours and machine cost are very low, therefore total cost is low). This case is predicted by SCHEMA 1. Both cases are presented in Table 8.4.

The cases are compared with the reference model.

Table 8.4. The properties of SCHEMA 1 and SCHEMA 2.

model	expected amount of rainfall	total cost	timeliness cost	case
SCHEMA 1	maximum	low	high	pessimistic
SCHEMA 2	minimum (=0)	high	low	optimistic

The farmer's planning is a bit more optimistic, compared with reality. For Week_1-9, the planning is almost the same as in reality, except for the last periods. Both planning and reality are worse than the planning of SCHEMA W. However, the difference in cost is not large but still does exist. The reason is that SCHEMA W uses less overtime hours.

A problem which is not visualized, but just detected and which SCHEMA cannot handle is the occurrence of so-called „state-indifferent" operations.

> Definition 8.1
> A *state-indifferent operation* has no immediate visual effect on the material, e.g. pesticide spraying.

The program SCHEMA cannot handle this kind of operation because each operation in SCHEMA has to perform a change of state of the material. Also, SCHEMA can only handle operations which do occur once only. An operation like pesticide spraying can occur more than once in a planning horizon. More research has to be done to solve this problem.

The main conclusions of this case are:

- SCHEMA W offers better results than the planning of the farmer (about 1.7% for total cost) and the real situation (about 3.2% for total cost). Improvement of the farmer's planning is therefore possible but not substantial, i.e. the effectivity of the decision process increases a little. But the efficiency of the decision process increases a lot. Therefore, SCHEMA is more important as a tool to improve the efficiency of the decision process than as a tool to improve the effectivity of the decisions;

- The solution of the optimistic version of SCHEMA, i.e. SCHEMA 2, contains lower cost than the solution of SCHEMA W, but the difference is small, about 0.7%. The weather forecast in this case is reliable enough because it almost gives the same results as real weather data. It is therefore justified to take the optimistic version of SCHEMA as solution (for Week_1-9);

- The pessimistic version, i.e. SCHEMA 1 cannot process the total amount of cereal due to workability constraints. Timeliness costs are therefore high, but other costs, like machine costs (which is mainly drying costs), are low. The difference in total cost with SCHEMA W is large, about 47.9% (for Week_1-9);

- The model cannot handle „state-indifferent" operations. On the contrary, the farmer uses a lot of these operations, especially during the time he cannot harvest. These operations are sometimes necessary and can restrict cost, e.g. the maintenance of machinery can restrict breakdown and the depending cost. The heuristic FLOS can be improved with this respect.

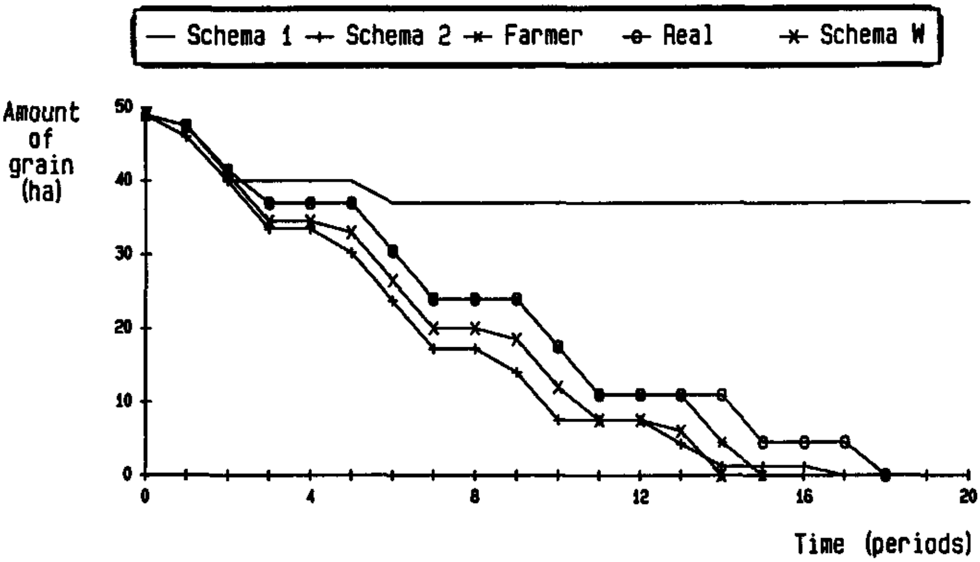


Figure 8.2.a. The amount of grain (ha) against the time (periods) for Week_1-9. SCHEMA 1, SCHEMA 2 and SCHEMA W are explained in the text, FARMER is the farmer's planning and REAL is the actual schedule.

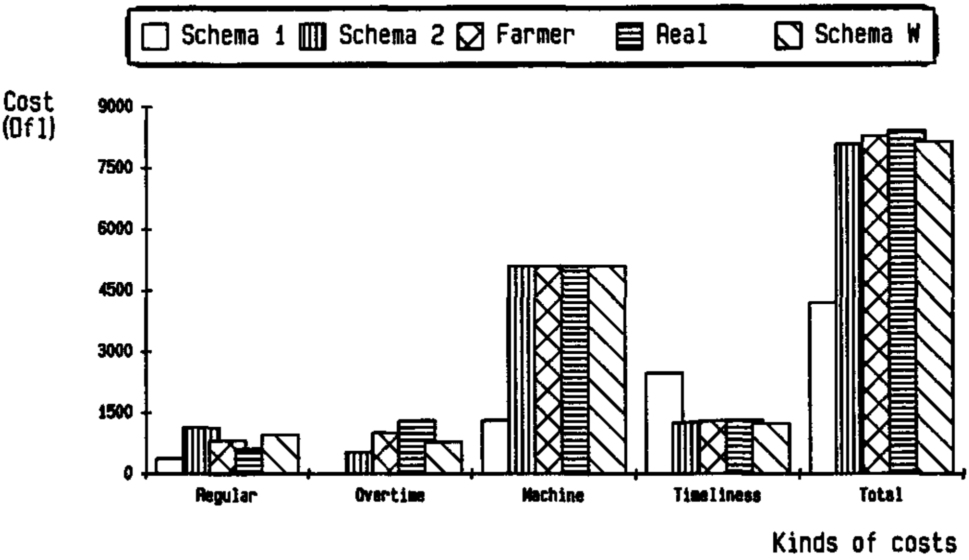


Figure 8.2.b. The different kinds of costs (*f*) for the grain harvest in Week_1-9. SCHEMA 1, SCHEMA 2 and SCHEMA W are explained in the text, FARMER is the farmer's planning and REAL is the actual schedule.

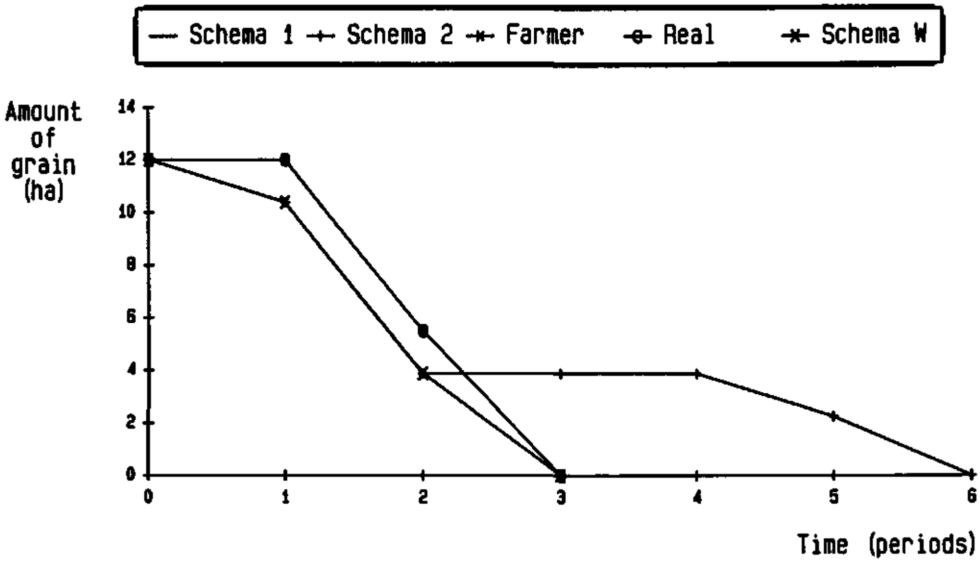


Figure 8.2.c. The amount of grain (ha) against the time (periods) for Week_8-9. SCHEMA 1, SCHEMA 2 and SCHEMA W are explained in the text, FARMER is the farmer's planning and REAL is the actual schedule.

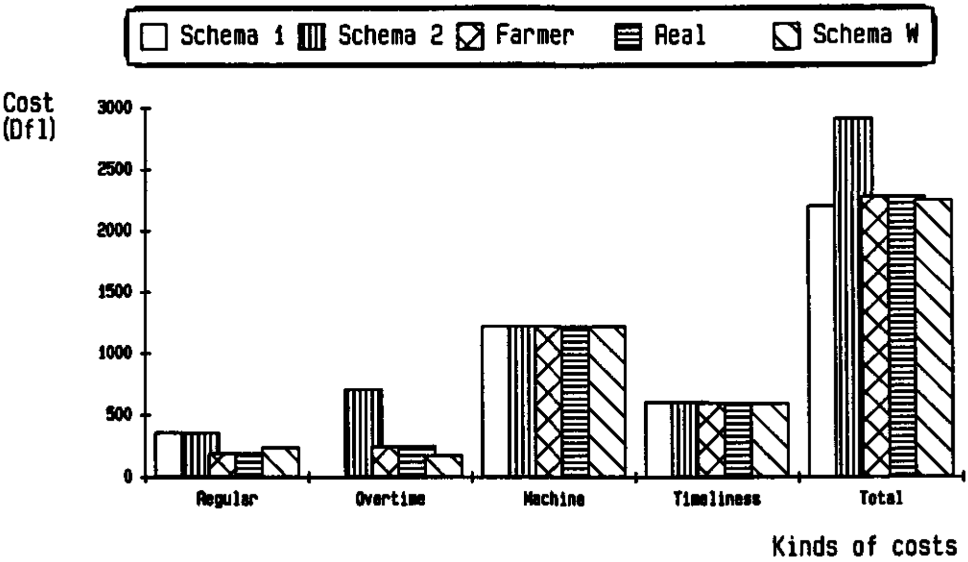


Figure 8.2.d. The different kinds of costs (*f*) for the grain harvest in Week_8-9. SCHEMA 1, SCHEMA 2 and SCHEMA W are explained in the text, FARMER is the farmer's planning and REAL is the actual schedule.

The sugarbeet and potato harvest

These two harvests will be discussed together because the harvest of sugarbeets was continuously alternated with the harvest of potatoes.

The harvest of sugarbeets and potatoes was done by the agricultural contractor. Only the transport of the harvest was done by the farmer and his labourer. The problem is that the contractor uses his own hours of labour. The farmer cannot control this. The planning of SCHEMA does not take this into account. Therefore, in most cases, the solution of SCHEMA can contain a better schedule.

The sugarbeet harvest was in Week_22-9, Week_6-10, Week_13-10 and Week_27-10. The potato harvest took place in Week_6-10, Week_13-10 and Week_20-10. There are two overlapping periods, i.e. Week_6-10 and Week_13-10. In these weeks, SCHEMA has to schedule both harvests. The harvest from week to week is discussed.

The results of Week_22-9 are visually presented in Figures 8.3.a and b. SCHEMA 1 offers cheap results, but it only involves timeliness cost, i.e. *no* processing of sugarbeets took place.

The farmer's planning seems too optimistic compared with the real situation.

Comparing reality with SCHEMA 2, it is shown that the same amount of sugarbeets was processed. But SCHEMA 2 offers a cheaper solution because it makes less demand on overtime hours.

A good comparison is not possible due to the lack of the reference model, i.e. the planning by SCHEMA W. Real weather data are missing for Week_22-9.

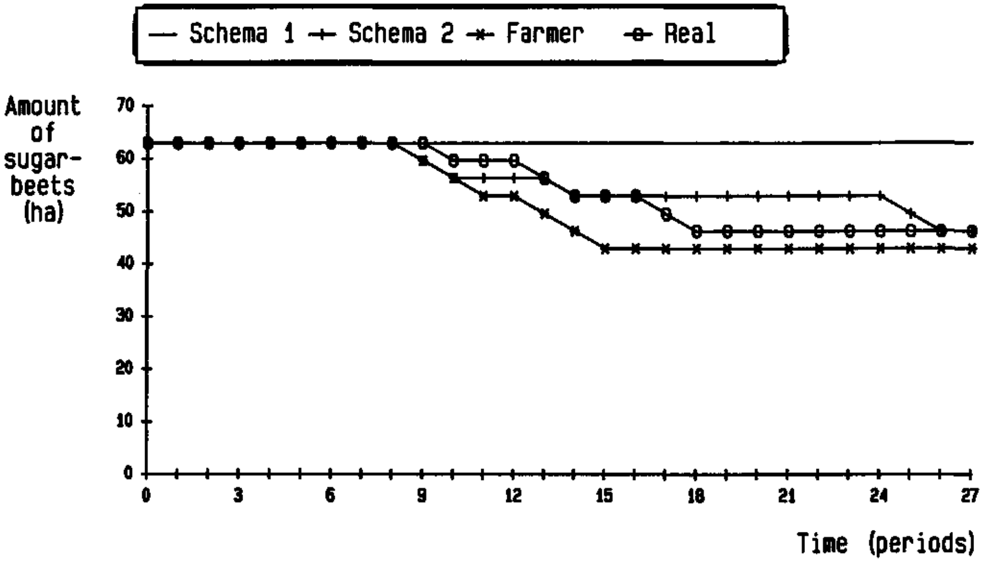


Figure 8.3.a. The amount of sugarbeets (ha) against the time (periods) for Week_22-9. SCHEMA 1 and SCHEMA 2 are explained in the text, FARMER is the farmer's planning and REAL is the actual schedule.

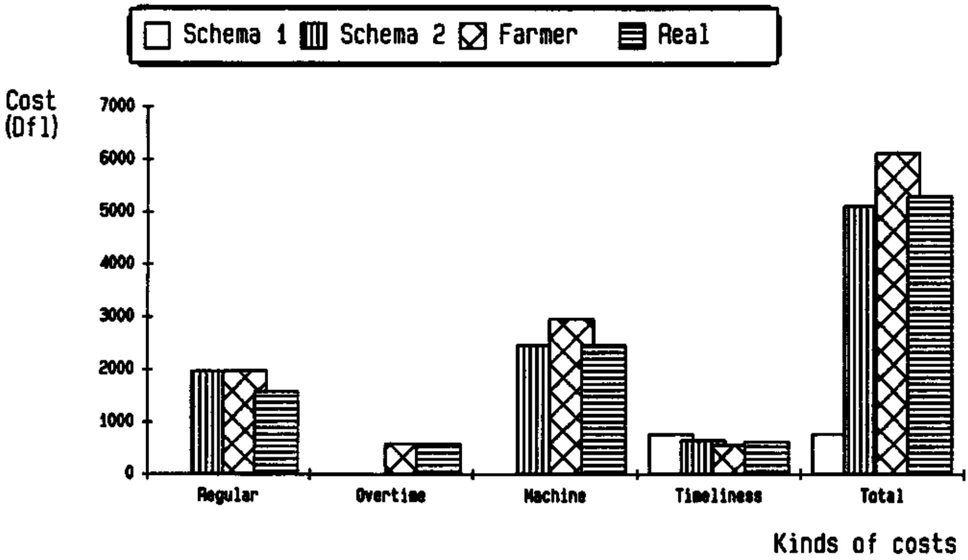


Figure 8.3.b. The different kinds of costs (*f*) for the sugarbeet harvest in Week_22-9. SCHEMA 1 and SCHEMA 2 are explained in the text, FARMER is the farmer's planning and REAL is the actual schedule.

In Week_6-10 (Figures 8.4.a, b and c), two harvests are analysed: sugarbeet and potato. Due to the workability constraints, SCHEMA 1 gives a schedule where nothing happens. SCHEMA 2 gives a schedule where only sugarbeets were harvested. In reality, only potatoes were harvested. This is also the farmer's planning, except that he has a too optimistic view.

In reality, the results contain lower costs compared to SCHEMA 2 (about 17.6%), but also less material was processed (11.55 ha potatoes in reality, compared with 33.53 ha sugarbeets for SCHEMA 2). The fact that nothing happens with the sugarbeets in reality is due to the schedule of the agricultural contractor. He does not work in Week_6-10 on the farm A93.

SCHEMA W proposes to do nothing which result in timeliness cost only. But the farmer does work, therefore, the conclusions are that the farmer works under bad conditions, i.e. the soil is too wet for a clean harvest, the soil moisture suction model can give wrong values, or the initial condition of soil is not properly stated.

Concluding, the program SCHEMA decides to focus attention on the sugarbeet harvest while the farmer plans to harvest potatoes. This difference is caused by the constraints associated with the agricultural contractor. The program SCHEMA does not use these constraints.

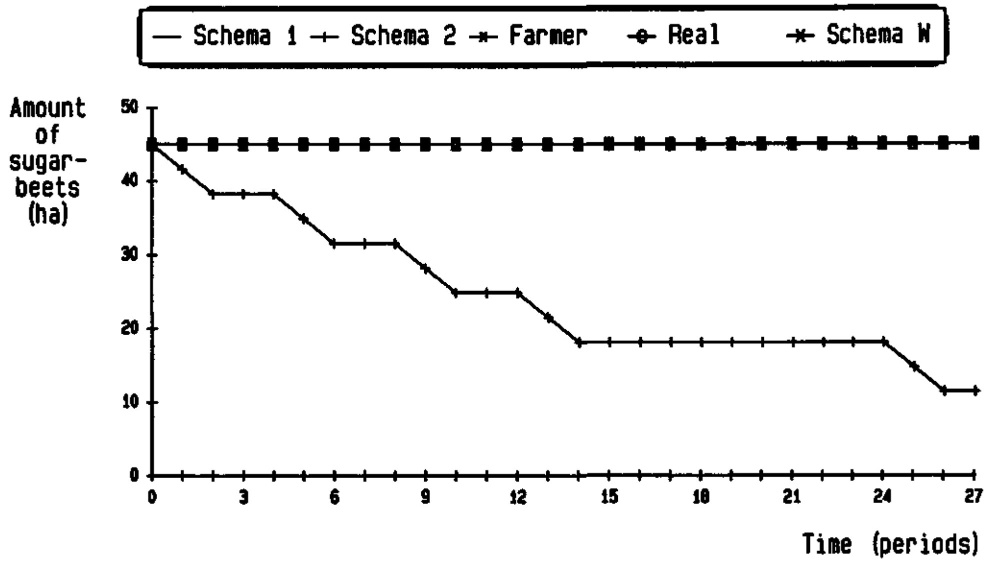


Figure 8.4.a. The amount of sugarbeets (ha) against the time (periods) for Week_6-10. SCHEMA 1, SCHEMA 2 and SCHEMA W are explained in the text, FARMER is the farmer's planning and REAL is the actual schedule.

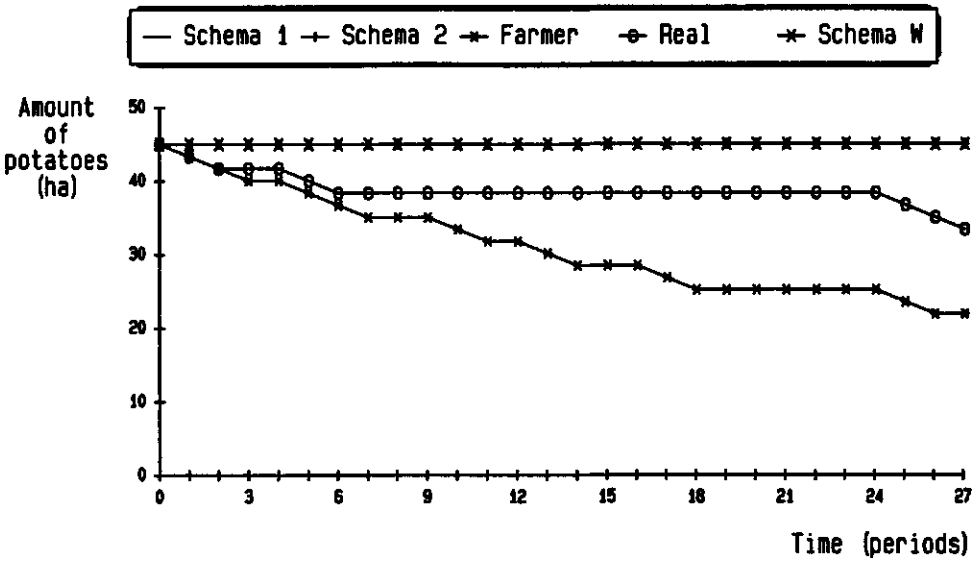


Figure 8.4.b. The amount of potatoes (ha) against the time (periods) for Week_6-10. SCHEMA 1, SCHEMA 2 and SCHEMA W are explained in the text, FARMER is the farmer's planning and REAL is the actual schedule.

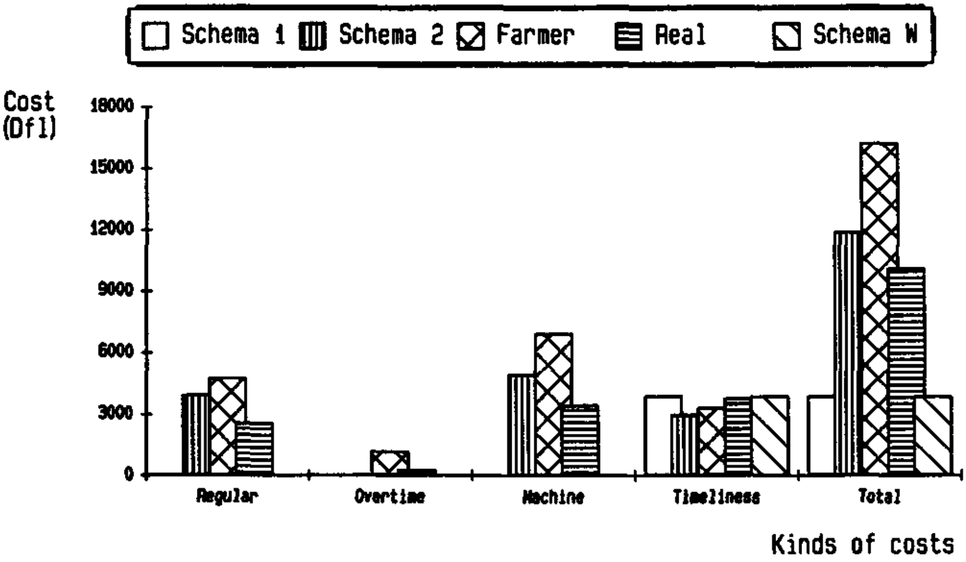


Figure 8.4.c. The different kinds of costs (*f*) for the harvest in Week_6-10. SCHEMA 1, SCHEMA 2 and SCHEMA W are explained in the text, FARMER is the farmer's planning and REAL is the actual schedule.

Week_13-10 (Figures 8.5.a, b and c) also contains the two harvests. The total cost is almost the same as in Week_6-10. The farmer's planning is too optimistic again. The program SCHEMA again puts more attention on the sugarbeet harvest while the farmer decides to harvest both the potatoes and the sugarbeets. In reality, both harvests take place. SCHEMA W predicts a schedule with less action than in reality. The latter can result in the same conclusions as given above, i.e. the farmer works under bad conditions, the soil moisture suction model can give wrong values, or the initial condition of soil is not properly stated.

Concluding, the farmer is more restricted by the agricultural contractor than SCHEMA, the contractor takes the decision to operate also when the situation (the state of the soil) is bad (or the soil moisture suction model gives wrong values or the initial condition is not properly stated). Restrictions from outside, i.e. the schedule of the agricultural contractor is dominant here.

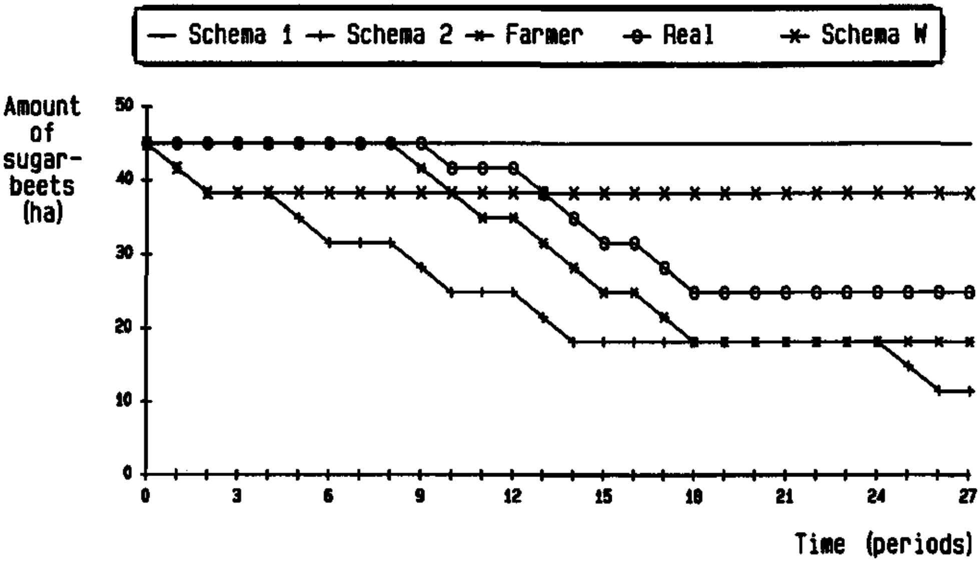


Figure 8.5.a. The amount of sugarbeets (ha) against the time (periods) for Week_13-10. SCHEMA 1, SCHEMA 2 and SCHEMA W are explained in the text, FARMER is the farmer's planning and REAL is the actual schedule.

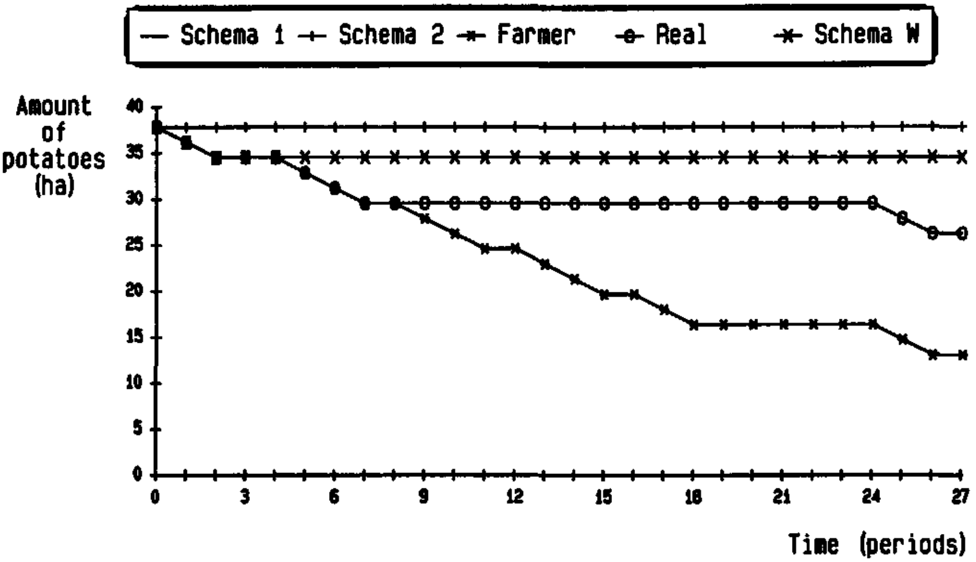


Figure 8.5.b. The amount of potatoes (ha) against the time (periods) for Week_13-10. SCHEMA 1, SCHEMA 2 and SCHEMA W are explained in the text, FARMER is the farmer's planning and REAL is the actual schedule.

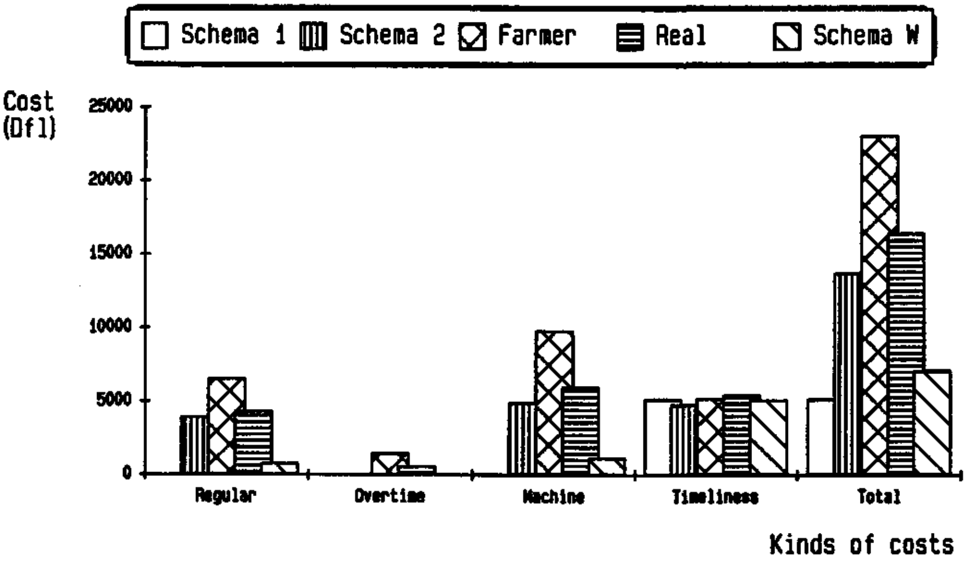


Figure 8.5.c. The different kinds of costs (*f*) for the harvest in Week_13-10. SCHEMA 1, SCHEMA 2 and SCHEMA W are explained in the text, FARMER is the farmer's planning and REAL is the actual schedule.

Only potatoes were harvested in Week_20-10 (Figures 8.6.a and b). SCHEMA 1 gives the worst solution, i.e. nothing can be done. The workability for SCHEMA 1 is zero for all the periods. SCHEMA 2 again is too optimistic compared with the reference model. The farmer's planning is too optimistic compared to reality, but both can perform better (according to SCHEMA W).

The difference in total cost between SCHEMA 2 and SCHEMA W is about 2.2%. The weather forecast gives almost the same information as real weather data. This also happens because the amount of rainfall is low. The difference between zero mm rain (input for SCHEMA 2) and the value extracted from real weather data is small.

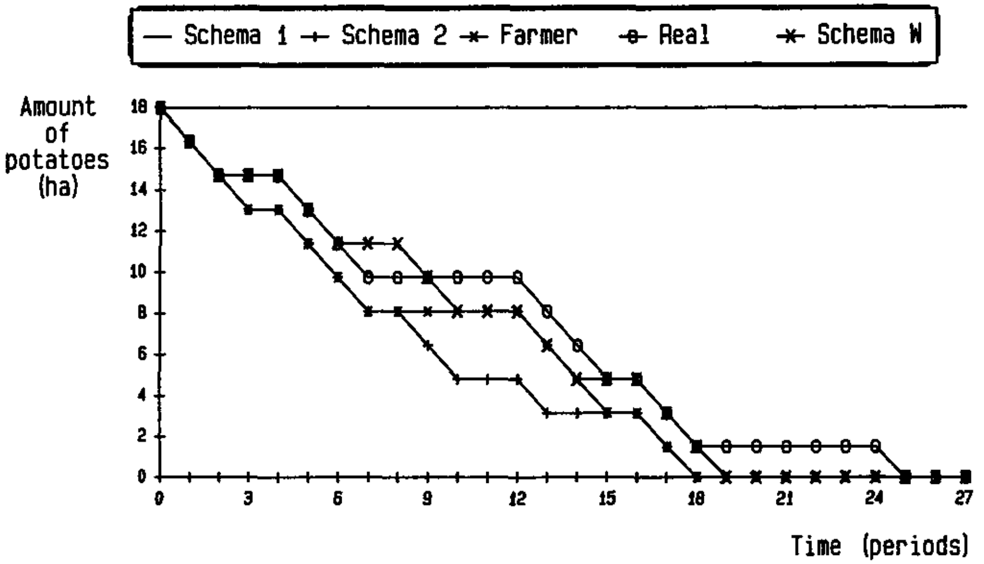


Figure 8.6.a. The amount of potatoes (ha) against the time (periods) for Week_20-10. SCHEMA 1, SCHEMA 2 and SCHEMA W are explained in the text, FARMER is the farmer's planning and REAL is the actual schedule.

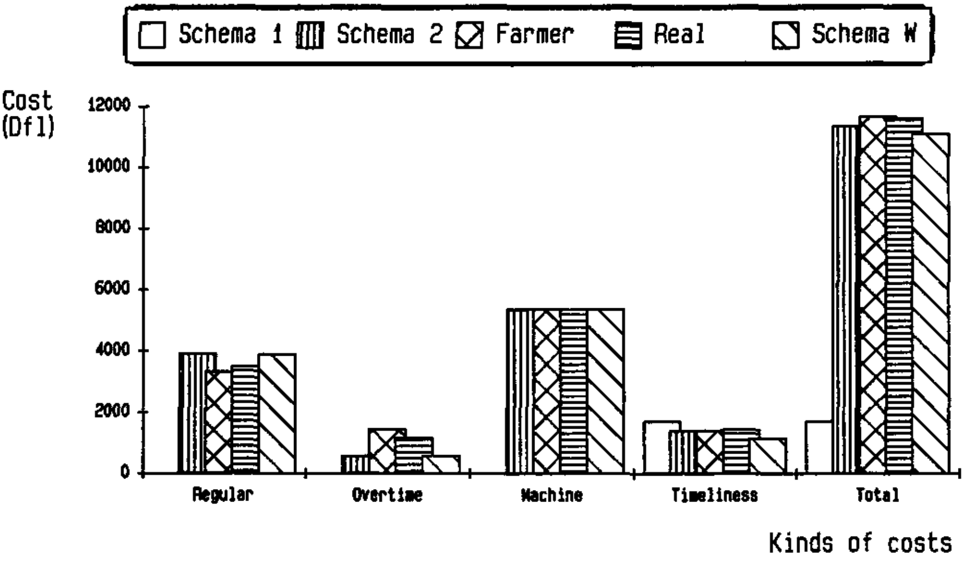


Figure 8.6.b. The different kinds of costs (*f*) for the potato harvest in Week_20-10. SCHEMA 1, SCHEMA 2 and SCHEMA W are explained in the text, FARMER is the farmer's planning and REAL is the actual schedule.

Week_27-10 contains only the harvest of sugarbeets (Figure 8.7.a and b). This is the only crop left at the end of October. For this week real weather data are not available. SCHEMA 2 gives a result with the highest cost, but do process the total amount of material. SCHEMA 1 is again the model with the worst workability data, and therefore, too pessimistic in processing. The farmer also is too optimistic concerning the progress of processing compared to reality.

Concluding, SCHEMA 1 almost always presents a non-workable situation, i.e. a situation where nothing can be done (except for week_27-10), while SCHEMA 2 (where the amount of rainfall is zero) is in general too optimistic. The farmer is always too optimistic compared with reality. The farmer also decides to work when conditions are not good enough. This is mainly caused by the restrictions of the schedule of the agricultural contractor.

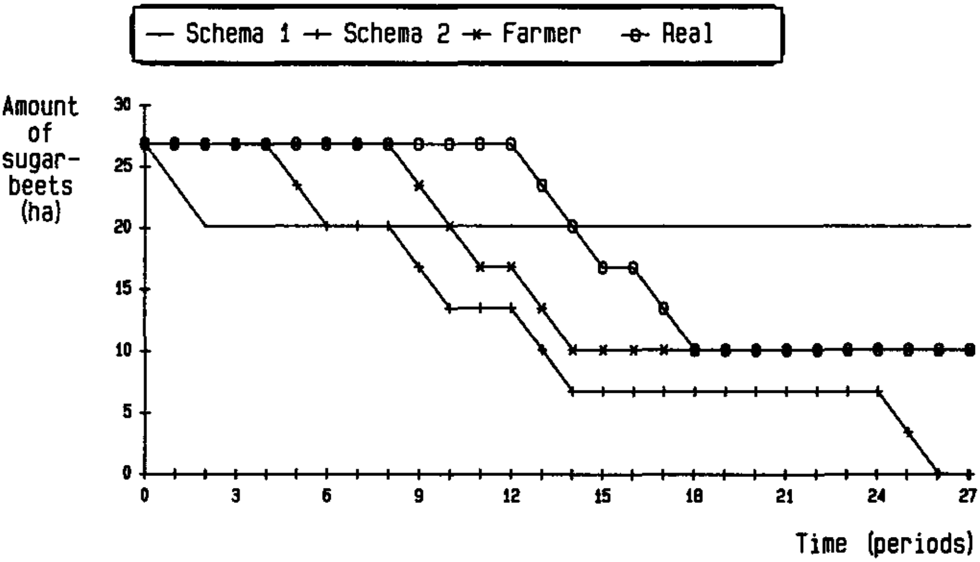


Figure 8.7.a. The amount of sugarbeets (ha) against the time (periods) for Week_27-10. SCHEMA 1 and SCHEMA 2 are explained in the text, FARMER is the farmer's planning and REAL is the actual schedule.

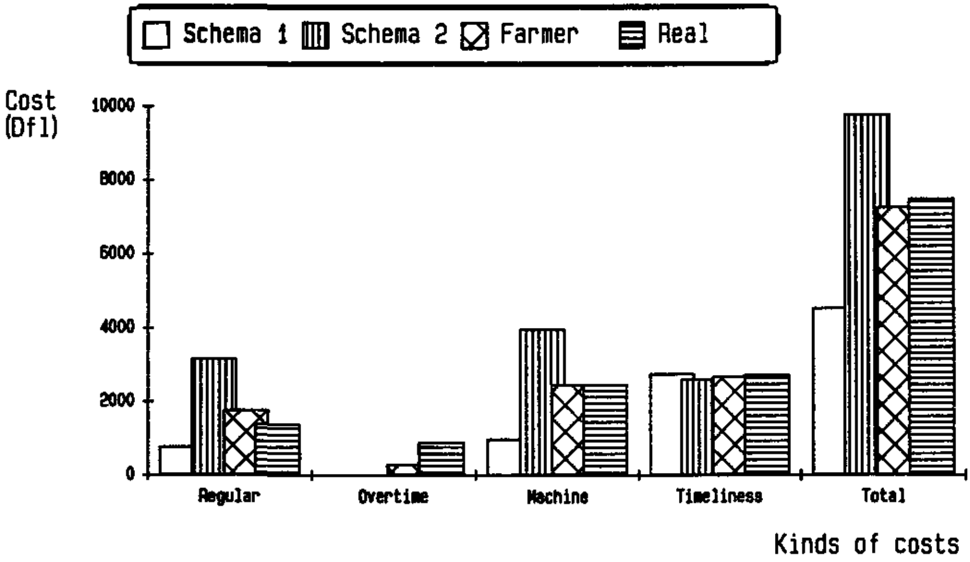


Figure 8.7.b. The different kinds of costs (f) for the sugarbeet harvest in Week_27-10. SCHEMA 1 and SCHEMA 2 are explained in the text, FARMER is the farmer's planning and REAL is the actual schedule.

Tillage

In Week_17-11, ploughing only is examined (Figures 8.8.a and b). SCHEMA 2 produces more ploughed land than the other schedules. The farmer's planning is almost the same as the planning by SCHEMA W. In fact, his planning offers cheaper results. In this case, the farmer is better than the heuristic FLOS (about 1.5% in total cost). Nevertheless, the farmer does not make use of this superiority, i.e. the reality shows a worse schedule. The reason may be that ploughing is not that important, the farmer can decide to slow down and put more attention on other operations (e.g. maintenance).

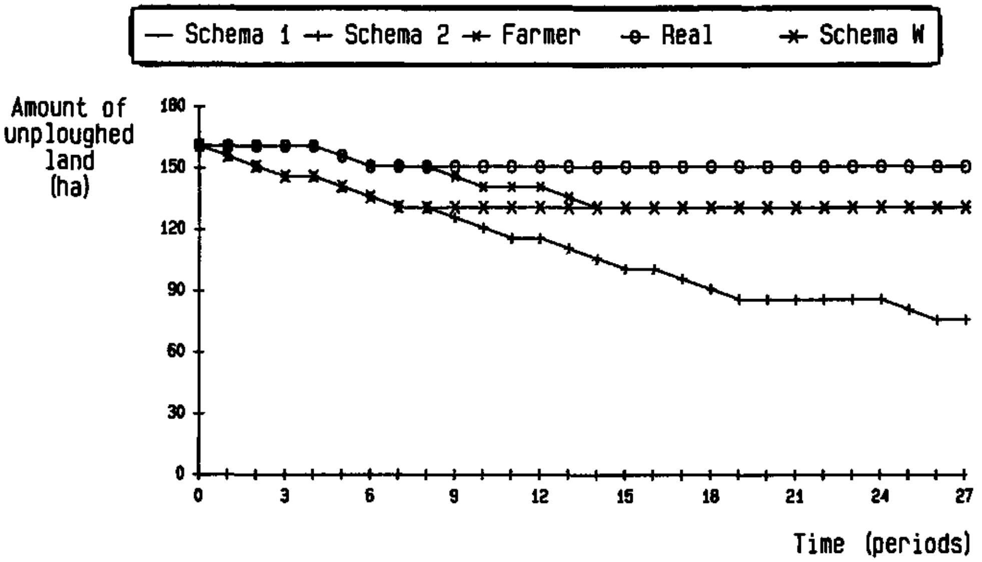


Figure 8.8.a. The amount of unploughed land (ha) against the time (periods) for Week_17-11. SCHEMA 1, SCHEMA 2 and SCHEMA W are explained in the text, FARMER is the farmer's planning and REAL is the actual schedule.

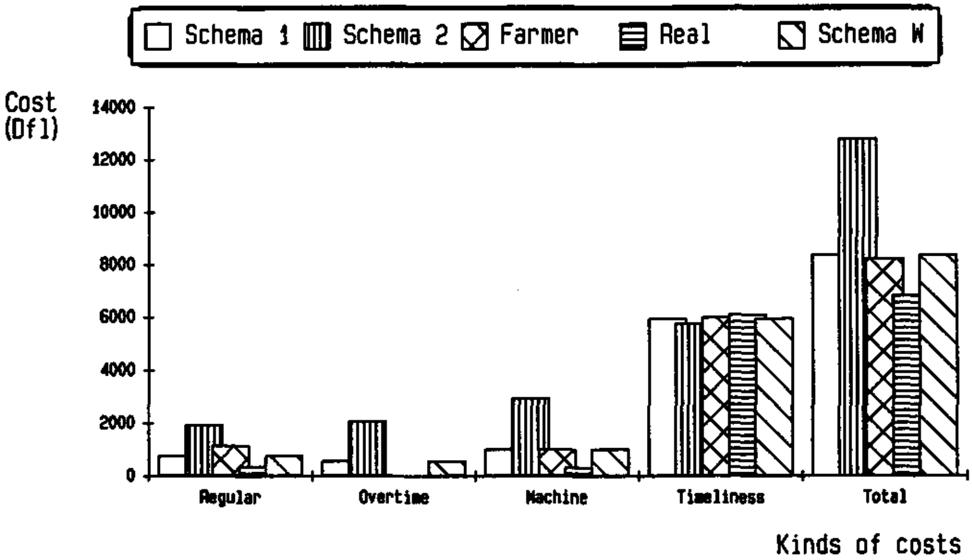


Figure 8.8.b. The different kinds of costs (*f*) for the tillage in Week_17-11. SCHEMA 1, SCHEMA 2 and SCHEMA W are explained in the text, FARMER is the farmer's planning and REAL is the actual schedule.

8.4. CONCLUSIONS AND DISCUSSION

The conclusions derived from this practical test are:

- The optimistic version of SCHEMA, i.e. SCHEMA 2 commonly offers a schedule with lower cost than the farmer's schedule and the actual schedule;
- Alternatively, the pessimistic version, i.e. SCHEMA 1 is unrealistic. The solution almost always contains a schedule where nothing can be done. For SCHEMA 1, the amount of rainfall is too high (the maximum amount of rain possible). In practice, this seldom occurs;
- The farmer's planning (planning under uncertainty) is, compared with the solution of the reference model (planning under certainty, afterwards with recorded data), certainly not bad. The difference between the solution of his planning and that of the reference model is small (in total cost about three to four percent);
- Still, the actual schedule is different from the planning. There is a difference of about seven to eight percent. The effectivity and the efficiency of the decision process can be improved by using FLOS (see also Chapter 7). It is possible to use the heuristic FLOS frequently (more times than once a week) and improve the planning and the reaction to changes of the environment (another weather forecast, machine failure, and so on);
- Due to small differences between the solution of SCHEMA 2 and the reference model, the conclusion is that the weather forecast can be used to derive a workability range. But, solutions have to be chosen in the following way:
    - If the weather forecast predicts a *low* amount of rainfall with a *low* probability, the solution of SCHEMA 2 (i.e. the solution with zero mm rain as input) has to be chosen;
    - If the weather forecast predicts a *certain* amount of rain with a *high* probability, the solution of SCHEMA 1 (i.e. the solution with a maximum amount of rain as input) has to be chosen because the difference in input between weather forecast and real weather data is small (see also Section 7.3). In the test case, SCHEMA 1 always gives bad results because the actual amount of rainfall was always low (see Table 8.5).
- The farmer often decides to work when the soil is too wet. It is possible that the soil moisture suction model and the grain moisture content formulae have to be improved. Also the classes of initial condition of soil and grain moisture can be further refined.

Conclusions not derived from the test results are:

- The model can safely be used in practical situations, but, the heuristic FLOS is not fitted yet for the so-called „state-indifferent" operations. Incorporation of the „state-indifferent" operations is still necessary;

Table 8.5. Several cases of rainfall (mm) and probability created to show the use by SCHEMA 1 and SCHEMA 2.

expected amount of rainfall	probability of rainfall	amount of rainfall used by SCHEMA 1	amount of rainfall used by SCHEMA 2	
1.00	0.10	10.00	0.00	1)
1.00	0.90	1.11	0.00	2)
20.00	0.90	22.22	0.00	3)
20.00	0.10	200.00	0.00	4)
5.00	0.50	10.00	0.00	5)

1) The difference between the expected amount of rainfall and the amount used by SCHEMA 2 is small, therefore the solution of SCHEMA 2 is used.

2) The difference between the expected amount of rainfall and the amount used by SCHEMA 1 is small, the solution of SCHEMA 1 is predicted.

3) The difference between the expected amount of rainfall and the amount used by SCHEMA 1 is also small, therefore the solution of SCHEMA 1 should be used.

4) The weather forecast can be used except in situations predicting a *high* amounts of rainfall with a *low* probability. The real values of such a situation are difficult to obtain.

5) In this case, it is better to use the expected amount of rainfall itself (which is five mm) instead of the values used by SCHEMA 1 and SCHEMA 2.

- Good timeliness functions of several materials like potatoes and sugarbeet are still needed;

- The user-friendliness of the program is not discussed in this chapter. From the several comments received and the interest in commercial application, the package appears to be user-friendly and performs its task well. But, the software package SCHEMA still requires a good input mechanism which is not restricted to SCHEMA, e.g. data-bases, to store information about materials, machinery and gangs.

Chapter 9

THE DECISION SUPPORT SYSTEM „SCHEMA”

9.1. DECISION SUPPORT SYSTEMS

A decision support system combines several aspects of the fields of management information systems, operations research and artificial intelligence. According to Morton (1971), a decision support system (a DSS)

- is a tool for the manager to support his decision making (especially for vague and ill-structured problems),
- puts more attention on support than on replacement of the decision process,
- tries to improve the effectivity of the decisions,
- integrates the potential of hardware, software, data-communication and several user-friendly computer models,
- makes the decision process more efficient.

The user of a DSS and the demands of a DSS have special characteristics. The most important characteristics are (see also Keen and Morton, 1978, and Wijngaard, 1986b):

- *Casual user.*

  Definition 9.1
  A *casual user* is a person who uses the computer but is not a software developer.

  Users of a DSS are mostly casual users, they are not involved with the computer daily. Therefore, they have to be stimulated according to their own field of interest;

- *Ill-structured problems.* It is not possible to describe the problem using pre-defined algorithms;

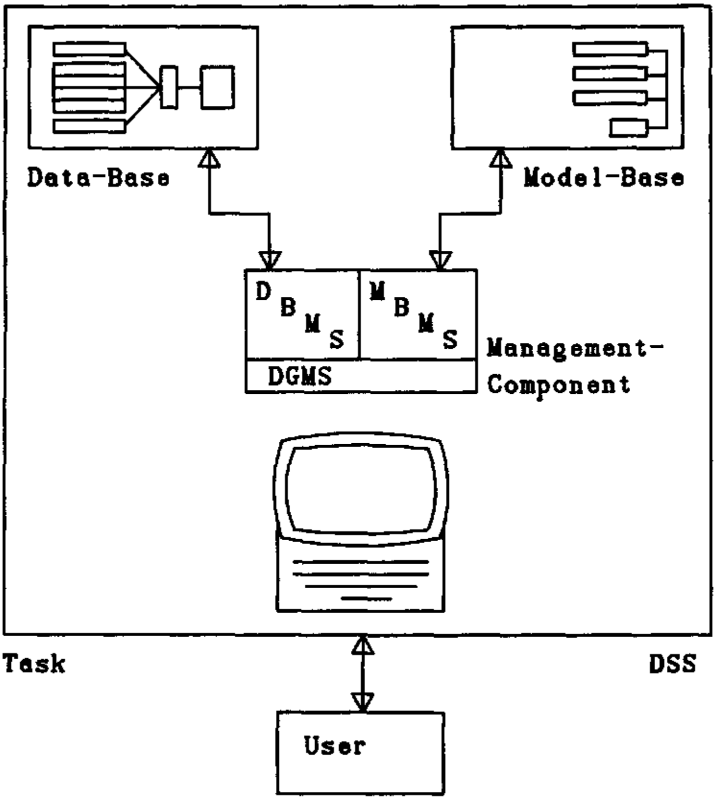


Figure 9.1. The common structure of a decision support system (DSS)

- *Intuition.* It must be possible for the user to use „his outlook on the matter" and use it as an input to the DSS;

- *Data are diverse.* Both operational and planning data of the business and data from the outside world are necessary. It must also be possible that the users own data can be used as an input;

- *Multiple objectives.* More than one goal must be satisfied. Often there are no quantitative values to determine the difference between several goals. The opinion of the decision maker is decisive;

- *Changing.* The development of a DSS is never finished. During development and even afterwards, continuous change and adaptation of a DSS is necessary.

The first design of a DSS contains three subsystems (Figure 9.1, see also Sprague, 1980):

- A *data component*, a data-base which must take account of different data. Besides structured data, also documents and text have to be stored;

- A *model component* with several tools for the desired algorithms;

- A *management component*, all data and models are being coordinated by the management component. This component combines:
  - DBMS, data-base management system,
  - MBMS, model-base management system,
  - DGMS, dialogue generation and management system.

The third component allows the operator to use the DSS with a common or specialized terminal. A clear presentation with a „presentation language" is important. This language must give presentations which support the „thinking process" of the casual user. Instead of long tables with quantitative values, it is better to give diagrams and figures.

The „dialogue language" (or the „action language") must also be based on the knowledge that the user is a casual user. Therefore, instead of an „instruction language" with several restrictions, it is better to make use of menus from which a choice can be made using function keys or a light pen. Naturally, help on every stated question must be available.

Around the heuristic FLOS (described in Chapter 7), the DSS SCHEMA (SCHEduling Multiple Activities) has been developed. This DSS is specially designed for a micro-computer (type PC, XT or AT) and can be run locally by the farmer. This is one of the demands stated in Chapter 6. In this chapter, the technical properties of the DSS (i.e. the software) will be described using a run as an example (see also Wijngaard, 1987a). The user of the DSS (the software package) can use the description in this chapter for help. The description in this chapter and Appendices C, D and E refer to further software development.

9.2. THE MAIN TECHNICAL PROPERTIES

The package SCHEMA has the following main technical properties (hardware and software demand):

Computer:	IBM PC, XT or AT, or compatible
Memory:	at least 256 kBytes
Operating system:	MS-DOS v.3.1 or later
Programming language:	Turbo-Pascal v.3.01A (Turbo Pascal, 1985)
Number of source lines:	4330
Number of modules:	40
dialogue-language:	Dutch or English

9.3. THE PROGRAM

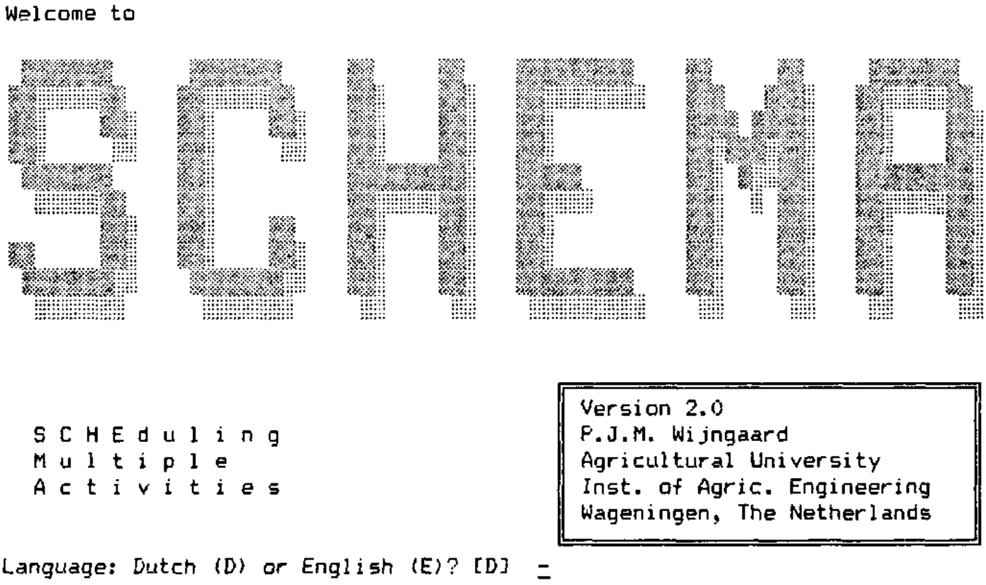
In this section, the program will be described, including:

- the access of data (input by file or by user);
- the structure of the internal data (the record structure);
- a run of the program;
- the format of the output.

The line in this section, i.e. the procedure for the user (the manual) is presented using roman numerals. This will be alternated with the description of the internal structure. The main program and all the modules are fully described in Appendix C. Firstly, the files needed to start the program must be identified (refer to Appendix D for the names of all the files and for a more detailed description of the contents of these files). The program itself is stored in the files:

SCHEMA.COM
SCHEMA.000
SCHEMA.001

I. To start the program the command SCHEMA is entered at monitor-prompt. The program starts with an opening picture (Figure 9.2) and asks which dialogue language is desired: D(utch) or E(nglish).



```
Welcome to

SCHEMA

  S C H E d u l i n g                 Version 2.0
  M u l t i p l e                     P.J.M. Wijngaard
  A c t i v i t i e s                 Agricultural University
                                      Inst. of Agric. Engineering
                                      Wageningen, The Netherlands

Language: Dutch (D) or English (E)? [D]  _
```

Figure 9.2. The opening picture of SCHEMA.

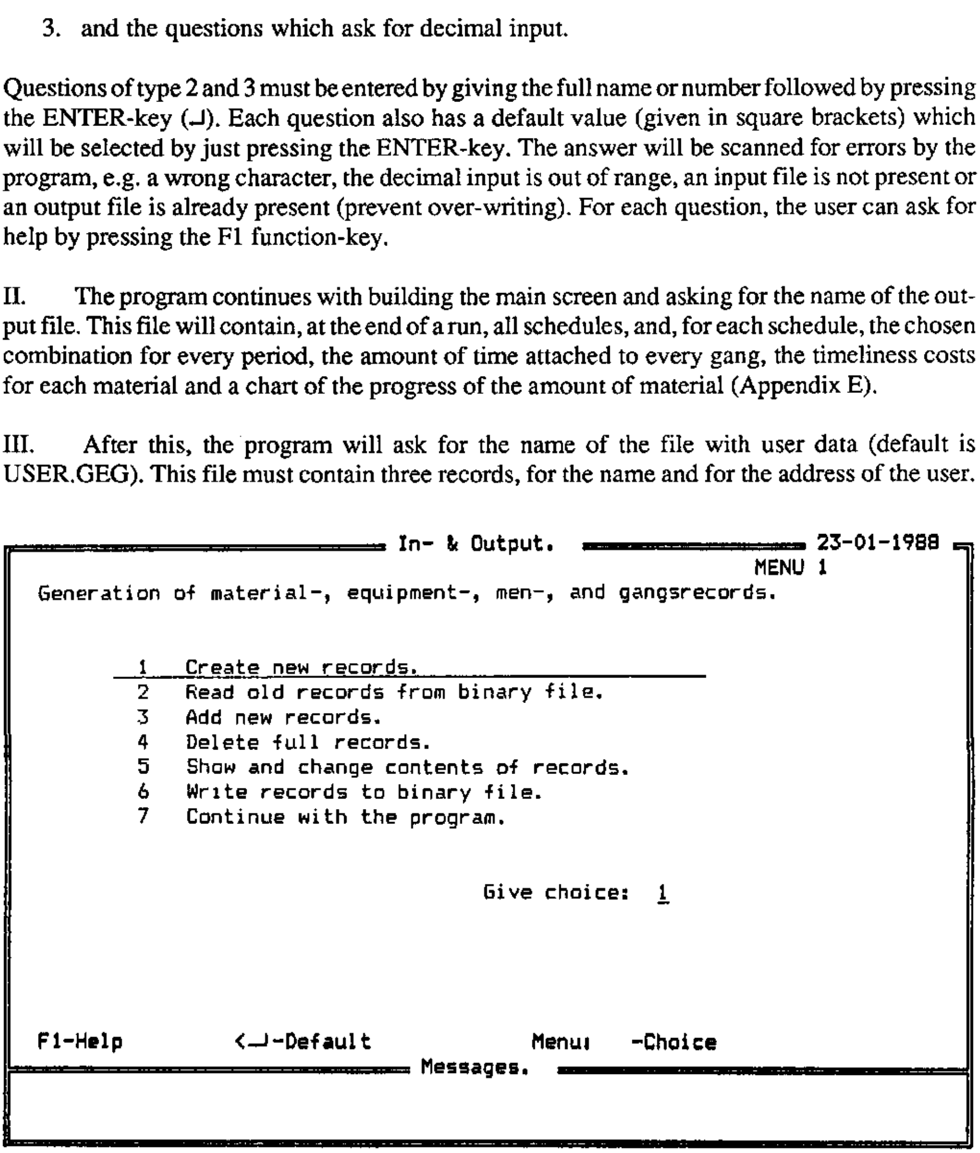
The program contains three types of questions:

1. those which need, as an answer, one character as input, e.g. D(utch) or E(nglish), or Y(es) or N(o). The user enters the answer by pressing the desired character key only;
2. the questions which ask for the name of an input or output file;
3. and the questions which ask for decimal input.

Questions of type 2 and 3 must be entered by giving the full name or number followed by pressing the ENTER-key (↵). Each question also has a default value (given in square brackets) which will be selected by just pressing the ENTER-key. The answer will be scanned for errors by the program, e.g. a wrong character, the decimal input is out of range, an input file is not present or an output file is already present (prevent over-writing). For each question, the user can ask for help by pressing the F1 function-key.

II. The program continues with building the main screen and asking for the name of the output file. This file will contain, at the end of a run, all schedules, and, for each schedule, the chosen combination for every period, the amount of time attached to every gang, the timeliness costs for each material and a chart of the progress of the amount of material (Appendix E).

III. After this, the program will ask for the name of the file with user data (default is USER.GEG). This file must contain three records, for the name and for the address of the user.



```
                              In- & Output.                    23-01-1988
                                                                   MENU 1
 Generation of material-, equipment-, men-, and gangsrecords.


          1   Create new records.
          2   Read old records from binary file.
          3   Add new records.
          4   Delete full records.
          5   Show and change contents of records.
          6   Write records to binary file.
          7   Continue with the program.


                                         Give choice:  1




 F1-Help          <↵-Default             Menu↑   -Choice
                              Messages.
```

Figure 9.3. The main menu („MENU 1") of SCHEMA.

IV. After entering the name of this file, the screen will show the first menu: „MENU 1" (Figure 9.3). With this menu, one can read the input files, create and manipulate internal data, and write the results of manipulated internal data to binary files. The menu has the following options:

1. *Create new records.* This option asks for the name of the input files (for the format of the input files, see Appendix E), then asks for each material, the optimal date and the final date of processing. The option reads these input files and builds for each material, each individual unit of machinery or men and each gang the structure of the record. This record is a collection of related data, a kind of archive. These structures are connected with pointers (Figure 9.4). The input files needed are:

    a. for the materials (default name is PERCEEL.GEG);

    b. for the order of materials, i.e. which material, under which conditions, will be delivered when another material is processed (default name is MAT_SEC.GEG);

    c. a file which contains the individual units (default name is EQUIPM.GEG);

    d. for the gangs (default name is GANG.GEG);

    e. and a file with a logic order of gangs (default name is GAN_SEC.GEG).

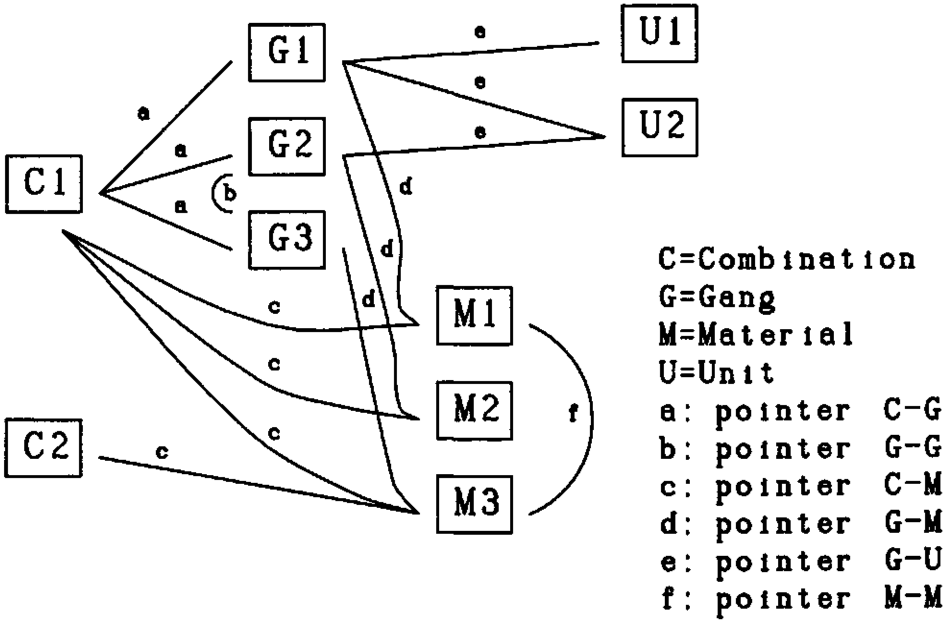


Figure 9.4. The connections of the records with pointers.

These files can be created by the user or delivered by a Data-Base Management System, like IBIS („Intern Bedrijfs Informatie Systeem", a project of the Institute of Agricultural Engineering, Wageningen, the Netherlands);

2. *Read old records from binary file.* This option reads binary files which are created by option 6. These files contain the already created records with contents and with the internal links by pointers. Creating new records with this menu option is faster than creating new records with menu option 1. It is necessary that the following files are present:

   PER_REC1.BIN,
   PER_REC2.BIN: records of materials;
   EQM_REC1.BIN,
   EQM_REC2.BIN: records of equipment and men;
   BEW_REC1.BIN,
   BEW_REC2.BIN: records of gangs.

   The files ???_REC1.BIN contain the data of the pointers, the files ???_REC2.BIN contain the contents of the records (Figure 9.4). If these files are not present then the records must be created with menu option 1. It is possible to manipulate the records with menu options 4 and 5. New records can be added with menu option 3;

3. *Add new records.* It is possible with this option to add new records to an existing set of records (when the existing set is created under option 2). The addition occurs in the same manner as under option 1. Therefore, the program needs the same number of files. Records already available will not be added;

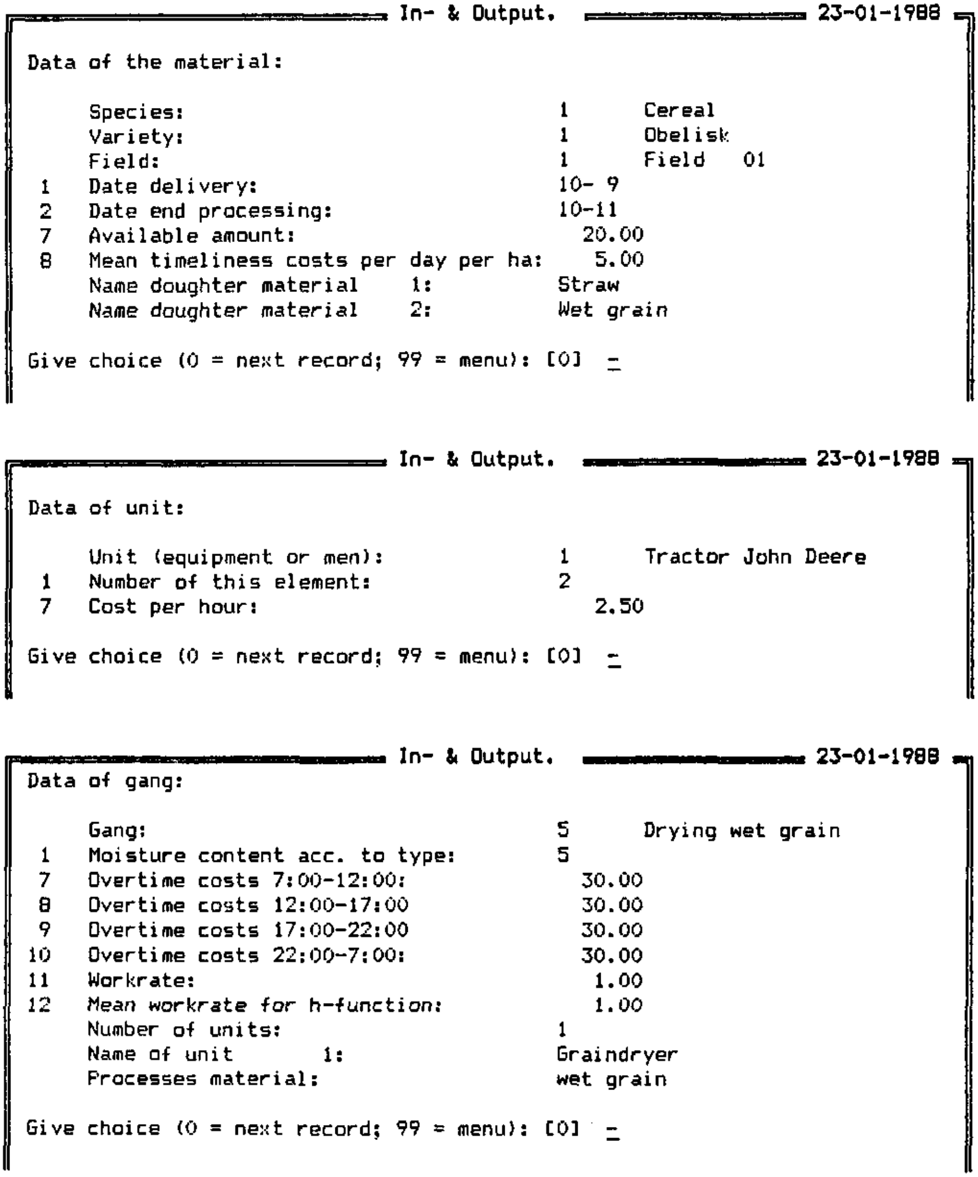
4. *Delete full records.* With this option, the second menu is presented: „MENU 2". Using this menu, complete records can be deleted. It is the users responsibility to delete also all the connected records if necessary (see also Figure 9.4);

5. *Show and change the contents of the records.* By choosing this option, „MENU 3" is displayed on the screen. This enables the user the possibility to look at and change the contents of each record (Figure 9.5);

6. *Write records to binary file.* The program will store all the records in binary files. These files are the same as stated under option 2. If the files are already present, the program will overwrite them. During a second run, the program can read these files with menu option 2;

7. *Continue with the program.* The program will continue.

V. If the user chooses option 7, the program will continue by creating all the possible combinations of gangs. This can be done automatically by using the following information: the total number of pieces of equipment and men, the total number of gangs and the attachment of equipment by each gang. The program can also read all the combinations from a file (default name is



```
═════════════════ In- & Output. ═════════════════ 23-01-1988

Data of the material:

    Species:                                 1      Cereal
    Variety:                                 1      Obelisk
    Field:                                   1      Field   01
 1  Date delivery:                           10- 9
 2  Date end processing:                     10-11
 7  Available amount:                          20.00
 8  Mean timeliness costs per day per ha:       5.00
    Name doughter material    1:             Straw
    Name doughter material    2:             Wet grain

Give choice (0 = next record; 99 = menu): [0]  _
```

```
═════════════════ In- & Output. ═════════════════ 23-01-1988

Data of unit:

    Unit (equipment or men):                 1      Tractor John Deere
 1  Number of this element:                  2
 7  Cost per hour:                              2.50

Give choice (0 = next record; 99 = menu): [0]  _
```

```
═════════════════ In- & Output. ═════════════════ 23-01-1988
Data of gang:

    Gang:                                    5      Drying wet grain
 1  Moisture content acc. to type:           5
 7  Overtime costs 7:00-12:00:                 30.00
 8  Overtime costs 12:00-17:00                 30.00
 9  Overtime costs 17:00-22:00                 30.00
10  Overtime costs 22:00-7:00:                 30.00
11  Workrate:                                   1.00
12  Mean workrate for h-function:               1.00
    Number of units:                         1
    Name of unit        1:                   Graindryer
    Processes material:                      wet grain

Give choice (0 = next record; 99 = menu): [0]  _
```

Figure 9.5. The content of the records material, unit (equipment or men) and gang.

COMBINAT.GEG). The latter must be present on disk when contract work is involved because the amount of equipment owned by the contract worker is not known.

The program has three alternatives to obtain a schedule:

1. By planning by the program;
2. By simulation — the program will ask for the name (default is SIMULAT.GEG) of a file which contains the assignment of combinations of gangs to all the periods;
3. By a combination of planning and simulation — the program will ask for the name (default is SIMULAT.GEG) of a file where the assignment of the combinations to *certain* periods is given. If the number of the combination equals 250, the program will recognize this as a demand to plan for the period concerned.

The last period of the schedule in the file must have the combination number zero. This causes the program to stop scheduling.

VI. After the user has chosen planning or simulation, the program will calculate the best sequence of gangs for the h-function (see Section 7.1). this is done internally. The program will ask for the weather forecast for a period of five days. The weather data can be derived from local weather forecast stations. The weather forecast has to be given interactively. It must contain the following data:

- the amount of rainfall ($mm \cdot d^{-1}$)
- the probability of rainfall (—)
- the reference evaporation ($mm \cdot d^{-1}$)

If the program also has cereal (wheat, barley and oats), or colza as a material record, the following information is also desired:

- the global radiation ($kJ \cdot (d \cdot cm^2)^{-1}$)

VII. The program will ask for the initial condition of soil and cereal („MENU 4" and „MENU 5"). The initial condition ranges from very dry to very wet (Table 9.1 and Section 7.3).

With this information, the program calculates the moisture content of grain using the formulae of Van Kampen (1969), and the soil moisture suction by using a simple model (Section 7.3). To do this the following files are required (see also Appendix D):

Table 7.9. The classes of conditions with the related soil moisture suction (cm) and the grain moisture content (%).

	soil moisture	grain moisture content	
class of condition	suction (cm)	species 1 *)	species 2 *) (%)
very dry	1000	10	6
dry	500	15	8
moist	100	21	12
wet	65	30	15
very wet	35	35	20

*) species 1 is wheat, barley and oats (%), and species 2 is colza (%).

SOIL.GEG:	contains the soil parameters for fourteen different soils (Rijtema, 1969, see Appendix F);
CR_TAB.GEG:	contains tables with data about the capillary rise for fourteen different soils (Rijtema, 1969, see Appendix F);
MOIST_D?.GEG:	contains the parameters for the formulae to calculate grain moisture and the parameters of the particular soil condition of the farm in question. The ?-sign can be 0 for soil, 1 for colza, 2 for barley, 3 for oats, and 4 for wheat (Appendix D).

Using the moisture content and the soil moisture suction, the program will search in files with climatological data to find a sequence of average moisture contents or suctions for the period *after* the period of five days weather forecast (for a full description of this procedure, see Section 7.3). The names of the climatological files are stored in the file:

MOIST_N?.GEG:	The ?-sign can be 0 for soil, 1 for colza, 2 for barley, 3 for oats, and 4 for wheat.

VIII. The actual schedule will be calculated now. The program calculates one or more schedules, and for each schedule, it will give the best possible combination for each period, from period to period. The results will be written immediately to the screen and to the output file. During this calculation, it is possible for the user to interrupt the program by pressing a key on the keyboard. The program will halt and „MENU 6" will appear on the screen. With this menu, the operator can continue or stop the calculation of the current schedule, the operator can toggle the screen output on and off and a chart of the progress of the amount of each material can be displayed (see also the description of the output-file in Appendix E).

IX. When the program is finished, it will calculate the amount of time and the costs attached to every gang, the timeliness costs of each material, and the chart of the progress of the amount of the material. All the results will be written to the output file (Appendix E).

X. The program ends by giving a closing picture (the same as the opening picture) and a friendly message.

9.4. THE PSEUDOCODE OF THE MAIN MODULE

The pseudocode of the main module of SCHEMA provides a summary. With this pseudocode, the flow of the program can be seen as discussed in Section 9.2. The tree-structure of the module is given in Appendix C. This section is primarily mentioned for software engineers (the beginning and end of a block are marked with the capitals B and E with a block number, when the action of a user is desired, There is a mark, U).

```
PROGRAM Schema

Declaration
```

Source of Procedures and Functions

```
B1  BEGIN

    Initialization

    Intro (begin):                     opening picture on screen

    OPEN files HE_MSG_?.BIN, QU_MSG_?.BIN and TEXT_H_?.GEG

    Building lay-out screen

    OPEN output file (default name is RESULTS.GEG)

U   Dat_input:                         input, creation, manipulation and output of
                                       all the records

    Calc_comb_gangs:                   Creation of combinations of gangs

U   Choice between simulation or planning

    IF „simulation is desired" THEN
B2  BEGIN
        OPEN file with simulation data (default name is SIMULAT.GEG)
        READ simulation data from file
        CLOSE file
E2  END IF „simulation is desired"

    Weather_clima:                     creation of sequence of gangs for the h-
                                       function

U   Weather_report:                    asks for the weather forecast for five days

U   Asks for the initial soil and grain condition. Choices are: very dry, dry, moist, wet and
    very wet. Determines the appropriate soil moisture suction and grain moisture content.

    Loop for different schedules (related to the weather-report).

    LOOP schedule-number is 1 TO 2
B3  BEGIN

        Head_of_output:                generates heading of output-file

        Calc_moist:                    calculates the sequence of moisture con-
                                       tents
```

```
      Calc_workab:     searches for the sequence of moisture contents in climatological files to find the continuation of moisture contents for the whole planning horizon (Section 7.3)

      Calculate the first timeliness cost if the optimal date of processing the material
      is before the current date

      Loop for number of periods

      LOOP period-counter is 1 TO total-number-of-periods
B4    BEGIN

          IF NOT „material is still available" THEN
B5        BEGIN
              STOP program
E5        END IF „material still available"

          Loop for all combinations of gangs

          LOOP combination-counter is 1 TO total-number-of-combinations
B6        BEGIN

              LOOP gang-counter is 1 TO number-of-gangs-per-combination
B7            BEGIN

                  IF „no material to process" OR „gang cannot work due to
                  workability constraints"  THEN
B8                BEGIN
                      EXIT LOOP combination-counter (B7—E7)
E8                END IF „no material to ...

                  Operation:   calculates value g-function

E7            END LOOP gang-counter

              Calculate timeliness costs

              H_function:      calculates value of h-function

              IF „a key on the key-board is pressed" THEN
B9            BEGIN
U                 User_action:  users interrupt
E9            END IF „a key is pressed"

E6        END LOOP combination-counter

          Calculate the combination „Do nothing"
```

```
                Calculate minimum. The choice of the best combination

                Calculate the value of the v-function

                Adjust amount of materials according to the best combination of gangs

                Show_on_dev:                show the results on the screen and write
                                            the results to the output file

                Adjust period counters

                IF „end of year reached" THEN
B10             BEGIN
                    STOP program
E10             END IF „end of year reached"


E4          END LOOP period-counter

            Calc_cost_all:                  calculate all kind of costs

E3      END LOOP schedule-number

        CLOSE all the files

        Intro (end):                        closing picture on screen

E1      END OF PROGRAM Schema
```

The details of the procedures and functions are fully described in Appendix C.

SUMMARY

This dissertation is concerned with operational planning models in farm management. Operational planning models are used to schedule, in time, different operations. Operations like harvesting, sowing, cultivating, and so on, are placed in a correct sequence in a planning horizon. The goal is minimization of costs like timeliness cost, overtime cost and additional costs (costs made by an agricultural contractor or drying of wet grain).

Chapter 1 gives an introduction to operational planning or scheduling models. A scheduling model gives, for each planning period, the amount of work that has to be performed. In a planning period, the sequence of operations has still to be determined.

Scheduling models are large in size (i.e. they often contain many decision variables). To keep the models manageable, they are often aggregated. Aggregation means in our case the division of the planning horizon in less planning periods (with the same length of planning horizon, the length of each planning period becomes larger). Therefore, less planning periods are now considered and the model will become more manageable. Another way is relaxing the model. In a relaxed model, the number of decision variables and the number of constraints are reduced.

Aggregated and relaxed models are commonly used, but their solutions are sometimes questionable, i.e. they are not always feasible in practice. Therefore, there are the following questions:

- As there are a lot of available scheduling models, which gives the most reliable results?
- Which level of aggregation will be most suitable and how relaxed can the models be and still get a solution which is feasible in practice?
- Is it possible to develop new models and algorithms performing better in practice?

Then Chapter 1 deals with four elements which are important to the scheduling models, i.e. firstly, labour, equipment, gangs and combinations of gangs, secondly, timeliness of materials and operations, thirdly, the weather, and fourthly, the workability of materials.

In *Chapter 2*, three commonly used scheduling models are introduced, they are based on dynamic programming, linear programming and simulation. These models will be used to answer the questions stated in Chapter 1. The models are deterministic, i.e. they use workability data from the past. This is because the commonly used models (e.g. used now by advisory services) are also based on workability data from the past.

The four elements stated in Chapter 1 are more explained and are more related to the models.

The three models are developed for use with „rounded" workability and „real" workability. With „rounded" workability, the number of workable hours, per planning period, are rounded creating uniform intervals where a material is workable during the whole planning period, or it is not workable at all. „Real" workability states that the real number of workable hours per planning period has to be considered. „Rounded" workability is introduced because our dynamic programming model has to make the decision for the whole planning period at once (e.g. a gang works the whole period or it does not work at all), and therefore, it needs to know if the whole planning period is workable or not.

The three models are developed for five levels of aggregation. For each level, the length of the planning period is different. These lengths are one hour, five hours, one day, one week and one month.

The models are calculated for the scheduling of the grain harvest on a farm with two men (the farmer with one labourer) and initial amounts of cereal from twenty and sixty hectares. The results are discussed in *Chapter 3*. The goal is the minimization of the total costs, which, in this dissertation, are the sum of timeliness cost of cereal, straw and bales,a overtime cost and cost made by the drying of wet grain.

Conclusions of this chapter are as follows. The dynamic programming model gives the most reliable results, however, the computing time is unacceptable long (about two to three hours CPU). The differences between the models at the 1-hour-level, 5-hour-level and day-level (level of aggregation) are small. Only the results of the models at week-level and at month-level are different from the results of a model at day-level. Therefore, the day-level can be used as an upper boundary for the level of aggregation (assuming that the model at the 1-hour-level gives the best results). The results of models using planning periods longer than a day are unreliable (compared with the model at 1-hour-level).

A relaxed version of the linear programming model is discussed in *Chapter 4*. The decision variables of the unrelaxed models represent combinations of gangs. The relaxed model uses individual units (e.g. a man, a combine harvester, a tractor) instead of combinations of gangs. This model is developed for a farm with two, three or four men (different from the models described in Chapters 2, 3 and 5 which are developed for a farm with two men) and it represents a group of models which are commonly used in practice.

The relaxed model gives, as solution, the number of hours for each individual unit per planning period. But, the model does not give the manner in which different combinations of these units are scheduled. Therefore, it is possible that contradiction and overestimation of the use of machinery and men arise.

In *Chapter 5*, a probabilistic version of the dynamic programming model is discussed. The probabilistic model is based on the probability of state transitions of workability. The probability of state transitions is based on workability data from the past. In practice, the expected value, or the 20-percentile point, of the probability distribution function is used to represent the workability.

The model gives, as a result, higher costs than the deterministic version, due to an imperfect knowledge of the workability data.

But, the effect of extraordinary periods (e.g. periods with an extremely high rate of rainfall and therefore with a minimum of workable hours) will be smoothed, due to the use of the probability of state transition. By using the probability of state transition, the average of workable hours over twelve years (1957—1968) is used. Years with a minimum of workable hours and the effect of these minimum workability on the solution of the model will not be discovered because it is not certain which year has minimum workable hours. And especially these years can have a large influence on the operational cost over the twelve years. Therefore, a probabilistic model as described in Chapter 5 can give a less reliable solution compared to the deterministic dynamic programming model.

The dynamic programming model is chosen as a base for further research. This model is now developed using a formulation commonly used in scheduling theory. This formulation is described in *Chapter 6*. A great disadvantage of the dynamic programming model is the long computing time. Therefore, three search techniques, i.e. hill-climbing, backtracking and best-first search, which may be used to obtain a solution faster, are discussed. The computing time is shorter, but the solution may not be optimal.

Hill-climbing is chosen as the search technique for the dynamic programming model because it gives the shortest computing time. This technique is supported with a heuristic evaluation function to reduce the difference between the solution obtained and the optimal solution. The heuristic developed is called FLOS (Farm Labour and Operations Scheduling) and is described in *Chapter 7*. A deterministic version (for comparison with the dynamic programming model) and a probabilistic version are developed (with „rounded" workability and five hours as length of the planning period).

The deterministic version uses workability data from the past. With the deterministic version, the first tests are performed and the results are compared with the dynamic programming, the linear programming and the simulation model (as described in Chapter 2). The probabilistic version makes use of the weather forecast (different from the probabilistic model as described in Chapter 5). The weather forecast is used as an input for a soil moisture suction model and grain moisture content formulae which are used to calculate workability. The use of weather forecast to calculate workability is a new approach in scheduling models in agriculture. For evaluation and validation of FLOS, it is tested with a large number of possible weather forecasts. The conclusions given in this chapter are:

- FLOS offers near-optimal results. The average difference in cost with the optimal solution (calculated with the dynamic programming model) is approximately three to four percent;
- FLOS is fast (the computing time is only a few seconds);
- It is small (only one state per stage has to be remembered), it fits on a micro-computer (the dynamic programming and the linear programming model described in Chapter 2 only fit on a large mainframe);
- FLOS can give a very detailed schedule. It is possible to use planning periods with a length of an hour, or even shorter with an acceptable computing time;
- Therefore, FLOS can be used locally by the farmer to improve effectivity of his farm management.

With FLOS, a test case in a real environment is investigated. This is described in *Chapter 8*. A harvest on an arable farm, owned by the Lake IJssel Polders Development Authority (RIJP), is scheduled. The harvest contains the harvest of cereal, potatoes, sugarbeet and beans. FLOS is used to calculate a schedule for each week in the months September, October and November of the year 1987. Five solutions are compared: two from FLOS, using the weather forecast (one solution based on the maximum amount of rain and one based on the minimum amount of rain); one from FLOS using actual weather data; the farmer's schedule (based on his experience) and the actual schedule. The main conclusions of this test case are:

- FLOS commonly offers a schedule with lower cost than the farmer's schedule and the actual schedule;
- The difference between the solution of the farmer's planning and that of FLOS, using actual weather data (and therefore calculated retrospectively), is small (in total cost three to four percent);

- The actual schedule (practice) is different from the planning (as given by FLOS or the farmer). There is an average difference of seven to eight percent. The effectivity of the farmer's decisions can be improved (with use of FLOS);
- It is possible to use FLOS frequently and to improve the farmer's reaction to changes in the environment;
- The weather forecast can be used to derive a reliable range with workability data for scheduling (at least for a short planning horizon).

Other results of this investigation are:

- The soil moisture suction model and grain moisture content formulae as used in FLOS can possibly be improved (the used models are simple);
- Timeliness functions of several materials like potatoes and sugarbeets are needed.

The last chapter of this thesis, i.e. *Chapter 9*, deals with the software package, SCHEMA (SCHEduling Multiple Activities), which is based on the heuristic FLOS. The package is developed for use on the micro-computer. It is completely menu-driven, has a full help-feature, catches every possible answer given by the user, has graphic capabilities, and gives a detailed output. Chapter 9 can be seen as a manual for a user of the package. Possible actions to be performed are alternated with the description of the internal behaviour of the package.

In Appendices A to G, the output of the linear programming model (App. A), the quantitative results of the models described in Chapter 2 (App. B), the modules of SCHEMA (App. C), the files of SCHEMA and the format of the input files of SCHEMA (App. D), the output of SCHEMA (App. E), the soil moisture suction model used to calculate the workability data used by FLOS (App. F.), and the manner of formulating the weather forecast (App. G) are described.

SAMENVATTING

Werkindelingsmodellen voor de landbouwbedrijfsvoering: een nieuwe aanpak

Dit proefschrift houdt zich bezig met modellen voor de operationele planning ter ondersteuning van de landbouwbedrijfsvoering. Modellen voor de operationele planning worden gebruikt om verschillende bewerkingen zoals oogsten, zaaien, cultiveren, enz. in een correcte volgorde en op het goede moment in de tijd te plaatsen. Het doel is de minimalisatie van kosten zoals tijdigheidskosten, kosten voor het maken van overuren en bijkomende kosten (bijvoorbeeld, kosten gemaakt door de loonwerker of kosten door drogen van nat graan).

Hoofdstuk 1 geeft een inleiding over modellen voor de operationele planning of werkindelingsmodellen. Een model voor bepaling van de werkindeling geeft, voor elke planningsperiode, de hoeveelheid werk welke verricht moet worden. In zo'n planningsperiode is de volgorde van bewerkingen nog nader te bepalen.

De omvang van werkindelingsmodellen is in het algemeen erg groot en onhandelbaar. Om nu deze modellen toch te kunnen gebruiken worden ze vaak geaggregeerd. Met aggregatie wordt in ons geval bedoeld het indelen van de planningshorizon in minder planningsperioden. Hierdoor worden de planningsperioden langer (de lengte van de planningshorizon blijft immers gelijk en er gaan minder planningsperioden in een horizon). Het model wordt daardoor kleiner. Een andere manier om modellen handelbaar te maken is relaxatie. Bij relaxatie krijgen de beslissingsvariabelen een meer eenvoudige structuur (bijvoorbeeld, combinaties van werkploegen worden gedeeld in afzonderlijke werkploegen). Het doel is het terugbrengen van het aantal beslissingsvariabelen en het aantal restricties.

Geaggregeerde en gerelaxeerde modellen worden in de praktijk vaak gebruikt terwijl de oplossingen niet altijd toepasbaar zijn in de praktijk. De volgende vragen worden daarom gesteld:

- Welk van de meest gebruikte werkindelingsmodellen geeft het meest betrouwbare resultaat?
- Hoever kan men gaan met aggregeren en relaxeren terwijl de oplossing van het geaggregeerde of gerelaxeerde model betrouwbaar blijft?
- Is het mogelijk om nieuwe modellen en algoritmes te ontwikkelen die beter voldoen in de praktijk?

Vervolgens worden er in hoofdstuk 1 vier elementen behandeld die belangrijk zijn in werkindelingsmodellen. Deze zijn ten eerste: arbeid, beschikbaar machinepark, werkploegen en combinaties van werkploegen; ten tweede: tijdigheid van gewassen (materialen); ten derde: het weer en ten vierde: de werkbaarheid van de materialen.

In *hoofdstuk* 2 zijn de drie meest gebruikte modellen beschreven. Deze worden gebruikt om de in hoofdstuk 1 gestelde vragen te beantwoorden. De modellen zijn gebaseerd op dynamische programmering, lineaire programmering en simulatie. Deze modellen zijn deterministisch (ze maken gebruik van werkbaarheidsgegevens uit het verleden) vanwege een goede vergelijking met de praktijk waar deze modellen thans veel gebruikt worden.

De vier elementen die genoemd zijn in hoofdstuk 1 worden verder toegelicht aan de hand van de drie werkindelingsmodellen.

De drie modellen zijn ontwikkeld voor gebruik met „afgeronde" en „reëele" werkbaarheid. Bij „afgeronde" werkbaarheid wordt het aantal werkbare uren per planningsperiode afgerond. Een materiaal is daarom werkbaar tijdens de gehele periode of het is in het geheel niet werkbaar. Bij „reëele" werkbaarheid wordt het werkelijk aantal werkbare uren per planningsperiode gebruikt. „Afgeronde" werkbaarheid is geintroduceerd voor ons dynamisch programmeringsmodel dat maar één beslissing levert voor de gehele planningsperiode (bijvoorbeeld een werkploeg werkt de gehele periode of het werkt in het geheel niet). Het model moet daarom weten of zo'n periode in het geheel werkbaar is of niet.

De drie modellen zijn ontwikkeld met vijf niveau's van aggregatie. Voor elk niveau is de lengte van de planningsperiode verschillend. Deze lengtes zijn één uur, vijf uur, een dag, een week en een maand.

De modellen zijn doorgerekend ter bepaling van de werkindeling van de graanoogst voor een bedrijf met twee man (de boer met zijn knecht) en een areaal grootte van twintig en zestig hectare. Het doel is de minimalisatie van de totale kosten. Deze zijn de som van de tijdigheidskosten van graan, stro en balen, de kosten voor overuren en de kosten die gemaakt worden bij het drogen van nat graan. De resultaten zijn besproken in *hoofdstuk 3* voor elk model en voor elke areaal grootte.

De conclusies zijn als volgt beschreven in dit hoofdstuk. Het dynamische programmeringsmodel geeft de meest betrouwbare resultaten (voor gebruik in de praktijk). Maar de rekentijd is onacceptabel lang (ongeveer twee tot drie uur). De verschillen in resultaat tussen de modellen op 1-uurniveau, 5-uurniveau en dagniveau (niveau van aggregatie) zijn gering. Alleen de resultaten van de modellen op weekniveau en maandniveau zijn zeer verschillend met die van een model op dagniveau. Het dagniveau kan daarom worden beschouwd als een bovengrens voor het niveau van aggregatie (ervan uitgaande dat een model op 1-uurniveau de beste resultaten levert). De resultaten van modellen die planningsperioden langer dan een dag gebruiken kunnen onbetrouwbaar zijn (vergeleken met het model op 1-uurniveau).

Een gerelaxeerde versie van het lineaire programmeringsmodel is beschreven in *hoofdstuk 4*. De beslissingsvariabelen van niet gerelaxeerde modellen geven de combinaties van werkploegen weer. Het gerelaxeerde model gebruikt individuele eenheden (bijvoorbeeld een man, een trekker, een maaidorser) in plaats van combinaties van werkploegen. Dit model is ontwikkeld voor een bedrijf met twee, drie of vier man (dit is verschillend van de modellen die ontwikkeld zijn voor een bedrijf met twee man en beschreven in de hoofdstukken 2, 3 en 5) en het weerspiegelt een groep van modellen die veel worden gebruikt in de praktijk.

Het gerelaxeerde lineaire programmeringsmodel geeft als oplossing het aantal uren per planningsperiode voor elke individuele eenheid. Maar het model geeft niet aan hoe verschillende combinaties van deze eenheden ingedeeld moeten worden. Daarom is het mogelijk dat er tegenstrijdigheden of een overschatting van gebruik van mens en machine in de oplossing zitten.

In *hoofdstuk 5* is een stochastische versie van het dynamische programmeringsmodel beschreven. Deze versie maakt gebruik van de kans om van de ene werkbaarheidstoestand over te gaan in een andere werkbaarheidstoestand. Deze kansen, en de daarop gebaseerde kansverdeling, zijn gebaseerd op werkbaarheidsgegevens uit het verleden. In de praktijk wordt de verwachtingswaarde of het 20-percentiel punt van deze verdeling gebruikt om de werkbaarheid weer te geven.

De stochastische versie geeft als resultaat hogere kosten dan de deterministische versie vanwege de onzekerheid met betrekking tot de werkbaarheidsgegevens.

De invloed van speciale perioden (bijvoorbeeld perioden met een grote hoeveelheid neerslag en daarom een minimum aan werkbare uren) wordt verminderd vanwege het gebruik van de kansverdeling. De kansverdeling is gebaseerd op twaalf jaar (1957—1968) werkbaarheidsgegevens. Jaren met een minimum aan werkbare uren en het effect op de oplossing van dat minimum worden niet ontdekt omdat niet bekend is welk jaar een minimum aan werkbare uren heeft. En juist die jaren kunnen een grote invloed hebben op de gemiddelde operationele kosten over de twaalf jaar. Het stochastische model zoals beschreven is in hoofdstuk 5 kan daarom minder betrouwbare resultaten opleveren dan de deterministische versie (in relatie tot het gebruik van de oplossing in de praktijk).

Het dynamische programmeringsmodel is gekozen als basis voor verder onderzoek. Het model is nu ontwikkeld aan de hand van de algemeen gebruikte indelingstheorie. Deze theorie is beschreven in *hoofdstuk 6*. Een groot nadeel van het dynamische programmeringsmodel is de lange rekenduur. Daarom worden drie zoektechnieken zijnde „hill-climbing", „backtracking" en „best-fist search" besproken. Deze technieken worden gebruikt om een oplossing sneller te vinden (de rekenduur wordt dan korter), maar er is een grotere kans dat deze oplossing niet optimaal is.

De techniek „hill-climbing" is gekozen om deel uit te maken van het dynamische programmerings algoritme omdat „hill-climbing" de kortste rekentijd heeft. Deze techniek wordt bijgestaan door een heuristische evaluatie functie om het verschil tussen de gevonden oplossing en een optimale oplossing zo klein mogelijk te houden. De heuristiek genaamd FLOS („Farm Labour and Operations Scheduling") die nu ontwikkeld is, is beschreven in *hoofdstuk 7*. Van deze heuristiek zijn een deterministische versie (voor vergelijk met het dynamische programmeringsmodel) en een stochastische versie ontwikkeld (met „afgeronde" werkbaarheid en vijf uur als lengte van een planningsperiode).

De deterministische versie maakt gebruik van werkbaarheidsgegevens uit het verleden. Met deze versie zijn de eerste tests verricht en de resultaten zijn vergeleken met het dynamische programmerings-, het lineaire programmerings- en het simulatiemodel (zoals beschreven in hoofdstuk 2). De stochastische versie maakt gebruik van een weersverwachting (dit model is verschillend van het stochastische model zoals beschreven is in hoofdstuk 5). Deze weersverwachting wordt gebruikt als invoer voor grondvocht- en gewasvochtmodellen die dienen om de werkbaarheid te bepalen. Het gebruik van het weerbericht ter bepaling van de werkbaarheid is een nieuwe aanpak voor werkindelingsmodellen in de landbouw. FLOS is getest met een groot aantal mogelijke weersverwachtingen ter evaluatie en validatie van de heuristiek. De conclusies beschreven in dit hoofdstuk zijn:

- FLOS geeft oplossingen die sub-optimaal zijn, het verschil in kosten met de optimale oplossing (volgens het dynamische programmeringsmodel) is gemiddeld ongeveer drie tot vier procent;
- FLOS is snel (de rekentijd bedraagt enkele seconden);
- Het is klein (per moment hoeft maar één toestand worden onthouden) en kan daarom worden doorgerekend met behulp van een „Personal Computer" (PC). Het dynamische

en het lineaire programmeringsmodel zoals beschreven in hoofdstuk 2 kunnen slechts worden doorgerekend met behulp van een „mainframe";

- FLOS kan een zeer gedetailleerde werkindeling geven. Het is nu mogelijk om planningsperioden van een uur (of zelfs korter) te gebruiken binnen acceptabele rekentijd;
- FLOS kan daarom worden gebruikt (locaal) door de boer om zijn bedrijfsvoering effectiever te maken.

Er is met FLOS tevens een praktijktest verricht. Deze is beschreven in *hoofdstuk 8*. De oogst op een akkerbouw bedrijf (onderdeel van de Rijksdienst voor de IJsselmeer Polders (RIJP)) is behandeld. Deze oogst bevat de oogst van graan, aardappelen, suikerbieten en bonen. FLOS is nu gebruikt om de werkindeling te berekenen voor elke week in de maanden september, oktober en november van het jaar 1987. Vijf oplossingen zijn met elkaar vergeleken: twee van FLOS, gebruik makende van een weersverwachting (een oplossing gebaseerd op de maximale hoeveelheid verwachte regen en een gebaseerd op de minimale hoeveelheid verwachte regen); een van FLOS gebruik makende van het werkelijke weer; de werkindeling van de boer (die slechts gebaseerd is op zijn ervaring) en de indeling zoals het in werkelijkheid heeft plaatsgevonden. De belangrijkste conclusies van deze test zijn als volgt:

- FLOS geeft in het algemeen een werkindeling waarvan de kosten lager zijn dan die van de werkindeling van de boer en de werkelijk gemaakte kosten;
- Het verschil tussen de planning van de boer en de werkindeling gegeven door FLOS (met gebruik van het werkelijke weer, dus retrospectief berekend) is gering (in totale kosten gemiddeld drie tot vier procent);
- De in werkelijkheid plaatsgevonden werkindeling is verschillend van wat de planning (gemaakt door FLOS of de boer) aangeeft. Er bestaat een verschil in kosten van gemiddeld zeven tot acht procent. De bedrijfsvoering van de boer kan dus nog effectiever worden gemaakt (door gebruik van FLOS);
- Het is mogelijk om FLOS zeer frequent te gebruiken en daarmee snel in te springen op korte termijn veranderingen in de omgeving, bijvoorbeeld het uitvallen van personeel, een plotselinge zware regenbui of een technische storing in een machine;
- De weersverwachting kan worden gebruikt om een betrouwbare reeks met werkbaarheidsgegevens te bepalen (tenminste voor een korte periode) die gebruikt kan worden ter bepaling van de werkindeling.

Verder komt uit dit onderzoek:

- Het grondvocht- en gewasvochtmodel verdienen verbetering, de gebruikte modellen zijn nog erg simpel en niet betrouwbaar genoeg op de lange termijn;
- Onderzoek naar de tijdigheidsfuncties van bijvoorbeeld suikerbieten en aardappelen is nodig.

Het laatste hoofdstuk van dit proefschrift, *hoofdstuk 9*, behandelt het programma SCHEMA („SCHEduling Multiple Activities"). Dit is ontwikkeld op basis van de heuristiek FLOS. Het programma is ontwikkeld voor gebruik op een PC. Het is volledig menu-gestuurd, heeft een uitgebreide help-faciliteit, heeft grafische mogelijkheden en geeft desgewenst een zeer gedetailleerde uitvoer. Hoofdstuk 9 kan worden beschouwd als een handleiding voor gebruik van het programma. Aanwijzingen over te nemen acties zijn afgewisseld met een beschrijving van het programma zelf.

Achtereenvolgens zijn beschreven in bijlagen A tot en met G: de uitvoer van het lineaire programmeringsmodel (bijl. A); de kwantitatieve resultaten van de modellen die beschreven zijn in hoofdstuk 2 (bijl. B); de modules van SCHEMA (bijl. C); de bestanden van SCHEMA en de wijze van opbouw van de invoerbestanden voor SCHEMA (bijl. D); de uitvoer van SCHEMA (bijl. E); het grondvochtmodel dat gebruikt wordt om de werkbaarheid te bepalen (bijl. F) en de wijze waarop een weersverwachting tot stand komt (bijl. G).

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LIST OF SYMBOLS

The list of symbols contain the symbols used in all chapters and appendices, except for Appendix F. The list contains the symbols with a description, and the section where the symbol is used first.

A_j	the initial amount of material j (ha),	(2.6)
B	the beginning of a block in a module (in SCHEMA),	(9.3)
BA_t	the amount of bales at end of period t (ha),	(2.5)
C-i	identification of a linear programming model using combinations and developed for a farm with i men (i = 2, 3, 4),	(4.1)
CE_t	the amount of cereal at end of period t (ha),	(2.5)
CD_{24}	identification of 24 sequences (for each year one) of T days moisture data calculated using climatological data,	(7.3.1)
CP_t	matrix with the processing capacities for combination k (or unit k, Chapter 4) and material j in period t (ha · period^{-1}),	(2.5)
CL_t	matrix with delivery capacities for combination k (or unit k, Chapter 4) and material j in period t (ha · period^{-1}),	(2.5)
c	the costs in a scheduling problem (optimality criterion),	(6.2)
DC	the fixed drying cost (f · period^{-1}),	(2.5)
$D_t(\mathbf{x}_{t-1})$	the set of all possible decisionvectors $\mathbf{d}_t$ given $\mathbf{x}_{t-1}$,	(2.5)
$\mathbf{d}_t$	the vector of decision variables or the decisionvector for period t,	(2.5)
$\mathbf{d}_t^*$	the best decisionvector for period t,	(7.1)
d_t^k	the decision variable representing the decision to operate with combination k (or unit k in Chapter 4) in period t,	(2.5)
dr_t^k	the actual drying cost for combination k in period t (f·period^{-1}),	(2.5)
E	the end of a block in a module (in SCHEMA),	(9.3)
ec_t^k	the actual additional cost incurred by combination k (or unit k in Chapter 4) in period t (f · period^{-1}),	(7.1)
e	the sequence number of the operation,	(6.2)
FLOS A	identification of the heuristic where the h-function uses additional jobs, but not overtime,	(7.2.1)
FLOS B	identification of the heuristic where the h-function does not use additional jobs and overtime,	(7.2.1)
FLOS C	identification of the heuristic where the h-function uses additional jobs and overtime,	(7.2.1)

FLOS D	identification of the heuristic where the h-function uses overtime, but not additional jobs,	(7.2.1)
FM	the sequence of moisture data in CD_{24} with as first point the point in CD_{24} where WD_5 was found,	(7.3.1)
f_t	the heuristic evaluation function,	(7.1)
G	identification of a general job-shop problem where the processing order may be different for each job,	(6.2)
G_t	the cost function expressing the costs incurred in period t ($f \cdot \text{period}^{-1}$),	(2.5)
g_t	function which provides information of the decision in period t, it calculates the cost incurred by decision d_t^k,	(7.1)
h_t	function which provides estimated information (i.e. the expected cost) gathered by the search from the state x_t, it gives information about the future,	(7.1)
I	identification of an integer variable.	(D.2)
i	the job number,	(6.2)
J	total number of materials,	(7.1)
j	the number of the material,	(2.5)
K	total number of combinations (or units in Chapter 4),	(7.1)
k	number of the combination (or unit in Chapter 4),	(2.5)
M	the number of constraints per period in the linear programming matrix,	(2.0)
MC_{old}	the moisture content at the beginning of the day (% wet basis),	(7.3.1)
MC_{new}	the moisture content at the end of the day, this value is assumed to be the moisture content for the whole day (% wet basis),	(7.3.1)
m	the number of machines or groups of machinery and men (e.g. a worker, a tractor) in a scheduling problem,	(6.2)
m.c.	the moisture content on wet basis (ASAE, 1986) (%),	(2.4)
n	number of jobs (e.g. harvesting, sowing) in a scheduling problem,	(6.2)
OC_t	the matrix with fixed overtime cost for period t ($f \cdot \text{period}^{-1}$),	(2.5)
$ORDV_{i,j,u}$	the order value of a gang (identified by job i and machine-set u) which processes material j, this is for use by the h-function,	(7.1.1)
ov_t^k	the actual overtime costs incurred by combination k (or unit k in Chapter 4) in period t ($f \cdot \text{period}^{-1}$),	(2.5)
P(i)	the total number of operations for job i,	(6.2)
PL_t	the length of the period t (h),	(2.6)
PLM_t	the length of the period t multiplied with the number of men (h),	(4.1)

$PWH_{i,j,u}$	the percentage workable hours in the planning horizon (%) of a gang (identified by job i and machine-set u) which processes material j, this is for use by the h-function (%),	(7.1.1)
p	the rainfall $(\mathrm{mm \cdot d^{-1}})$,	(7.3.1)
$Q_{i,u}$	total number of sub-jobs of job i,	(6.2)
Q_t	workability condition in period t,	(5.1)
R	identification of a real variable.	(D.2)
REAL60	identification of the models using real workability and with an initial amount of sixty hectares,	(3.3)
ROUN20	identification of the models using rounded workability and with an initial amount of twenty hectares,	(3.1)
ROUN60	identification of the models using rounded workability and with an initial amount of sixty hectares,	(3.2)
rad	the radiation $(\mathrm{cal \cdot (d \cdot cm^2)^{-1}}$, $1\ \mathrm{cal \cdot (d \cdot cm^2)^{-1}} = 42\ \mathrm{kJ \cdot (d \cdot m^2)^{-1}})$,	(7.3.1)
S	identification of a string variable.	(D.2)
SF_t	the amount of stubble at end of period t (ha),	(2.5)
ST_t	the amount of straw at end of period t (ha),	(2.5)
s	representing a node in a network,	(6.3)
T	the total number of periods in the planning horizon,	(2.0)
T_t	the transformation function from stage t–1 to stage t, expressing the decrease or increase in amounts (ha) of the materials,	(2.5)
$\mathbf{tc}_t$	vector with the fixed timeliness cost for period t for all the materials $(f \cdot (\mathrm{period} \cdot \mathrm{ha})^{-1})$,	(2.5)
TM_t	the total timeliness costs for period t for all the materials $(f \cdot \mathrm{period}^{-1})$,	(2.5)
t	number of the stage and the number of the period in front of this stage,	(2.5)
U	a part of a module (in SCHEMA) where the action of the user of the program is desired,	(9.3)
U-i	identification of a linear programming model using individual units and developed for a farm with i men (i = 2, 3, 4),	(4.1)
u	the number of the machine or group of machinery and men required to perform the operation,	(6.2)
V_t	the value function, it gives the value for a certain state at a certain stage t after calculating the whole dependent network in front of this state (f),	(2.5)
v_t	function which provides information (i.e. the calculated cost) gathered by the search up to state x_{t-1} (at the beginning of period t),	(7.1)

W_{rate}	the working rate for clustered gangs (processing more than one material simultaneously, $ha \cdot h^{-1}$),	(7.1.1)
WD_5	identification of a sequence of five days moisture data calculated using the weather forecast,	(7.3.1)
WE_t	the amount of wet grain at end of period t (ha),	(2.5)
$WK_t^j(k)$	the number of workable hours for material j processed by combination k (or unit k in Chapter 4) in period t,	(2.6)
$w_\mu(i)$	sub-job μ of job i (for w_μ, the processing time is equal to the length of the period),	(6.2)
x_t	the statevector representing the amount of materials at the end of period t (ha),	(2.5)
x_t^j	the state variable representing the amount of material j at the end of period t (ha),	(2.5)
$\cdot$	multiplication sign (American system),	(2.5)
α	represents the number of jobs in a scheduling problem,	(6.1)
$\alpha/\beta/\gamma/\delta$	identification of a scheduling problem,	(6.1)
β	represents the number of machines in a scheduling problem,	(6.1)
γ	indicates the type of machine ordering per job,	(6.1)
δ	indicates the optimality criterion of a scheduling problem, e.g. the minimization of cost or the minimization of flow time,	(6.1)
μ	number of a sub-job,	(6.2)
Π_t	the probability transition matrix representing the probability of transition from state Q_{t-1} in period t−1 to state Q_t in period t,	(5.1)
$\theta(i)$	number of the first non-scheduled sub-job of the job i,	(6.2)

Appendix A

THE OUTPUT OF THE LINEAR PROGRAMMING MODEL

This appendix contains a part of the output of the reportwriter of SCICONIC. This reportwriter formats the output of the linear programming model described in Chapter 2. This linear programming model uses real workability (Chapter 2). The output contains the following information (see Table A.1):

- the value of the objective function (*f*);
- the amount of each material at the end of each period (until the amount is zero, ha), with the total timeliness cost (*f*);
- the amount of time used by each gang in each period (to process the materials) with the amount of overtime used (h);
- the drying cost (*f*);
- the total costs which are the sum of the timeliness cost, overtime cost, and drying cost (*f*).

The difference between the value of the objective function and the total costs is due to the timeliness cost of stubble and wet grain which are not taken into account.

Table A.1. A part of the output of the reportwriter of SCICONIC.

```
**************************************************
******     L I N E A R  P R O G R A M M I N G     ******
******             O U T P U T                    ******
******                                            ******
******     S C H E D U L I N G      F A R M       ******
******         O P E R A T I O N S                ******
**************************************************

Scheduling daymodel 1957

Objective function value:             1625.29578
```

MATERIALS

Amount of cereal

Starting amount:		60.00000	ha
End of period	1	50.00000	ha
End of period	2	42.00000	ha
End of period	3	35.00000	ha
End of period	4	25.00000	ha
End of period	5	18.00000	ha
End of period	6	18.00000	ha
End of period	7	10.00000	ha
End of period	8	8.00000	ha
End of period	9	0.00000	ha

Timeliness cost cereal: 739.89587

Amount of straw

End of period	2	6.00000	ha
End of period	4	10.00000	ha
End of period	8	2.00000	ha
End of period	9	2.00000	ha
End of period	10	2.00000	ha
End of period	11	2.00000	ha
End of period	12	2.00000	ha

Timeliness cost straw: 32.80000

.... (other materials)

....

OPERATIONS

Harvesting cereal, two men

End of period	1	5.00000	h
End of period	2	4.00000	h
End of period	3	3.50000	h
End of period	4	5.00000	h
End of period	5	0.50000	h
End of period	7	2.00000	h
End of period	8	1.00000	h
End of period	9	2.00000	h

```
Cost of extra hours:                    210.00000

          ......... (other operations)
          .........
DRYING

Drying wet grain

Drying costs:                             0.00000

TOTAL COSTS                            1362.69592
```

Appendix B

THE QUANTITATIVE RESULTS OF THE MODELS

This appendix contains the quantitative results of the models described in Chapter 2 (LP is linear programming and DP is dynamic programming). The description in Chapter 3 refers to the tables given in this appendix. The explanation of the table heads are:

overt = the overtime cost;
dry = the drying cost;
cereal = the timeliness cost of cereal;
straw = the timeliness cost of straw;
bales = the timeliness cost of bales;
total = the total costs which are the sum of the overtime cost, the drying cost and the timeliness costs of cereal, straw and bales.

The dimension of all costs is *f*. Mean is the average over twelve years, and Std is the sample standard deviation.

Table B.1. Simulation, ROUN20, 5-hour-level.

year	overt	dry	cereal	straw	bales	total
1957	100	0	74	30	102	306
1958	256	525	126	101	129	1137
1959	200	600	310	117	133	1360
1960	125	600	139	46	90	1000
1961	100	300	160	21	218	799
1962	100	600	110	21	218	1049
1963	300	0	91	73	157	621
1964	250	600	150	63	48	1111
1965	300	600	90	21	48	1059
1966	238	600	589	137	123	1687
1967	75	300	69	31	102	577
1968	75	300	74	46	36	531
Mean	177	419	165	59	117	936
Std	89	234	149	40	60	388

Table B.2. LP, ROUN20, 5-hour-level.

year	overt	dry	cereal	straw	bales	total
1957	0	0	138	14	0	152
1958	0	50	377	0	0	427
1959	50	150	692	7	0	899
1960	50	100	366	16	0	532
1961	100	0	85	176	0	361
1962	100	300	135	41	0	576
1963	100	0	188	0	36	324
1964	0	0	475	0	0	475
1965	50	0	265	129	0	444
1966	100	150	1075	14	0	1339
1967	0	0	140	54	0	194
1968	200	100	105	7	0	412
Mean	63	71	337	38	3	511
Std	61	94	295	57	10	323

Table B.3. DP, ROUN20, 5-hour-level.

year	overt	dry	cereal	straw	bales	total
1957	0	0	60	108	0	168
1958	0	0	400	54	0	454
1959	263	300	456	28	54	1101
1960	300	0	381	68	0	749
1961	100	0	81	176	0	357
1962	150	300	111	62	54	677
1963	200	0	121	26	0	347
1964	0	0	421	81	0	502
1965	100	0	181	176	0	457
1966	350	600	526	61	428	1965
1967	0	0	121	81	0	202
1968	100	0	81	68	0	249
Mean	130	100	245	82	45	602
Std	125	195	175	49	123	503

Table B.4. Simulation, ROUN20, day-level.

year	overt	dry	cereal	straw	bales	total
1957	50	0	50	83	256	439
1958	475	600	150	83	256	1564
1959	150	600	416	82	275	1523
1960	150	600	116	82	276	1224
1961	100	0	50	106	256	512
1962	50	600	50	83	342	1125
1963	200	0	50	83	256	589
1964	375	600	150	83	256	1464
1965	375	600	50	83	256	1364
1966	375	600	550	213	256	1994
1967	50	0	50	83	256	439
1968	100	0	50	83	256	489
Mean	204	350	144	96	266	1061
Std	154	309	166	38	25	543

Table B.5. LP, ROUN20, day-level.

year	overt	dry	cereal	straw	bales	total
1957	0	0	126	0	0	126
1958	0	0	426	0	0	426
1959	0	300	576	0	0	876
1960	0	0	426	0	0	426
1961	100	0	88	121	0	309
1962	100	300	88	13	0	501
1963	0	0	126	0	0	126
1964	0	0	451	0	0	451
1965	100	0	188	67	0	355
1966	200	150	1116	13	0	1479
1967	0	0	126	0	0	126
1968	50	0	126	0	0	176
Mean	46	63	322	18	0	448
Std	66	119	304	38	0	389

Table B.6. DP, ROUN20, day-level.

year	overt	dry	cereal	straw	bales	total
1957	0	0	71	108	0	179
1958	0	0	371	108	0	479
1959	250	300	500	26	0	1076
1960	0	0	371	108	0	479
1961	0	0	71	216	0	287
1962	100	300	85	67	0	552
1963	0	0	71	108	0	179
1964	0	0	371	108	0	479
1965	0	0	171	216	0	387
1966	100	0	1550	13	0	1663
1967	0	0	71	108	0	179
1968	0	0	71	108	0	179
Mean	38	50	315	108	0	510
Std	77	117	420	61	0	443

Table B.7. Simulation, ROUN20, week-level.

year	overt	dry	cereal	straw	bales	total
1957	0	0	21	63	86	170
1958	300	600	2392	358	86	3736
1959	300	0	1244	358	86	1988
1960	350	600	229	197	1383	2759
1961	300	600	396	358	86	1740
1962	300	600	396	358	86	1740
1963	200	0	229	7600	0	8029
1964	300	600	396	1111	86	2493
1965	350	0	229	197	1383	2159
1966	300	600	1244	358	86	2588
1967	0	0	6500	0	0	6500
1968	300	0	1244	358	86	1988
Mean	250	300	1210	943	288	2991
Std	122	313	1801	2114	513	2185

Table B.8. LP, ROUN20, week-level.

year	overt	dry	cereal	straw	bales	total
1957	0	0	334	0	0	334
1958	775	600	700	235	0	2310
1959	300	0	1700	110	0	2110
1960	600	600	600	0	0	1800
1961	0	0	1176	0	0	1176
1962	450	600	700	83	0	1833
1963	600	0	600	0	0	1200
1964	450	600	700	434	0	2184
1965	400	0	600	0	0	1000
1966	300	600	1706	110	0	2716
1967	0	0	6500	0	0	6500
1968	450	0	1700	434	0	2584
Mean	360	250	1418	117	0	2146
Std	254	309	1675	165	0	1542

Table B.9. DP, ROUN20, week-level.

year	overt	dry	cereal	straw	bales	total
1957	200	0	333	360	0	893
1958	500	600	700	470	0	2270
1959	300	0	1700	110	0	2110
1960	500	600	600	288	0	1988
1961	300	600	700	110	0	1710
1962	300	600	700	110	0	1710
1963	450	0	600	0	1142	2192
1964	300	600	700	868	0	2468
1965	200	0	600	398	0	1198
1966	300	600	1700	110	0	2710
1967	0	0	6500	0	0	6500
1968	300	0	1700	868	0	2868
Mean	304	300	1378	308	95	2385
Std	139	313	1687	303	330	1418

Table B.10. Sim., ROUN60 & REAL60, 1-hour-level.

year	overt	dry	cereal	straw	bales	total
1957	996	375	591	291	265	2518
1958	765	840	1040	340	381	3366
1959	720	1350	1489	303	408	4270
1960	935	1552	821	304	694	4306
1961	805	1260	974	323	331	3693
1962	748	1590	1040	257	356	3991
1963	775	450	760	525	599	3109
1964	625	1260	899	300	328	3412
1965	862	1440	689	455	476	3922
1966	905	1335	2708	698	557	6203
1967	670	870	693	349	500	3082
1968	868	1020	1045	419	424	3776
Mean	806	1112	1062	380	443	3804
Std	110	405	570	127	126	919

Table B.11. LP, ROUN60 & REAL60, 1-hour-level.

year	overt	dry	cereal	straw	bales	total
1957	690	0	807	99	0	1596
1958	659	60	1393	288	0	2400
1959	711	90	2175	329	0	3305
1960	1069	184	1418	134	0	2805
1961	593	60	1700	265	0	2618
1962	527	564	2411	204	0	3706
1963	659	0	828	295	0	1782
1964	552	168	1479	144	0	2343
1965	520	0	1326	322	0	2168
1966	663	480	3613	465	0	5221
1967	523	36	925	414	0	1898
1968	418	72	690	907	0	2087
Mean	632	143	1564	322	0	2661
Std	163	188	837	215	0	1014

Table B.12. Simulation, ROUN60, 5-hour-level.

year	overt	dry	cereal	straw	bales	total
1957	1031	0	557	278	479	2345
1958	750	1200	946	413	636	3945
1959	750	1500	1352	293	299	4194
1960	987	1500	797	394	784	4462
1961	844	1163	999	216	642	3864
1962	738	1500	876	196	609	3919
1963	875	0	757	617	663	2912
1964	600	1500	851	287	468	3706
1965	800	1350	640	367	763	3920
1966	950	1350	2639	869	589	6397
1967	725	1050	510	487	456	3228
1968	900	1050	1209	348	382	3889
Mean	829	1097	1011	397	564	3898
Std	125	540	569	189	149	978

Table B.13. LP, ROUN60, 5-hour-level.

year	overt	dry	cereal	straw	bales	total
1957	600	0	757	61	0	1418
1958	625	375	1227	318	54	2599
1959	725	600	1934	18	0	3277
1960	1108	650	1243	62	18	3081
1961	500	225	1581	162	54	2522
1962	625	1050	1700	122	125	3622
1963	919	0	962	473	81	2435
1964	550	350	1372	136	54	2462
1965	550	100	1344	325	54	2373
1966	775	750	3534	274	0	5333
1967	792	100	973	457	18	2340
1968	500	100	818	1288	0	2706
Mean	689	358	1454	308	38	2847
Std	184	337	745	344	39	956

Table B.14. Simulation, ROUN60, day-level.

year	overt	dry	cereal	straw	bales	total
1957	1025	0	515	286	803	2629
1958	1000	1200	956	366	720	4242
1959	650	1350	1548	257	949	4754
1960	925	1350	656	263	920	4114
1961	875	900	666	436	917	3794
1962	488	1650	748	344	821	4051
1963	775	0	431	687	697	2590
1964	650	1050	900	287	659	3546
1965	850	1500	616	340	871	4177
1966	975	1500	2656	964	664	6759
1967	738	450	521	412	632	2753
1968	675	600	916	437	503	3131
Mean	802	963	927	423	763	3878
Std	167	577	620	207	139	1150

Table B.15. LP, ROUN60, day-level.

year	overt	dry	cereal	straw	bales	total
1957	600	0	820	93	0	1513
1958	775	450	1685	243	53	3206
1959	550	450	2142	87	0	3229
1960	700	600	1105	228	0	2633
1961	400	0	1311	296	0	2007
1962	650	1275	1184	66	0	3175
1963	763	0	857	491	53	2164
1964	550	200	1459	160	0	2369
1965	350	0	1267	525	0	2142
1966	800	750	3520	242	0	5312
1967	825	0	1008	385	53	2271
1968	550	0	402	1376	0	2328
Mean	626	310	1397	349	13	2696
Std	154	409	802	356	24	977

Table B.16. Simulation, ROUN60, week-level.

year	overt	dry	cereal	straw	bales	total
1957	650	0	187	381	1184	2402
1958	1275	1800	4228	1424	1486	10213
1959	550	0	4580	995	1726	7851
1960	1275	1800	812	1507	4272	9666
1961	775	900	1755	995	1726	6151
1962	1350	1800	2498	1088	414	7150
1963	600	0	812	22800	0	24212
1964	900	900	4228	2218	414	8660
1965	825	0	812	901	3090	5628
1966	1200	900	5008	772	2334	10214
1967	0	0	19500	0	0	19500
1968	700	0	6483	634	585	8402
Mean	842	675	4242	2810	1436	10004
Std	391	779	5218	6321	1306	6039

Table B.17. LP, ROUN60, week-level.

year	overt	dry	cereal	straw	bales	total
1957	300	0	1135	0	0	1435
1958	1425	1800	5550	870	0	9645
1959	450	0	6030	165	0	6645
1960	1700	1800	2474	360	430	6764
1961	1000	450	3171	0	0	4621
1962	1050	1800	3600	330	0	6780
1963	1025	0	5901	0	1713	8639
1964	1000	900	5550	1467	0	8917
1965	800	0	2520	0	0	3320
1966	1400	900	6752	183	0	9235
1967	0	0	19500	0	0	19500
1968	1000	0	8358	1137	0	10495
Mean	929	638	5878	376	179	8000
Std	487	778	4773	505	499	4525

Table B.18. Simulation, REAL60, 5-hour-level.

year	overt	dry	cereal	straw	bales	total
1957	1020	330	554	337	756	2997
1958	940	960	1036	338	593	3867
1959	725	1440	1448	324	823	4760
1960	955	1470	766	347	883	4421
1961	785	1290	910	356	726	4067
1962	635	1530	1070	379	437	4051
1963	780	330	698	501	929	3238
1964	630	1260	822	296	707	3715
1965	800	1290	643	386	893	4012
1966	910	1320	2567	795	560	6152
1967	697	825	643	420	656	3241
1968	885	990	1058	401	506	3840
Mean	814	1086	1018	407	706	4030
Std	129	413	548	133	160	835

Table B.19. LP, REAL60, 5-hour-level.

year	overt	dry	cereal	straw	bales	total
1957	610	0	641	13	0	1264
1958	715	319	1016	146	4	2200
1959	590	315	1903	29	24	2861
1960	930	345	1258	98	0	2631
1961	450	524	1389	154	0	2517
1962	600	1320	764	14	0	2698
1963	650	0	716	258	78	1702
1964	500	420	1216	47	0	2183
1965	450	220	1148	132	16	1966
1966	700	630	3243	142	31	4746
1967	380	96	781	417	33	1707
1968	480	100	835	579	39	2033
Mean	588	357	1243	169	19	2376
Std	151	362	724	173	24	881

Table B.20. Simulation, REAL60, day-level.

year	overt	dry	cereal	straw	bales	total
1957	1008	225	517	361	788	2899
1958	935	930	930	359	669	3823
1959	750	1410	1424	362	731	4677
1960	885	1380	712	327	1240	4544
1961	861	1170	953	384	657	4025
1962	730	1410	713	440	640	3933
1963	830	240	578	588	1231	3467
1964	620	1275	745	358	830	3828
1965	840	1440	654	365	761	4060
1966	870	1680	2561	712	813	6636
1967	725	810	612	407	734	3288
1968	865	840	961	425	576	3667
Mean	827	1068	947	424	806	4071
Std	105	470	564	113	214	945

Table B.21. LP, REAL60, day-level.

year	overt	dry	cereal	straw	bales	total
1957	590	0	740	33	0	1363
1958	735	150	971	145	40	2041
1959	590	405	1913	49	0	2957
1960	705	555	1118	58	0	2436
1961	400	240	1490	126	0	2256
1962	668	1320	729	69	0	2786
1963	655	0	882	140	19	1696
1964	433	200	1368	80	0	2081
1965	354	80	1180	281	0	1895
1966	710	1056	2821	192	0	4779
1967	366	0	1020	170	32	1588
1968	526	180	674	527	0	1907
Mean	561	349	1242	156	8	2315
Std	141	429	613	137	14	905

Table B.22. Simulation, REAL60, week-level.

year	overt	dry	cereal	straw	bales	total
1957	595	60	187	434	1870	3146
1958	565	540	313	756	2967	5141
1959	605	1140	276	609	2676	5306
1960	710	1080	187	672	2248	4897
1961	635	990	294	605	2888	5412
1962	620	1560	379	650	2963	6172
1963	455	540	187	699	2945	4826
1964	585	0	187	399	1107	2278
1965	475	1020	187	711	2635	5028
1966	825	1200	1304	1402	1723	6454
1967	575	540	187	853	2930	5085
1968	510	300	348	819	323	2300
Mean	596	748	336	717	2273	4670
Std	100	488	313	254	860	1370

Table B.23. LP, REAL60, week-level.

year	overt	dry	cereal	straw	bales	total
1957	510	0	406	0	0	916
1958	610	0	537	0	0	1147
1959	1019	21	798	0	0	1838
1960	630	180	872	0	0	1682
1961	300	420	891	0	0	1611
1962	180	744	1233	0	0	2157
1963	682	210	569	188	0	1649
1964	525	0	406	0	0	931
1965	700	0	631	0	0	1331
1966	670	1200	1580	0	0	3450
1967	740	0	481	0	0	1221
1968	616	120	761	0	0	1497
Mean	599	241	764	16	0	1619
Std	213	377	351	54	0	684

Table B.24. Simulation, REAL60, month-level.

year	overt	dry	cereal	straw	bales	total
1957	380	0	187	355	618	1540
1958	0	0	187	381	622	1190
1959	0	0	187	381	622	1190
1960	615	0	187	381	622	1805
1961	0	0	187	381	622	1190
1962	0	0	187	365	619	1171
1963	340	0	187	546	468	1541
1964	0	0	187	381	622	1190
1965	0	0	187	381	622	1190
1966	540	0	187	329	613	1669
1967	0	0	187	381	493	1061
1968	320	0	187	381	622	1510
Mean	183	0	187	387	597	1354
Std	239	0	0	53	55	243

Table B.25. LP, REAL60, month-level.

year	overt	dry	cereal	straw	bales	total
1957	0	0	1845	0	0	1845
1958	0	0	4716	0	0	4716
1959	0	0	4717	0	0	4717
1960	160	0	4717	0	0	4877
1961	0	0	4717	0	0	4717
1962	0	0	4717	0	0	4717
1963	570	0	1869	0	0	2439
1964	0	0	1845	0	0	1845
1965	0	0	1845	0	0	1845
1966	60	0	4717	0	0	4777
1967	0	0	1845	0	0	1845
1968	0	0	4717	0	0	4717
Mean	66	0	3522	0	0	3588
Std	166	0	1476	0	0	1443

Appendix C

THE MODULES OF SCHEMA

C.1. SCHEMA WITH ITS MAIN MODULES

In this section, the means of operating (by keying) the main modules of SCHEMA will be shown (Figure C.1). The description of the modules is given in Section C.2. All the modules which are called by more than one other module are left out to make the scheme clear. The description of the modules and the correct calling scheme of these modules are given in Section C.2.

C.2. THE DESCRIPTION OF THE MODULES

The function of each module of SCHEMA is described in this section (see also Chapter 9). Descriptions are in alphabetical order. For each module, the status (function or procedure, and used as overlay or not), by which module(s) it is called, in which file it is stored, and a short description of the purpose of the module is given (the knowledge of the PASCAL-language is assumed).

Afgen (function,non-overlay).
Called by: Calc_moist.
Stored in file: CAL_MOIS.PAS
Purpose:

This function extracts the nearest x- and y-values using a table-value (input of the function) from several tables used by the procedure Calc_moist. For example, if the table-value is 5 and the table is as follows:

		x-values		
		3	6	9
y-values	5	1	2	8
	10	3	6	11

table-values

then the function will return the x-value 6 and the y-value 10 (nearest table-value is 6).

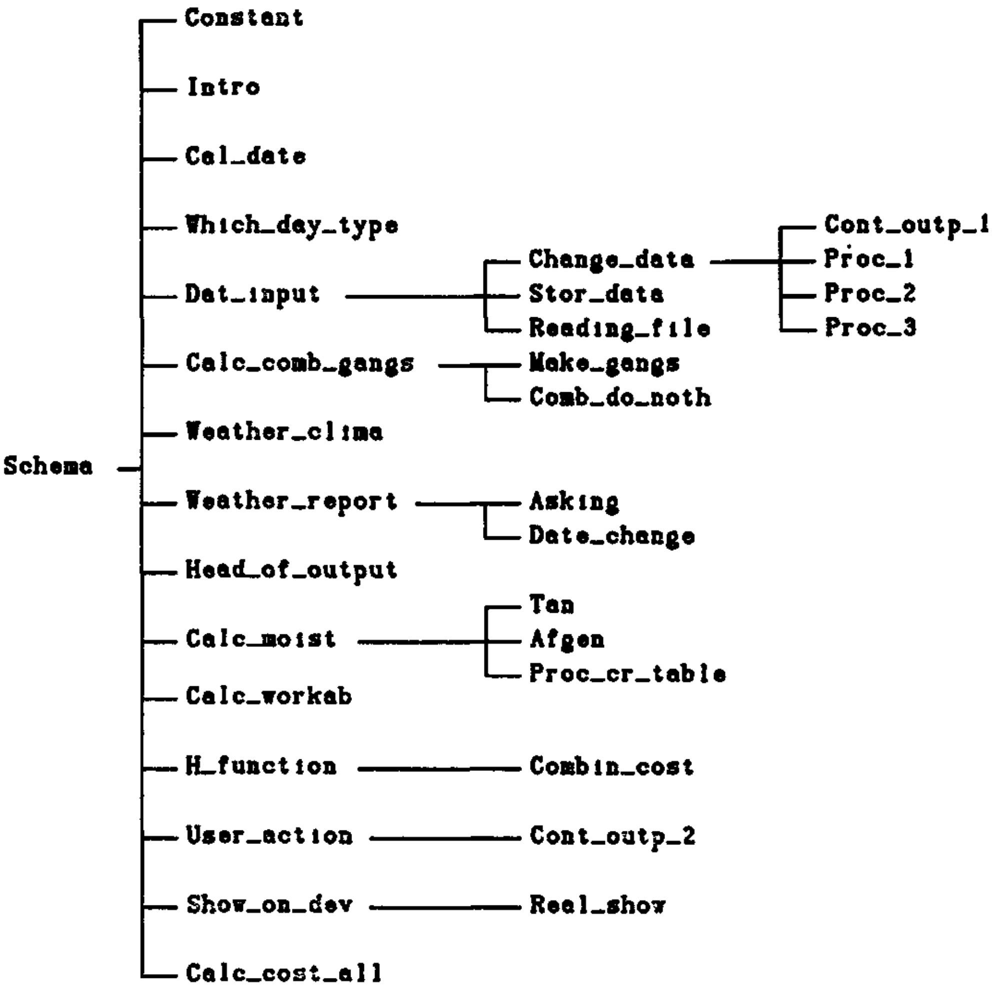


Figure C.1. The calling scheme of the main modules of SCHEMA.

Asking (procedure,non-overlay).
Called by: Weather_report.
Stored in file: WEA_REP.PAS
Purpose:

Contains the questions for requesting the weather report data and collects the answers. It immediately checks for errors made by the user of the program.

Beep (procedure,non-overlay).
Called by: Help_quest, Schema.
Stored in file: SCHEMA.PAS
Purpose:

This procedure gives a two-tone beep (frequency 700 and 400 Hz) when errors or messages are shown on the screen.

Cal_date (function,overlay).
Called by: Schema.
Stored in file: CAL_DATE.BOX
Purpose:

This function gets the system date from the operating system.

Calc_comb_gangs (procedure,overlay).
Called by: Schema.
Stored in file: CAL_COMB.PAS
Purpose:

This procedure calculates the combinations of gangs. The combinations are made using the number of gangs and the constraints on machinery and men. The combinations can also be read from file. This file is created by the user of the program. If contract work is involved, the module immediately asks for a file instead of creating the combinations. This is because the user of the program does not know the number of pieces of machinery brought in by the agricultural contractor. The module also creates a gang where nothing happens (combination „Do nothing", see also Appendix E).

Calc_cost_all (procedure,overlay).
Called by: Schema.
Stored in file: CAL_COST.PAS
Purpose:

This procedure calculates all kinds of different costs, e.g. the timeliness cost, the cost of overtime and regular time, and the machine cost for each gang, and it creates a graph of progress of amount of materials processed.

Calc_moist (procedure,overlay).
Called by: Schema.
Stored in file: CAL_MOIS.PAS
Purpose:

This procedure calculates a range of moisture suction (cm) for soil, using the model described in Appendix F and a range of moisture content (%) of grain (for wheat, colza, barley and oats) using the formulae of Van Kampen (1969). Both the model and the formulae use the weather forecast and the initial conditions of soil and grain.

Calc_workab (procedure,overlay).
Called by: Schema.
Stored in file: CAL_WORK.PAS
Purpose:

This procedure calculates the expected workability for the planning horizon *after* the first five days (the workability for these days are calculated using procedure Calc_moist). The procedure is fully described in Section 7.3.1. The workability for the whole planning horizon is obtained now.

Change_data (procedure,overlay).
Called by: Dat_input.
Stored in file: CHANGE.PAS
Purpose:

This procedure can show, delete and change full records and the contents of the records of materials, machinery and men, and gangs. This is described under option IV presenting „MENU 1" in Section 9.2.

Comb_do_noth (procedure,non-overlay).
Called by: Calc_comb_gangs.
Stored in file: CAL_COMB.PAS
Purpose:

This procedure creates the combination „Do nothing". This is a dummy combination of gangs (see also module Calc_comb_gangs and Appendix E).

Combin_cost (procedure,non-overlay).
Called by: H_function.
Stored in file: H_FUNCT.PAS
Purpose:

A procedure assisting the calculation of the value of the h-function.

Constant (declaration).
Called by: —
Stored in file: CONSTANT.PAS
Purpose:

A declaration part of SCHEMA. It contains constants for the total number possible materials, machinery, men, and gangs. The change of these constants has only effect after recompilation of the source of SCHEMA.

Cont_outp_1 (procedure,non-overlay).
Called by: Change_data.
Stored in file: CHANGE.PAS
Purpose:

This procedure checks that the output fits on the screen. If it does not fit, the data on the screen have to scroll, and so a pause for the user, to read the output, is introduced.

Cont_outp_2 (procedure,non-overlay).
Called by: User_action.
Stored in file: USER_ACT.PAS
Purpose:

The same as Cont_outp_1.

Dat_input (procedure,overlay).
Called by: Schema.
Stored in file: DAT_INP.PAS
Purpose:

This procedure reads data from a terminal, from the database output-files or from the predefined record-files. These data contain information about materials, machinery and men, and gangs (the files are fully described in Appendix D). Using these data, the procedure creates the records (see Section 9.2).

Date_change (procedure,non-overlay).
Called by: Weather_report.
Stored in file: WEA_REP.PAS
Purpose:

Used by requesting the weather forecast. The procedure changes the date from one day to the next and checks if end of year has been reached. If end of year has been reached, the program will stop requesting more data from the weather forecast.

Datum_read (procedure,non-overlay).
Called by: Change_data, Dat_input.
Stored in file: DATUM_RD.BOX
Purpose:

This procedure reads the dates of processing the materials, i.e. the optimum date and the final date, from the terminal (see Chapter 9).

H_function (procedure,non-overlay).
Called by: Schema.
Stored in file: H_FUNCT.PAS
Purpose:

This procedure calculates the value of the h-function (fully described in Section 7.1.1).

Head_of_output (procedure,overlay).
Called by: Schema.
Stored in file: HEAD.BOX
Purpose:

This procedure creates a heading for the output-file with use of the file-variable „main_out_file" (the heading is visually presented in Appendix E).

Help_quest (procedure,non-overlay).
Called by: Calc_moist, Calc_workab, Change_data, Datum_read, Dat_input, Mul_read, Point_rd, Schema, User_action, Weather_report.
Stored in file: HELP_QU.PAS
Purpose:

This procedure gives help and questions or messages. The data for Help_quest (the strings with questions or help) are extracted from two binary files (QU_MSG_?.BIN and HE_MSG_?.BIN, ? can be E(nglish) or D(utch)).

Intro (procedure,overlay).
Called by: Schema.
Stored in file: INTRO.BOX
Purpose:

This procedure gives an introductory picture and a picture at the end of a run of the program (see Figure 9.1). It also asks if the dialogue-language has to be Dutch or English.

Make_gangs (procedure,non-overlay).
Called by: Calc_comb_gangs.
Stored in file: CAL_COMB.PAS
Purpose:

The actual procedure in Calc_comb_gangs checks the number of machinery and men, and creates the combinations of gangs (see also procedure Calc_comb_gangs).

Mul_read (procedure,non-overlay).
Called by: Change_data, Datum_read, Dat_input, Schema, Weather_report, User_action.
Stored in file: MUL_READ.PAS
Purpose:

This procedure reads input data for every question. It reads the F1-key (for help), the return-key (↵) and the delete-keys and responds on every error made by the user.

Operation (procedure,non-overlay).
Called by: H_function, Schema.
Stored in file: OPERAT.PAS
Purpose:

This procedure calculates the amount of material that may be processed or delivered in a period. It calculates the value of the g-function.

Point_rd (procedure,non-overlay).
Called by: Change_data, Dat_input, Schema, User_action.
Stored in file: POINT_RD.PAS
Purpose:

This procedure handles all kinds of menu's. It reads the return-key (↵), the F1-key (for help) and the up-arrow (↑) and down-arrow (↓) keys. It shows the selected choice (see „MENU 1" to „MENU 6" described in Chapter 9).

Proc_1, Proc_2, Proc_3 (procedure,non-overlay).
Called by: Change_data.
Stored in file: CHANGE.PAS
Purpose:

Procedures used by Change_data, it contains parts of the source which have to be repeated more than once in the module Change_data.

Proc_cr_table (function,non-overlay).
Called by: Calc_moist.
Stored in file: CAL_MOIS.PAS
Purpose:

This function reads the tables with CR (capillary rise) and D (downward percolation) data (see also module Afgen and Appendix F). It shows the table-value.

Progr_stop (procedure,non-overlay).
Called by: Calc_moist, Calc_workab, Dat_input, Schema.
Stored in file: SCHEMA.PAS
Purpose:

Stops the program if an essential file is not found by the program in the default directory.

Reading_file (procedure,non-overlay).
Called by: Dat_input.
Stored in file: DAT_INP.PAS
Purpose:

This procedure asks for the name of a file and checks if file is present or not. If the user enters the return-key (↵) as the answer, the module takes a default as name of the file.

Reading_yes_no (procedure,non-overlay).
Called by: Dat_input, Schema, Weather_report.
Stored in file: SCHEMA.PAS
Purpose:

Handles questions with yes or no as the only answers possible.

Real_show (procedure,non-overlay).
Called by: Show_on_dev.
Stored in file: SHOW_DEV.PAS
Purpose:

This is the actual procedure used by Show_on_dev which arranges the output to the screen or to a file.

Schema (main program).
Called by: —
Stored in file: SCHEMA.PAS
Purpose:

This is the main module. This program calculates, at operational level, a schedule for a certain planning horizon for a farm. For more information: use HELP in the program or read this dissertation (for a description of the software, see Chapter 9).

Show_on_dev (procedure,non-overlay).
Called by: Schema.
Stored in file: SHOW_DEV.PAS
Purpose:

This procedure displays all the output on the specified device of output (terminal or file). The procedure is, like the input-procedures device-dependent. An example is given in Appendix E.

Stor_data (procedure,overlay).
Called by: Dat_input.
Stored in file: STOR_DAT.BOX
Purpose:

This procedure writes the records (the data and the pointers to the records) to binary output-files.

Tan (function,non-overlay).
Called by: Calc_moist.
Stored in file: CAL_MOIS.PAS
Purpose:

This function calculates the tangent value.

User_action (function,overlay).
Called by: Schema.
Stored in file: USER_ACT.PAS
Purpose:

With this function, the progress of the amount of material processed can be requested, screen mode can be changed or the program can be stopped. The module is requested after an user's interruption (by pressing a key during the execution of the program).

Weather_clima (procedure,overlay).
Called by: Schema.
Stored in file: WEA_CLI.PAS
Purpose:

This procedure calculates the sequence of gangs and the average working rate for use by the h-function (see Section 7.1.1).

Weather_report (procedure,overlay).
Called by: Schema.
Stored in file: WEA_REP.PAS
Purpose:

This procedure asks for the weather forecast: the rainfall (mm and probability), the reference evaporation (mm) and the global radiation (kJ). The information will be requested for five days. See also the modules Asking and Date_change.

Which_day_type (procedure,overlay).
Called by: Schema.
Stored in file: DAY_TYP.BOX
Purpose:

Determines the type of the day for the given date (commonly the date given by the operating system).

Examples of the format of each file, with a description of each parameter will be given in succession. The parameter has the label I for integer, R for real, and S? for string where ? stands for the length of the string (in characters). Freedom of choice exists for the format for the integer and real variables.

PERCEEL.GEG

This file contains the information on all the materials on field and the materials produced when materials on field have been processed.

```
1   Winter wheat         1   Obelisk      60.0   1   Field 01       5.0
2   Straw                0                 0.0   1   Field 01       5.4
3   Bales on the field   0                 0.0   1   Field 01      21.1
⇓   ⇓                    ⇓   ⇓             ⇓     ⇓   ⇓              ⇓
1   2                    3   4             5     6   7              8
```

1 (I) = id. number of the material.
2 (S20) = name of the material.
3 (I) = id. number of the variety.
4 (S20) = name of the variety.
5 (R) = area (ha).
6 (I) = id. number of the field.
7 (S20) = name of the field.
8 (R) = timeliness cost of the material (linearly decrease in value, $f\cdot \mathrm{d}^{-1}$).

MAT_SEC.GEG

This file contains the following information; which materials will be produced under which conditions when another material is being delivered.

```
1  2  2  0.00   9999.00   4  19.00    23.00
2  1  3  0.00   9999.00
⇓  ⇓  ⇓  ⇓         ⇓      ⇓  ⇓          ⇓
1  2  3  4         4      3  4          4
```

1 (I) = the id. number of the material which will be processed (see PERCEEL.GEG).
2 (I) = total number of materials delivered.
3 (I) = id. number of material delivered (see PERCEEL.GEG).
4 (I) = range of moisture content (for grain and colza in %, for soil in cm), this is the condition under which the material will be delivered (if this condition is always true then the moisture content ranges from 0 to 9999).

EQUIPM.GEG

This file contains the data about the amount of equipment and the number of men, with the cost per hour.

```
1   Tractor 01         2.50  0  2
1   Tractor 02         2.40  0  2
3   Man 01            10.50  1  2
3   Man 02            10.50  1  2
5   Grain harvester    7.40  0  1
6   Straw baler        4.50  0  1
⇓   ⇓                  ⇓     ⇓  ⇓
1   2                  3     4  5
```

1 (I) = the id. number of an individual unit (of machinery or men).
2 (S20) = the name of the unit.
3 (R) = the costs (labour, fuel, depreciation, and so on, $f\cdot\mathrm{h}^{-1}$).
4 (I) = indication of machinery or men, 0: the unit is a piece of machinery, 1: the unit is a man.
5 (I) = total number of this unit.

GANG.GEG

All the information about the gangs is stored in this file.

```
1   Grain harvest/1 man   1 4 0.0  0.0 10.0  1000.0 1.0 1.5 5  1 3 5 8 8
2   Grain harvest/2 man   1 4 0.0  0.0 20.0  2000.0 2.0 1.5 7  1 1 3 3 5 8 8
3   Baling of straw       2 0 0.0  0.0 10.0  1000.0 2.0 2.0 3  1 3 6
⇓   ⇓                     ⇓ ⇓ ⇓    ⇓    ⇓      ⇓    ⇓   ⇓   ⇓     ⇓
1   2                     3 4 5    5    5      5    6   7   8     9
```

1 (I) = id. number of gang.
2 (S20) = name of the gang.
3 (I) = id. number of material which the gang must process (see PERCEEL.GEG).
4 (I) = number used to identify the type of model which must be used to calculate the moisture content; 0 = soil, 1 = colza, 2 = barley, 3 = oats, 4 = wheat, and 5 = no model used (the material is always workable, e.g. drying of wet grain).
5 (R) = overtime costs for every period (morning, afternoon, evening and night, in $f\cdot\mathrm{h}^{-1}$).
6 (R) = working rate ($\mathrm{ha}\cdot\mathrm{h}^{-1}$).
7 (R) = average working rate ($\mathrm{ha}\cdot\mathrm{h}^{-1}$) for the h-function. If two or more gangs process the same material, this parameter must be the average of the working rates of those gangs.
8 (I) = total number of equipment used by the gang.
9 (I) = the id. numbers of equipment or men used by the gang (see EQUIPM.GEG).

GAN_SEC.GEG

The h-function needs a logic sequence of gangs to evaluate the future progress of the processing of materials. This sequence is created using the users view. The information is not used by the g-function. Therefore, this information will not predict the actual outcome of the heuristic FLOS, it only helps the h-function (SCHEMA builds clusters of gangs using this information, see Section 7.1.1).

```
1  3
2  3
3  4
⇓  ⇓
1  2
```

1 (I) = the id. number of the first gang (see GANG.GEG).
2 (I) = the id. number of the next gang in the sequence (see GANG.GEG).

COMBINAT.GEG

This file is optional, and only used when the user wants to create the combinations of gangs personally. The file must be present on disk when contract work is involved in the scheduling.

```
1  1  1
2  1  2
3  1  3
4  2  1  3
⇓  ⇓  ⇓
1  2  3
```

1 (I) = the id. number of the combination.
2 (I) = the total number of gangs in the combination.
3 (I) = the id. numbers of the gangs (see GANG.GEG).

SIMULAT.GEG

This file is optional and can be used for input of prescribed combinations in a period for a simulation or for a combination of planning and simulation. When the number of the combination (parameter two) equals 250, a planning must be performed for the period concerned. The last period must have the combination number 0 to indicate the end of the scheduling. The combination numbers are derived from COMBINAT.GEG and given by the program.

```
1    24
2     3
3    24
4    24
5   250
6     0
⇓     ⇓
1     2
```

1 (I) = the number of the period (4 periods per day, at the momentary development stage of the program, all periods in the planning horizon have to be given).

2 (I) = the id. number of the combination or an indication to plan (is 250) or to stop (is 0, see also COMBINAT.GEG).

MOIST_D0.GEG

This file contains the initial information of the particular type of soil on which the farm is situated. These data are input of a soil moisture suction model described in Appendix F.

```
12 40.0  2.0 0.0 0.0 30.0  100.0   3.0   3 110.0    5000.0  8.0
 ⇓  ⇓     ⇓   ⇓   ⇓   ⇓      ⇓      ⇓    ⇓   ⇓         ⇓     ⇓
 1  2     3   4   5   6      7      8    9  10        11    12
```

1 (I) = the id. number of the soil (1—14, see SOIL.GEG).
2 (R) = the clod angle or furrow angle (degrees, normally between 30° and 45°).
3 (R) = the surface roughness (cm, 1—2 = untilled land, 6—8 = tilled with light equipment, and 20 is contour ploughed land).
4 (R) = slope angle of the land (degrees).
5 (R) = quantity of water actually stored on top of the land (cm, commonly 0 cm).
6 (R) = mean rooting depth (cm).
7 (R) = initial ground water depth (cm).
8 (R) = mean leaf area index (cm^{2}·cm^{-2}).
9 (I) = crop stage (1 = initial stage, 2 = crop development stage, 3 = mid-season stage, and 4 = late season stage).
10 (R) = the drain depth (cm).
11 (R) = the drain spacing (cm).
12 (R) = the drain radius (cm).

MOIST_N?.GEG

All the names of the climatological files have to be stored in this file. The ?-sign stands for the identification number of the moisture content model (see GANG.GEG). The description of the use is given in Chapter 7 (Section 7.3).

```
SO_63_JU.BIN
SO_64_JU.BIN
SO_65_JU.BIN
     ⇓
     1
```

1 (S??) = name of the climatological file. This file contains a sequence of moisture contents for the particular soil or grain. The length of the name is optional (must satisfy the format which the operating system prescribes).

Appendix E

THE OUTPUT OF THE SOFTWARE PACKAGE SCHEMA

This appendix describes an example of the output of SCHEMA. A schedule for the grain harvest is calculated.

The input

The materials processed with the starting area are:

• cereal	30	ha
• straw	0	ha
• bales	0	ha
• wet grain	0	ha

The operations performed (by the gangs with the work-rate) are:

• Grain harvest with one man	1	$\text{ha}\cdot\text{h}^{-1}$
• Grain harvest with two men	2	$\text{ha}\cdot\text{h}^{-1}$
• Straw baling	2	$\text{ha}\cdot\text{h}^{-1}$
• Bale loading	2	$\text{ha}\cdot\text{h}^{-1}$
• Drying of wet grain	1	$\text{ha}\cdot\text{h}^{-1}$

The cost of regular time is ƒ5.00 per hour and the cost of overtime is ƒ10.00 per hour (the night period, i.e. 22:00—7:00, has high cost of overtime, i.e. ƒ1000.00 per hour, because the user of SCHEMA does not want to work at night). The cost of drying is ƒ30.00 per hour. Periods with overtime hours are the evening periods (17:00—22:00), the night periods (22:00—7:00), the Saturdays and the Sundays (item; the cost values are just examples, they are not realistic).

The planning period has a length of five weeks. No problems are predicted by the weather forecast, i.e. no rain is expected.

The output

The output contains:

- the schedule;
- the hours (h) and costs (*f*) of regular time and overtime spent by each gang;
- the cost of machinery for each gang (*f*);
- the timeliness cost (*f*) and the maximum amount (ha) of material detected on the field;
- for each material, a graph of the progress of processing.

The schedule contains for each period:

- the date (day, type and number of the day, type and number of the period);
- the chosen combination, i.e. the „best" combination of gangs selected with the materials processed by this combination;
- the material available on field at the end of a period and/or processed by the chosen combination (ha);
- the value of the v-function, i.e. the total cost (calculated at the *end* of the *current* period, this includes the value of the g-function for the *current* period), and the value of the h-function (the expected total cost) (*f*). For these functions, the total costs are the sum of the cost of overtime, the timeliness cost and any additional cost (e.g. drying cost).

E.1. AN EXAMPLE OF THE OUTPUT

The listing (the output of SCHEMA) is as follows (notes, in the black boxes, are explained at the end of the listing):

```
           USER:   IMAG, Ir. P.J.M. Wijngaard
                   Mansholtlaan 10-12
                   6708 PA Wageningen


                   W   W   OOO   RRRR   K   K
                   W   W  O   O  R   R  K   K
                   W   W  O   O  R   R  K  K
                   W   W  O   O  RRRR   KKK
                   W W W  O   O  R R    K  K
                   WWWWW  O   O  R  R   K   K
                   W   W   OOO   R   R  K   K

 SSSS   CCCC  H   H  EEEEE  DDDD   U   U  L       III  N   N   GGGG
S        C      H   H  E      D   D  U   U  L        I   N   N  G
S        C      H   H  E      D   D  U   U  L        I   NN  N  G
 SSS   C      HHHHH  EEEE   D   D  U   U  L        I   N N N  G
    S  C      H   H  E      D   D  U   U  L        I   N  NN  G GGG
    S  C      H   H  E      D   D  U   U  L        I   N   N  G   G
SSSS    CCCC  H   H  EEEEE  DDDD   UUUUU  LLLLLL  III  N   N   GGG
```

```
NUMBER:        1
CHANCE:        1.00000                                                       1

--------------------------------------------------------------------------------
Wednesday 18-Aug-1987, 07:00—12:00, day-number: 322, period-number: 1

Operate with combination:           2
        Grain harvest/2 men         Cereal

Amount of material at end of period                       on field    harvest.
        Cereal                 Field 01                   25.00 ha     5.00 ha
        Straw                  Field 01                    5.00 ha     0.00 ha   2

Value v-function (total cost):      ƒ31.67      Value h-function:    ƒ2230.87   3
--------------------------------------------------------------------------------
Wednesday 18-Aug-1987, 12:00—17:00, day-number: 322, period-number: 2

Operate with combination:           10
        Straw baling                Straw
        Bale loading                Bales on the field

Amount of material at end of period                       on field    harvest.
        Cereal                 Field 01                   25.00 ha     0.00 ha
        Straw                  Field 01                    0.00 ha     5.00 ha
        Bales on the field     Field 01                    0.00 ha     5.00 ha

Value v-function (total cost):      ƒ57.71      Value h-function:    ƒ1889.79
--------------------------------------------------------------------------------
Wednesday 18-Aug-1987, 17:00—22:00, day-number: 322, period-number: 3

Operate with combination:           2
        Grain harvest/2 men         Cereal

Amount of material at end of period                       on field    harvest.
        Cereal                 Field 01                   15.00 ha    10.00 ha
        Straw                  Field 01                   10.00 ha     0.00 ha

Value v-function (total cost):      ƒ184.58     Value h-function:    ƒ1522.44
--------------------------------------------------------------------------------
Wednesday 18-Aug-1987, 22:00—07:00, day-number: 322, period-number: 4

Operate with combination:           16
        Do nothing

Amount of material at end of period                       on field    harvest.
        Cereal                 Field 01                   15.00 ha     0.00 ha
```

```
          Straw                Field 01                   10.00 ha     0.00 ha

     Value v-function (total cost):       f232.96     Value h-function:   f1238.56
--------------------------------------------------------------------------------------
     Thursday 19-Aug-1987, 07:00—12:00, day-number: 323, period-number: 5

     Operate with combination:          10
          Straw baling                  Straw
          Bale loading                  Bales on the field

     Amount of material at end of period                  on field     harvest.
          Cereal               Field 01                   15.00 ha     0.00 ha
          Straw                Field 01                    0.00 ha    10.00 ha
          Bales on the field   Field 01                    0.00 ha    10.00 ha

     Value v-function (total cost):       f248.58     Value h-function:    f555.06
--------------------------------------------------------------------------------------
     Thursday 19-Aug-1987, 12:00—17:00, day-number: 323, period-number: 6

     Operate with combination:          2
          Grain harvest/2 men           Cereal

     Amount of material at end of period                  on field     harvest.
          Cereal               Field 01                    5.00 ha    10.00 ha
          Straw                Field 01                   10.00 ha     0.00 ha

     Value v-function (total cost):       f265.04     Value h-function:    f614.46
--------------------------------------------------------------------------------------
     Thursday 19-Aug-1987, 17:00—22:00, day-number: 323, period-number: 7

     Operate with combination:          10
          Straw baling                  Straw
          Bale loading                  Bales on the field

     Amount of material at end of period                  on field     harvest.
          Cereal               Field 01                    5.00 ha     0.00 ha
          Straw                Field 01                    0.00 ha    10.00 ha
          Bales on the field   Field 01                    0.00 ha    10.00 ha

     Value v-function (total cost):       f370.25     Value h-function:     f75.73
--------------------------------------------------------------------------------------
     Thursday 19-Aug-1987, 22:00—07:00, day-number: 323, period-number: 8

     Operate with combination:          16
          Do nothing
```

```
Amount of material at end of period                on field     harvest.
          Cereal               Field 01             5.00 ha      0.00 ha

Value v-function (total cost):        ƒ379.62   Value h-function:    ƒ18.35
```

```
Friday 20-Aug-1987, 07:00—12:00, day-number: 324, period-number: 9

Operate with combination:         1
          Grain harvest/1 man     Cereal

Amount of material at end of period                on field     harvest.
          Cereal               Field 01             2.50 ha      2.50 ha
          Straw                Field 01             2.50 ha      0.00 ha

Value v-function (total cost):        ƒ385.04   Value h-function:    ƒ47.58
```

```
Friday 20-Aug-1987, 12:00—17:00, day-number: 324, period-number: 10

Operate with combination:         10
          Straw baling            Straw
          Bale loading            Bales on the field

Amount of material at end of period                on field     harvest.
          Cereal               Field 01             2.50 ha      0.00 ha
          Straw                Field 01             0.00 ha      2.50 ha
          Bales on the field   Field 01             0.00 ha      2.50 ha

Value v-function (total cost):        ƒ387.65   Value h-function:    ƒ46.98
```

```
Friday 20-Aug-1987, 17:00—22:00, day-number: 324, period-number: 11

Operate with combination:         16
          Do nothing

Amount of material at end of period                on field     harvest.
          Cereal               Field 01             2.50 ha      0.00 ha

Value v-function (total cost):        ƒ390.25   Value h-function:    ƒ30.57
```

```
Friday 20-Aug-1987, 22:00—07:00, day-number: 324, period-number: 12

Operate with combination:         16
          Do nothing

Amount of material at end of period                on field     harvest.
```

```
          Cereal               Field 01                       2.50 ha     0.00 ha

     Value v-function (total cost):      ƒ394.94     Value h-function:       ƒ2.73
----------------------------------------------------------------------------------
     Saturday 21-Aug-1987, 07:00—12:00, day-number: 325, period-number: 13

     Operate with combination:           6
          Grain harvest/1 man            Cereal
          Straw baling                   Straw

     Amount of material at end of period                     on field    harvest.
          Cereal               Field 01                       0.00 ha     2.50 ha
          Straw                Field 01                       0.00 ha     2.50 ha
          Bales on the field   Field 01                       2.50 ha     0.00 ha

     Value v-function (total cost):      ƒ443.43     Value h-function:      ƒ83.33
----------------------------------------------------------------------------------
     Saturday 21-Aug-1987, 12:00—17:00, day-number: 325, period-number: 14

     Operate with combination:           4
          Bale loading                   Bales on the field

     Amount of material at end of period                     on field    harvest.
          Bales on the field   Field 01                       0.00 ha     2.50 ha

     Value v-function (total cost):      ƒ455.93     Value h-function:       ƒ0.00 4
----------------------------------------------------------------------------------
```

TOTAL HOURS AND COST FOR EVERY GANG.

```
Gang:           Grain harvest/1 man
Number men:              1
Man hours:            2.50  h      Labour cost:          ƒ12.50
Overtime hours:       2.50  h      Overtime cost:        ƒ25.00
Number machines:         4
Machinery hours:     20.00  h      Machinery cost:       ƒ57.00

Gang:           Grain harvest/2 men
Number men:              2
Man hours:           15.00  h      Labour cost:          ƒ75.00
Overtime hours:      10.00  h      Overtime cost:       ƒ100.00
Number machines:         5
Machinery hours:     62.50  h      Machinery cost:      ƒ173.75
```

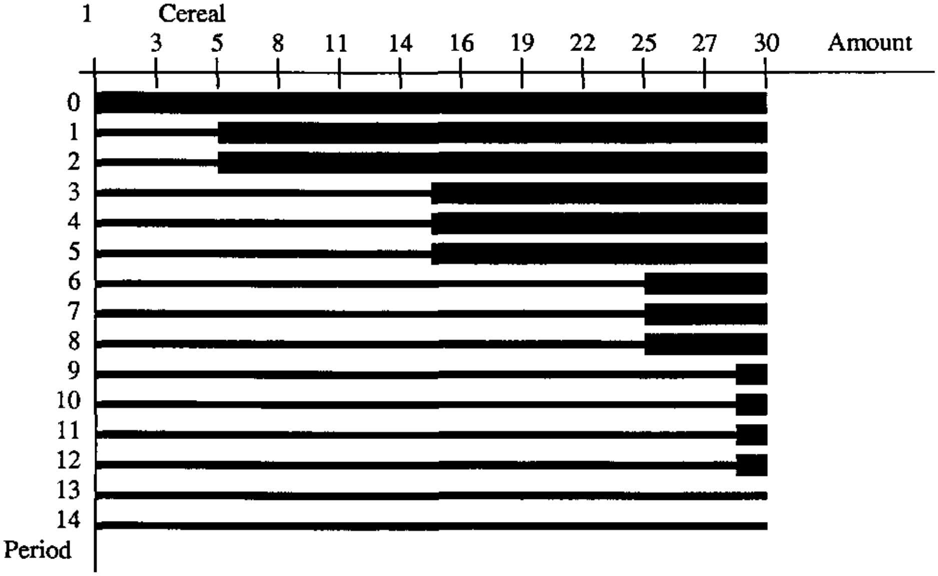
```
Gang:            Straw baling
Number men:               1
Man hours:             8.75  h     Labour cost:         ƒ43.75
Overtime hours:        6.25  h     Overtime cost:       ƒ62.50
Number machines:          2
Machinery hours:      30.00  h     Machinery cost:     ƒ105.00

Gang:            Bale loading
Number men:               1
Man hours:             8.75  h     Labour cost:         ƒ43.75
Overtime hours:        6.25  h     Overtime cost:       ƒ62.50
Number machines:          6
Machinery hours:      90.00  h     Machinery cost:     ƒ116.25

Gang:            Drying wet grain
Number men:               0
Man hours:             0.00  h     Labour cost:          ƒ0.00
Overtime hours:        0.00  h     Overtime cost:        ƒ0.00
Number machines:          1
Machinery hours:       0.00  h     Machinery cost:       ƒ0.00

TOTAL:
Man hours:            35.00  h     Labour cost:        ƒ175.00
Overtime hours:       25.00  h     Overtime cost:      ƒ250.00        5
Machinery hours:     202.50  h     Machinery cost:     ƒ452.00
```

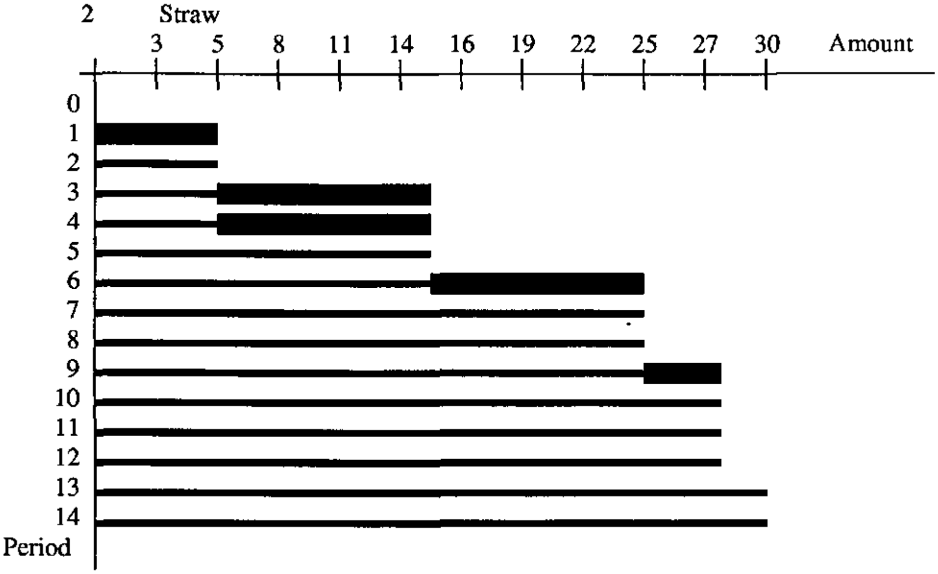
TIMELINESS COST AND MAXIMUM AVAILABLE AMOUNT FOR EVERY MATERIAL.

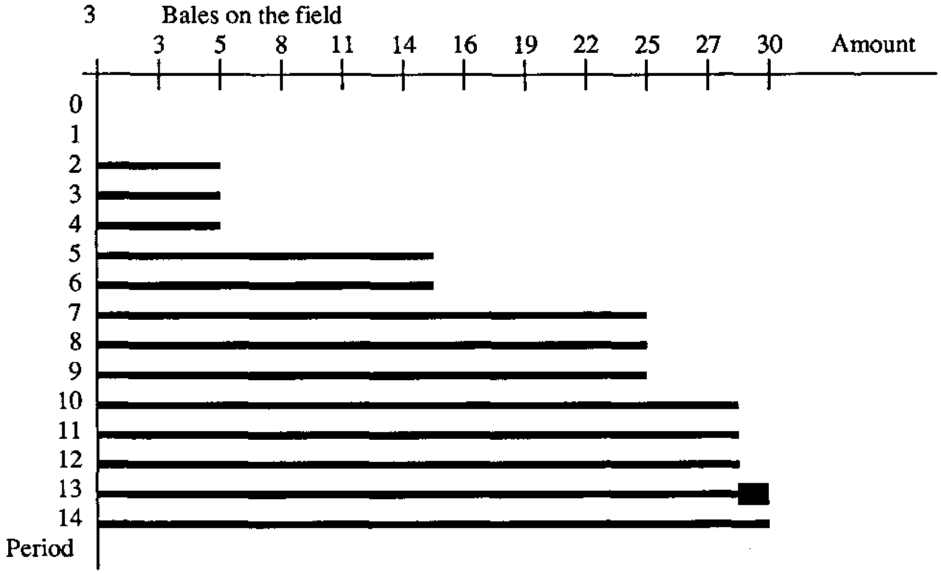
```
     1     Cereal               Field 01      ƒ143.75     30.00  ha
     2     Straw                Field 01       ƒ51.19     10.00  ha
     3     Bales on the field   Field 01       ƒ10.99      2.50  ha
     4     Wet grain            Field 01        ƒ0.00      0.00  ha

TOTAL TIMELINESS COST:          ƒ205.93                                6
```

PROGRESS OF THE AMOUNT OF MATERIAL.

▬ = Processed amount (ha); ■ = Available amount (ha).







Notes

1 These are the number of the schedule and the probability. The probability is the product of probabilities of rainfall, given by the weather forecast (the probability of rainfall is given per day, see Section 7.3).

2 Five hectares of cereal are processed with five hectares of straw being produced, twenty-five hectares of cereal remains on the field. Note that the full capacity of the gang is not used, i.e. only half the period is used. This is because the cereal cannot be processed in the first half of the period due to workability constraints (i.e. the grain is too wet due to dew). This counts only for the morning periods (7:00—12:00).

3 The value of the v-function represents the total cost. This is the sum of the overtime cost and the timeliness cost. This period is a period with regular hours, therefore, the current value of the v-function only represents the timeliness cost. The value of the h-function represents the expected total cost (this is again the sum of overtime and timeliness cost).

4 For the last period, the value of the v-function is the exact sum of overtime cost (see item 5) and the timeliness cost (see item 6). There are no drying costs involved (see the total hours for the gang „drying wet grain").

5 See item 4.

6 See item 4.

Appendix F

THE SOIL MOISTURE SUCTION MODEL

F.1. INTRODUCTION

This appendix contains the description of a simple soil moisture suction model. This model is fully described by P.M. Driessen (1983) and it is taken without modifications. This model has a simple structure. There are a lot of better, more detailed models (Dyer and Baier, 1981; Witney et al., 1982; Jeevananda Reddy, 1983; Belmans et al., 1983; Martínez-Lozano et al., 1984), but they need detailed data like fraction of clouds, air and soil temperature, information about soil layers and the flux between those layers. These data are not supplied by weather forecast stations. Therefore, a simple soil moisture suction model has been used. The formulae used in this model are tested by Driessen (1983). They are also tested by Goense (1987) for a N-layer model (i.e. the top soil layer is divided in more than one layer) and this model is tested for several soils in Surinam. The model did perform well.

F.2. THE MODEL

For the calculation of the workability, the heuristic FLOS (Farm Labour and Operations Scheduling) must keep track of the actual amount of soil moisture stored in the root zone. This is executed using a water balance equation which compares, for a given period of time, incoming water in the root zone with water losses. It quantifies the differences between the two as a change in quantity of soil moisture stored in the rooted top soil. This rooted top soil, or „root zone", is a continuous soil layer with an upper boundary (the soil surface), and a lower boundary at a depth of RD cm (the rooting depth). Water enters and leaves the root zone via these two boundaries but there is also removal of water directly from within the root zone, i.e. the water taken up by plant roots. This uptake is almost quantitatively discharged as transpiration (Figure F.1).

A change in the quantity of soil moisture in the root zone, incurred during a time interval of Δt days (for use by SCHEMA, Δt is stated 1), can thus be described with a water balance equation of the following nature:

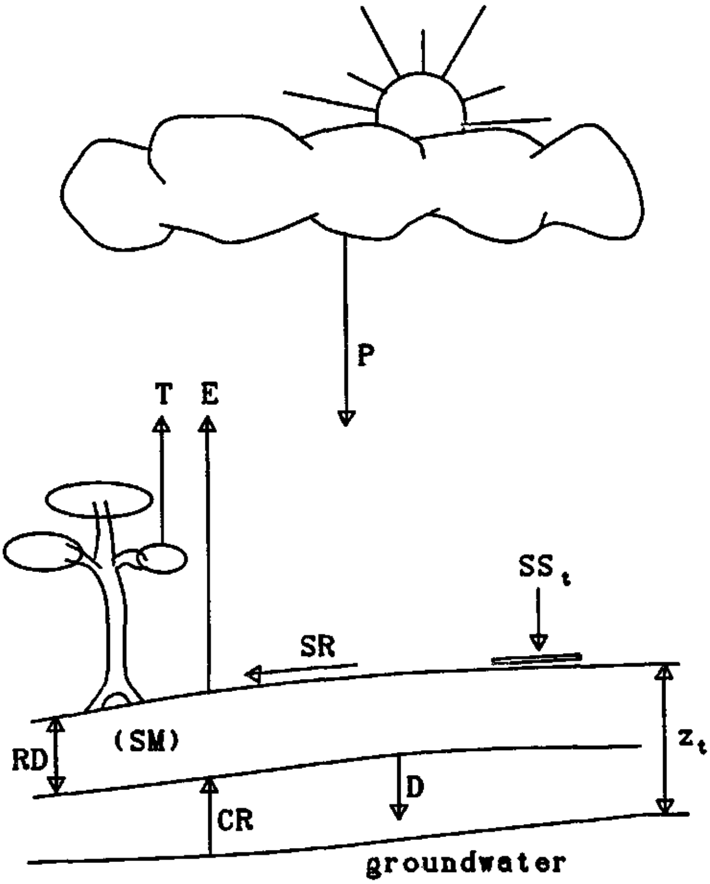


Figure F.1. The schematic representation of the variables of the soil moisture suction model.

$$RSM \cdot RD \cdot \Delta t = IM \cdot \Delta t + (CR - D) \cdot \Delta t - T \cdot \Delta t$$

where,

RSM	is the rate of change in moisture content of the root zone	$(cm^3 \cdot cm^{-3} \cdot d^{-1})$
RD	is the mean rooting depth	(cm)
IM	is the rate of net influx through the upper root zone boundary	$(cm \cdot d^{-1})$
(CR – D)	is the rate of net influx through the lower root zone boundary	$(cm \cdot d^{-1})$
CR	is the rate of capillary rise	$(cm \cdot d^{-1})$
D	is the downward percolation	$(cm \cdot d^{-1})$
T	is the rate of crop transpiration	$(cm \cdot d^{-1})$

The actual infiltration of water during a period with a length of Δt days can be described as:

$$IM \cdot \Delta t = P \cdot \Delta t + I_e \cdot \Delta t - E \cdot \Delta t + DS \cdot \Delta t - \Delta(SS_{max} - SS_t) - SR$$

where,

IM	is the rate of net influx through the upper root zone boundary	$(\mathrm{cm} \cdot \mathrm{d}^{-1})$
P	is the actual precipitation rate	$(\mathrm{cm} \cdot \mathrm{d}^{-1})$
I_e	is the effective irrigation rate	$(\mathrm{cm} \cdot \mathrm{d}^{-1})$
E	is the actual evaporation rate	$(\mathrm{cm} \cdot \mathrm{d}^{-1})$
DS	is the rate of decline of surface storage	$(\mathrm{cm} \cdot \mathrm{d}^{-1})$
SS_{max}	is the maximum surface storage capacity	(cm)
SS_t	is the initial surface storage at the beginning of the period	(cm)
SR	is the surface run off	(cm)
Δt	is the duration of the time interval	(d)

The actual precipitation rate (P) is given as input by the user of the heuristic FLOS (for the first five days of the planning horizon, see Chapter 7 for details).

The effective irrigation rate (I_e) represents the net input of irrigation water into the root zone. It may be measured directly in the field, e.g. with rain gauges in the case of sprinkler irrigation. More often, only the gross amount of water released at the projects headwork is measured and then effective water inputs are approximated by multiplying the rate of water release at the headwork with an overall efficiency factor:

$$I_e = I \cdot E_p$$

where,

I_e	is the effective irrigation rate	$(\mathrm{cm} \cdot \mathrm{d}^{-1})$
I	is the rate of water release at headwork	$(\mathrm{cm} \cdot \mathrm{d}^{-1})$
E_p	is the overall efficiency factor	(—)

And

$$E_p = E_a \cdot E_b \cdot E_c$$

where,

E_a	is the field application efficiency factor	(—)
E_b	is the field canal efficiency factor	(—)
E_c	is the conveyance efficiency factor	(—)

For the heuristic FLOS, no irrigation is assumed, therefore, I has the value 0.

The actual evaporation from the soil surface depends on:

1. the potential evaporation rate, determined by the evaporative demand of the atmosphere (E_0 in cm·d^{-1}, this value is given as input by the user of the heuristic FLOS, i.e. the reference evaporation rate in the weather forecast, Chapter 7);

2. the hydraulic permeability of the surface soil;

3. the shading effect of the canopy (LAI, i.e. the leaf area index).

In the absence of a crop, the maximum rate of evaporation, E_m (cm·d^{-1}) is assumed equal to the potential evaporation rate, E_0. In the case where the rate of water loss through evaporation is lower than the rate at which capillary rise of groundwater, CR (cm·d^{-1}), can supply water to the soil surface, the actual rate of evaporation, E, equals the maximum rate, E_m, and:

$$E = E_m = E_0 \cdot e^{(-0.4 \cdot LAI)} \qquad \text{if } E_m \leq CR$$

where,

LAI	is the leaf area index	(cm^2·cm^{-2})
CR	is the rate of capillary rise	(cm·d^{-1})

And, if $E_m > CR$, then:

$$E = E_0 \cdot e^{(-0.4 \cdot LAI)} \cdot \frac{SM_\phi - SM_{16000}}{SM_{f.c.} - SM_{16000}} \qquad \text{if } E_m > CR$$

where,

SM_ϕ	is the soil moisture content (also given as input by the user at the beginning of the first period, for the other periods, it is calculated)	(cm^3·cm^{-3})
SM_{16000}	is the ultimate moisture content	(cm^3·cm^{-3})
$SM_{f.c.}$	is the moisture content at field capacity. In the Netherlands, field capacity is traditionally positioned at ϕ = 100 cm (ϕ = soil moisture suction)	(cm^3·cm^{-3})

SM_ϕ is the soil moisture content and SM_ϕ can be satisfactorily described by:

$$SM_\phi = SM_0 \cdot e^{(-\gamma \cdot (Ln\phi)^2)}$$

where,

SM_0	is the total pore space	(cm^3·cm^{-3})
γ	texture-specific constant	(—)
ϕ	is the soil moisture suction	(cm)

In a number of situations, agricultural land may be flooded. The quantity of water which can be potentially stored on top of the land (SS_{max}, in cm) is determined by the surface properties and the slope angle of the land. The surface storage capacity is mathematically described as:

$$SS_{max} = 0.5 \cdot d \cdot \frac{\sin^2(\sigma-\delta)}{\sin\sigma} \cdot \frac{(\tan(\sigma+\delta))^{-1} + (\tan(\sigma-\delta))^{-1}}{2 \cdot \cos\delta \cdot \cos\sigma}$$

where,

SS_{max}	is the surface storage capacity	(cm)
d	is the surface roughness	(cm)
σ	is the clod angle or furrow angle	(degrees)
δ	is the slope angle of the land	(degrees)

In most cases, the clod/furrow angle, σ, lies between 30 and 45°; the field slope, δ, of land which can be used for agriculture is commonly lower than 17° (= 30 percent). The surface roughness, d, is of the order d = 20 cm for contour-ploughed land, d = 6 to 8 cm for land tilled with light equipment and d = 1 to 2 cm for untilled land.

The decline of surface storage, $DS\cdot\Delta t$, the increase of surface storage, $\Delta(SS_{max}-SS_t)$, and the surface runoff, SR, can be calculated in one step. Firstly, IM_{max} is calculated as follows:

$$IM_{max} = S_0 \cdot (1 - SM_\phi/SM_0) \cdot (\Delta t)^{0.5} + A\cdot\Delta t$$

where,

IM_{max}	is the maximum infiltration of water into the surface soil	(cm)
S_0	is the standard sorptivity rate	$(cm\cdot d^{-0.5})$
A	is the transmission zone permeability	$(cm\cdot d^{-1})$

Secondly, Q is calculated:

$$Q = P\cdot\Delta t + I_e\cdot\Delta t - E\cdot\Delta t - IM_{max}$$

Q	is the difference between supply and maximum infiltration capacity	(cm)

Now, there are three cases:

Case 1: Q = 0 (this is the equilibrium situation in which the supply can just be handled by the soil's infiltration capacity), then

$$IM\cdot\Delta t = (P + I_e - E)\cdot\Delta t$$
$$DS = 0$$
$$\Delta(SS_{max} - SS_t) = 0$$
$$SR = 0$$

Case 2: $Q < 0$ (the supply is lower than the infiltration capacity), then identify the initial surface storage, SS_t, and if:

$-Q > SS_t$ (excess infiltration capacity exceeds initial storage) then:

$$IM \cdot \Delta t = (P + I_e - E) \cdot \Delta t + SS_t$$
$$DS \cdot \Delta t = SS_t$$
$$\Delta(SS_{max} - SS_t) = 0$$
$$SR = 0$$

$-Q \leq SS_t$ (excess infiltration capacity is equal to or lower than initial storage) then:

$$IM \cdot \Delta t = IM_{max}$$
$$DS \cdot \Delta t = IM_{max} - (P + I_e - E) \cdot \Delta t$$
$$\Delta(SS_{max} - SS_t) = 0$$
$$SR = 0$$

Case 3: $Q > 0$ (the surface supply exceeds the infiltration capacity), then calculate the available surface storage capacity, $SS_{max} - SS_t$, and if:

$Q > (SS_{max} - SS_t)$ (excess supply exceeds available storage capacity) then:

$$IM \cdot \Delta t = IM_{max}$$
$$DS = 0$$
$$\Delta(SS_{max} - SS_t) = SS_{max} - SS_t$$
$$SR = (P + I_e - E) \cdot \Delta t - IM_{max} - (SS_{max} - SS_t)$$

$Q \leq (SS_{max} - SS_t)$ (excess supply is equal to or lower than storage capacity) then:

$$IM \cdot \Delta t = IM_{max}$$
$$DS = 0$$
$$\Delta(SS_{max} - SS_t) = (P + I_e - E) \cdot \Delta t - IM_{max}$$
$$SR = 0$$

Now, it is possible to calculate IM, although CR, D and T have to be calculated. CR is the rate of capillary rise, D the rate of percolation, and T the transpiration rate. Of CR and D, only the difference between both, i.e. CR – D, is required. A generally applicable procedure for the calculation of $(CR - D) \cdot \Delta t$ is as follows. Firstly, the total hydraulic head at the lower root zone boundary, H_{RD}, is established by subtracting from the matric head, ϕ, the distance between lower root zone boundary and the water table:

$$H_{RD} = \phi - (z_t - RD)$$

where,

z_t	is the depth of groundwater	(cm)

Then, again, there are three cases:

Case 1: $H_{RD} = 0$, then $(CR - D)\cdot\Delta t = 0$.

Case 2: $H_{RD} > 0$, then $(CR - D)\cdot\Delta t = CR\cdot\Delta t$ (CR is given as input).

Case 3: $H_{RD} < 0$, then $(CR - D)\cdot\Delta t = -k_\phi\cdot\Delta t$, and k_ϕ is calculated as follows:

If $\phi \le \phi_{max}$ then: $k_\phi = k_0 \cdot e^{(-\alpha\cdot\phi)}$

If $\phi > \phi_{max}$ then: $k_\phi = a \cdot \phi^{-1.4}$

where,

ϕ_{max}	is the texture-specific suction limit	(cm)
k_ϕ	is the hydraulic conductivity rate at ϕ	$(cm\cdot d^{-1})$
k_0	is the texture-specific saturated hydraulic conductivity	$(cm\cdot d^{-1})$
α	is a texture-specific empirical constant	(cm^{-1})
a	is a texture-specific empirical constant	$(cm^{2.4}\cdot d^{-1})$

The maximum transpiration rate under conditions of optimum water supply is a function of the total surface area of all transpiring leaves and of the potential transpiration rate T_0 (in $cm\cdot d^{-1}$). Assuming proportionality between light interception by the leaf surface and transpiration, the maximum transpiration rate is expressed as:

$$T_m = (1 - e^{(-0.8\cdot LAI)})\cdot T_0$$

The potential transpiration rate, T_0, is found by subtracting evaporation from the potential evapotranspiration rate, ET_0. The potential transpiration rate can be written as:

$$T_0 = ET_0 - 0.1\cdot E_0$$

and:

$$ET_0 = E_0 \cdot \text{Crop-factor}$$

The actual transpiration rate, T, can be quantified for any value of SM_ϕ with the aid of the following set of equations:

If $SM_\phi \ge SM_{10}$: $T = 0$

If $SM_{10} > SM_\phi \ge SM_{100}$: $$T = \frac{SM_{10} - SM_\phi}{SM_{10} - SM_{100}} \cdot T_m$$

If $SM_{100} > SM_\phi \ge SM_\phi(cr)$: $T = T_m$

If $SM\phi(cr) > SM_\phi \geq SM_{16000}$: $$T = \frac{SM_\phi - SM_{16000}}{SM_\phi(cr) - SM_{16000}} \cdot T_m$$

If $SM_{16000} > SM_\phi$: $$T = 0$$

And:

$$SM_\phi(cr) = (1 - p) \cdot (SM_{100} - SM_{16000}) + SM_{16000}$$

where,

p	is the soil water depletion fraction	(—)

Now all the parameters for the rate in change of moisture content, RSM, have been calculated. The new moisture content, and accordingly, the new value of the soil moisture suction can also be calculated. However not only the moisture content is changing. The depth of groundwater, z_t, and the surface storage, SS_t, are changing too.

Change of moisture content

$$SM_{\phi,t+\Delta t} = SM_{\phi,t} + RSM \cdot \Delta t$$

$SM_{\phi,t}$	is the soil moisture content at the beginning of period t	$(cm^3 \cdot cm^{-3})$
$SM_{\phi,t+\Delta t}$	is the new soil moisture content at the beginning of period $t + \Delta t$	$(cm^3 \cdot cm^{-3})$

Change of groundwater depth

$$\Delta z = \frac{(D_{max} + (CR - D)) \cdot \Delta t}{SM_0}$$

$$D_{max} = k_0 \cdot \frac{\pi \cdot m_t}{\pi \cdot m_t + L \cdot Ln(L/\pi \cdot r)}$$

$$m_t = (z_t - DD)/0.5$$

where,

Δz	is the change in groundwater depth	(cm)
D_{max}	is the drainage rate	$(cm \cdot d^{-1})$
m_t	is the hydraulic head midway between the drains	(cm)
L	is the drain spacing	(cm)
r	is the drain radius	(cm)

DD	is the drain depth	(cm)

Change of surface storage

If $(P + I_e - E)\cdot\Delta t - IM_{max} > SS_{max} - SS_t$ then:
$SS_{(t+\Delta t)} = SS_{max}$

If $(P + I_e - E)\cdot\Delta t - IM_{max} > 0$ and $\leq (SS_{max} - SS_t)$ then:
$SS_{(t+\Delta t)} = SS_t + (P + I_e - E)\cdot\Delta t - IM_{max}$

If $(P + I_e - E)\cdot\Delta t - IM_{max} < - SS_t$ then:
$SS_{(t+\Delta t)} = 0$

If $(P + I_e - E)\cdot\Delta t - IM_{max} < 0$ and $\geq - SS_t$ then:
$SS_{(t+\Delta t)} = SS_t + (P + I_e - E)\cdot\Delta t - IM_{max}$

F.3. THE INPUT

Some variables have to be supplied by the user. Two of them are part of the weather forecast, and one is the initial condition of the soil. Values for these variables will be requested during the run of the program SCHEMA. These variables are:

P	is the actual precipitation rate (the rainfall)	$(cm\cdot d^{-1})$
E	is the reference evaporation rate	$(cm\cdot d^{-1})$
SM_ϕ	is the initial soil moisture content	$(cm^3\cdot cm^{-3})$

The weather forecast gives the evaporation rate from a water surface. The soil moisture model needs the evaporation rate of a green surface which is 0.83 times the rate of a water surface (Doorenbos and Pruit, 1975).

In file SOIL.GEG (see Appendix D), texture-specific parameters of 14 different soils are stored (Rijtema, 1969; Doorenbos and Pruit, 1975). These texture-specific parameters (see also Table F.1) are:

SM_0	is the total pore space	$(cm^3\cdot cm^{-3})$
γ	texture-specific constant	(—)
S_0	is the standard sorptivity rate	$(cm\cdot d^{-0.5})$
A	is the transmission zone permeability	$(cm\cdot d^{-1})$
ϕ_{max}	is the texture-specific suction limit	(cm)
k_0	is the texture-specific saturated hydraulic conductivity	$(cm\cdot d^{-1})$
a	is a texture-specific empirical constant	$(cm^{2.4}\cdot d^{-1})$
α	is a texture-specific empirical constant	(cm^{-1})

Table F.1. The texture classes with several parameters.

Texture class	SM_0	γ	S_0	A	ϕ_{max}	k_0	a	α
coarse sand	0.395	0.1000	50.16	119.23	80	1120.0	0.1	0.2240
loamy sand	0.391	0.0286	19.20	30.33	175	50.0	10.9	0.0500
fine sand	0.364	0.0288	21.44	17.80	200	26.5	16.4	0.0398
fine sandy loam	0.504	0.0207	17.57	9.36	300	12.0	26.5	0.0248
silt loam	0.509	0.0185	14.46	5.32	300	6.5	47.3	0.0200
loam	0.503	0.0180	11.73	3.97	300	5.0	14.4	0.0231
loess loam	0.455	0.0169	13.05	8.88	130	14.5	22.6	0.0490
sandy clay loam	0.432	0.0096	19.05	16.51	200	23.5	33.6	0.0353
silty clay loam	0.475	0.0105	6.15	1.18	300	1.5	36.0	0.0237
clay loam	0.445	0.0058	4.70	0.76	300	1.0	1.7	0.0248
light clay	0.453	0.0085	10.74	2.66	300	3.5	2.8	0.0274
silty clay	0.507	0.0065	3.98	0.80	50	1.3	28.2	0.0480
heavy clay	0.540	0.0042	1.93	0.15	80	0.2	4.9	0.0380
peat	0.863	0.0112	7.44	1.86	50	5.3	6.8	0.1045

In the file CR_TAB.GEG the vertical distance of capillary flow (the groundwater depth, in cm) is given (in the form of a table) in relation to flow rate, CR, and matric suction, ϕ, for each soil texture class (Rijtema, 1969).

In the file MOIST_D0.GEG, the specific data of the type of soil possessed by the user, are given. These data are (see also Appendix D):

d	is the surface roughness	(cm)
σ	is the clod angle or furrow angle	(degrees)
δ	is the slope angle of the land	(degrees)
SS_t	is the initial surface storage (commonly zero cm)	(cm)
RD	is the mean rooting depth	(cm)
z_t	is the depth of groundwater	(cm)
LAI	is the leaf area index	$(cm^2 \cdot cm^{-2})$
Crop_factor	is the crop stage (1 = initial stage, 2 = crop development stage, 3 = mid-season stage, and 4 = late season stage (Doorenbos and Pruit, 1975))	(—)
L	is the drain spacing	(cm)
r	is the drain radius	(cm)
DD	is the drain depth	(cm)

Appendix G

METHODS OF WEATHER FORECASTING

This appendix deals with the methods of weather forecasting. The text is derived from Wickham (1970). In principle forecasting the changes of the weather is a simple problem. We need to know, firstly, the state of the atmosphere at some given time and, secondly, the physical laws which govern the changes of that state. In practice, however, very great difficulties are encountered in both these aspects. Although a huge number of weather observations are made every day, the great majority of these are made at the very bottom of the atmosphere from observing stations on land. Before anything like a complete description of its present state can be obtained we need far more measurements of the conditions at upper levels over the sea. This is impossible due to the fact that essential entities fluctuates with frequencies of ten Hertz or more, with related scales of length of less than one meter in all the dimensions.

A further difficulty in the scientific approach to weather forecasting is that, although the physical laws describing the changes of state of the atmosphere are well known in general, a precise mathematical formulation of these laws is often extremely complex. Exact solutions of the mathematical equations are frequently impossible to find because of the mutual interactions between one variable and another. Even with the most modern techniques and equipment, simplifications have to be made. And in making these simplifications there is inevitably some departure from the reality of the actual atmosphere.

Another difficulty is that there is a lack of knowledge of physics especially in the field of turbulence and radiation.

However, successful attempts are made to forecast the weather. These attempts are based on two different approaches:

1.a. *The objective approach*, in which the equations expressing the physical changes in the atmosphere are formulated and solved by computers to the greatest degree of accuracy that is at present possible. The equations are necessarily only rather approximate statements of the physical laws, and their solutions are also only approximate. This approximation is also caused by the lack of knowledge and observations, and the limits of computers;

1.b. *The objective approach* also deals with the statistical relations between expected quantities. They are often called the „objective expectations";

2. *The subjective approach*, in which meteorologists attempt to predict future changes by taking into account both their general theoretical knowledge and also their practical experience of the normal evolution of weather situations in the past.

Forecasts must be worded so that they seem to be precise statements, but this does not imply that the forecaster's confidence in their likely accuracy is equally precise. A forecast is not a statement of what the weather will be, it is a statement of what (in the forecaster's opinion) it is most likely to be. It is in this sense that it should be considered.

Numerical forecasting

Scientists in the past have considered that ultimately the most rewarding approach to weather forecasting would be to use the basic mathematical equations that describe the structure and motion of the atmosphere in order to calculate, in some way, how the weather would change in the future.

Methods of forecasting where a large number of equations have to be solved in order to predict numerical values at a grid of points, are known as numerical forecasting methods. The success of these methods depends largely on the simplifications made in the original equations. On many occasions this would lead to quite acceptable forecasts. But there are other times when this simplification might be too sweeping. Then the resulting theoretical atmosphere which was described could be significantly different from the real atmosphere, and the forecast changes would also be largely unreal.

Computers and weather forecasting

It is important to realize the present limitations of numerical forecasting methods. There still remains a wide variety of forecasting problems which cannot be tackled by numerical methods using a computer. The computed forecasts that are currently produced provide a framework of predicted contour lines and isobars. In any balanced view of forecasting laboratories of the future it is clear that new computational techniques and the traditional expertise of the forecaster will both be required.

All forecasts, whether they are derived by computation or by subjective methods, depend a great deal for their success on the quantity and quality of the basic observational data. The latter point is one that produces big problems in numerical forecasting because computers are not like human beings, who detect erroneous observations by the light of nature. A computer must be given very precise rules to enable it to distinguish between correct and incorrect values. These rules are not all easy to formulate in such a way that, while errors are rejected, the occasional extreme value which is in fact correct and of great importance, is accepted.

But some small-scale weather phenomena and anything having a limited vertical extent, such as fog, are still far from being forecast in detail by numerical methods. In such fields, and wherever he can use his powers of judgement and critical appreciation of diverse kinds of inhomogeneous data, the forecaster will always be required to complement speed and routine reliability of the basic forecast framework that is produced by numerical methods using computers.

CURRICULUM VITAE

Peter Jacobus Maria Wijngaard was born in Amsterdam on September 29, 1961. After receiving his elementary education in Amsterdam, he moved to Lelystad where he took his school-leaving examination (*Atheneum B*) at the *Scholengemeenschap Lelystad* in 1979.

In 1979, he started the study Forest Technique at the Agricultural University in Wageningen and he graduated with honour in 1985 with Forest Technique as main subject and Operational Research and Computer Science as secondary subjects.

He began with his PhD-studies in 1985 at the Agricultural Engineering Department and the Mathematics Department, Section Operational Research, both of the Agricultural University, Wageningen, and at the Institute of Agricultural Engineering (IMAG), Wageningen.

During these studies, he visited several international congresses and he was invited to the EURO Summer Institute, Finland (as only delegate of the Netherlands) in 1987 (EURO is the European Organization of Operational Research).