Rapports PSS Nº 31
(Chapter 1, 2, 3 and 4)

Production Soudano-Sahélienne (PSS)
Exploitation optimale des éléments nutritifs en élevage

Projet de coopération scientifique

Land use analysis using multiple goal linear programming
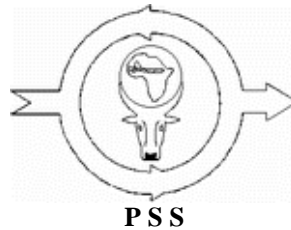
A course manual

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1. Introduction to the course

At the beginning of this course Gerrard Winstanly (1650) is quoted:

Do not all strive to enjoy the land? The gentry strive for the land, the clergy strive for the land, and buying and selling is an art whereby people endeavour to cheat one another of the land. (A New Yeers Gift to the parliament and Armie, 1650)

This is a quote from a long time ago, but the message he tried to convey, that land was a basic necessity that all sections of society tried to enjoy, has always been and still is valid. This implies that for the same piece of land, there are often several intended uses. Clearly, this may lead to conflict situations. A very old example of such a conflict situation is the following:

`Abram was very rich in cattle, silver and gold. And he went on his journeys to the south, to Bethel, to the place where his tent had been before, between Bethel and Ai, to the place of the altar that he had made there before: and there Abram called on the name of the Lord. And Lot, who

went with Abram, also had flocks, and herds, and tents. And the land was not able to bear them, while they were dwelling together. Their possessions were too great, they could not stay together. And there was strife between the herdmen of Abram's cattle and the herdmen of Lot's cattle. ..

And Abram said to Lot: Please, let there be no strife between me and you, and between my herdmen and your herdmen; for we are brothers. Is not the whole land before you? Please, separate yourself from me; if you go to the left, I will go to the right. If you will go to the right, then I will go to the left.' (the Bible, Genesis 12:2-9)

In our days land has become even more scarce. Almost nowhere conflicts can be resolved by simply separating, like in the case of Abram and Lot, because in most parts of the world we are no longer in a situation that there is still `new' land that can be used. This observation implies that it is to be expected that conflicts will be more and more difficult to resolve. A second implication is that today land use is increasingly intensive, which often leads to a degradation of this precious resource. Degradation of a part of the land leads to an increasing pressure on land that is still of good quality, and the danger exists to end up in a downward spiral. As land becomes more scarce, it also becomes more important that its utilization is sustainable. Not only the present generation but also future generations should be able to enjoy the benefits of the land.

In many places worldwide attention has been given to development of techniques, mainly decision supporting, that accommodate the problems that accompany the above mentioned two points. This course endeavors to play a role in acquainting participants with the latest state of the art techniques. On purpose we refrain from using the term `land use planning' as is so often done by many authors on this topic. The term `land use planning' only too often gives the connotation that results of a study are converted into a set of actions which will lead to the realization of a desired goal. Everybody involved in land use studies knows that usually this is not the case. These studies increase the understanding and insight of present or intended land use and as such contribute to policy making and decision making. Hardly ever are these studies directly followed by a `blue-print' of actions which are to be taken. It is not the researcher who takes any action and indeed it often is not the policy maker who takes any direct action. In the end it is often at the farm household level that decisions are made concerning the utilization of land, especially in developing countries. We have therefore preferred to use the term Land Use Analysis (LUA), with which we follow, among others, Schipper (1996).

A second remark concerning the title is that the analysis is not limited to the use of land only, but, in principle, also includes other natural resources, and, for example, labor. For this reason it might have been preferable to replace the word `land' by `natural resources' or `agricultural resource use'. The main reason why this was not done, is that in the literature the term land use has become so widely used for the type of study with which this course deals, that it would be misleading not to use it. Another justification is that other natural resources and their use are always related to the use of land. Thus, land refers not only to the land itself, but also to everything it carries or contains as other resource, like trees, water, nutrients, and organic matter.

1.1. Objectives of the course

Recent developments in research have provided useful tools for LUA. This course will strictly limit itself to the analysis of land use for agricultural purposes. It will, however, be possible to show the effects for non-agricultural purposes. Land used for agriculture cannot be used for non-agricultural activities. As Fresco (1994, p 5) states:

`During the last decade, the combined use of simulation models, expert systems, and geographic information systems, various types of data bases and multiple goal planning techniques have allowed us to formulate technical options for land use in a much more precise and varied way. Not as one dimensional blue prints, but as scenarios for policy choices.'

The presentation of scenarios is not a new technique; it is already well-known in demography and economic planning. Scenarios are not to be confused with forecasts: they do not predict but allow us to explore technical options based on explicit assumption given a set of goals. More specifically, the cost of attainment of one goal can be expressed in terms of the reduction of the attainment of other goals, thus forcing the policy makers and land users to make explicit choices. In other words land use models may help to make potential conflicts more visible'.

Within the context of the PSS project a model was developed that can be used as an instrument for exploring options for sustainable land use in arable agriculture and livestock husbandry in the sudano-sahelian zone of West Africa. The model can also be used to demonstrate the trade-off between different conflicting objectives.

The *general objective* of this course is to utilize the experience gained during the PSS project and to acquaint course participants with the techniques and methodology developed in the project. This is consistent with the objective of this project to support and strengthen local research capacity in Mali.

To achieve this general objective the following will be done during the course:

1. acquaint course participants with the latest state of the art techniques of analysis in the field of land use analysis. This will be done by explaining and describing these techniques of analysis.

2. in order to deepen understanding and insight of these land use analysis techniques, course participants will exercise with these techniques.

3. show how these techniques have actually been applied in LUA. Course participants will be introduced to two case studies, one conducted by the Netherlands Scientific Council for Government Policy (WRR, 1992), the other one conducted by the PSS project carried out by the Institut Economie Rurale (IER, Bamako, Mali) and the Institute for Agro-biological and Soil fertility research (AB-DLO, Wageningen, The Netherlands).

1.2. Organization of the manual

The central question that will be addressed in Chapter 2 is: Land use analysis: why? We have already briefly touched on this subject in Chapter 1, however, the question will be answered in more depth in Chapter 2. This will be done by presenting a general discussion and the motivations for the two major case studies mentioned above.

When considering LUA studies one comes across many techniques of analysis. The technique of analysis that one may consider most appropriate will depend on the objectives of a study. In this course, only brief attention will be given to the various techniques. Main focus of the course is to acquaint participants with those techniques that can be used to analyze strategic options for development. Particular attention will be given to linear programming (LP) and to multiple criteria decision making (MCDM). Both techniques of analysis are very often used in LUA studies and an understanding of them is essential. They will be treated in Chapter 3. Problems concerning LUA today have become so complex that solving them without the use of computers and highly sophisticated software packages has become unthinkable. There are two computer packages that will be used during this course, namely LP88 and XPRESS. The former will mainly be used to introduce linear programming and the latter to exercise with more complicated problems. The two computer packages will be introduced at the end of Chapter 3.

In Chapter 4 the general methodology for explorative LUA is presented and discussed. This is done by focusing on the following components of explorative land use analysis studies: (1) system definition, (2) land evaluation, (3) concepts and definitions concerning the quantification of input - output relations, (4) the identification and quantification of constraints, (5) policy views and objective functions, (6) interactive multiple goal linear programming, (7) generation of land use scenarios and finally, (8) sensitivity analysis.

The manner in which the LUA methodology - described in Chapter 4 - was actually used in the European case study and in the PSS case study is described in Chapters 5 and 6 respectively. As this course particularly focuses on the work that has been done in the PSS project, the European case study will be treated in less detail. In Chapter 6, course participants will have the opportunity to exercise with a technical coefficient generator and the MGLP model that were developed by the researchers of the PSS project. These exercises will give more insight to participants concerning the strong and weak points of such studies. The last part of Chapter 6 will introduce the case study that is to be developed by the course participants. Using knowledge that they have accumulated during earlier stages of the course, for a specified region in Mali, the course participants will:
* make a study proposal that will be presented and discussed,
* generate the required data, making use of a technical coefficient generator,
* develop a multiple goal linear programming model;
* generate scenarios,
* conduct sensitivity analysis,
* interpret the results
* and finally, write a brief report, that will be presented and discussed in a plenary session.

With the aid of the TCG and the MGLP model it should be possible to execute this case study in relatively little time, and to concentrate on the policy views, the quantification of objectives and the development of scenarios.

2. Why explorative land use studies?

2.1. Introduction

Facing the future, everybody is in favor of sustainable development and it is likely that people take it as the guiding principle for their view on future development and future land use. However, everyone seems to have an own idea about sustainability. Sustainable development is hard to make operational, because of the various dimensions of sustainability (ecological, economic and social dimensions), the uncertainties about relations between these dimensions, and the difficulty to balance consequent environmental, economic and social risks. No wonder that there are many perceptions of sustainable development, which can be classified according to the perceptions of environmental risks and societal risks, e.g., the possibility to realize societal changes (WRR, 1995).

Explorative land use studies aim at revealing and quantifying the trade-off between the different perceptions of sustainable development and the

conflicting objectives involved. They aim at showing policy makers consequences of different policy aims for land use and thus at helping them in choosing aims.

In explorative land use studies the future possibilities are considered with an open mind. In these studies the past is not used as a measure for the future. Existing political, economical and societal structures are not taken for granted or extrapolated to the future, but they are treated in an explicit way. New possibilities are explored by combining technical possibilities with explicit political or societal desires. Explorative studies do not give blue prints how to arrive at new situations; they just present static end views. Realizing new technical possibilities and changing political or social structures is often a matter of political desire and an appropriate policy. Obviously, therefore, these studies need a follow up in order to answer questions of how to realize the end views and the appropriate policy instruments.

Explorative land use studies can be carried out for various reasons. As stated, ultimately the aim is to operationalize options for sustainable development. More down to earth, immediate motives can be various. Reclamation of a new territory can be a reason to carry out an explorative study. Setting of research priorities may be a factor. There may be problems with agricultural production, either shortage of food (in some Third World countries) or overproduction (e.g. in the European Union). Socio-economic problems with agricultural employment and farmers' income may play a role. Environmental issues and nature or landscape conservation may be motives.

In this chapter the general methodology for explorative land use studies is introduced. After this introduction a historical overview of the literature on explorative land use studies is given with special reference to the motives to carry out such studies. Finally, an extensive description is given of the immediate motives to carry out two examples of explorative studies, which are used as case studies in this course.

2.2. General methodology

Figure 2.1 highlights the general building blocks of the methodology for explorative land use studies.

The central technique that is used in the methodology is the Interactive Multiple Goal Linear Programming technique. IMGLP is a linear programming technique, not with one but with several objective functions. In each run of an IMGLP model, one objective function is optimized while the other objectives are used as constraints. Upper or lower bounds can be put on these `goal constraints'. For different policy views land use scenarios can be generated by optimizing and putting bounds on the most relevant combination of objectives. Chapter 3 deals with the principles and backgrounds of linear programming and the IMGLP method.

The IMGLP model is fed with different kinds of information. First of all, input-output relations on agricultural production, based on a land evaluation, are fed into the model. The input-output tables represent the quantification of different production activities on specific land units. They tell us the required inputs to produce certain outputs on a land unit with certain climatic and soil characteristics. Different production ecological concepts are used for a systematic and scientific quantification of the input-output relations.

Secondly, technical or fixed constraints are formulated which represent information about the various resources, such as area, water and available nutrients (manure). They can also be used to quantify more normative constraints like the consumption and trade of agricultural products in the system.

Finally a set of objective functions is distilled from the prevailing policy views that can be distinguished in the society of the system under study. Usually the objectives concern ecological, agricultural, economic and social aspects of sustainability.

With these three blocks of information the IMGLP model can be built. Land use scenarios can be generated with the IMGLP model for each of the policy views in the society of the system, by optimizing and putting upper or lower bounds on the most relevant combination of objectives for each of these policy views. The results for the scenarios include the values for the objective functions and the optimal regional land allocation (maps). Policy makers can now see how their priorities affect land use and how the effects are distributed over the system under study.

Figure 2.1 General methodology for explorative land use studies.

2.3. Examples of different applications of the methodology for explorative land use studies

The methodology for explorative land use studies presented in this course is rather new. Examples of explorative land use studies are not numerous. The examples differ in the time horizon of the study; some are more explorative (distant future) than others (near future).

The methodology builds on the work presented in Veeneklaas (1990). In that work, technical and economic analysis is dovetailed. A simple structured input-output model with technical relations was constructed. Poorly understood behavioral and normative relations are represented as constraints. The methodology uses an operations research technique, interactive multiple goal linear programming, an iterative procedure which makes it possible to deal with various objectives. This procedure was first used by Nijkamp & Spronk (1980) and Spronk & Veeneklaas (1983).

The Netherlands Scientific Council for Government Policy used the methodology in its study Scope for growth (WRR, 1987), focusing on the economic future of the Netherlands and on environmental issues.

For typical agricultural or land use problems several studies using the methodology have been carried out for the regional level. De Wit *et al*. (1988) presented a case study for a Mediterranean agro-pastoral region, the semi-arid zone in the Mediterranean Basin located in the northern Negev of Israel. Agricultural activities in that region consist of sheep husbandry and dryland farming. The approach resulted in options reflecting the various viewpoints or policy views for that region. Three viewpoints were distinguished: traditionalists, settlement agency, settlers' view, each with different opinions on the relevance of various objectives concerning development aid, the area under extensive systems, the import of concentrates, employment, the number of settlers in the region and the desired consumption. Table 2.1 gives an example of scenarios for the three policy views. The different attitudes against the various objectives affect the land use and the use of various sheep breeds.

The first real agricultural application of the method is that in the Mariut project (Ayyad & Van Keulen, 1987). That project aimed at assessing the potentials of different agricultural systems for the purpose of regional planning in the Northwestern coastal zone of Egypt. The main agricultural activities distinguished in the region were fruit production (olive and fig trees), barley production and animal husbandry (sheep and goat meat production). Optional land use systems were formulated and their economic feasibility and impact on the natural resources were investigated. The results aimed at helping planners to introduce or promote those systems.

An extensive study using the methodology, was carried out for the fifth region of Mali, in the framework of the second five-year plan, formulated in cooperation with the World Bank (Van Keulen & Veeneklaas, 1993). The study aimed at increasing insights in the agricultural production systems in the Region, and their major constraints, as a basis for the formulation of a land use plan, that would take into account the potentials of the natural resources and the development objectives of the various actors involved in the development process. This study is used as a case study in this course. This Chapter will discuss the background and motives to carry out this study.

The Netherlands Scientific Council for Government Policy carried out the study `Ground for Choices' (WRR, 1992; Rabbinge & Van Latesteijn, 1992) for future land use in the European Community. Their study shows the conflicts arising from increasing agricultural productivity, market saturation, differences in production and productivity within the EC and increasing concern for regional employment, environment, nature and landscape. This study is also used as case study in the course. This Chapter will discuss the background and motives of this study.

In Costa Rica a more or less explorative study is carried out for the Atlantic Zone, in the USTED study (Alfaro *et al*., 1994). Problems with the marketing of agricultural products and growing concern about loss of bio-diversity, sustainable exploitation of natural resources and widespread land speculation were arguments for the Wageningen Agricultural University to carry out a study on future land use in the Atlantic Zone.

Table 2.1 Summary of results of the IMGLP model for three policy views, in the case study for a Mediterranean agropastoral region

		traditionalists	settlement	settlers agency	unit
bounds on the goals					
development aid	=	0	0	0	$/year
extensive system	≥	600	75	75	10^3 ha
imported concentrates	=	0	free	free	kg
hired labour	≤	free	200	free	p. year
results for objectives					
employment		13000	15000	10600	p. year
settlers		11740	14800	6000	p. year
linear growth rates settlers		43	74	0	p. year/year
hired labour		1260	200	4600	p. year
consumptive income		121	196	169	10^6 $
consumptive income/settler		11	14	28	10^3 $/year
some results on land use					
nitrogen fertilizer use		1600	650	608	10^3 kg
phosphorus fertilizer use		243	866	643	10^3 kg
area wheat/fallow		0	0	0	ha
area wheat/wheat		8400	3700	100	ha

area wheat/legume	851	15100	16900	ha
total area wheat	9251	18800	17000	ha
area extensive systems	60	12	8	10^3 ha
number of sheep of various breeds				
Awassi systems	0	0	0	ewe eq.
improved Awassi systems	122300	42700	35300	ewe eq.
Merino systems	15100	75300	70500	ewe eq.
Finn cross systems	10	27200	27100	ewe eq.
total number of sheep	137410	145200	132900	ewe eq.

Source: De Wit *et al*. (1988).

The principles of the methodology are also used in studies at farm level. Schans (1991) carried out a study for the optimization of arable farming systems that integrate economic and ecological goals. Farming systems in the Dutch Flevopolders with ware potatoes as a major cash crop were used as a case study. Similar studies were carried out for dairy farming systems (Van de Ven, 1994) and arable farms with flowerbulb-based rotations in the Netherlands (Rossing *et al.,* 1997). New research projects are started in 1994, to investigate possibilities for mixed farming systems (arable and dairy systems) in the Netherlands, both at the farm and regional level.

Stroosnijder & Van Rheenen (1993) applied the methodology for small mixed farms in East Java, taking into consideration aspects of food security, farmer's welfare and environmental concern. The results of this study are published in Van Rheenen (1995).

2.4. Background and motives of the case: Competing for limited resources in the 5th region of Mali

2.4.1. General characteristics on the economy of Mali

The principal characteristics of the economy of Mali are essentially those of most of the developing countries, that is (Table 2.2) .

Table 2.2 The national product of Mali in 1990, its subdivision and some other characteristics of the malian economy of Mali (in billion F cfa)

		distribution of the GNP	%
gross national product	666	primary sector	45.6
growth rate in volume (%)	1.0	food crops	13.1
per capita GNP (thousands of F cfa)	82.4	cash crops	3.4
		animal production	22.9
imports	168	fisheries	0.9
of which : food products	19	tree plantations	5.2
machines and cars	60		
oil products	15	secondary sector	12.8
exports	94	industry	6.5
of which : cotton	44	mines	1.5
livestock	25	art	1.3
gold and diamonds	13	buildings. public works	3.6
exports/imports (%)	56		
		tertiary	37.0
trade balance (exp. - imp.)	-74	transport	4.7
goods and services balance	-96	trade	17.9
current balance	-34	services	14.4
balance of payments	20		
budget :			

- receipts	250	import tax	4.6
- expenditures	261		
- deficit	11	total	100
public debt			
- current	1046		
- services	19		
- ratio service/exports (%)	20		

Source: DNSI, 1992.

* The per capita Gross National Product (GNP) is low (around US $270).
* The primary sector is the largest contributor to the GNP, almost 50 %, which is for almost 100 % accounted for by crop and animal production. The contribution of the tertiary sector is around 37 % of GNP. The contribution of industrial activities to GNP is still weak, and is mainly constituted by cotton, cloth, sugar, non alcoholic drinks, cigarettes and electricity.
* Imports are essentially machines and cars (36 % in 1990), followed by food products and oil products.
* Main export products are: cotton (47 % in 1990), livestock, gold and diamonds
* The trade balance is negative
* The budget has an important deficit
* Mali has a big public debt, which is greater than the GNP for one year. And although the debt service is about 25 % of the value of exported products, the debt is not becoming smaller.

Like many other African countries, Mali is in a period of transition where its economic environment is concerned. The Structural Adjustment Programs (SAP) that are carried out are characterized by less state intervention at many societal levels and various other economic reforms. The most important measures taken in this program are the progressive liberalization of the cereal market, the reform of the cotton marketing, limitation of public expenditure (especially salaries), and finally the reform of the public sector : liquidation, privatization and rehabilitation. To strengthen the SAP, the Franc CFA has undergone a devaluation of 50 %, which should help Mali and other countries with the same currency to become more competitive.

Crop and livestock husbandry

Only around 4 % of the area of Mali is arable land, 75 % of which is actually occupied by crops (Table 2.3). Food crops occupy 85 % of cropped area in Mali. Cash crops occupy only a relatively small area and also represent a relatively small percentage of total product value (7,6 % of the added value of the primary sector). Cereals represent 90 % of area under food crops. This predominance of cereals is also crucial for livestock, as it implies a big availability of byproducts that can be used as animal feed. Groundnut and cowpea yield considerable quantities of good quality hay.

Prices of a number of important crops are given in Table 2.4.

Table 2.3 Potential land occupation in Mali

	area
total area	124 million ha
arable land	5.2 million ha
cropped area	3.9 million ha

Source: Project PIRL cited by DNSI (1991).

Table 2.4 Producer prices for various crops (F cfa kg^{-1}), 1980-90

	cultures				
year	millet, sorghum	maize	rice	groundnut	cotton (1st choice)
1981	35	35	38	40	55
1982	43	45	50	45	55
1983	45	48	55	55	65

1984	50	50	60	na	65
1985	50	50	60	na	75
1986	55	55	70	na	85
1987	55	55	70	na	85
1988	50	36	70	68	85
1989	42	33	70	69	85
1990	63	51	78	na	85
1991	80	56	81	na	93
1992	47	36	58	na	93
1993	51	41	na	101	na
1994	45	37	na	na	na

(na : not available)

Sources: (DNSI, SIM/PAM, DPAER/IER)

Population, education and health

In 1987 Mali had a population de 7,7 million habitants (DNSI, 1991d), which comes down to an average population density of 6 inhabitants per km^2. The growth rate is around 2.7 % per year (Banque Mondiale, 1994). The population is not evenly distributed between the 7 administrative regions, because 75 % of the population is concentrated on 25 % of the territory in the regions of Ségou, Sikasso, Mopti, and Koulikoro and in the town of Bamako (see Table 2.5). The regions of the North, Gao and Tombouctou, to which is recently added the region of Kidal, have less than 900,000 inhabitants in 1987, while they occupy more than 60 % of the national territory. The demographic data show that the population is essentially rural (78 %).

The sedentary population represents 96 %, the nomadic population 4 %. There are many ethnic groups in Mali, of which the most important (numerically) are : Bambara, Malinké, Sarakolé, Sonrhaï, Dogon, Sénoufo, Bobo, Minianka, Fulani, Maure and Tamachecks. The nomadic ethnies are mainly pastoralists: the Fulani, the Maures and the Tamacheck.

Table 2.5 Structure of the population of the Mali according to various ways of classification

socio-demographic category	%	administrative region	%	density
< 8 year	24	Kayes	13.9	8.9
8-14 year	22	Koulikoro	15.6	12.5
15-59 year	48	Sikasso	17.0	18.7
> 60 year	6	Ségou	17.4	20.7
urban	22	Mopti	16.6	16.2
rural	78	Tombouctou	6.0	0.9
nomad	4	Gao	5.0	1.2
sedentary	96	Bamako	8.5	2612

Source: DNSI (1991d, Tables 5a, 7, 13, 15)

The distribution of the active population per sector is given in Table 2.6. The data show that the primary sector occupies the first place, which underlines again the importance of this sector for the malian economy.

Table 2.6 Distribution of human labor force among economic sectors

sector	%
primary sector (agriculture, animal husbandry, tree plantations, fishery)	82
secondary sector (industry, mines, art, buildings and public works)	6
tertiary sector (transport, trade, service, administration, others)	12

Source: DNSI (1991e, page 40)

The statistics for the educational sector in Mali (Table 2.7) show that relatively few children go to school. 24 % for primary education is even the lowest figure of the entire West African region. In other countries in this region, the percentage is on average 61 % and varies from almost 30 % (Niger) to almost 100 % (Cap Vert). During the last decade the fraction of children going to school has had a tendency to decline. The fraction of girls going to school is only half of that of the boys.

Table 2.7 Education indicators in Mali

fraction going to school rate	%	literacy rate	%
primary education			
- total	24	total	17
- boys	30	men	23
- girls	17	women	11
secondary education	6		

Table 2.8 summarizes some health indicators of Mali. Child mortality is very high, 161 of 1000 children die before the age of one year. For the other sub-Saharan African countries this is 104, and in developed countries only 8. Mortality rates of children under five years of age, almost 25 %, is for over 70 % due to diseases that can be prevented with adequate medical care, like malaria, tetanus, respiratory infections, and diarrhea. Another problem is malnutrition, of which almost one of three children under five years suffers.

Table 2.8 Health and nutrition indicators in Mali

life expectancy	48 year
infant mortality (0-12 month)	161/1000
malnutrition (< 5 year)	31 %
vaccination rate (children)	25 %

2.4.2. The PSS project

The PSS project is a cooperative project between Mali and the Netherlands. The project lasted from 1991 to 1996.

The main objectives of the project were to:
* contribute to the development of sustainable and economically viable agricultural production systems
* strengthen the local research capacity through training of national scientists

The study region is the sudano-sahelian zone, characterized by rainfall between 300 and 900 mm year^{-1} in West Africa. In this zone the two main types of agricultural production, crop and animal husbandry, are strongly linked. Production of grass, leaves, and fruits on rangelands, fodder crops, crop residues and agro-industrial products serve as animal feed, while dung and animal traction, by-products of animal production activities, are used in crop production. Moreover, buying animals is a means of savings for many farmers.

In the sudano-sahelian zone cropped areas and rangelands are characterized low yields, which are due in the first place to low soil fertility, not, in this region, to lack of water (Penning de Vries & Djitèye, 1982; Van Keulen & Breman, 1990). Water availability is nevertheless a big problem, mainly because of the great variability in rainfall (Vierich & Stoop, 1990). Soil poverty is worsened by a strong demographic growth, which leads to degradation of land and other natural resources. This corroborates even more the rural production possibilities. On cropped land the fallow periods are shortened, while the quantities of organic matter and nutritive elements don't suffice to restore soil fertility (Van de Pol, 1992). Rangelands suffer from overgrazing, causing erosion, loss of perennial species and decreasing number of trees. Animal production also suffers from low productivity, with as a key problem the lack of good quality feed, especially in the dry season (Penning de Vries & Djitèye, 1982).

Technically speaking, solutions to the various problems may exist. Van Keulen & Breman (1990) show that agricultural productivity could be boosted with the use of more nutritive elements (especially nitrogen and phosphorus), provided that the organic matter balance is in equilibrium. Higher input of nutrients would also increase the ecological sustainability of the primary production. As the quantity of organic matter used to fertilize the fields is not sufficient to maintain an equilibrium on the nutrient balances an increase in the use of chemical fertilizers seems to be a

conditio sine qua non for sustainable agricultural development.

In animal production higher productivity is to be attained by an increasing use of feed supplements (crop residues, fodder crops, agro-industrial products), while lowering the pressure on the natural rangelands. This option requires a higher production of supplements. Thus, animal production systems would also profit from the use of fertilizer in primary production, either directly, by its use for fodder crops, fodder banks and improved rangeland systems, or indirectly through its use in food crops and cash crops, which would lead to an increase in quantity and in quality (higher concentration of nutrients) of crop residues.

At present the indicated solutions are not applied at a large scale. This is due to a number of factors, among which the cost of fertilizer. This shows that it is necessary to analyze not only technical but also socio-economic aspects of the problem. The systems research of the PSS project had as its objective to analyze in an integrated manner the various technical options (varying according to the climatic region) and the socio-economic conditions, taking into account the availability of resources, the need for sustainable production and the objectives of the region.

2.5. Background and motives of the case: Four perspectives for the rural areas in the European Community (Rabbinge et al., 1994a)

The European Community - History and statistical data

The European Economic Community (European Union since 1993) was founded in 1957 in Rome to encourage a general economic integration of West-Germany, the Netherlands, Belgium, Luxembourg, France and Italy. The first aim was one common market with free movement of people, commodities, services and capital. In 1968 the customs union came about: the customs duties between the six member states were gradually abolished and one common tariff against non-member states was set up. Also in 1968 a Common Agricultural Policy started. The purposes of this policy were already formulated in 1957 in the treaty of Rome:
* increasing the agricultural productivity;
* taking care for a reasonable standard of living for the agrarian population;
* stabilization of the markets;
* guaranteeing the food supply for reasonable prices for the consumers.

In 1973 the UK, Denmark and Ireland joined the EC, in 1981 Greece and in 1986 Spain and Portugal.

Currently, the EC counts 12 member states, with an area totalling 229 million ha. The largest countries are France and Spain and the smallest countries are Luxembourg, Belgium and the Netherlands. The EC counts 324 million inhabitants (4.2 % of the world population), of which most people live in the UK, Germany, France and Italy (Table 2.9). The most densely populated countries are the Netherlands and Belgium and the least densely populated countries are Ireland, Greece and Spain. The growth of the population is expected to amount less than one promille per year.

Table 2.9 The area, population, population density and the percentage of employment in agriculture in the European Community (excluding the former East Germany)

country	area (mil. ha)	population (millions)	pop./area (/km^2)	% empl. in agriculture
EC-12	229	324	143	7.6
Denmark	4.3	5.1	119	5.8
UK	25	57	233	2.4
Ireland	7.0	3.5	50	15.8
FR Germany	25	61	246	4.5
Netherlands	3.5	15	368	4.8
Belgium	3.1	10	323	3.2
Luxembourg	0.3	0.4	143	3.9
France	55	56	101	7.2
Italy	31	57	190	9.8
Greece	14	10	76	26.6
Spain	52	39	77	14.3
Portugal	9.3	10	111	21.2

Source: Eurostat (1989)

Table 2.10 Total area, agricultural area, percentage agricultural area (% AA) and the percentage grassland in the EC-12 (excluding the former East Germany

country	area 10⁶ ha	agr. area 10⁶ ha	% AA	% grassland
EC-12	229	129	56	21
Denmark	4.3	2.8	65	5
UK	25	18	75	46
Ireland	7.0	5.7	82	66
FR Germany	25	12	48	18
Netherlands	3.5	2.0	58	33
Belgium	3.1	1.4	46	21
Luxembourg	0.3	0.1	48	27
France	55	31	57	22
Italy	31	18	57	16
Greece	14	5.7	41	13
Spain	52	27	52	13
Portugal	9.3	4.5	49	8

Source: Eurostat (1989).

In the EC there are 128 million places of work. There are large differences in employment over the different economical sectors between the different member states. On average 7.6 % of the people is employed in agriculture, 33.2 % is employed in industry and 59.2 % is employed in services. In the UK only 2.4 % is employed in agriculture, whereas in Greece more than 25 % is employed in agriculture.

The European community is located between 35 and 60 N and is surrounded by the North Sea, the Atlantic Ocean and the Mediterranean. The climate in the EC can be divided in four categories: (i) a sea climate in the north-west with moderate winters, cool summers and constant precipitation throughout the year; (ii) a land climate in the east with cold, dry winters and warm summers;

(iii) the Mediterranean climate in the regions around the Mediterranean with moderate, humid winters and warm, dry summers and (iv) the mountain areas with their own climate.

About 56 % of the total area consists of agricultural land (129 million ha - Table 2.10). This percentage varies for the member states between 41 % (Greece) and

82 % (Ireland). The percentage grassland of this agricultural area varies greatly among the different countries: 5 % in Denmark and 66 % in Ireland.

Table 2.11 gives some information about the current and potential wheat yields in the different member states. Yields are highest in the Northern states: the Netherlands, UK, Denmark, Belgium and Germany and lowest in the Southern states: Portugal, Spain, Greece and Italy. The actual average wheat yield in the EC amounts 5.1 ton ha^{-1}. For potatoes the average yield is 28 ton ha^{-1}. Between the individual countries the potato yields vary between 9.0 ton ha^{-1} in Portugal and 43 ton ha^{-1} in the Netherlands.

Table 2.12 shows the production of the main agricultural products. For many products self-sufficiency is more than 100 % and this was one of the reasons to start a study, carried out by the Netherlands Scientific Council for Government Policy (WRR): Four perspectives for the rural areas in the European Community.

Background of the study

In general terms the Common Agricultural Policy of the EC was rather successful: most goals were achieved. However, there are also problems. At present the situation in EC agriculture can be characterized as follows:

a. Due to an increasing productivity in the Community a situation of self-sufficiency for most agricultural products was realized (Table 2.12).

b. After self-sufficiency was reached, productivity growth continued to rise. This has led to overproduction with major budgetary consequences. The system of guaranteed prices for most agricultural products requires an increasing amount of money from the European tax payer to finance.

c. At the same time attention has grown for other goals than agricultural production. Environment, employment and farmers income are nowadays tightly linked to developments in agriculture. The considerable overuse of pesticides and plant nutrients due to their low prices, has created immense environmental problems in some parts of the EC.

d. There is a growing tension between the EC and the world market, especially the USA. In the GATT negotiations the price policy for agricultural products in the EC was a hot issue.

Table 2.11 The distribution of wheat production within the EC (excluding the former East Germany), the actual wheat yields and the actual wheat yields as percentage of the calculated Potential (PP) or Water-limited production (WLP) as a measure for the management level in the EC-12

country	production volume (% of EC-total)	wheat yield (ton ha^{-1})	actual production as % PP	actual production as % WLP
Denmark	2.6	6.3	67	95
UK	16.9	6.8	62	77
Ireland	0.7	3.8	62	69
FR Germany	13.4	6.2	60	67
Netherlands	1.4	7.4	74	85
Belgium	1.6	6.4	62	72
Luxembourg	0.0	4.3	40	53
France	39.8	5.9	54	67
Portugal	0.5	1.6	12	24
Spain	7.6	2.5	26	60
Italy	12.5	3.8	29	37
Greece	3.0	2.5	31	38

Source: De Koning & Van Diepen (1992).

Developments in productivity show a steady increase all over the world. In Figure 2.2 the increase in yield per hectare for wheat is shown. Both the UK and the USA show an ongoing rise in productivity especially after World War II. Of course these developments will not go on forever, although until now there is no slowing-down. When and at which level the maximum will be reached is not very clear. Because of this increasing productivity it seems possible to guarantee food security within the Community with only a relatively small number of farmers on a relatively small area. Much space and work force can be used for other aims, like nature conservation and recreation.

The study of the WRR was aimed at defining the limitations to this growth in productivity. In the end those limitations will define the possibilities of agriculture.

Table 2.12 Production and self-sufficiency percentage of some agricultural products in the EC-12 (excluding the former East Germany

product	production (mil. tons)	selfsufficiency %
wheat	72	124
barley	47	118
grain maize	26	96
total cereals	154	114
potatoes	42	103
sugar	13	136
wine	17	104
vegetables	45	106

milk	113	102 (cheese)
		115 (butter)
meat	31	102
eggs	5	102

Source: Eurostat (1990).

Figure 2.2 *Development of soil productivity for wheat in the UK and the USA. Source: Rabbinge & Van Latesteijn, 1992.*

The study of the WRR was aimed at defining the limitations to this growth in productivity. In the end those limitations will define the possibilities of agriculture in the Community. The limitations are of three types:

1. technical limitations: there is a well defined yield maximum for each crop, given crop properties and climatic conditions. This tells us how much useful product can be produced when plants grow under optimal conditions.

2. demand limitations: now that population growth in the EC has almost come to a standstill, consumption will no longer rise.

3. limitations that stem from policy objectives: socio-economic aims in the field of nature conservation, recreation and the like.

2.6. Exercises

1. Why are explorative land use studies needed? Summarize the arguments and present them in the group.

2. On the basis of the information that you have received concerning the European study and the PSS study indicate in which ways they are similar and in which ways they are different.

3. Explain what the main differences are between explorative and predictive land use analysis studies.

3. Linear programming and multiple criteria analysis

3.1. Introduction

In the methodology for explorative land use studies operations research (mathematical programming) techniques are used, which help us to select the best option(s) from numerous alternatives. The main technique which is used is Interactive Multiple Goal Linear Programming, a Linear Programming technique. Although it is not necessary to know and understand all the ins and outs of this technique, a short introduction about the theory and principles is indispensable. If one wants to know more about operational research techniques, we advise them to study a handbook, e.g. Hendriks & Van Beek (1991; in Dutch), Hillier & Lieberman (1989; in English) and Romero & Rehman (1989; in English about multiple criteria analysis).

Before dealing with multiple criteria optimization techniques and with Interactive Multiple Goal Linear Programming in particular (3.3), we will deal with Linear Programming (3.2). The only essential difference between the two techniques is that in LP there is only one objective (e.g. financial return or numbers of hectares), that is optimized, whereas in IMGLP there are several objectives to be optimized. In this course, the theory and principles of Linear Programming will be treated by means of an example (3.2.1). The problem in this example will be solved along `three ways':
* graphically;
* algebraically;
* computer software (LP88/XPRESS).

The final part of this chapter introduces the LP88 and XPRESS software, which is used in this course (3.4).

3.2. Linear programming

3.2.1. An example

A farmer in Spain with no possibility to irrigate, wants to achieve a maximum harvestable dry matter production from two crops: wheat and potatoes. One hectare of wheat yields 2 tons dry matter (coefficient in the objective function: 2) and one hectare of potatoes yields 5 tons (coefficient in the objective function: 5).

The farmer faces three constraints:
1. he has only 6 hectares of arable land;
2. the farmer is not allowed to grow more than 4 ha wheat, because of the MacSharry rules;
3. on a certain plot, potatoes may not be grown more than once every two years.

Of course the number of hectares with wheat and potatoes are non-negative. The mathematical formulation of this problem is given in Scheme 1.

Scheme 1 An example of an LP-problem.

---

maximize $\{w = 2x_1 + 5x_2\}$ (in t) (1)

subject to

$x_1 + x_2 \leq 6$ (total area constraint) (2)

$x_1 \leq 4$ (market constraint wheat) (3)

$x_2 \leq 3$ (area constraint potatoes) (4)

$x_1 \geq 0, x_2 \geq 0$ (5)

where x_1 = number of hectares under wheat (ha)

x_2 = number of hectares under potatoes (ha)

3.2.2. Decision variables or activities, constraints and objective function

An LP-problem consists of:
* decision variables or activities (x_1: the number of ha with wheat and x_2: the number of ha with potatoes) in the system;

* the (resource) constraints (Relation 2-5): they determine the feasible combinations of the decision variables or activities;
* objective function (Equation 1): this function describes the aim of optimization and measures how `good' a certain combination of decision variables is.

Scheme 2   *The general algebraic form of an LP-problem, the canonical form.*

maximize $\{w = c_1 x_1 + c_2 x_2 + \ldots + c_n x_n\}$

subject to:

$a_{11} x_1 + a_{12} x_2 + \ldots + a_{1n} x_n \leq b_1$
$a_{21} x_1 + a_{22} x_2 + \ldots + a_{2n} x_n \leq b_2$

$a_{m1} x_1 + a_{m2} x_2 + \ldots + a_{mn} x_n \leq b_m$

$x_1 \geq 0, \; x_2 \geq 0, \; \ldots, \; x_n \geq 0$

or in vector and matrix notation:

maximize $\{w = c'\underline{x}\}$

subject to:

$A\underline{x} \leq \underline{b}$ (A is an (m x n) matrix)
$\underline{x} \geq 0$

$$c' = (c_1, c_2, \ldots, c_n) \qquad \underline{x} = \begin{pmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{pmatrix} \qquad \underline{b} = \begin{pmatrix} b_1 \\ b_2 \\ \vdots \\ b_m \end{pmatrix}$$

$$A: \begin{pmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & & \vdots \\ a_{m1} & a_{m2} & \cdots & a_{mn} \end{pmatrix}$$

Scheme 2 The general algebraic form of an LP-problem, the canonical form.

3.2.3. Formulation

Scheme 2 shows the general algebraic form of an LP-problem. This is the canonical form of the LP-problem. The matrix A is the matrix of coefficients of the LP-problem. This matrix has the dimension: m (rows constraints) x n (columns activities).

Example: Our LP-problem can be written with matrix A (dimension 3 x 2) and vector $\underline{b}$:

$$A: \begin{pmatrix} 1 & 1 \\ 1 & 0 \\ 0 & 1 \end{pmatrix} \qquad\qquad \underline{b}: \begin{pmatrix} 6 \\ 4 \\ 3 \end{pmatrix}$$

Scheme 3   *The standard form of an LP-problem.*

maximize $\{w = c_1x_1 + c_2x_2 + ... + c_nx_n\}$

subject to

$$a_{11}x_1 + a_{12}x_2 + ... + a_{1n}x_n + y_1 = b_1$$
$$a_{21}x_1 + a_{22}x_2 + ... + a_{2n}x_n + y_2 = b_2$$

$$a_{m1}x_1 + a_{m2}x_2 + ... + a_{mn}x_n + y_n = b_m$$

or in vector and matrix notation:

max $\{w = c'\underline{x}\}$

subject to

$A\underline{x} = \underline{b}$ (A is an (m x n) matrix)

$\underline{x} \geq 0$

$c' = (c_1, c_2, ..., c_n)$

$$\underline{x} = \begin{pmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \\ y_1 \\ \vdots \\ y_n \end{pmatrix} \quad \underline{b} = \begin{pmatrix} b_1 \\ b_2 \\ \vdots \\ b_m \end{pmatrix} \quad A: \begin{pmatrix} a_{11} & a_{12} & \cdots & a_{1n} & 1 & 0 & \cdots & 0 \\ a_{21} & a_{22} & \cdots & a_{2n} & 0 & 1 & \cdots & 0 \\ \cdot & \cdot & \cdots & \cdot & 0 & 0 & \cdots & 0 \\ \cdot & \cdot & \cdots & \cdot & 0 & 0 & \cdots & 0 \\ \cdot & \cdot & \cdots & \cdot & 0 & 0 & \cdots & 0 \\ a_{m1} & a_{m2} & \cdots & a_{mn} & 0 & 0 & \cdots & 1 \end{pmatrix}$$

Scheme 3 The standard form of an LP-problem.

3.2.4. Transformations

Besides the canonical form of the LP-problem, there is also the *standard form* (Scheme 3).

In this formulation the inequalities A $\underline{x} \leq \underline{b}$ are replaced by the equations A$\underline{x}$=$\underline{b}$, by introducing so called `*slack variables*':

The inequality [Sigma] $a_{ij}x_j$ b_i is equivalent to the equality [Sigma] $a_{ij}x_j + y_i = b_i$ ($y_i \geq 0$), in which y_i is a slack variable.

Example:

Our example can be reformulated in the standard form by adding the slack variables y_1, y_2 and y_3:

max $\{w = 2x_1 + 5x_2 + 0y_1 + 0y_2 + 0y_3\}$

subject to

$x_1 + x_2 + y_1 = 6$

$x_1 + y_2 = 4$

$x_2 + y_3 = 3$

x_1, x_2, y_1, y_2 and $y_3 \geq 0$

A number of transformations exists by means of which any LP-problem can be reformulated in its equivalent standard or canonical form:
1) max $\{\underline{c}'\underline{x}\}$ is equivalent to max $\{\underline{c}'\underline{x} + k\}$ and vice versa;
2) max $\{\underline{c}'\underline{x}\}$ is equivalent to max $\{k\underline{c}'\underline{x}\}$ (k>0) and vice versa;
3) max $\{\underline{c}'\underline{x}\}$ is equivalent to min $\{-\underline{c}'\underline{x}\}$ and vice versa;
4) a decision variable x_j ($x_j \leq 0$) can be replaced by $x_j^* = -x_j$ ($x_j^* \geq 0$);

5) a variable x_j which can either be negative or positive can be replaced by $x_j = x_j^+ - x_j^-$, where $x_j^+ = \max\{x_j, 0\}$ and $x_j^- = \max\{-x_j, 0\}$, so $x_j^+ \geq 0$

and $x_j^- \geq 0$;
6) the inequality [Sigma] $a_{ij}x_j \leq b_i$ can be replaced by: [Sigma] $a_{ij}x_j + y_i = b_i$, where $y_i \geq 0$;

7) the inequality [Sigma] $a_{ij}x_j \geq b_i$ can be replaced by: [Sigma] $a_{ij}x_j - y_i = b_i$, where $y_i \geq 0$.

Examples:
1) max $\{2x_1 + 5x_2\}$ is equivalent to max $\{2x_1 + 5x_2 + 100\}$;

2) max $\{2x_1 + 5x_2\}$ is equivalent to max $\{2000x_1 + 5000x_2\}$;

3) max $\{2x_1 + 5x_2\}$ is equivalent to min $\{-2x_1 - 5x_2\}$;

4) $\{x_1 - x_2\}$ ($x_2 \leq 0$) is equivalent to $\{x_1 + x_2^*\}$ ($x_2^* = -x_2$; $x_2^* \geq 0$);

6) the inequality x_1 4 can be replaced by $x_1 + y_1 = 4$, where $y_1 \geq 0$;

7) the inequality $x_2 \geq 8$ can be replaced by $x_2 - y_2 = 8$, where $y_2 \geq 0$.

3.2.5. Assumptions and restrictions

There are some assumptions/restrictions underlying linear programming:
1) the objective function and the constraints must be linear in the decision variables; non-linear functions could be split up in smaller `linear' parts;
2) all parameters are assumed to have fixed and known values;
3) the variables are assumed to be real (continuous); it is possible to include integer variables (mixed integer programming), but this requires special solving methods (e.g. the Branch-and-Bound method), which can dramatically increase the computing time.

3.2.6. Solutions

Linear programming problems can be solved graphically if the problem comprises only two decision variables. When the problem comprises more than two decision variables it can only be solved algebraically, e.g. by means of the so called *simplex-algorithm*. The graphical method is illustrated for our example in Figure 3.1

Figure 3.1 Graphic representation of a linear programming model. The solution space (shaded) and iso-profit lines (dashed lines) Source: Rossing, 1989.

Graphically it can be understood that there are four classes of solutions of LP-problems (Figure 3.2), depending on the characteristics of the solution(s):
* unique solution (Figure 3.2a);
* alternative solutions (Figure 3.2b);
* unbounded solutions (Figure 3.2c);
* no feasible solution (Figure 3.2d).

For the classes of unique and alternative solutions it is clear that the optimal solution(s) lay(s) at the border of the *feasible space* (solutions that meet the constraints but which are not necessarily optimal), and an unique solution lays at an angular point of the feasible space.

Figure 3.2 Four classes of solutions of LP problems. Source: Hendriks & Van Beek (1991).

Figure 3.2.a(a): Unique solution

3.2.7. Simplex-algorithm

For problems with more than two decision variables the simplex-algorithm is the most important tool to solve linear programming problems. Computer software is indispensable to solve practical LP-problems, because they often comprise over thousand variables. The simplex-algorithm will be illustrated with our example, with just two decision variables.

The simplex tableau: The first step is to write the LP-problem in its standard form. In our example this can be done by adding the slack variables y_1, y_2 and y_3 to the constraints (2), (3) and (4) respectively (compare Schemes 1 and 4). Subsequently, the first *tableau* is made (Scheme 4).

The Right Hand Side (RHS) of all tableaus (the b-values) should be non-negative: if the first tableau comprises negative RHS-values, transformation(s) should be carried out. The first tableau (and all other tableaus) should comprise an *unity basis*, with the dimension of the number of rows. The variables `belonging to the unity vectors' are called the *basic variables* (in Tableau 1: y_1, y_2 and y_3). The bottom row of the tableau represents the objective function formulated in such a way that the objective value w is expressed in the *non-basic variables* (in other words: activities that increase the value of the objective function get a negative coefficient and activities that decrease the value of the objective function get a positive coefficient; basic variables get the zero coefficient in the objective function; the objective function in our example expressed in the non-basic variables: $w-2x_1-5x_2=0$).

A *basic feasible solution* of an LP-problem is a solution with non-negative values for all basic variables and zero values for the non-basic variables (in that way the basic feasible solution can be read from the RHS of the tableau). A basic feasible solution coincides with an angular point of the feasible space. In the iterations of the simplex-algorithm we move from one angular point to another and thus (according to one of the important propositions of linear programming) from one basic feasible solution to another, until the optimal basic feasible solution has been found (if such a solution exists). It can be proven that if an optimal feasible solution exists, an optimal basic feasible solution also exists. The *simplex-algorithm* tells us how to move from one angular point (basic feasible solution, tableau) to another and when to stop this procedure, because the optimum solution(s) has (have) been found. The simplex-algorithm will be explained very briefly and incompletely by means of our example.

Tableau 1 comprises the three unity vectors for the three slack variables. The two decision variables are the non-basic variables and thus zero in the basic feasible solution (angular point O in [Figure 3.1](#)). In the first iteration the best candidate for the entering basic variable is one of the current non-basic variables which increase the objective function at the fastest rate (i.e. the decision variable with the most negative coefficient in the bottom row of the tableau). The leaving basic variable is the basic variable which reaches zero first as the entering basic variable is increased. In our example, x_2 is the variable which contributes most per unit to the objective function. This variable can be increased until constraint 3 becomes limiting, i.e. $x_2 = 3$ (angular point A in Figure 3.1); y_3 leaves the basis. By means of a so called `pivot-operation' around the pivot (marked with an asterix in Tableau 1), Tableau 2 is generated. The value of the objective function has increased from zero to 15 (3*5).

Scheme 4   The simplex tableaus of our LP-example.

$$\max \{w = 2x_1 + 5x_2\}$$

$x_1 +$	$x_2 +$	y_1			$= 6$
x_1		$+$	y_2		$= 4$
	x_2		$+$	y_3	$= 3$
$x_1,$	$x_2,$	$y_1,$	$y_2,$	y_3	≥ 0

LP-problem in standard form

non basic variables   basic variables

x_1	x_2	y_1	y_2	y_3	b
1	1	1	0	0	6
1	0	0	1	0	4
0	1*	0	0	1	3
-2	-5	0	0	0	0

unity basis

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Tableau 1

x_1	x_2	y_1	y_2	y_3	b
1*	0	1	0	-1	3
1	0	0	1	0	4
0	1	0	0	1	3
-2	0	0	0	5	15

Tableau 2

x_1	x_2	y_1	y_2	y_3	b
1	0	1	0	-1	3
0	0	-1	1	1	1
0	1	0	0	1	3
0	0	2	0	3	21

Tableau 3

Scheme 4 The simplex tableaus of our LP-example.

Mathematically, the pivot a_{kp} can be found in the column of the new basic variable x_p, such that $b_k/a_{kp} = \min \{b_i/a_{ip}|$ for all $a_{ip} > 0\}$. In the pivot-operation the row comprising the pivot is divided by a_{kp}, so that the pivot gets the value 1. Subsequently, the row comprising the pivot is added to or subtracted from the other rows so that the pivot column (including the coefficient of the bottom row) represents an unity vector. In summary:

Step 1. Selection of pivot column: column with most negative value in bottom row;
Step 2. Selection of pivot row: row with smallest ratio between b-value and positive element in the pivot column;
Step 3. Derive the new pivot row: dividing each element in the pivot row by the pivot;
Step 4. Derive other rows: substracting (or adding) a suitable multiple of the pivot row from (or to) each of the other rows, such that all other elements in the pivot column equal zero.

The next step is to check whether the solution which has been found after the pivot operation is optimal or not: in other words check whether the objective function can be increased by increasing any non-basic-variable. This can be done by checking whether there are any non-basic variables with a negative coefficient in the bottom row of Tableau 2. Again, the variable with the most negative coefficient is selected and again the leaving basic variable is the basic variable which reaches zero first as the entering basic variable is increased. In our example, x_1 is the variable which now contributes most to the objective function. This variable can be increased until constraint 1 becomes limiting, i.e. $x_1 = 3$ (angular point B in Figure

3.1) and y_1 leaves the basis. By means of a pivot-operation around the pivot (marked with an asterix in Tableau 2) Tableau 3 is generated. The value of the objective function has become 21. Now no negative values can be found in the bottom row of Tableau 3 and the objective function cannot be further increased; the solution is optimal.

3.2.8. Post-optimal analysis or sensitivity analysis

Solving an LP-program provides more information about an optimal solution than just the value of the objective function, the levels of the decision variables and the slack or surplus in the constraints. An integral part of solving LP models is the sensitivity analysis. It is concerned with studying possible changes in the optimal solution as a result of making certain changes in the original model.

The matrix notation of an LP-problem reads:

Max {w = $\underline{c}\underline{x}$}

subject to:

$A\underline{x} \leq \underline{b}$
$\underline{x} \geq 0$

The coefficients a (in A), b and c of this problem are often subject to variability or uncertainty. It is important to know how the optimum solution of the LP-problem changes when coefficients change. The following analyses give information on these changes: the *shadow price* and *right hand sides ranging* for changes in the b-values, the *coefficients of the objective function ranging* and the *reduced cost* for changes in the c-values. Unfortunately, all these analyses refer only to partial changes in coefficients: a change in one coefficient simultaneously.

Shadow prices

In the optimum tableau of an LP-problem the coefficients of the bottom row in the columns of the slack variables, the so called `shadow prices', tell us the increase (or decrease in case of a negative shadow price) in the value of the objective function when the constraint is relieved with one unit. In our example: only constraints 1 and 3 have a shadow price: constraint 2 is not binding. If the right hand side of constraint 1 would be increased with one unit, the objective function would increase with 2 (the optimum solution would be: one extra unit x_1: the objective function increases with 2). If the right hand side of constraint 3 would be relieved with one unit, the objective function would increase with 3 (the optimum solution would be: one extra unit x_2 at the expense of one unit x_1: the objective function increases with 5-2=3).

Right hand sides ranging

In order to keep the same optimal basic feasible solution, the allowed changes in the right hand sides of the constraints can be deduced from the final tableau. We will only demonstrate graphically how to determine the allowed changes in the right hand sides without a change in the optimal basis (Figure 3.3):

Constraint 1: if the right hand side would be greater than 7, constraint 2 in stead of constraint 1 becomes limiting and y_1 enters the basis at the expense of y_2; if the right hand side becomes smaller than 3, y_3 enters the basis at the expense of x_1.

Constraint 2: if the right hand side decreases with more than one unit, this constraint becomes limiting and y_2 leaves the basis for y_1.

Constraint 3: for a right hand side between 2 and 6 the optimal basis does not change; beyond this range either y_2 leaves the basis for y_1, or x_1 leaves the basis for y_3 .

Coefficients of the objective function ranging

The optimal tableau also gives information about the sensitivity of the optimal solution for changes in values of the coefficients in the objective function. We will not deal with how to calculate this from the final tableau. It can be deduced from Figure 3.3 that B stays the optimal solution for objective coefficient values for x_1 between zero and 5 and for x_2 between 2 and infinity. Of course, the value of the objective function changes.

Reduced cost

Zero variables (variables that are not in the optimum solution) have so called `reduced cost'. This reduced cost indicates the amount by which the objective coefficient of the zero variable must be changed before the particular variable would have a positive value in the optimum solution. Thus, reduced cost gives the minimum change in the c-coefficient of a particular zero variable necessary to make that zero variable more attractive than a current non-zero variable. In our example both variables (x_1 and x_2) are non-zero variables (selected in the optimum solution), thus both have no reduced costs.

[Figure 3.3](#) Sensitivity analysis of the optimal solution.

3.2.9. Example of a linear programming problem: Communal farming in Tagota Village in Mara Region, Tanzania

This example is taken from the book `Doing Mathematics in a Developing Country' published by Tanzania Publishing House, p. 63-67 (see Schweigman (1979)). The example was worked out by the former student G.C.N. Sibuti, who comes from Tagota village in Tanzania. The data in this example are based on his own experience and on interviewing in the village.

Tagota is an Ujamaa Village in Mara region, Tanzania, where a hundred families live. They grow maize as a major crop. During the growing season for maize each family uses all labour on the cultivation of maize. The people use ox-ploughs but they are discussing whether to hire a tractor. Moreover it is suggested that herbicides are applied to avoid weeding. The aim of this study is to investigate whether or not a tractor should be hired and herbicides should be applied.

Instead of considering the entire population, we will study here the farming of an average family in the village, which consists of 5 people. It may be assumed that on the average each family has an ox-plough. To study a family instead of a whole village is acceptable, because all families grow maize in the same way.

To analyze this problem we start immediately with the introduction of variables and the formulation of constraints. By setting up the formulation we will find out what type of information and statistical data we need.

The statement that we have to determine whether a tractor should be hired or not and whether herbicides should be used, is not very quantitative. In fact we want to know how many acres have to be ploughed by a tractor and for how many acres herbicides are to be bought, if it is to be useful at all. Realizing this, the choice of variables for this example will not be surprising. We introduce:

x_1 the acreage where maize is grown, a tractor is used for ploughing and weeding is done manually;

x_2 the acreage where maize is grown, a tractor is used for ploughing, and herbicide is used;

x_3 the acreage where maize is grown, an ox-plough is used for ploughing and weeding is done manually;

x_4 the acreage where maize is grown, an ox-plough is used for ploughing and herbicide is used.

Note that the total acreage used for maize is $x_1+x_2+x_3+x_4$.

There is enough land, so the `land constraint' need not be included. To formulate the labour constraint, first the timing of ploughing, planting, weeding and harvesting will be considered. The timing is illustrated in the table below.

Table 3.1 Timing of agricultural activities for the cultivation of maize in Tagota village, Tanzania.

month	activity
January	weeding
February	weeding
March	
April	harvesting
May	harvesting
June	
July	
August	
September	

October	ploughing and planting
November	ploughing and planting
December	ploughing and planting

The following data on labour input have been learned from the farmers:

Ploughing and planting in October to December:

a tractor needs 1 hour to plant an acre and also 15 man-hours of family labour are needed for clearing, (1)
preparation and planting. Note: the ploughing is done twice,
the first time for clearing, the second time for planting (2)
An ox plough needs three days of 4 hours to plough an (3)
acre and 60 man-hours of family labour are needed. (4)
Note: the ploughing is done twice. (5)

Weeding in January and February:

if no herbicide is used the weeding takes 15 man-days of 9 hours =
135 man-hours per acre; (6)
if herbicide is used weeding is not necessary, but it takes 5 hours
to spray one acre during the planting period. (7)

Harvesting in April and May:

harvesting is done manually and it takes 30 man-hours to harvest
an acre of maize. (8)

With the aid of this information we can formulate the following labour constraints, taking into account that one month has 25 working days. The constraint for the use of a tractor for ploughing during the months October to December is given by:

$$2(x_1 + x_2) \leq 75*8 \ (9)$$

where it is assumed that one tractor can be hired throughout the whole period, each working day for 8 hours. Use has been made of (1) and (2).

The constraint for the use of an ox-plough during the months October to December is given by:

$$24(x_3+x_4) \leq 75*4 \ (10)$$

where use has been made of (3) and (5). The oxen are only prepared to pull for 4 hours a day.

The human labour constraint during the planting, weeding and harvesting periods are given by:

$$30(x_1+x_2) + 120(x_3+x_4) + 5(x_2+x_4) \leq 75*5*9 \ (11)$$

for the period of planting from October to December. Use has been made of (1), (2), (4), (5) and (7). The people work 9 hours a day.

$$135(x_1+x_3) \leq 50*5*9 \ (12)$$

for weeding in the period January and February. Use has been made of (6).

$$30(x_1+x_2+x_3+x_4) \leq 50*5*9 \ (13)$$

for the harvesting period in April and May. Use has been made of (8).

The yield of maize per acre is 900 kg, independent of the use of a tractor or herbicides. The annual consumption of maize by the family is estimated as 720 kg. The food requirement constraint may be written as:

$900(x_1+x_2+x_3+x_4) \geq 720$. (14)

Several choices of the objective function are possible, for instance:
1) Maximization of total production:
max: $900(x_1+x_2+x_3+x_4)$

2) Maximization of the net revenue of selling the surplus production:
max: $0.80*(900(x_1+x_2+x_3+x_4)-720)-100(x_1+x_2)-100(x_2+x_4)$, (15)

where use is made of the fact that the selling price of 1 kg of maize is 0.80 Shilling, the cost of hiring a tractor to plough one acre is 50 Shilling and the cost of the herbicide is 100 Shilling per acre. The costs of using the ox-plough are small in comparison with the tractor, hence these costs are omitted.

We consider objective function (15). The linear programming problem (9)-(15), where the variables have also to be non-negative, may be written as:

maximize: $620x_1+520x_2+720x_3+620x_4 -576$,

where the variables x_1, x_2, x_3 and x_4 are subject to:

$2x_1 + 2x_2 \leq 600$

$24x_3 + 24 x_4 \leq 300$

$30x_1 + 35x_2 +120x_3 +125x_4 \leq 3375$

$35x_1 +135x_3 \leq 2250$ (16)

$30x_1 + 30x_2 + 30x_3 + 30x_4 \leq 2250$

$900x_1 +900x_2 +900x_3 +900x_4 \geq 720$

$x_j \geq 0$ j = 1,2,3,4

The solution is given by:

$x_1 = 7.4$, $x_2 = 58.3$, $x_3 = 9.3$, $x_4 = 0$ acres.

It follows that it seems to be beneficial to hire a tractor, but the ox-plough is to be used as well. Some herbicide should be bought but on a certain plot of (7.4 + 9.3) acres the weeding is done manually. During the planting period the ox-plough is not used the whole time, 77.8 hours are idle. All the available manual labour is fully used in the planting period, the weeding period and the harvesting time. The production of maize is much more than the consumption. The expected revenue is 41,016 Shilling. Instead of relying on these dry figures it is worth investigating some alternatives. If no tractor is used what is the impact on the revenue obtained? Does this differ very much? The same should be investigated if no herbicide is bought. Will it make much difference, if we maximize the yield instead of the net revenue? What is the income per head?

3.2.10. Software for solving LP-problems

Many computer software packages are available to solve LP-problems. The packages differ in the dimension of the problems they can solve, the required hardware and the users interface. The dimension of the problem that can be solved depends on the number of restrictions, the number of decision variables, the number of integer variables and the number of non-zero coefficients in the matrix, the so-called `density of the matrix'.

An LP software package mostly consists of several parts (Figure 3.4):
* *MG-Generator (MGG)*. An MG-Generator is a higher programming language specifically suitable for linear programming. With an MG-Generator the LP-model can be `mathematically' described in a way closely related to the mathematical formulation which can easily be converted to computer code.
* *Matrix Generator (MG)*. The Matrix Generator transforms data from a *database* to a simplex tableau by means of the mathematical formulation of the LP-model made with the MG-Generator. Checking, changing or scaling the data would be almost impossible without an MG. The result of

the Matrix Generator is an <u>MPS-file</u> (Mathematical Programming System Format-file). This MPS-file is a standard file in which the matrix is unequivocally and compactly described. In the file a number of sections can be distinguished (see example):
* Name: the name of the problem;
* Rows: type and name of the rows (including the objective function);
* Columns: per column the name and the non-zero coefficients are given. The name or number of the row gives the right position of the coefficients;
* RHS: the Right Hand Side or the b-vector;
* Endata: the end of the file.

[Figure 3.4](#) *LP software. Source: Hendriks & Van Beek (1991).*

In most recent software packages the function of the MG (linking the data to a model) is carried out by the MG-Generator (MGG) routine.

* *The Solver or simplexroutine*. The Solver comprises the simplex-algorithm and usually also post-optimal analysis and mixed integer programming algorithms.
* *The Report-Writer (RW)*. The Report Writer is a program that processes the output (e.g. the report-file) of the Solver, so that the user can easily read and interpret the results.

Example of MPS-file (our LP-problem: growing wheat and potatoes):

```
NAME            EXAMPLE GROWING WHEAT AND POTATOES
ROWS
N 1             (objective function)
L 2
L 3             (constraints)
L 4
COLUMNS
X₁ 1            2.0000
X₁ 2            1.0000
X₁ 3            1.0000              (variable, number of row, c or a coefficient)
X₂ 1            5.0000
X₂ 2            1.0000
X₂ 4            1.0000
RHS
RHS 2           6.0000
RHS 3           4.0000              (Right Hand Sides or b-values, number of row, b coefficient)
RHS 4           3.0000
ENDATA
```

Table 3.2 shows several examples of LP-software packages. For this course use will be made of LP88 and XPRESS

Table 3.2 Examples of LP-software. Source: Hendriks & Van Beek (1991)

name	supplier	hardware
MPSX-MIP	IBM	mainframe
SCICONIC	SCICON Ltd.	mainframe and mini
OMP	B&P	mini and PC
XPRESS-MP	Dash Ass.	PC-AT386
LINDO	LINDO Systems	mini and PC

PC-Prog	QMS	PC
GAMS/MINOS	World Bank	mainframe to PC

3.3. Multiple criteria optimization problems

For optimization problems with one objective, and constraints which are linear in the decision variables, linear programming can be used to find the optimal solution. However, in most optimization problems (e.g. concerning land use) there are several objectives that the `stake holder' wants to satisfy. The stake holder is usually seeking a good compromise amongst several (conflicting) objectives. In situations with more than one objective it is also possible to use linear programming techniques with the simplex algorithm.

Before dealing with the most important multiple criteria optimization techniques (3.3.4), the conceptual differences between attributes, objectives, goals and constraints are discussed (3.3.1), the idea of efficient or a Pareto optimal solution is introduced (3.3.2) and the concept of trade offs is presented (3.3.3).

The approach and text of sections 3.3.1-3.3.4 originates from the handbook of Romero & Rehman (1989) on Multiple Criteria Analysis for agricultural decisions.

3.3.1. Attributes, objectives, targets and goals

The stake holder can establish his preference according to various *attributes* , e.g. the value added or the level of employment (by a set of activities). Attributes can be measured independently from a stake holder's desires and in many cases can be expressed as a mathematical function of the decision variables. *Objectives* imply the maximization or minimization of (the functions representing) one or several attributes and reflect the values of the stake holder, e.g. maximizing the value added or minimizing unemployment. A *target* is an acceptable level of an attribute. A *goal* is an attribute with a certain target, e.g. the stake holder wants a value added of at least $100.000,=. In general goals take the form $f(x) >/< t$ or $f(x) = t$, where t is a parameter representing the aspiration level or target value. Summarized, according to Romero & Rehman (1989), `in a farm planning problem gross margin is an attribute; to maximize gross margin, an objective; and, to achieve a gross margin of at least a certain target, a goal. Finally, a *criterion* is a general term comprising the three preceding concepts. That is, criteria are the attributes, objectives or goals to be considered relevant for a certain optimization problem.'

Goals and constraints have the same mathematical structure and look exactly the same as both of them are inequalities/equations. A difference between them may lay in the meaning attached to the RHS of the (in)equality: with goals the RHS is a target aspired by the stake holder, which may be achieved or not; with constraints, the RHS must be satisfied. Thus goals could be considered as soft constraints which can be violated without producing infeasible solutions. The amount of violation can be measured by introducing positive and negative *deviational variables* or *slack variables* (see linear programming). For example, the goal referring to the achievement of a value added of $100,000,= by the activities x_1 and x_2 adding $1000,= and $5000,= per unit, respectively, can be represented as follows:

$$1000x_1 + 5000x_2 + n - p = 100,000$$

The variables n and p account for deviations from the achievement of a goal from its target. For example, if the actual value added is only $75,000, then n = 25,000; if the value added is $125,000, then p = 25,000 (thus, either n or p is non-zero). Thus, a goal can be expressed as follows:

ATTRIBUTE + DEVIATIONAL VARIABLES = TARGET

or in mathematical terms:

$$f(x) + n - p = t$$

3.3.2. Pareto optimal or efficient solutions

Romero & Rehman (1989) state: `*The efficient or Pareto optimal solutions are feasible solutions such that no other feasible solution can achieve the same or better performance for all the criteria under consideration and they are strictly better for at least one criterion. In other words, a Pareto optimal solution is a feasible solution for which an increase in the value of one criterion can only be achieved by degrading the value of at least one other criterion.*'

Example:
A problem with the following three feasible solutions, whose performance according to three attributes is as follows:

	Gross margin (dollars)	Seasonal labour (hours)	Emission (kg N/ha)
Solution 1	80,000	500	100
Solution 2	80,000	600	100
Solution 3	90,000	700	120

The stake holder wants to maximize gross margin and to minimize seasonal labour and emission. It is clear, that the second solution is non-efficient, since it offers the same gross margin and emission, but requires more seasonal labour. The first and third solution are Pareto optimal.

According to Romero & Rehman (1989): `All the Multiple criteria optimization techniques aim to obtain solutions which are efficient in the Paretian sense. Even within the multi-objective programming approach the first step to be taken consists in obtaining the set of feasible solutions which are efficient. That is, the feasible set is partitioned into two disjoint subsets. The subset of feasible and non-efficient solutions and the subset of feasible and efficient solutions. After that the preferences of the optimizer are introduced to establish a compromise within the feasible and efficient subset.'

3.3.3. Trade-offs amongst criteria

The trade-off between two criteria (objectives) means the amount of achievement of one criterion that must be sacrificed to gain an unitary increase in the other one, e.g. the trade-off value between gross margin and seasonal labour for solution 1 and 3 in the preceding example was:

$T13 = (90,000-80,000) / 700 - 500 = 50$

This trade-off indicates that each hour of decrease of seasonal labour implies a mean decrease of $50,= of gross margin. The trade-offs values, besides being a good index for measuring the opportunity cost of one criterion in terms of another criterion, also play a key role in the analysis of interactive techniques.

At first the concept of trade-offs may seem rather similar to that of shadow prices. However, there is a clear difference. The trade-off between two objectives (or an objective and a constraint) is defined as the change in an objective function for a *particular* change of another objective/ constraint. It is usually calculated by comparing results of *two or more* optimizations. The linearity of the trade-off within the ranges of the optimum values of the objective functions (in the preceding example: between 90,000-80,000 and 700-500) is not considered. Shadow prices are defined only for an *unitary* change in the right hand side of a constraint; the shadow prices are valid only for that unitary change. They can be calculated for *each* optimization.

3.3.4. Multiple criteria decision making techniques

The former definitions and concepts allow us to give a rough classification of the main multiple criteria optimization approaches. It is not the aim to understand all ins and outs of all techniques, but to present an overview so one will be able to recognize different techniques when reading literature. The examples have been taken from Romero & Rehman (1989).

Goal programming (GP)

Specified goals are available for each of the objectives. The deviations from the desired targets and what is actually achieved are minimized by the addition of positive and negative deviational variables permitting either the under- or over-achievement of each goal. The minimisation process can be undertaken in different ways. The most widely used in practice are:

a) *Lexicographic Goal Programming (LGP)* or *absolute or pre-emptive goal programming* (Dutch: doelprogrammering met absolute prioriteiten): absolute or pre-emptive weights to the deviational variables. There is a clear order in the priorities for the different objectives. First, it is tried to approach the goal of the most important objective. Subsequently, the less important objectives are pursued under the restriction that the approach to the goal of an objective with a lower priority does not enlarge the gap with the goal of an objective with a higher priority. See example LGP.

b) *Weighed Goal Programming (WGP)* or *relative or non-pre-emptive goal programming* (Dutch: doelprogrammering met relatieve prioriteiten): relative or non pre-emptive weights to the deviational variables. The different objectives are more or less comparable. The deviations from the different goals of the objectives are weighed such that this represents the relative importance of the different objectives. See example WGP.

Examples LGP and WGP

Given the LP-problem:

Max $z = f(x_1, x_2) = 6250x_1 + 5000x_2$

Subject to:

$550x_1 + 400x_2 \leq 15,000$ (c_2)
$750x_1 + 575x_2 \leq 22,000$ (c_3)
$1050x_1 + 825x_2 \leq 29,000$ (c_4)
$1375x_1 + 1025x_2 \leq 36,000$ (c_5)
$120x_1 + 180x_2 \leq 4,000$ (c_6)
$400x_1 \leq 2,000$ (c_7)
$450x_2 \leq 2,000$ (c_8)
$35x_1 + 35x_2 \leq 1,000$ (c_9)
and $x_1, x_2 \geq 0$

In this example x_1 and x_2 represent crop A and crop B. The objective function represents the net present value of investment of the two crops. c_2-c_9 represent constraints concerning working capital (c_2-c_5), casual labour (c_6-c_8) and mechanization (c_9).

As an example of a Goal Programming (GP) model, we assume that the above cited set of inequalities is treated as a set of goals instead of a set of constraints. For each goal, two non-negative variables (the deviational variables n and p) are introduced to convert an inequality into an equation. For the objective function a target value of 200,000 is assumed:

$6,250x_1 + 5,000x_2 + n_1 - p_1 = 200,000$ (g_1)
$550x_1 + 400x_2 + n_2 - p_2 = 15,000$ (g_2)
$750x_1 + 575x_2 + n_3 - p_3 = 22,000$ (g_3)
$1,050x_1 + 825x_2 + n_4 - p_4 = 29,000$ (g_4)
$1,375x_1 + 1,025x_2 + n_5 - p_5 = 36,000$ (g_5)
$120x_1 + 180x_2 + n_6 - p_6 = 4,000$ (g_6)
$400x_1 + n_7 - p_7 = 2,000$ (g_7)
$450x_2 + n_8 - p_8 = 2,000$ (g_8)
$35x_1 + 35x_2 + n_9 - p_9 = 1,000$ (g_9)

As an example of Lexicographic Goal Programming (LGP), assume that the stake holder's first priority is made up of goals concerning working capital (g_2-g_5). These first goals must be satisfied in an absolute and pre-emptive way; the stake holder wants to minimize $p_2 + p_3 + p_4 + p_5$. The second priority is made up of goal g_9 (mechanization): the stake holder wants to minimize p_9. The third priority is made up of goal g_1 (net present value): minimize n_1. The last priority is given to the minimisation of hired casual labour: minimize $p_6 + p_7 + p_8$. The stake holder is also allowed to attach weighing factors to the goals within the same priority. Without weighing factors, the whole LGP minimisation problem is:

Min $a = [(p_2 + p_3 + p_4 + p_5), (p_9), (n_1), (p_6 + p_7 + p_8)]$

Using one of the possible algorithms, the optimum solution is:

$x_1 = 19.18$ $x_2 = 9.38$

$n_1 = 33,250$ $p_1 = 0$

$n_2 = 699 \; p_2 = 0$

$n_3 = 2,221 \; p_3 = 0$

$n_4 = 1,122 \; p_4 = 0$

$n_5 = n6 = 0 \; p_5 = p_6 = 0$

$n_7 = 0 \; p_7 = 5,672$

$n_8 = 0 \; p_8 = 2,221$

$n_9 = 0 \; p_9 = 0$

This solution permits complete achievement of the goals of the first two priorities. The goal of the third priority was not reached: a negative deviation of 33,250. For the goals of the last priority only g_6 was completely satisfied.

In Weighed Goal Programming (WGP) all the goals are considered simultaneously. Assume that the stake holder considers goals g_2-g_5 as rigid constraints. Thus, we have a WGP-problem with five goals (g_1, g_6-g_9) and four constraints (g_2-g_5). It can be calculated that the maximum net present value with the four rigid constraints g_2-g_5 is 175,600. The variables in the objective function must represent relative deviations from the targets rather than absolute deviations because of the widely different units of measurements used for the different goals. Thus, the model minimizes the sum of the relative deviations from targets:

Minimize: $W_1 * (n_1/175,600) + W_6 * (p_6/4,000) + W_7 * (p_7/2,000) +$

$W_8 * (p_8/2,000) + W_9 * (p_9/1,000)$

subject to g_2-g_5, g_1 and g_6-g_9.

$W_1, ..., W_9$ represent the weights attached to the deviational variables. Mathematically this is an orthodox LP-problem and requires no extension of the Simplex algorithm.

Multi-Objective Programming (MOP)

The stake holder must take his decision in a multiple objective environment where defined goals do not necessarily exist. MOP attempts to distinguish the Pareto-optimal feasible solutions from the non-Pareto ones. The elements of this efficient set are feasible solutions such that there are no other feasible solutions that can achieve the same or better performance for all the objectives and they are strictly better for at least one objective. Within the efficient set, the trade-offs between criteria can be considered. Different techniques exist to generate or approximate the efficient set: a) graphically; b) constraint method; c) weighing method; d) multi-objective simplex method. Only the graphical method is illustrated.

Example MOP

As an illustration of Multiple-Objective Programming we now suppose that the stake holder has two objectives: a) maximize the net present value (g_1) and b) minimize the number of hours of casual labour hired for harvesting (g_7 plus g_8; since min(x) is equivalent to max(-x), min($400x_1 + 450x_2$) is equivalent to max ($-400x_1 - 450x_2$)). For the purpose of illustration a constraint representing: `minimum crop area of 10 ha' has been added. We then have the following problem:

Eff $Z(x) = [Z_1(x), Z_2(x)]$

(Eff: efficient set, pareto optimal solutions)
where
$Z_1(x) = 6,250x_1 + 5,000x_2$

$Z_2(x) = -400x_1 - 450x_2$

subject to
$550x_1 + 400x_2 \leq 15,000$

$750x_1 + 575x_2 \leq 22,000$

$1,050x_1 + 825x_2 \le 29,000$

$1,375x_1 + 1,025x_2 \le 36,000$

$120x_1 + 180x_2 \le 4,000$

$35x_1 + 35x_2 \le 1,000$

$x_1 + x_2 \ge 10$

$x_1, x_2 \ge 0$

Figure 3.5 Feasible set in the decision variable space. Source: Romero & Rehman, 1989.

Figure 3.6 Image of the feasible set in the objective space. Source: Romero & Rehman, 1989.

Table 3.3 Extreme points of the feasible set F

extreme points	decision variables		objective functions	
	pear trees (ha) x_1	peach trees (ha) x_2	Z1 (NPV) $	Z2 (casual labour) hours
A	10	0	62,500	4,000
B	26.18	0	163,625	10,472
C	19.18	9.38	166,775	11,893
D	0	22.22	111,111	10,000
E	0	10	50,000	4,500

Source: Romero & Rehman, 1989

Since the first three constraints are implied by the fourth, we can omit these constraints. This problem can be solved graphically. The feasible set F can be presented by the polygon ABCDE in Figure 3.5 and the five extreme points of this region along with the values for both objectives are shown in Table 2. The five extreme points of the example in the objective space are plotted in Figure 3.6. From this figure it can be easily deduced that the segments connecting A', B' and C' represent the efficient set in the objective space for the problem analyzed and the segments connecting A, B and C in Figure 3.5 represent the efficient set in the decision variable space. The points of F' which do not lie on A'B'C' are inferior or nonefficient because they offer less net present value and equal (or more) casual labour for harvesting, or equal (or less) net present value and more casual labour for harvesting than any point belonging to the boundary itself. The slopes of the two segments A'B' and B'C' represent the trade-offs (or opportunity costs) between the attributes being considered.

Compromise Programming (CP)

According to Romero & Rehman (1989) compromise programming can to some extent be regarded as a natural and logical complement to MOP. It determines the optimal solution from the Pareto subset. CP starts with the identification of an ideal or utopian solution and it assumes that any stake holder seeks a solution as close as possible to the ideal point. To achieve this closeness a distance function is introduced into the analysis:

$$L_p(W) = \left[\left(\sum_{j=1}^{n} W_j d_j\right)^p\right]^{1/p}$$

in which W_j represent the weights for each of the objectives, and d_j the relative degree of closeness between the j [th] objective and its ideal. If all W_j equal one and p=2, $L_2(W)$ equals the pythagorean concept of distance (e.g. the distance between (2,6) and (5,2): $L_2(W) = [(2-5)^2 + (6-2)^2]^{1/2} = 5$). In CP the distance function is minimized.

Romero & Rehman (1989) discuss the relative advantages and disadvantages of GP, MOP and CP (page 99-103).

Example CP
In CP the stake holder seeks a solution as close as possible to the ideal point (which is the point with optimal values for each of the objectives), by means of a distance function. It can be deduced from Table 3.3 that the ideal solution is the solution with NPV (=net present value) = 166,775 and Casual labour = 4,000. In Table 3.4 the relative distances between each extreme efficient point (A', B' and C') and the ideal point have been

calculated for the three measures of distance L_1, L_2 and L.

As an illustration the details of calculating the relative distance between point B'and its ideal, according to the L2 metric for W1 = 3 and W2 = 1, are given below:

$$L2(3,1) = [3^2((166{,}775 - 163{,}625)/(166{,}775 - 62{,}500))^2 + 1^2((4{,}000 - 10{,}472)/(4{,}000 - 11{,}893))^2]^{1/2} = 0.825$$

Table 3.4 Compromise programming (discrete approximation)

		A'	B'	C'	Z^*_j	Z_{*j}
NPV (Z_1)		62,500	163,625	166,775	166,775	62,500
casual labour (Z_2)		4,000	10,472	11,893	4,000	11,893
d_1		1	0.030	0		
d_2		0	0.820	1		
L_1	$W_1 = 1$	1	0.850	1		
L_2	$W_2 = 1$	1	0.820	1		
$L_{[yen]}$		1	0.820	1		
L_2	$W_1 = 2$	2	0.860	1		
L_2	$W_2 = 2$	2	0.860	1		
$L_{[yen]}$		2	0.820	1		
L_1	$W_1 = 3$	3	0.910	1		
L_2	$W_2 = 1$	3	0.825	1		
$L_{[yen]}$		3	0.820	1		

Source: Romero & Rehman (1989).

Table 3.4 shows that given the structure of weights W_j of the three extreme efficient points, B' is the nearest to the ideal point, whatever measure of distance is used. In other words, the point B' in the objective space or the point B in the decision variable space is the best compromise solution, according to this `Discrete approximation of the Best-compromise solution' (we will not deal with the continuous CP-technique).

Interactive Multiple Criteria Decision Making approaches

This approach implies a progressive definition of the stake holder's preferences through an interaction between him and the model. The interaction becomes a dialogue in which the model responds to an initial set of the stake holder's preferences or trade-offs, and then when this response has been examined another set is offered and so on. Thus the process proceeds in an interactive and iterative way until the stake holder has found a satisfactory solution. Most of the interactive methods can be classified according to the kind of information that is required iteratively from the stake holder during the interactive process. The kind of information can be summarized in three types of questions to the stake holder:

1) What is your trade-off between the objectives (e.g. between costs of production and nitrogen emission)?

2) Do you accept an increase in costs of $1000,=, along with a decrease in nitrogen emission of 50 kg/ha?

3) Do you accept an option with $1000,= costs, 700 hours of casual labour and 120 kg N/ha emission?

The first two questions require information (directly or indirectly) about the stake holder's trade-offs between various objectives. This type of questions, especially the first, may be hard to answer. In the third question the stake holder is asked whether he accepts a given feasible efficient

solution. If the stake holder does not accept the solution, he should indicate which objectives should be improved. The method of Zionts and Wallenius is one of the most popular multiple criteria optimization approaches with the second type of questions to the stake holder. The STEM method and the Interactive Multiple Goal Linear Programming (IMGLP) method are methods with the third type of questions to the stake holder. The IMGLP approach has been used several times in land use problems.

Often, when exploring options for land use the goals for the different objectives are not very clear. Moreover, it is not clear which objective should have the highest priority. Both the goals of the objectives and the priority of the objectives depend on the policy view of the stake holder. The policy view differs between various stake holders. The IMGLP technique is a suitable tool for these kinds of multicriteria problems. De Wit *et al*. (1988), discussing the IMGLP technique, state: `...*satisfactory solutions, from the point of view of the `user', may be obtained in subsequent iteration cycles by tightening one of the goal restrictions and repeating the iteration cycle for the other objectives. The choice of the goal restrictions and the degree to which they are tightened, reflect the specific interests of the user. This stepwise maximization of the objectives under increasingly tighter restrictions on the other goals reduces the solution space. In that way, the costs of satisfying one objective in terms of what must be sacrificed on the other objectives is expressed. At last the user is faced with a solution space in which he cannot improve on any of his objectives without sacrificing on another one, and where he has to make a choice. Hence, the user becomes aware of the possibilities of exchange between the various objectives in his own solution space, i.e. he obtains the opportunity cost of one objectives in terms of the other objectives. Of course, users with different interests and aspirations are found to end up in different corners of the initial solution space* .'

The IMGLP procedure consists of a number of optimizations rounds, each round comprising several optimizations. In each optimization run, the model is optimized for one objective function, while the other objectives are used as constraints. Upper or lower bounds can be put on these `goal constraints'. In the so called `zero round' of the procedure, in subsequent runs, the model is optimized for each of the objective functions, without putting any upper or lower bounds on the goal constraints. In this zero round the feasible space (`playing field') for the objective functions is determined. These extreme values of the objective functions are important in choosing upper or lower bounds for goal constraints in scenarios. In the zero round the compatibility of objective functions is not examined. In subsequent rounds upper or lower bounds are put on relevant (from the stake holder's point of view) objective functions, and the model is optimized for an, also relevant, objective function. In this way the compatibility of and the trade offs between objective functions is investigated.

The IMGLP method is illustrated with a simple example using only two objective functions, agricultural area and the use of pesticides for agriculture in a region (after Spharim *et al.*, 1992). The results for the zero round are given in Figure 3.7. The minimum agricultural area, without any upper limit on pesticides is 32 million ha (coinciding with an use of pesticides of 87 million kg - point A), and the minimum use of pesticides without any bound on area is 33 million kg a.i. (coinciding with an agricultural area of 43 million ha - point B). If points A and B coincide, both objectives are completely tied, so that realization of one brings with it the realization of the other. There is no conflict between both objectives.

Figure 3.7 Graphical illustration of IMGLP procedure with two objective functions (i) minimization of the use of pesticides and (ii) minimization of the agricultural area. Source: Spharim et al. (1992).

Point W1 (87, 43) represents use of pesticides when agricultural area is minimized and agricultural area when the use of pesticides is minimized. The stake holder does not have to accept higher (worse) values for these objectives. The point U1 (33, 32) combines the lowest pesticide use with the lowest agricultural area, and may be considered as an utopian solution, because it is impossible to realize the optimum of two partially conflicting objectives simultaneously.

Given the utopian solution U1 and the worst combination W1, the stake holder is asked now which of the upper values of the objectives he wants to lower and to what extent. It should be pointed out to him that he does not commit himself because any value can be reconsidered. Let us assume that he first wants to ensure that the use of pesticides does not exceed 45 million kg. The most unfavourable combination of objective achievement is then W2 (45, 43) as in Figure 3.7b. To elucidate what minimum agricultural area can be achieved with this upper bound on the use of pesticides, a second iteration of the model is necessary. This yields point C (45, 38). The utopian alternative now moves to U2 (33, 38). This is the price that has to be paid for lowering the upper bound for the use of pesticides.

Now suppose that after all, the stake holder is satisfied with an agricultural area of 40 million ha. The minimum use of pesticides is then 37 million kg (Point D (37,40)). If the stake holder is satisfied with this solution the procedure stops, otherwise he may continue until he arrives at an appropriate solution.

The procedure is in principle the same if more than two objectives are considered, but then the number of optimizations needed to arrive at a satisfactory solution increases rapidly with the number of objectives. The results of a zero round with maximization objective functions can be tabulated as in Table 3.5 (after Veeneklaas, 1990).

Table 3.5 Results of zero round of an IMGLP model with N objective functions (Veeneklaas, 1990)

zero round	results of the optimizations for objective	worst value	best value

	1	i	N		
objective 1	b_1	.	.	W_1	b_1
. . .	.	.	.	.	.
objective i	.	b_i	.	W_i	b_i
. . .	.	.	.	.	.
objective N	.	.	b_N	W_N	b_N

The diagonal elements b_i represent by definition the best attainable values of each row in the matrix of results. The worst values w_i correspond to the lowest value of row i in the matrix of results. For each goal i no lower value then w_i needs to be accepted. The initial freedom of choice for each objective - the difference between the worst and best value - is made explicit in this way.

The next step consists of selecting out of the w-vector the objective with the worst value considered most unacceptable and formulating a higher lower bound for that objective. Let us select objective i. The optimum found for goal i in the zero round of course forms the upper limit to which the right hand side of this objective can be raised. Suppose the desired lower bound for objective i is M_i, then a new cycle of optimizations can be performed with this lower bound for objective i. The results of that optimization round are given in Table 3.6.

Table 3.6 Results of first round of an IMGLP model with N (maximization) objective functions (Veeneklaas, 1990)

first round	lower bound	results of the optimizationsfor objective			worst value	best value
		1	i	N		
objective 1	$> W_1$	B_1	.	.	W_1	B_1
. . .		.	.	.	.	.
objective i	$> M_i$	.	b_i	.	M_i	b_i
. . .		.	.	.	.	.
objective N	$> W_N$	.	.	B_N	W_N	B_N

Of course the optimum for objective i is still b_i, but the optimum values for the other objective functions are probably lower, because of the

required lower bound for objective i. Comparison of the best values of the zero round (Table 3.5) with those of the first round (Table 3.6) can reveal possible conflicts between objectives. No change in optimum value for a particular objective implies the absence of conflict in this stage between this objective and the one for which a lower bound has been given (objective i). In early cycles this may be possible, but in later cycles this becomes more rare.

The optimization procedure consists of subsequent optimization rounds as described above. In each step the `costs' are revealed of safeguarding a minimum level for a particular objective in terms of maximum attainable levels for the other objective functions. This information helps in deciding which minimum requirement to tighten next, and to what extent. In this way the feasible combinations of goal values can be explored until only one combination is left. In general the procedure is stopped at an earlier stage, leaving an area within which all the objective functions have acceptable values: the `window of opportunities' or `space of solutions'.

Romero & Rehman (1989) summarize the main advantages and disadvantages of the interactive approach of multiple criteria optimization:

Advantages:
a) It represents a learning process for the stake holder permitting him to better understand the system being analyzed.
b) The information required involves only the local preferences of a stake holder, that is his attitude towards a certain solution or with respect to a certain set of trade-offs.
c) In general the assumptions underlying an interactive method are much less restrictive than those required to use a non-interactive technique.

Some difficulties of the interactive approach are:
a) The effort and involvement required from the stake holder in using the model is considerably more when compared with the non-interactive methods.
b) The assumption that the stake holder makes all his decisions consistently; particularly, when inconsistencies can be common.

3.4. Optimization software used in this course

3.4.1. LP 88

The LP88 optimization software is a simple computer programme that will be used to let the course participants become acquainted with using a PC to solve optimization problems. In this Section the manner in which LP88 can be used is explained. This will be done only very briefly and will be done with the aid of a simple example.

Suppose a farmer can cultivate two crops, maize and cassava. The gross margins per ha for the maize is $1,000 and for cassava $750. The labour requirement per ha for maize is 50 mandays and for cassava 75 mandays. The size of the farm is 10 ha and the farmer has available 350 mandays. The problem we will solve using the LP 88 software is: how much land should the farmer allocate to which crop in order to obtain the highest possible level of gross margins. Here step for step it will be shown how this problem can be solved with LP88.

* Once the LP88 software has been installed the programme can be started by typing LP88.

* If your PC is connected to a printer, type the printer where it says `Destination for listings (printer or file name)'. If your printer is not connected to a printer, just type PR.txt.

* Now go to `BEGIN' and press `Enter'.
* Press F1 (= setup).
* Press F2 (= New problem).
* Enter name for new problem. This could be for example `test1'.
* Press `enter'.
* The problem is a maximization problem so type `MAX'.
* There are two constaints, so type `2'.
* There are two non-slack variables, so type `2'.
* Type `F3' so that the matrix is displayed.
* It is advisable to give your activities and constraints recognisable names. For the activities these could be for example:

X_1 = Maize

X_2 = Cassav

For the constraints, for example:
Y1 = Labour
Y2 = Land

Once you have filled in your activity matrix it will look as follows:

Return	1000	1750		
Land	1	1	$\leq$	10
Labour	50	75	$\leq$	350

* After pressing `F10' twice you enter `F2'
* If you now press enter the problem will be solved. Can you interpret the results?

3.4.2. XPRESS

An example

The second package is introduced with the use of an example. Consider a farm with an active population of 15 and a certain availability of land. Three cases, A, B and C, will be examined with an availability of land of 4, 6, and 2 ha, respectively. The problem under consideration is how to divide total area between the two crops maize (M) and cotton (c) in order to maximize net revenue. Other essential data are the following:

	unit	maize	cotton

net revenue	F cfa ha^{-1}	35,000	50,000
labor requirement (peak period)	active ha^{-1}	3	5

The problem for case A can be translated into the following linear programming problem:

Max :	35,000 *	AreaM	+	50,000 *	AreaC			{objective function}
subject to:		AreaM	+		AreaC	$\leq$	4	{restriction land availability}
	3 *	AreaM	+	5 *	AreaC	$\leq$	15	{restriction labor availability}
		AreaM	$\geq$	0	AreaC	$\geq$	0	{non-negativity conditions}

The decision variables are AreaM and AreaC, the areas under maize and cotton, respectively. The technical coefficients used in this problem are the coefficients of the decision variables in the objective function (35,000 and 50,000) and in the restrictions (1, 1, 3, and 5) and the right hand sides (4 and 15), that represent in this case the availability of the resources (land and labor). For cases B and C one only has to change the right hand side of the land restriction from 4 to 6 and 2, respectively.

The solutions for the three cases A, B, and C can be summarized as follows:

	A	B	C
AreaM	2.5	5	0
AreaC	1.5	0	2
Land			
Availability	4	6	2
Utilization	4	5	2
Shadow price	12,500	0	50,000
Labor			
Availability	15	15	15
Utilization	15	15	10
Shadow price	7500	11667	0
Value of objective function	162,500	175,000	100,000

The solution indicates the values of the decision variables, information on the restrictions and the values of the objective function. In case B it is only the labor availability that limits the value of the objective function. This function is maximized when labor productivity is maximized, which explains the choice for growing only maize. Growing this crop yields a labor productivity of 35,000/3 (F cfa active^{-1}), for cotton this value is 50,000/5. The land is (relatively) abundant so that only 5 of the 6 ha are used. An increase of the land area would not have any effect on the optimal solution. That can also be seen from the shadow price of the land which indicates its marginal value (in the unit of the objective function per unit of the restriction, here in F cfa ha^{-1}), in other words, the value with which the objective function would increase if the area would increase by one unit (ha). For case B this value is zero for the land. For the labor one finds a marginal value of 11,667 F cfa active^{-1} (in the peak period). An additional active would then be used to cultivate more maize, one third of an ha, which would add 35,000/3=11,667 to the net revenue.

In case C it is labor that is relatively abundant. Its marginal value is zero. In this situation one should maximize the monetary value of the activities per unit of land, which is done by growing only cotton (50,000 ha^{-1} against 35,000 ha^{-1} for maize). Note that this could change the moment that there would be more land available. The marginal value of one ha is thus 50,000 F cfa ha^{-1}. This value could also be interpreted as the maximum price a decision maker would be willing to pay for one additional ha of land, according to the model.

Situation A is somewhat more complex, because both resources limit the maximum value of the objective function. Both resources have a positive marginal value, but these values are lower than in cases B and C, in which the other resource is abundant. That is the reason why the value of labor and that of land are maximized simultaneously. One finds therefore a solution in which the two crops are used.

Two economic principles are thus illustrated on the basis of the results for the three situations A, B, and C:

*The law of diminishing net returns of a production factor is illustrated if one considers the marginal value of land as a function of its availability. One starts at 2 ha (case C) and moves to cases A and B (4 and 6 ha, respectively). The marginal value of land decreases from 50,000 (c) to 12,500 (A) and then becomes zero (B).

*With the increase of the availability of a production factor (here : land), as long as it is a limiting production factor, the efficiency (or productivity) of the other production factors (here : labor) increase. The marginal value of labor increases from zero (c) to 7,500 (A), and then to 11,667 (B) as a consequence of the increase in land availability. It is this principle that forms an important argument for intensification and the use of external inputs.

The modelling language

In XPRESS-MP, as in many LP packages, first the model file is read by what is called `the modeller'. On the basis of the specification of the variables, the restrictions, the objective function and the technical coefficients this program transforms the model in its proper LP form. The second phase consists of calculation of the optimal solution, which is done by the `optimizer'. The solution is then written to a text file that can be imported by any text editor, and also by spreadsheets like, for example, MS-EXCEL.

In order to introduce the LP package XPRESS-MP, it is useful to come back to the problem introduced previously and to present the problem in a form that is readable for the package.

MODEL example				! Name of the model
VARIABLES				
AreaM				! Area under maize [ha]
AreaC				! Area under cotton [ha]
CONSTRAINTS				
obj :	35000 *	AreaM + 50000 *	AreaC $	! objective function
land :		AreaM +	AreaC < 4	! land restriction
labor:	3 *	AreaM + 5 *	AreaC < 15	! labor restriction

This model consists of the following sections:
MODEL in this section the model is given a name
VARIABLES this section declares the variables to be used
CONSTRAINTS specifies the restrictions, including the objective function. The model recognizes an objective function, if the expression after the colon is not an equation, or an inequality, but ends with a dollar sign ($). The non-negativity constraints that all variables have to satisfy, are included automatically and do not have to be specified. The order in which the constraints and the objective function are specified is not important.

Observe the format and the objective function. Each restriction has a name, followed by a colon, and then specification of the restriction in a way that is very similar to the mathematical specification. One of the differences is that one only uses the `<', and `>' signs in stead of the mathematical symbols `≥' and `≤', respectively. Also observe that the text following an exclamation sign (!) is comment and does not have any impact on the model as such. For human comprehension comments in the model text are nevertheless very useful.

For an LP problem with, say, two hundred in stead of two variables, their declaration becomes tedious, and the specification of the restrictions and of the objective function can become difficult (the lines may become very long, and errors may be difficult to trace). That is why facilities are created to make it easier to specify the model. These facilities are explained by specifying the same problem again in a different form.

MODEL example	! Name of the model
LET NAcul = 2	! Number of cultural activities
LET lab_av = 15	! labor availability [man]
LET land_av = 4	! land availability [ha]
VARIABLES	
Acul (NAcul)	! Agricultural activities [ha]
TABLES	
lab_cul(NAcul)	! Labor input agr. activities [man ha^{-1}]

rev_cul(NAcul)   ! Net revenue for agr. activities [F cfa ha^{-1}]

DISKDATA
lab_cul   = c:\xpress\data\lab_cul.dat
rev_cul   = c:\xpress\data\lab_rev.dat

CONSTRAINTS
obj :   SUM(j=1:NAcul) rev_cul(j) * Acul(j) $! objective function
land :   SUM(j=1:NAcul) Acul(j) < land_av   ! land restriction
labor: SUM(j=1:NAcul) lab_cul(j) * Acul(j) < lab_av   ! labor restr.

Consider first the familiar parts in this model specification. The MODEL part has not changed. In the VARIABLES section one finds in stead of two names just one name (Acul). This one variable name however has a dimension that is given between brackets (NAcul=2). So this one line defines two variables: Acul1 and Acul2. These variables correspond to the variables AreaM and AreaC used in the former model specification. If one would have assigned the value 200 to NAcul, using the statement LET NAcul=200, the one line in the VARIABLES section would have defined 200 variables.

In the CONSTRAINTS section de names of the restrictions and the objective function have not changed. The expressions that follow the colon, however, have. For the case of the objective function, the expression indicates the sum, for j=1 to NAcul, of the products of the coefficients rev_cul(j) and the variables Acul(j). If the values o f rev_cul(j) are properly defined (35000 and 50000), the objective function corresponds exactly to the objective function in the previous model specification. Similarly, the restrictions for land and labor can be shown to be the same as in the previous model, if also lab_cul(j) has the proper values, and if the right hand sides (land_av and lab_av) have the proper values. It can be verified that the right hand sides are indeed equal to the ones used in the former model specification.

The tables lab_cul and rev_cul are declared in the TABLES section, where it is indicated what their dimensions are. In both cases the dimension is equal to that of the variable Acul. The dimension is defined by a LET statement. This type of statement can be inserted in any of the model sections. The values of the two tables cannot be found in the model specification, because they are stored in files, that are mentioned in the DISKDATA section. If these files contain the right coefficients, than the two model specifications represent the same LP problem.

In conclusion, the new sections used are the following:

TABLES declares names and dimensions of tables in which coefficients can be stored.

DISKDATA indicates the name of the file containing the data with which a table is to be filled.

It is not the right place to go into detail as far as the possibilities of XPRESS-MP concerns. In what follows a few important extensions are given, with examples. This may serve to give the reader an impression of the package.

* more than one dimension can be given
aa(5,10,2) !defines a 3 dimensional table or variable aa with in total 5*10*2 entries

* conditional statements (indicated by |). The example shows how in an equation the cultivated area is calculated for soiltype number one. ('| soil_cul(j)==1' means: for which soil_cul(j) equals 1)
car1 : arcul1 = SUM(j=1:NAcul | soil_cul(j)==1) Acul(j)

* with the use of indices, it is possible to generate a (large) number of restrictions in only one line. The first example shows how the cultivated area can be defined for all soil types in the model. The second example shows how one line generates Nsoil times Nnut restrictions.
car (s=1:Nsoil) : arcul(s) = SUM(j=1:NAcul | soil_cul(j)==s) Acul(j)
nut(s=1:Nsoil, n=1:Nnut) : any expression using the indices s and n

* it is possible to make calculations in order to change (part of) the coefficients. This is done in another model section: ASSIGN. The first example redefines the coefficients in the table rev_cul, with a multiplication by 1.2. The other example shows how to calculate 12 coefficients of a table (calctab) without using other tables. In all case the tables should have been declared in the TABLES section. ASSIGN

rev_cul(j=1:NAcul) = 1.2 * rev_cul(j) ! example 1

calctab(qqht=3:12) = exp(qqht^(-5.42))*12 + ln(qqht)
calctab(2) =5
calctab(1) = calctab(2)^4.23 ! ^ indicates `raised to the power'

* more than one objective function can be defined, for example:

obj1 : Netrev $
obj2 : Capcost + Labcost - SUM(ii=1:5) SALES(ii) $
obj3 : Meatprod $

3.5. Exercises

(Exercises 1-5 are taken from or based on Hendriks & Van Beek (1991))
Formulation of LP-problems

(1) Transform the following LP-problem to the standard form:

Min {20x1 - 10x2 + 30x3 + 1992}

$-x_1 + 2x_2 + 3x_3 = 4$

$3x_1 - x_2 + 2x_3 \leq 9$

$2x_1 + x_2 - x_3 \geq 2$

$x_1 \geq 0, x_2 \leq 0, x_3 = $ free

(2) Transform the following LP-problem to the standard form:

Min {w = 4x1 + 5x2 + 6x3} $x_1 - 2x_2 + 3x_3 \leq 6$

$-2x_1 + 3x_2 - x_3 \geq 7$

$x_1 + x_2 + x_3 = -3$

$x_1 \geq 0, x_2 \leq 0, x_3 = $ free.

(3) A farmer wants to draft an optimal plan for his farm for the months May until

October.

activities	labour requirement in hours ha^{-1}						benefit $ ha^{-1}
	May	June	July	Aug.	Sept.	Oct.	
wheat	2			45			2500
potatoes	24	17	5		198		4000
sugar beats	158	98	11			120	4500
available labour (h)	350	300	250	250	400	400	

He owns 60 ha.
Crop rotation constraints:

* wheat can be grown on max 1/2 of the total area,
* potatoes max 1/3 of the total area,
* sugar beets max 1/4 of the total area.

The farmer wants to maximize the benefit for the entire farm. Formulate this problem as an LP-problem.

Solving LP-problems

(4) Given the following LP-problem:

$$\max \{w = 3x_1 + x_2\}$$

$$x_1 + x_2 \leq 5$$
$$x_1 + 2x_2 \leq 8$$
$$x_1 \leq 4$$
$$x_1 \geq 0, x_2 \geq 0$$

a. solve this problem graphically.
b. make the simplex tableau.
c. solve this problem with the simplex algorithm.
d. mark in the figure of a. the angular points corresponding to the basic solutions of c.
e. with how many units does the objective function increase, when
* constraint 1 is relieved with one unit;
* constraint 2 is relieved with one unit;
* constraint 3 is relieved with one unit.
f. carry out a sensitivity analysis for the right hand sides of the constraints.
g. carry out a sensitivity analysis for the coefficients of the objective function.

(5) Solve the following LP-problem with the simplex algorithm

Max $\{w = 6x1 - 15x2 + 8x3\}$

$$-x_1 + x_2 - x_3 \leq 1$$
$$x_1 - 2x_2 + x_3 \leq 7$$
$$* \ x_1 + 2x_2 + x_3 \leq 4$$

$$x_1, x_2, x_3 \geq 0$$

(6) Using the LP88 optimisation software

(Exercise developed by C.Schweigman (1993), pp. 55 - 57)

a) A one year farming plan has to be set up for a situation where a piece of land of size A available for farming consists of two parts with different fertility of soil. On both parts, the sizes which are A_1 and A_2, the same crops may be grown, but the yields differ. In order to make an agricultural plan a linear programming model is to be set up. As in [Section 3.2.9](#), the variables x_j , j =1,2,....,n are introduced; let $q \leq n$ and x_j, j = 1,2,....,q refer to the crops grown on part A_1 and variables $x_{q+1}, x_{q+2},....., x_n$, refer to the crops grown on part A_2. Then the following two constraints are applicable:

$$x_1 + x_2 + ... + x_q \leq A_1$$
$$x_{q+1} + x_{q+2} + ... + x_n \leq A_2$$

b) Discuss how the linear programming model of Section 3.2.9 for the planning of maize production in Tagota village, Tanzania, should be modified, if two pieces of land with different fertility are available for the production of maize. On one of them the yield of maize and all labour input data are the same as in Section 3.2.9, on the other part, however, the yield of maize is 20 % higher, but the human labour inputs in (11) and (12) are 30 %, and in (13) 20 % higher. The food requirement constraint may be left out of consideration. Show that the modified linear programming formulation is given by:

Maximise 620 x1+520 x2+720 x3+620 x4+764x5+664x6+864 x7+764x8-576

Where the variables are subjected to:

$2x_1 + 2x_2 + 2x_5 + 2x_6 \leq 600$

$24x_3 + 24x_4 + 24 x_7 + 24x_8 \leq 300$

$30x_1 + 35x_2 + 120x_3 + 125x_4 + 39 x_5 + 44x_6 + 156 x_7 + 161x_8 \leq 3375$

$135x_1 + 135x_3 + 175.5x_5 + 175.5x_7 \leq 2250$

$30x_1 + 30x_2 + 30x_3 + 30x_4 + 36 x_5 + 36x_6 + 36 x_7 + 36x_8 \leq 2250$

$x_j \geq 0, j = 1,2...,8.$

What is the precise meaning of the variables? Introducing the slack variables $x_1, x_2, ..., x_{13}$ to replace the inequalities by equalities the constraints may be written as:

$2x_1 + 2x_2 + 2x_5 + 2x_6 + x_9 = 600$

$24x_3 + 24x_4 + 24 x_7 + 24x_8 + x_{10} = 300$

$30x_1 + 35x_2 + 120x_3 + 125x_4 + 39 x_5 + 44x_6 + 156 x_7 + 161x_8 + x_{11} = 3375$

$135x_1 + 135x_3 + 175.5x_5 + 175.5x_7 + x_{12} = 2250$

$30x_1 + 30x_2 + 30x_3 + 30x_4 + 36 x_5 + 36x_6 + 36 x_7 + 36x_8 + x_{13} = 2250$

$x_j \geq 0, j = 1,2...,13.$

The solution of this linear programming problem is given by:

$x_3 = 7,9; x_5 = 6,7; x_6 = 49.2; x_9 = 488,2; x_{10} = 110,3$ acre.

$x_1 = x_2 = x_4 = x_7 = x_8 = x_{11} = x_{12} = x_{13} = 0$

Verify this by solving the linear programming problem on a computer or by making the following calculations. Express the basic variables x_3, x_5, x_6, x_9 and x_{10} in the non basic variables $x_1, x_2, x_4, x_7, x_8, x_{11}, x_{12}, x_{13}$. Substitution of these variables into the objective function will lead to a linear function in the non-basic variables with all negative coefficients; Why does this imply that the solution has been found?

c) Verify in a similar way the solution of (16).

(7) Using the LP88 optimization software

Growing food crops or cash crops?

(Exercise developed by C.Schweigman (1985), pp. 66 - 69)

In a village in Mwanza region, Tanzania, six hundred adults participate in the farming of cotton as cash crop and maize and cassava as food crops. It will be investigated here whether it is preferable to buy maize or cassava on the local market in order to spend more time to the production of cotton. In the village cotton is planted in November or December, maize and cassava in November, December, January or February. The following variables are introduced:

x_1 the acreage for cotton planted in November and December in ha.

x_2 the acreage for maize planted in November and December in ha.

x_3 the acreage for maize planted in January and February in ha.

x_4 the acreage of cassava planted in November and December in ha.

x_5 the acreage of cassava planted in January and February in ha.

The labour inputs in the different months in mandays per ha for cotton, maize and cassava are given in table below.

Labour inputs per two months in mandays per hectare to grow cotton, maize and cassava in Mwanza region in Tanzania.

area	x1	x2	x3	x4	x5
crop	cotton	maize	maize	cassava	cassava
planting time	Nov-Dec	Nov-Dec	Jan-Feb	Nov-Dec	Jan-Feb
Jan-Feb	19	15	20	5	35
Mar-Apr	12	0	5	0	5
May-Jun	13	4	0	0	0
Jul-Aug	37	0	2	0	0
Sep-Oct	14	0	0	0	0
Nov-Dec	33	35	0	35	0

With the aid of the data in the above table and taking into account that 600 people participate in the cultivation and one month has 25 working days, the labour constraints may be formulated as:

$19x_1 + 15x_2 + 20x_3 + 5x_4 + 35x_5 \leq 30,000$ (Jan-Feb)

$12x_1 + 5x_3 + 5x_5 \leq 30,000$ (Mar-Apr)

$13x_1 + 4x_2 \leq 30,000$ (May-Jun)

$37x_1 + 2x_3 \leq 30,000$ (Jul-Aug)

$14x_1 \leq 30,000$ (Sep-Oct)

$33x_1 + 35x_2 + +35x_4 \leq 30,000$ (Nov-Dec)

Yields per hectare, annual consumption and prices of maize, cassava and cotton

crop	yield per ha in kg	annual consumption in kg	purchasing or selling price per kg in Sh.
maize	1500	143,000	1
cassava	2000	72,000	1
cotton	2000		1.9

Define the variables v1 and v2 as follows:

v1 the amount of maize to be purchased annually in kg,
v2 the amount of cassava to be purchased annually in kg.

The food requirement constraints have the following form:

$1500(x_2 + x_3) + v1 = 143,000$

$2000(x_4 + x_5) + v2 = 72,000$

In the case of the food requirement the sign = is written instead of the $\geq$ since the possibility of selling a surplus of these crops is not taken into account in this example. No capital constraints or land constraints have to be considered, so there remain only the non-negativity constraints:

$x_j \geq 0, j = 1,2,....,5$

$v_i \geq 0, i = 1,2.$

If the villagers want to maximize the annual net revenue the objective may be formulated as:

maximize $3800x_1 - v1 - v2$,

where the value 3800 follows from the yield and selling price for cotton given in the above table, and the coefficients of v1 and v2 corresponds to

the purchasing prices given in the same table. Note that the prices are expressed in Tanzanian shillings.

Verify that the solution of the linear programming problem is given by:

$x_1 = 811$; $x_2 = 93$; $x_3 = 3$; $x_5 = 36$ ha

$x_4 = v1 = v2 = 0$

This implies that it is not beneficial to purchase maize or cassava. In the months November, December, January, February, July and August all labour is used.

(8) Using the LP88 computer software

A Pakistani farmer (developed by Professor J.M. Boussaard)

A Pakistani farmer owns 15 acres of land, and his family can supply the labour equivalent of 5 men/year. He can chose between 4 crops, with the following costs and returns:

crops	yield (t or Rs (rupees) acre^{-1})	cost (Rs acre^{-1})	price (Rs t^{-1} or Rs acre^{-1})
wheat	3	1040	1055
rice	2	1826	3276
sugar cane	6	3789	1686
fodders (and cattle raising)	5669	1669	1

At the same time the estimated number of working days for each crop is as indicated:

crop	working days per acre
wheat	13.5
rice	32.0
sugar cane	94.0
fodders (and cattle raising)	53.0

Crop water requirements are as follows:

crop	water requirements (1000 cubic feet/acre)
wheat	20
rice	80
sugar cane	60
fodders	30

The number of usable working days per worker is about 100 a year. Wheat occupies land in the winter, rice in the summer and sugar cane and fodder, all the year.

Please - using the LP88 computer software package - do the following:

(a) Build up a L.P. matrix representing the farm. Notice that the farmer is short of cash, sothat the overall cost cannot exceed 30 000 rupees. In addition, one acre of land is allowed 17 000 cubic feet of water.

Solve the problem

(b) It is possible to lease land, for a cost of 2000 rupees per year, to hire labour, for 30 rupees per day, and to get water from the neighbours, at

4.72 rupees per cubic feet.

Modify the model in order o allow these new activities. Solve it.

(c) It is possible to borrow money at a rte of 14 %. Introduce this possibility into the model, and solve it.

Conclusion?

(d) The standard deviations of receipts are as follows:

crop	standard deviations of receipts
wheat	317
rice	1431
sugar cane	1271
fodders	904

The minimum required for the farm family is about 30 000 rupees. Build up the FLCP risk matrix associated with the last model, and solve it.

Conclusion?

(9) Using the XPRESS optimisation software

Given the LP problem of our example in the syllabus:

Scheme 1. An example of an LP-problem.

---

maximize $\{w = 2x_1 + 5x_2\}$ (in tons)   (1)

Subject to

$x_1 + x_2 \leq 6$ (total area constraint)   (2)

$x_1 \geq 4$ (market constraint wheat)   (3)

$x_2 \leq 3$ (area constraint potatoes)   (4)

$x_1 \geq 0, x_2 \geq 0$ (5)

where x_1 = number of hectares under wheat (ha)

x_2 = number of hectares under potatoes (ha)

---

a. Solve this problem in XPRESS
b. Add a crop activity sugar beet with a dry matter yield of 4 ton/ha.
c. Change the area constraint for potatoes in an area constraint for potatoes and sugar beet: $x_2 + x_3 \leq 3$.

d. Solve this new LP-problem.
e. Which crop activity has a `reduced cost'. Why? Explain this reduced cost.

(10) Solve the problem of exercise 4 and the questions under 4e, f and g with XPRESS.

(11) Solve the problem of exercise 5 with XPRESS

(12) Using the XPRESS optimisation software

Interactive Multiple Goal Linear Programming using XPRESS

Given the following IMGLP problem (compare with the `example' given in text):

A farmer wants to draft an optimal plan for his farm for the months May until October. He can grow three crops: wheat, potatoes and sugar beets. The labour requirements per month per hectare (May-October) for these three crops are given in the Table. The benefit per ha, the pesticide use, and the available labour are also given in a Table. Further the farmer faces the following constraints:

* he owns 60 ha of land;
* he wants to grow a crop on at least 3/4 of the farm area;
* potatoes can be grown on max. 1/3 of the farm area;
* sugar beets can be grown on max. 1/4 of the farm area.

The farmer wants to maximize the financial benefit for his farm.

a) Write this problem as a linear programming problem.
b) Write the LP problem in XPRESS.
c) Optimize the model.
d) Suppose that the farmer can buy extra casual labour. For which month would you advice the farmer to buy extra labour?
e) In the Table information is given on the pesticide use (kg a.i./ha) for each of the crops. Next to the financial benefit, another objective function of the farmer is the minimization of the use of pesticides on his farm. Write the problem as an IMGLP-model in XPRESS.
f) Make a Tables as in Tables 3.5 and 3.6 of your syllabus. Start with a zero round. Subsequently an upper or lower bound can be put on one of the objective functions, while optimizing the other, etc.. Proceed, until you end up with a satisfactory solution.
g) Suppose that the farmer also owns cattle. As a consequence, a third objective of the farmer for the arable part of his farm, is the minimization of labour input (in hours). Include this third objective in the model and carry out a zero and first round of this IMGLP model. Present the results as in Tables 3.5 and 3.6 of your syllabus.

Table - Labour (hours)

	May	June	July	Aug	Sept	Oct
wheat (per ha)	2	2	2	5	0	3
potato (per ha)	5	2	2	2	15	2
sugar (per ha)	3	21	4	0	0	9
total available (per month)	160	320	160	200	200	200

Table - Benefits and pesticide use

	benefit ($/ha)	pesticides (kg a.i./ha)
wheat	2500	5
potato	4000	15
sugar	4500	10

4. Methodology for explorative land use studies

In this chapter various aspects of the methodology for explorative land use studies are presented and discussed. Figure 4.1 summarizes the various aspects of the methodology and is an extension of Figure 2.1 in Chapter 2.2. The basis of the quantification of input-output relations concerning agricultural activities is formed by a land evaluation (Chapter 4.2). Subsequently the basic definitions and concepts which are important in the quantification of input-output relations are presented (Chapter 4.3). Chapter 4.4 deals with quantification of the various constraints and Chapter 4.5 with the identification of policy views and objective functions. The generation of land use scenarios with the IMGLP method is presented in Chapter 4.6 and finally aspects which are important in a sensitivity analysis are discussed in Chapter 4.7. However, before a detailed description of the methodology is given, clear choices concerning the boundaries of the system to be studied should be made (Chapter 4.1).

Figure 4.1 The various aspects of the methodology for explorative land use studies.

4.1. Defining the system

The system must be defined in roughly three dimensions: time, space and influence of man. The time horizon of the study depends, of course, on the aims and motives of the study. However, generally the time horizon is at least 15 years, such that `trend breaks' are possible. The time horizon affects the choices concerning the production techniques.

The motives and aims of the study also determine the system definition in space. For studies at the regional level, the borders of the system are usually determined by geographical and administrative factors. The methodology can be applied to a region within a country (The fifth region of Mali, The Atlantic Zone of Costa Rica), to a country, to a group of countries (The European Union), or to (part of) a continent. Studies at the farm level can be carried out for example for one specific farm, for a specific farm type or for an average farm in a specific region.

Definition of the system in the dimension `influence of man' is most complex. Choices concerning economical sectors (agriculture, recreation, industry, etc.) and agricultural production systems (arable cropping, animal husbandry, horticulture, fish production, etc.) are relatively easy. However, choices concerning the social and economical factors and constraints to be involved in the study are much more difficult. What to do with (current) infrastructure, (current) level of knowledge of farmers, (current) management techniques and (current) social structures? The longer the time horizon and the more explorative the study, the more variable these factors may be. Political desire and appropriate policy may influence these factors. The longer the time horizon of the study (e.g. 25 years), the more optimal these factors could be assumed or the more they can be excluded in the model. Anyhow, it is important to be very explicit about the choices concerning definition of the system in the dimension `influence of man'.

4.2. Land evaluation

In explorative land use studies one is not primarily interested in current land use and current production techniques, but also in potential or new land use types and new production techniques which might become feasible within the time horizon of the study.

In a land evaluation the characteristics of soil and climate in spatial units are confronted with the requirements for various forms of land use. This confrontation can be a qualitative one, a spatial unit is suitable for a certain form of land use or not, or a quantitative one, which also gives information on how suitable a unit is for a certain form of land use. Special courses on land evaluation are given at the Wageningen Agricultural University (Driessen & Konijn, 1992).

Qualitative land evaluation. Relevant soil characteristics include topography, stoniness, texture and acidity. Important climate factors of course are temperature, day length and precipitation. The forms of land use can be characterized by its general purpose: e.g. agriculture, nature, landscape and recreation. If we focus on agriculture, the crops which are grown and the degree of mechanization which is used to grow these crops determine the soil and climate requirements. Different groups of crops with different requirements can be distinguished. Perennial crops and annual crops can be distinguished. Within the annual crops, generally the requirements which the soil must satisfy decline from root and tuber crops to cereals and finally grass. The requirements which the climate must satisfy, especially differs between C_3 and C_4 species, e.g. wheat and rice versus maize, millet and sorghum. The degree of mechanization has its implications for the requirements on soil and climate. In explorative studies production techniques with various degrees of mechanization should be included to show consequences of mechanization. This is particular clear for developing countries, in which mechanization is not common yet, but also in industrialized countries in which various way of weed control are possible: chemical, mechanical and with manual labor.

An important question is the scale at which the land evaluation should take place. Usually this scale is determined by the level of detail of soil maps and climatic data, administrative sub-regions within the system under study, and pragmatic arguments. Figure 4.2 illustrates that it is important to aggregate or average as late as possible: first calculate, then average.

Quantitative land evaluation. For areas suitable for a specific form of land use as e.g. growing crops, potential or water-limited crop yields (see Chapter 4.3) can be calculated by using crop growth simulation models. Crop growth models for this purpose, must be simple without too much detail. Ideally, they only require a few important parameters on soil, climate and crop characteristics.

Figure 4.2 The influence of averaging rainfall on its calculated yield response. The yield is underestimated by averaging in the lower rainfall region (A) and overestimated in the higher rainfall region (B) (De Wit & Van Keulen, 1987).

4.3. Quantification of input-output relations: Concepts and definitions

4.3.1. Introduction

In land use studies using the linear programming technique, information on land use is translated in input-output relations. Agriculture can be defined as the human activity in which energy from the sun is fixed, using other inputs as good as possible. This activity results in desirable outputs, e.g. grain, and, inevitably, in undesired outputs, such as nitrogen losses. Inputs can be applied for the realization of outputs in numerous ways.

Input-output relations can be considered from the question `what is possible' (exploration) considering the time horizon chosen or from the question `what happens'. In answering the question `what is possible', bio-physical possibilities are identified which can be curtailed by socio-economic, agronomic and environmental factors. Possibilities to grow a certain crop and the corresponding yield are determined by bio-physical factors like climate and soil and production ecological processes. In research with the central question `what happens', the current situation is described and characterized. The analysis aims at the way actual inputs and outputs are determined by production ecological, socio-economic and environmental factors.

In explorative studies input-output relations should be defined from the question `what is possible'. For a good and systematic quantification of input-output relations in explorative studies, a general terminology and some concepts are important.

4.3.2. Target-oriented approach - complete information

Inputs can be classified in various ways. An important classification in production ecology is that of substitutable and non-substitutable inputs. Non-substitutable inputs like water and nutrients are taken up by the plant, and sometimes incorporated (nutrients). They fulfil a specific and essential role; no mutual substitution between these inputs is possible. Substitutable inputs are not incorporated in the plant. They can replace each other, up to a certain degree. Examples are labor, mechanization and pesticides.

Outputs can be subdivided in desirable outputs, the crop yield or parts of it, and undesirable outputs to the environment, the emissions, such as nutrient losses and pesticides, or `immissions', such as nutrient depletion of the soil.

Both inputs and outputs are expressed in physical units. The use of inputs can be expressed per unit area or per unit desired output. The efficiency of the use of inputs is defined as the input per unit desired output. The emissions can also be expressed per unit desired output and per unit area.

As stated, inputs can be used for production of outputs in numerous ways. However, inputs are not used without any intention, but with a specific aim, related to the desired outputs, but also related to factors like risk and uncertainty. The adjustment of inputs to the desired outputs is an attractive approach in production ecological analysis of input-output relations, which is called the *target oriented approach*. In the definition of inputs and outputs, knowledge on the processes involved is used. The potential outputs primarily depend on the crop characteristics and the circumstances under which a crop is grown, especially temperature and radiation. By aiming at a specific output, the amounts of water and nutrient can be quantified, using the knowledge concerning uptake and use of resources. Subsequently, the required crop protection for the realization of the output is quantified.

In the target-oriented approach complete information is supposed, i.e. the output which can be realized and the required inputs are known a priori; factors like risk and uncertainty (e.g. due to weather conditions) are ignored. Further, it is assumed, that in explorative research not more water, nutrients or pesticides are used than necessary, according to the available knowledge and technique.

4.3.3. Production level, production situation, production technique and production orientation

Input-output relations according to production ecological principles can be characterized with the terms production levels, production situation, production technique and production orientation.

The *production level* points at the production of desired output per unit area. In production ecology various production levels can be distinguished according to three groups of production factors: growth defining, growth limiting and growth reducing factors (Figure 4.3). The growth defining factors include factors that, at optimum supply of all inputs, determine growth and production from a plant's point of view: CO_2 -concentration, radiation, temperature and crop and cultivar characteristics. The growth limiting factors comprise water and nutrients, taken up by and (partly) incorporated in the plant. The growth reducing factors include weeds, diseases, pests and pollution. The various inputs that are used in growing a crop, affect production via these production factors.

Figure 4.3 Production situation, production levels and associated principal growth factors (Rabbinge et al., 1994b).

The three production levels that can be distinguished with these three groups of production factors are: potential production level, water and nutrient limited production (attainable) levels and actual production levels. The potential production level is dictated by growth defining factors; the crop is optimally supplied with water and nutrients and is completely protected against growth reducing factors. At water or nutrient limited production level, the production is lower due to a lack of water or nutrients. The actual production level is determined by a lack of water, nutrients and incomplete crop protection against growth reducing factors. As a matter of fact, there are many water and nutrient limited and actual production levels at one potential production level, dependent on the degree of lack of water and of nutrients, and dependent on the degree of damage due to growth reducing factors.

An input-output relation is location specific. The location can be characterized by the *production situation*, i.e. the conditions under which a crop activity takes place and which are more or less a given fact for that crop activity. These conditions are hard to manipulate, and they affect the potential production level and/or the required inputs to realize a certain production level. The other way around, the activity hardly affects the production situation. The production situation includes the following factors:

(i) climate, especially temperature, radiation and humidity;

(ii) soil characteristics which affect the uptake-efficiency of the non-substitutable inputs water and nutrients (such as pF-curve, clay fraction, texture, pH and organic C-concentration);

(iii) biotic factors in soil and environment, hardly affected by the crop activity itself (e.g. `pressure' of pest and diseases).

The resource pools of water and nutrients in the soil which are available for a crop, are not included in the production situation. These pools can be easily manipulated by the application of inputs.

If two production situations only differ in soil characteristics or biotic factors, the potential production levels in these production situations do not differ. With the same input levels, however, the attainable and actual production levels will be higher in the good production situation than in the bad production situation. If the climatic factors also differ between the two situations, the potential production levels will also differ (Figure 7).

The *production technique* stands for the complete (way of) use of non-substitutable and substitutable inputs to realize a certain production level in a certain production situation. Since some inputs are substitutable (e.g. labor, mechanization or pesticides) a certain production level in a particular production situation can be achieved with various production techniques.

A *production activity* (or an input-output relation) stands for the growth of a crop or cropping system fully characterized by its inputs and outputs. The same production technique applied in two different production situations results in different outputs and thus in two different production activities.

With the former concepts and the target-oriented approach, still numerous input-output relations can be defined in each production situation. We need the concept *production orientation*, which denotes the aim of the production activity and which directs the quantification of a particular input-output relation. Aims of production activities could be: a high soil productivity, high resource use efficiencies, low emissions per unit product, low emission per unit area, no external inputs, etc..

4.3.4. Aggregation level and time horizon of input-output relations

The input-output relations are derived for the level of crop or cropping system. For studies at the regional level, the role of the farm and the farmer are neglected; production factors like area, labor and mechanization are assumed to be variable. For studies at the farm level, the role of the farm and the farmer are kept explicit. The assumptions on farm area, labor availability and mechanization depend on the time horizon of the study.

The time horizon of an explorative study should be reflected in the time horizon of the input-output relations. Input-output relations in static models, like linear programming models, should be defined in such a way that they can hold for many years or cycles of the crop rotation. This implies that the resource pools in the soil should not change as a result of the production activity, unless explicitly desired, as for instance could be true for P-saturated soils. Further, the production situation should be maintained, e.g. the application of soil tillage to maintain or repair soil structure.

4.3.5. Quantification of non-substitutable inputs

Based on the amount of water used by the crop to produce one kg dry matter (transpiration coefficient) at a certain temperature, radiation level and humidity, the water uptake for a certain production level can be quantified (Van Keulen & Van Laar, 1986). Since each of the nutrients has a specific function within the plant, the nutrients cannot be substituted mutually and their concentrations are more or less fixed. In this way the nutrient uptake for a particular production level can also be calculated (Van Keulen, 1986; Driessen, 1986).

Not all non-substitutable inputs available in the soil are taken up by the crop. The difference between supply and uptake of water or a nutrient, or in other words, the efficiency of the uptake of the various inputs, depends on (i) the level of the other inputs (and thus the production level), because of the interaction between various inputs (De Wit, 1992), and (ii) the production situation, especially the physical and biological characteristics of the soil. The levels of the other inputs (i) are manipulated in order to realize a certain production level. An appropriate adjustment of the inputs has a positive effect on the uptake of water and nutrients. A crop which is optimally protected against pests and diseases will use water and nutrients more efficiently. In a favorable production situation (e.g. a favorable pF curve or pH), water and nutrients are used more efficiently and less inputs are required to realize a certain uptake and production level than in unfavorable production situations (ii).

The available water and nutrient pools in the soil are often insufficient to realize an uptake that meets the entire requirement for a desired production level. The resource pools, therefore, have to be supplemented with irrigation water and external nutrients. The external inputs can be applied in various ways. Nutrients can be supplied in inorganic and organic form. The frequency of input application may differ: one application at the start of the season, or split applications spread over the season. Finally the spatial distribution of applied inputs is important: broadcast or row application. The way in which the requirements of a crop are met also affects the uptake efficiency and thus the required input level. In explorative research it is assumed that not more inputs are applied than strictly necessary according to available techniques. Efficient and saving techniques are applied.

4.3.6. Quantification of substitutable inputs

Next to the non-substitutable inputs, also substitutable inputs are required to realize a certain production level. The crop must be protected against weeds, diseases and pests by for instance crop protection techniques and crop rotation. Since it does not matter for a crop how it is protected, as long as it is protected, we speak about substitutable inputs: herbicides or weeding machines, pesticides or crop rotation. Not all pesticides, however, can be substituted by other inputs, for instance some fungicides.

The choice for substitutable inputs depends on the production orientation. In economical aims, the mutual price ratios determine the optimum mix of substitutable inputs. In explorative research other aims may be important as well, for instance ecological or social aims; inputs which are favorable from an economical point of view (e.g. pesticides) can be substituted by labor.

4.3.7. Emissions and immissions

Undesired outputs are inevitable in production activities. If we suppose an equilibrium situation in which the available nutrient pools in the soil do not change as a result of a production activity, then it is clear that the difference between the input of nutrients (thus available nutrients minus soil pools) and the uptake by the crop disappears from the system (leaching, denitrification, volatilization, etc.). Emission also occurs when using pesticides. This may apply to the applied compound itself, or to its degradation products.

With similar input levels, in good production situations higher yields can be achieved than in bad production situations. Therefore, at similar input levels per hectare, the emissions per unit product and per unit area are lower in a good production situation than in a bad production situation.

Next to emission, `immission' may occur; if not all nutrients taken up by the plant are supplied by external inputs, the nutrient pools in the soil decrease.

Not always, equilibrium situations are pursued. Sometimes emissions or `immissions' are desired. It can be desired to improve soil fertility by building up soil pools. In the case of saturated soil, for instance with phosphorus, `immission' can be desirable.

4.3.8. Production functions or technology sets

Relations between one input and one output can be represented mathematically and graphically in a *production function*. The concept of production functions is however limited, because generally several inputs are varied simultaneously and some inputs have a discontinuous nature. Because of positive interaction between various inputs, generally it is not rational to consider relations between just one input and an output, but to tune a mix of inputs to realize a certain output. Some inputs have a discontinuous nature, for instance the use of pesticides or the use of some kind of machine. The use of such an input, opens the possibility of realizing a higher production level with the right mix of the other inputs; a technology jump. It is important to include essential technology sets in the linear programming model for the land use study.

Examples of technology jumps (and sets) at crop or cropping system level can be found by comparing yields and belonging inputs for the growth of some kind of crop some decades ago and the growth of that crop nowadays. Table 4.1 gives the technology sets of 1972, 1982 and 1992 for the growth of sugar beets in two areas in the Netherlands. Yields and a selection of inputs are given. In both areas yields have increased, whereas the N rates did not change or decreased. Different cultivars were used and the crop protection has been fine tuned. The number of spraying increased, but the amount of active ingredient per spraying decreased. Chemical crop protection against weeds was partly replaced by mechanical techniques.

Table 4.1 also illustrates the difference in production situation. In both regions the output/input ratio was improved in the course of the decades, but this was more true for the `Centraal kleigebied' than for the `Veenkoloniën'. With the same or less inputs, higher yields are realized in the better production situation (`Centraal kleigebied') than in the worse production situation (`Veenkoloniën').

4.4. Identification and quantification of constraints

The constraints in the linear programming model can be roughly classified in resource constraints and product and demand constraints.

The resource constraints comprise e.g. area constraints, water constraints, nutrient/manure constraints and labor constraints. The area, and sometimes the water constraints, are a result of the land evaluation.

The product constraints `regulate' the conversion of arable cropping products or roughage to industrial products or feed, and the conversion of feed to animal products. The demand constraints `regulate' the demand for agricultural products produced in the system, which is related to several factors:
* the trade situation and the policy views on the future trade situation (free trade or autarky);
* population and population growth;
* dietary patterns of the population.

The dietary patterns depend on the increase in real disposable income and on inflation. As the living standard rises, the consumption of basic food requirements flattens out, in both absolute and per capita terms. The total consumption of food, however, continues to rise on account of a shift in demand towards more expensive, high-protein products such as meat and cheese.

Table 4.1 The outputs and a selection of inputs for the growth of sugar beets in 1972, 1982 and 1992, *in two production situations (`Centraal kleigebied' and `Veenkoloniën')*

outputs/inputs	1972	1982	1992
'Centraal kleigebied'			
yield (ton ha^{-1})	56	59	68
cultivar (-)	Kawepoly	Monohil	Univers
fertilizer use (kg ha^{-1}):			
N	160	160	140
P$_2$O$_5$	100	100	100
K$_2$O	80	310	145
crop protection:			
pesticides (kg a.i. ha^{-1}):			
herbicides	10	7	7
others	2.6	0.5	1.2
treatments (number):			
spraying	4	3	6
weeding	0	1	2
'Veenkoloniën'			
yield (ton ha^{-1})	45	48	51
cultivar (-)	Kawepoly	Monohil	Univers
fertilizer use (kg ha^{-1}):			
N	160	160	160
P$_2$O$_5$	120	90	50
K$_2$O	200	285	200
crop protection:			
pesticides (kg a.i. ha^{-1}):			
herbicides	13	18.5	13
others	1	4.5	1
treatments (number):			
spraying	4	5	7
weeding	0	2	3

4.5. Policy views and objective functions

In the subsequent step in the methodology various policy views concerning land use problems should be identified, e.g. views emphasizing self-sufficiency of food, free market and trade, nature conservation, environmental issues, etc. They can be distilled from policy documents issued by the relevant governments or donor agencies and from interviews with policy makers and representatives of societal organizations.

Policy views can be operationalized by means of objective functions that are minimized or maximized in the IMGLP-procedure. For instance, the policy view with great concern for environmental issues can be operationalized by the objective functions `the use of nutrients or pesticides per hectare or per unit product', that are minimized.

The objectives must be quantifiable, each in their own dimensions and the quantification must be linked to land use in the system. More over, the objective functions must be mutually conflicting, at least up to a certain extent and not totally. If the objectives form extensions of one another the model cannot generate alternative allocations. If on the other hand the objectives are totally mutually conflicting, the results will be meaningless since the loss in terms of one objective will automatically mean the gain in terms of another.

Not all policy views can be easily quantified with objective functions, e.g. nature development or conservation. These kinds of views have strong spatial components, that are hard to catch in a mathematical function. Such views should be confronted with the generated scenarios in various evaluation steps (*ex post* analysis).

4.6. Interactive multiple goal programming

In the former steps of the methodology an IMGLP model is formulated. In the following step the technical coefficients about the production of and the demand for agricultural products are confronted with the objective functions representing the different policy views. This is the most important *interactive* part of the methodology. Of course stakeholders can interact earlier in the process, e.g. by assisting in defining the system, identifying production techniques and identifying policy views, but particularly in this part they are confronted with the consequences of choices in priorities they make.

Firstly, the `playing field' is determined by optimizing each of the objective functions, without putting (heavy) restrictions on the other objective functions. These are called the zero rounds. Worst and best values are determined for each of the objective functions. The initial freedom of choice for each objective -the difference between the best and worst value- is made explicit to the stakeholder in this way.

In the next step the stakeholder has to select the objective with the worst value which he considers as most unacceptable. A tighter bound for that objective has to be formulated. Subsequently the stakeholder is confronted with the results of a new series of optimization runs and has to select again an objective with a value which is unacceptable to him. This procedure continues until the stakeholder is satisfied with the results.

Ideally the procedure should follow the steps described above, but is not followed in both case studies. In the EC-study, ideally the different groups, e.g. farmers organizations, nature conservation organizations and so on, should have been invited. In the Mali-study, local and national authorities and representatives of the different donor agencies were only invited once. They were confronted with several scenarios, differing because emphasis was put on different objectives. However, they had no opportunity to make other choices than the scientists executing the study had made for them.

Apparently it is difficult in such land use studies to organize an interactive step with the stakeholders. This might be due to the numerous stakeholders involved at different levels of a decision process. Furthermore the high hierarchical levels of both studies imply that several groups acting at lower hierarchical levels, are less interested. For them, the methodology is difficult to understand and, additionally, the LP software-packages are not user friendly. It also takes much time to run the models.

4.7. Generating land use scenarios

In giving more or less weight to some of the policy objectives in relation to others different scenarios can be developed representing the different policy views. In developing the scenarios trade-off between the different goals become clear.

In both studies the executing scientists made a choice to create scenarios related to the different policy views in stead of following a real interactive procedure with stakeholders. The stakeholders at higher integration levels are politicians. Since their policy views are commonly written down in programs, the scientists executing the studies have selected and earmarked them according to the objective which is getting the highest priority in that policy view.

The differences between the scenarios in both studies indicate that there is room for policy change.

4.8. Sensitivity analysis

The results of an analysis with the IMGLP technique can be sensitive to various aspects. In each of the steps in the methodology, we make choices and use `guestimates'. We deliberately ignore complex issues. For instance, we average values and thus eliminate variation in technical coefficients in time and in space and we neglect stochastic aspects, subjects we can not deal with up till now. Evidently, a sensitivity analysis should be part of the land use studies. However, given the enormous number of technical coefficients used and choices made throughout the process, sensitivity analysis was always limited to only some aspects in the studies carried out so far. We will illustrate the need for a sensitivity analysis by going through the examples found in literature.

In defining the system, choices are made on the spatial unit within the system, for which a land evaluation is carried out, and for which specific input-output coefficients are defined. This implies that within these units heterogeneous sub-units or sub-regions are aggregated. An example of the effects of aggregation on results with land use models is given by Rabbinge & Van Ittersum (1994), showing that using aggregated data in an LP-model results in less extreme values after optimization. They supposed, that a particular region is divided in four land evaluation units of 1000 ha each. The wheat yields with a certain production technique in these units are supposed to be 8, 6, 4 and 2 t ha^{-1} for unit 1, 2, 3, and 4, respectively. The objective of the optimization is to minimize the area in the region required to produce 10 000 ton wheat. In Figure 4.4 the effect of aggregating units 1 and 2 and units 3 and 4 is shown. Without aggregation, the minimum area is 1333 ha (1000 ha in unit 1 with 8 t ha^{-1} and 333 ha in unit 2 with 6 t ha $^{-1}$), whereas after aggregation the minimum area is 1429 ha (1429 ha in unit 1 + 2 with an average yield of 7 t ha^{-1}). This example shows that the level of aggregation has an effect on the results of the optimization.

The choices which production techniques, products and policy views are included in the study are extremely crucial. The sensitivity of changing policy views are commonly tested by changing e.g. the targets of objective functions. If scenario building is really done in an interactive way, thus in close collaboration with stakeholders, the outcome of the land use study should not result in a big surprise. Part of our exercises deals with this type of sensitivity analysis. In other exercises it is shown that the choice to add one or more production techniques does influence the results in the way that the `solution space' or `window of opportunities' can be enlarged.

Figure 4.4 *The effect of aggregation of four land evaluation units of each 1000 ha to two units of 2000 ha each on the minimum agricultural area required to produce 10000 ton wheat in the region (4000 ha total) (see text).*

All work on system definition, choices for production techniques, products and policy views results in an LP-model which can be simply represented by:

MIN/MAX (c' x)

subject to:

A(x) $\leq$ b

These LP-models are sensitive to:
* the input-output relations (technical coefficients, the values for a):
* the physical or normative boundaries (the values for b);
* the coefficients of the objective functions (the values for c).

LP-software has a standard sensitivity analysis for part of these values (shadow prices, Right Hand Side ranging and ranging of the coefficients of the objective functions; see Chapter 3.2.8). However, in defining the technical coefficients, we use an enormous number of values, which can be criticized. Testing the model for sensitivity to changes in these values is hardly done and is mainly limited to some values as e.g. prices for inputs (fertilizers) or outputs (cereals). Bessembinder (in press) argues that more attention should be paid to the *uncertainty* of other technical coefficients as e.g. the fertilizer use efficiency. The sensitivity of a model should not only be tested for changes in technical coefficients but also for changes in assumed restrictions (RHS=Right Hand Side values).

In estimating technical coefficients often average values are used. In practice values can vary in time and in space. This is e.g. the case for production estimates at different rainfall regimes. Figure 4.2 shows the relation between yield and rainfall. Since the relation is curvilinear, yields are underestimated in the lower rainfall region and overestimated in the higher rainfall region.

Nevertheless, *stochastic* aspects are completely neglected. In practice the distribution or succession of low and high values in time is also very important. E.g. in livestock production based on natural pastures two subsequent dry years are much more disadvantageous than two years alternated by a normal or wet year.

Whether we deal with heterogeneity in space (see example of aggregating land units) or in time (see example with production levels at different

rainfall regimes), the credo `first calculate and then average' is valid. Heterogeneity and curvilinearity in input relations should be retained as long as possible and their consequences should be included in the evaluation phase.

4.9. General discussion

The stages and steps that are included in a land use analysis study, generally speaking, are shown in Table 4.2

Table 4.2 Stages and steps included in land use analysis studies

stage		step	
1	model preparation	1	determination of goal variables and constraints
		2	system definition and time horizon determination
		3	data generation
2	model construction	4	development of the IMGLP model
3	model utilization	5	construction of the playing field
		6	conducting sensitivity analysis
		7	scenario construction

This Chapter has discussed the methodological aspects of explorative land use studies. Very often these studies leave insufficient time for the utilization of the IMGLP model with stakeholders in the use of land. Consequently, results are generated, however, the interpretation of these results and their translation for policy making is limited. IMGLP then becomes MGLP. In this regard LUA studies leave room for improvement. This can be found particularly in the field of quick and efficient generation of data, required for the study.

LUA studies have a tendency to be very data intensive. This makes it extra necessary that the data requirements are made explicit at a very early stage of a LUA project. The expressed data requirements have to be very carefully evaluated considering the objectives of the study. Each time when conducting a LUA study the following questions should be asked:
* what is the purpose of the LUA study that we are going to conduct?
* what implications does that have for the type of data that we are going to need?; and
* how can we obtain that data in the quickest and most efficient manner?

Only when these questions are given serious consideration, a situation can be avoided where too much time is spent on stage 1 of a LUA study and too little time on stage 3 as is often the case with LUA studies.

4.10. Exercises

1) Give five different examples of a system, clearly indicate the boundaries.

2) Indicate what the differences are between qualitative and quantitative land evaluation.

3) Write down as briefly as you can what the differences are between production level, production situation, production technique and production orientation.

4) Why is a distinction made between substitutable and non-substitutable inputs.

5) For the region that you live in formulate at least four policy views concerning land use.

6) Considering the answers that you gave to question (5) indicate which type of sensitivity analysis you consider most important.

7) In which ways is a playing field (also called a potency matrix) different from a scenario?

Chapter 5 and 6

Rapports PSS Nº 31
(Chapter 5 and 6)

Land use analysis using multiple goal linear programming

A course manual

5. The European Community case study

Description of this case study is based on Rabbinge *et al.* (1994) and WRR (1992)

5.1. System definition

The system to be analyzed was the European Community (EC) with 12 member states, excluding the territory of the former GAR (East-Germany; the study started in 1988). In the study, the EC was subdivided in 58 regions, the political administrative units at NUTS-1 level (Figure 5.1). The relation between the system and the rest of the world depends on the policy views under consideration. Both a situation with free trade and one with autarky have been considered.

Figure 5.1 The political administrative units at NUTS-1 level in the EC.

As a result of the objectives of the study, as described in Chapter 2, the entire region is considered as one `farm', effects of differences in farm size and type were not studied. Only those agricultural activities that require the use of land as a production factor were considered per region. Pig and poultry raising were treated as industrial processes with an agricultural input. Horticulture was not considered at all. Crops and livestock that are included in the model were those which are already usual in the EC: new crops are not considered. Limitations due to the current presence of processing industry, infrastructure or lack of knowledge are not considered, since in the long run (25 years) it could be that these factors are not a serious constraint anymore. For all regions within the system the production possibilities are defined by the features of the crop, soil and climate.

5.2. Land evaluation

In the first part of the land evaluation, the qualitative part, the soil map of the EC, an agro-climatic map distinguishing 109 zones and a map with the NUTS-1 regions (Figure 5.2) were combined, which resulted in a map with about 4200 Land Evaluation Units (LEU's), each comprising a unique combination of soil unit, climatic region and NUTS-1 region.

Figure 5.2 Example of an overlay of soil map, agro-climatic map and a map with the NUTS-1 regions for a part of Europe.

Subsequently, these LEU's were confronted with the soil and climatic requirements of three types of crops: grass, cereals and root crops. The requirements were defined in terms of e.g. texture, slope, drainage, rooting depth, salinity and temperature. The definition of the requirements was based on the workability of the soil with appropriate machinery and the minimum soil conditions allowing crop growth. The criteria were increasingly severe for the three crop types. From the qualitative selection procedure it follows that (part of) a LEU is either suitable or unsuitable for mechanized crop cultivation. Figure 5.3 shows the percentage of area per country suitable for grass, cereal and root crop production.

After this qualitative part of the land evaluation, the production potentials of the suitable LEU's under water-limited and potential conditions were calculated with the crop growth simulation model WOFOST. This model simulates growth, development and yield of a field crop, and the water balance of the soil, under defined weather and soil conditions.

Figure 5.3 Percentage of agricultural area suitable for root crops, cereals and grass.

5.3. Input-output combinations

General. As stated before, in an explorative study current agricultural practices are not the proper starting point. One could consider the in/output tables of the `best farmers' in a certain region as the criterion for the possibilities of all farmers in that region. However, this might imply specific structural differences between regions e.g. differences in education or farm sizes, that may have disappeared at the end of the time horizon of a study. In the study about the Rural areas in the EC, production ecological concepts and the most efficient application techniques of the various resources required for a crop to grow were applied to quantify production activities in all regions of the EC. Differences in management and business structure are therefore not taken into account. This assumption implies that within the time-frame of the study, there could be no longer any differences in education level and industrial structure between regions in the system. It should be judged whether this is plausible.

In the EC study 5 forms of land use were included: arable crops, grassland and animal husbandry, permanent crops like fruit trees and olives, forestry and nature. In the case study and in this section special attention is paid to the quantification of the arable cropping activities and the grassland activities. Literature and expert knowledge were used to quantify the production activities.

Arable cropping and grassland. In the EC study all input-output relations for arable crops were defined

for the cropping system level. Some 40 crop rotations were defined using expert knowledge. The most heavily demanding crop in the rotation determined the area suitable for that crop rotation. Three production orientations were defined for arable cropping and for grass: a Yield Oriented Agriculture (YOA), an Environment Oriented Agriculture (EOA) and a Land use Oriented Agriculture (LOA). For the YOA and EOA activities were defined both with and without (rain fed) irrigation.

For the quantification of the input-output relations in YOA, the results of the quantitative land evaluation derived with crop growth simulation models were used as a starting point. The simulated yields were corrected for inevitable harvesting losses and losses due to soil-borne diseases as a result of too narrow crop rotations. The required inputs to realize the outputs were estimated by using expert knowledge. To arrive at an economic optimum some substitution of agro-chemical by labor and/or capital is permitted.

The production activities in an Environment Oriented Agriculture were defined by means of literature and expert knowledge. In these activities the use of pesticides was lowered with ca 70 % on an average (compared to the use in YOA). Part of the pesticides were substituted by mechanical forms of crop protection, but the decreased use of pesticides also resulted in some 20 % yield loss.

Finally for grass and wheat crops activities in a Land use Oriented Agriculture were defined. No pesticides were used in these activities and soil productivity was low.

Livestock activities. Livestock uses feed derived from arable crops or roughage (e.g. grass and silage maize). Basically the feed requirements of livestock could be expressed in some nutritional components, i. e. Metabolizable Energy (ME), Digestible Crude Protein (DCP), and (for ruminants) in structural material because of the need for fibrous material. So in the LP-model, both the nutritive value of arable products and roughage as the feed requirements of livestock could be expressed in ME, DCP and structural material.

Nature. Besides this quantitative definition of agricultural activities, the preferred locations for nature conservation and development were shown in a map. This technical information, based on a set of criteria, is also used as an input for the scenarios in a post model analysis.

5.4. Constraints

Besides area and labor constraints a set of water constraints and a set of manure constraints were included in the EC model. The water constraints quantified the upper limits on water that can be used for irrigation for each of the regions. These upper limits were determined by precipitation, soil water pools and run-off. The manure constraints were also defined for each region. In these constraints it is required that all manure produced by cattle in a region is used for arable farming or roughage production in that same region.

Since industrial processing activities were also included in the model, not only demands for primary products like milk or sugar beets were modelled, but also those for products like cheese, butter or sugar.

In quantifying the demand for agricultural products, two trade situations were distinguished, one with free trade and one with autarky, and two diets, one according to current feeding customs and one with more animal products. The population growth was estimated at less than 0.1 % per year.

5.5. Policy views and objective functions

In the EC-study four policy views are distinguished. One policy view is focusing on free market and trade: economic productivity and minimization of costs are the prevailing characteristics. The second policy view aims at regional development: to maintain employment and promote income in the agricultural sector are the dominant aims. The third policy puts the highest priority on nature development and landscape conservation: here the conservation of the landscape and development of natural conditions have the highest priority. Agricultural production should be restricted to the smallest area possible. The last policy view aims at protection of the environment: the negative side effects of agriculture should be minimized, which is translated in minimization of pesticide and artificial fertilizer use.

The policy views are quantified in eight objectives, two agricultural objectives, two socio-economic objectives and four environmental objectives (Table 5.1). Nature and landscape objectives turned out to be very difficult to implement. Objectives related to nature and landscape are site- or location-specific, making it difficult to define a general rule that models these objectives. Therefore *ex post* analyses were performed to provide information on the fulfilment of these objectives. For instance by designing a map concerning the nature development or conservation and by confronting the map with a nature and landscape scenario.

Table 5.1 Objectives incorporated in the EC-study (Rabbinge & Van Latesteijn, 1992)

class of objective		objective
agricultural	1	maximize soil productivity
	2	minimize costs of agricultural production
socio-economic	3	maximize total employment in agriculture
	4	minimize regional decrease in agricultural employment
environmental	5	minimize loss of nutrients per unit of acreage
	6	minimize loss of nutrients per unit of product
	7	minimize input of pesticides per unit of acreage
	8	minimize input of pesticides per unit of product

5.6. Land use scenarios

In the EC-study four scenarios have been developed by putting different priorities and bounds to the

various objective functions.

Scenario A: Free market and free trade.

In the free trade scenario agriculture is treated as any other economic activity. Production takes place at the lowest possible costs. Starting point is a free world market for agricultural products with minimal restrictions on social services and environment. The policy view dominating in this scenario, was close to the policy view of the USA in the negotiations for the General Agreement on Tariffs and Trade (GATT).

Scenario B: Regional development.

In this scenario regional employment within the EC has the highest priority. Income generation for farmers within the agricultural sector is of main importance. The policy view dominating in this scenario can be seen as continuation and extension of today's EC-policy.

Scenario C: Nature and landscape.

In this scenario highest priority is given to maintain existing nature areas as much as possible. A spatial separation between nature habitats and agricultural areas is created. Next of areas strictly restricted for nature conservation, areas are chosen for human activity. This scenario represents the policy view of nature conservation organizations.

Scenario D: Environmental protection.

The most important policy view in this scenario is to prevent alien substances from entering the environment. Different from the former scenario the main aim is not to preserve or stimulate certain plant and animal species, but to protect soil, water and air. There is no spatial separation of nature and agricultural areas, but rather integration. Agriculture can be practised everywhere, but under strict regulations for environmental protection. This scenario represents the policy view of integrated agriculture.

Figure 5.4 Agricultural land use, employment, nitrogen loss and pesticide use in the four scenarios and in the current situation (Van Latesteijn & Rabbinge, 1992).

Each of these four scenarios results in a different land use, employment, loss of nitrogen and use of pesticides. However, there are some results that are common for the four scenarios (Figure 5.4).

All scenarios show a drastic decline in use of land for agricultural purposes. The total area in the four scenarios varies between 26 and 92 million hectares, whereas currently 130 million hectares are used for agricultural purposes (Figure 5.4 a). Another result is that 1.5 to 2.9 million man years would suffice for the total agricultural production in stead of the 6 million man years that are involved in the primary production at present (Figure 5.4 b). Further the loss of nitrogen and the use of pesticides can be reduced

dramatically (Figure 5.4 c and d). For instance for pesticides 21 to 154 million kg of active ingredient would suffice in stead of more than 400 million kg at present.

Maps derived with the results of the model further demonstrate the location of land use and production techniques under different policy views. Two alternative policy views are given as examples (Figure 5.5). The first policy view, Scenario A, is based on free market and free trade. Costs of production are minimized. The second policy view, scenario B, concerns stimulation of regional employment in a situation of autarky in the EC; regional employment is maximized. Figure 5.5 a (scenario A) and 5.5 b (scenario B) show the locations of cereal production under these two alternative policy views. The volume of production is similar, but the location differs. In scenario B the production is spread wider across the union in order to fulfil the objective of regional employment. In Scenario A only the most efficient regions are used for production. In Figure 5.5 c and d, the locations of grassland are shown in the two scenarios. These maps are to be interpreted together with the previous two. The allocation in Scenario A (Figure 5.5 c) clearly shows that grasslands in some areas near the Mediterranean are optimal in terms of minimizing production costs; this may be an effect of the longer growing season in the Southern regions.

Figure 5.5 The allocation of cereal production (a, b) and grass production (c, d) in Scenarios A (a, c) and B (b, d). The shading indicates the percentage of the suitable area per region that is actually used. Rabbinge & Van Latesteijn, (1992).

5.7. The EC study: a summary

Immediate motives and objectives of the study

There were several motives to carry out this study for the EC:

a. The productivity in agriculture production continues to rise, and after a situation of self-sufficiency was reached, a situation with overproduction arose. Because of the system of guaranteed prices for most agricultural products, this requires an increasing amount of money.

b. There is a growing tension between the EC and the world market. In the GATT negotiations the protected prices for agricultural products in the EC were a hot issue.

c. Attention has grown for other goals than agricultural production: environment, nature, employment and farmers income.

The study `Four perspectives for the rural areas in the European Community' (WRR, 1992) aimed at defining the limitations to the growth in productivity and at exploring the consequences of different policy views for developments within the rural areas of the EC.

5.7.1. System definition

* Spatially the system is defined by the 12 member states of the EC (excluding the former GAR). This system was subdivided in 58 administrative sub-regions.
* The time horizon for the study is ca 25 years (2015).
* Only the soil bound part of the agricultural sector is considered i.e. arable farming, permanent crops, forestry and animal production; horticulture was not considered.
* Limitations due to the current presence of processing industry, infra-structure or lack of knowledge are not considered. The production techniques included in the model were quantified using the principle of best technical means: tradition, level of knowledge, available farm equipment and layout and size of parcels are no limitation.
* Effects of farm sizes are not included: the entire region is considered as one farm.

5.7.2. Land evaluation

* A qualitative land evaluation was carried out based on the EC soil map, an agro-climatic map and the crop requirements. Three indicator crops with increasing requirements were distinguished: grass, cereals and root crops; new crops were excluded. The requirements of these crops were confronted with the soil and climatic characteristics in ca 4200 Land Evaluation Units.
* Subsequently, a quantitative land evaluation was carried out based on crop growth simulation models, both for a water limiting situation and a potential (irrigated) situation.

5.7.3. Quantification of input-output combinations

* Three production orientations were defined for arable cropping:
* Yield Oriented Agriculture: high soil productivity;
* Environmental Oriented Agriculture: reasonable high yields, but with reduced chemical inputs;
* Land use Oriented Agriculture: no use of chemical inputs.
* Many crop rotations were defined. The output for the different production activities was taken to be a certain percentage of the yields calculated by simulation models. The in/output tables were generated for the entire crop rotations (on a yearly basis) by means of literature and expert knowledge; the inputs were defined in a target oriented way. The production activities were quantified according to the concept of best technical means: both the available knowledge and the available means of production are optimally applied.
* For permanent crops a distinction has been made between an intensive and an extensive maintenance variant. For forestry a distinction is made between existing forestry and types of forestry that could be introduced (three classes of tree species have been distinguished).
* Animal production techniques are divided in techniques with milk or meat as output and in intensive and extensive techniques depending on the use of feed other than roughage.
* Processing activities for human consumption products and animal feed can be distinguished. Pig and poultry raising are considered as industrial processes not using land.
* Input/output tables for processing techniques and animal production techniques were generated by

means of literature and expert knowledge. In the model grass, silage maize and arable products are converted to standard feed comprising energy, proteins and fiber, which were fed to the animals. Grass, silage maize and arable products are `mathematically converted' to metabolizable energy, digestible crude protein and fiber and directly fed to the animals.
* Products for human consumption: flour/malt, potatoes, sugar, fruit, meat, eggs, milk and milk products, timber.
* Intermediate products: roughage, arable products and by-products of processing activities which can be fed to animals.

5.7.4. Identification and quantification of constraints

The demand for agricultural products depends on:
1. policy view (autarky or free-trade, see point 5.4);
2. population and population growth;
3. dietary pattern of the population.

ad 1. For policy views 1 and 3 free trade (the im/export flows were assessed with econometric models) and for policy views 2 and 4: autarky.
ad 2. Population growth was estimated from statistics;
ad 3. Two diets were formulated: (i) one according to present dietary patterns using statistics and (ii) a modified diet with greater emphasis on high-protein products from animals (as may be expected when the living standards rise).

5.7.5. Policy views and objective functions

Policy views
1) Free market and free trade: agriculture is treated in the same way as other economic activities.
2) Regional development: priority to regional development of employment within the EC, which creates income in the agricultural sector.
3) Nature and landscape: greatest possible effort is made to conserve natural habitats, creating zones which divide them from agricultural areas.
4) Environmental protection: keep alien substances from entering the environment as much as possible.

Objective functions
* Agro-technical objectives: (i) maximization of land productivity; (ii) minimization of costs of agricultural production.
* Socio-economic objectives: (iii) maximization of total employment in land-based agriculture; (iv) maximization of regional employment in land-based agriculture.
* Environmental objectives: (v) minimization of loss of nutrients per hectare; (vi) minimization of loss of nutrients per unit product; (vii) minimization of input of crop protection agents per hectare; (viii) minimization of input of crop protection agents per unit product.
* Objectives that cannot be incorporated in the model: objectives with respect to the landscape, recreation and nature conservation. These objectives have strong spatial aspects, which can not be captured in

mathematical functions. The objectives were formulated by means of maps and in *ex post* analyses the fulfilment of these goals was analyzed.

5.7.6. Interactive procedures and land-use scenarios generated

In a first round the `playing field' was determined by optimizing each of the objective functions in subsequent runs, without putting (heavy) restrictions on the other objective functions. Subsequently, the different scenarios were generated by tightening the most relevant objective functions of a policy view. For policy view 1 the agro-technical objectives are most relevant. In policy view 2 the socio-economic objectives have a high relevance, and in policy view 3 and 4 the environmental objectives have a high priority.

5.7.7. Sensitivity analysis

* It was analyzed whether changes in goals for the different objectives result in large changes of the regional allocation of agricultural production in the EC 12. The allocation turned out to be very sensitive for small changes in the goals for the costs of agricultural production. This opens the possibility for influencing the allocation of agriculture over the regions.
* The aggregate model results for the entire EC, i.e. the values for the objective functions, are far less sensitive to changes in parameters.
* Finally trade-off between various objectives were investigated: the gain in one objective relative to the corresponding loss in another objective.

In the evaluation phase of the study the following issues were considered:
* The conflicts between objectives concerning landscape and nature conservation with strong spatial aspects on the one hand and the four land use scenarios on the other hand.
* Common differences between the scenarios and the actual situation.
* Differences in values for the objective functions between the different scenarios: scope for policy.
* Trade off between the different objectives.
* Differences in agricultural production between situations with self-sufficiency and free trade.
* The effects of a change in dietary patterns on agricultural production.

5.8. Exercises

1) In the European study three production orientations were defined. Indicate which ones and argue why they were chosen.

2) For Mali, which production orientations would be appropriate and motivate them.

3) Give an interpretation of the results of the European Community study.

6. The PSS study of the Sudano Sahelian zone of Mali

In Sub-Saharan African countries and in particular in the Soudano sahelian zone, agro-ecological and socio-economic constraints limit agricultural production. Until now, none of the technically feasible solutions are applied at a large scale. This was a reason for the PSS project to develop a methodology with which it would be possible to research different technological options for development while also taking into consideration socio-economic aspects. The analysis also takes into consideration the availability of resources, the relationship between agriculture and animal husbandry and development objectives for the geographical region sustainability. In addition to animal husbandry activities, the project researched crop production systems. This has to be done in an integrated way, because in the region these two are also more and more integrated. A simple cost benefit analysis is not sufficient for this. Another aspect which has to be included in the analysis is the existence of multiple objectives for development, which might be conflicting.

The technique of analysis that was used is multiple goal linear programming. For the application of this technique it is necessary to quantify the resources of the region under consideration, to define and quantify the inputs and outputs of the technological options for crops, pasture, and animal husbandry activities. The socio-economic environment (prices of inputs and outputs) and the development objectives should also be made explicit. A description of the resources is presented in Section 6.2 and for more detail on this topic the reader is referred to Sissoko *et al.* (1996). In section 6.3 the methodology used to define technical options and the manner in which the inputs and outputs are defined for the different crop and animal activities is presented. For more detail, the reader is referred to the PSS research reports (Quak *et al.*, 1996 and Bakker *et al.*, 1996).

In Section 6.4 the constraints that were included in the linear programming model are presented. Section 6.5 presents the development objectives and the prices that were chosen.

The multiple goal linear programming methodology was used to explore possibilities for sustainable agricultural production (Figure 6.1). Information is required on the following topics: the availability of resources, production possibilities (technical options for production), the objectives of the decision makers and the economic conditions (prices). Based on this knowledge the optimal solution is calculated for a series of combinations of prices and the goal levels of the different objectives. The optimal solution contains a value for the objective function and also a value is given for all the other variables that are included in the model. The opportunity cost of the utilization of the different resources and final products and intermediaries due to the allocation of resources is also given in the final solution.

The results of the optimal solution are compared with the actual situation so that recommendations can be made to policy makers and researchers for the steps that have to be taken to reach the optimal solution.

Figure 6.1 Phases in MGLP modeling

6.1. The definition of the system

Figure 6.2 is a schematic illustration of a production system. The figure shows that with the aid of the resource base, final products are produced. These final products have a certain value, because they can be consumed or sold. There are many ways to use resources for different kinds of production. In the linear programming language these ways of production, the technical options are described quantitatively and they are called `activities'. An activity utilizes inputs to produce outputs. The outputs need not only be final products but can also be intermediary products, which do not directly have a value for consumption or sale, but are utilized for other activities.

Figure 6.2 The production process of the activities.

There are three main types of activities, crops (including wood production), animal husbandry and pasture. An illustration of the types of activities that are included in the multiple goal linear programming model is presented in figure 6.3. In the crop activities (including wood production), the resources (land, labor, capital) and the other inputs (compost, manure and draft power) are utilized for the production of the main crops (millet, sorghum, cotton, maize, wood, etc.) and the secondary products (leaves, stems) that are used for animal husbandry purposes. These secondary products can also be used in other ways, as is illustrated in Figure 6.3. The animal husbandry activities utilize labor, capital, fodder and produce milk, meat, manure and animal traction. The pasture `activities' produce fodder (and also wood for cooking) and utilize land as an input. These different activities have different quantities of inputs and outputs and hence technical coefficients in the model. The final products of the main crops and animal husbandry activities are valued against their prices and transformed in possible revenues. The main intermediary products (Figure 6.3 and Figure 6.6) are organic material and nutrients (nitrogen, phosphorus, potassium), fodder, residues of crops and traction power. Note that the term `nutrients' may also include organic material. For the intermediary products (except traction) a distinction is made for two types of utilization: the field and the farm. The connection between the two types is the transport: the transport of manure (organic material en nutrients) of the farm to the field and the transportation of residuals of the field to the farm. As far as capital is concerned, this resource, shown in figure 6.3, it should be noted that it is not really treated as a resource. In many scenarios the monetary balance is calculated, and no constraint concerning the value of this balance is included in the model, although this would be possible.

Figure 6.3 Relational diagram of the main components of the MGLP model.

6.2. Resources of the Soudano-Sahelian zone of Mali

6.2.1. Introduction

The research area of the Production Soudano Sahelian (PSS) project is the Soudano Sahelian zone, where the annual rainfall varies from 300 mm to 900 mm, the area is 4.56 millions of square km with a population of 5.1 million inhabitants, which is equal to 70 % of the population of Mali. To analyze the agricultural possibilities and diversity in the zone, a classification was made of more or less homogeneous

zones. The methodology that was used to derive homogenous zones is described in Section 6.2.2. A description of the resources is given in Section *4.2.1.3*. And in Section *4.2.2.* there is description of the resources, the socio-economic environment and the institutional infrastructure in Koutiala district.

6.2.2. The sub-zones and the agro-ecological units

As mentioned in Chapter 6.1 one of the objectives of the Systems research was to explore possibilities for sustainable agricultural development in the sudano-sahelian zone. In this zone there is a great deal of variation concerning climate (rainfall), soils, and demographics. All these parameters, that are mentioned here, influence the production possibilities. It is for that reason that the zone is not treated as a single entity, but is divided into more or less homogenous units.

Table 6.1 Division of the Sudano-Sahelian zone in sub-zones per administrative region and rainfall zones

rainfall (mm/an)	Kayes	Kouli-koro	Ségou	Mopti	Koutiala Yorosso	Tombouctou Ouest	Tombouctou Est + Gao
100							
200						3.0	3.1
300							3.2
400		2.1		3.3			
500	1.1	2.2		3.4			
600	1.2	2.3	3.5				
700	1.3	2.4	3.6				
800					3.7		

The subdivision resulted in 15 sub-zones. The main criteria that was used for the division into zones was rainfall. A sub-zoning that is based on rainfall will give three long horizontal bands from the east to the west. These bands will go through different administrative regions of Mali.

To limit the size of the sub-zones and to get sub-zones that are smaller and more homogenous in regard to demographic density, the long bands were subdivided and boundaries were placed in the north-south direction. For these boundaries it also became possible to make use of the administrative boundaries, because many statistical data are found at the regional administrative level.

Figure 6.4 Zonation of the sudano sahelian zone by the PSS project.

Figure 6.4 and Table 6.1 present the delimitation of the different sub-zones in zone that were studied. The sub-zones are distinguished with the aid of a code, which consists of two numbers.

The first number indicates the location (1: West, 2: Central, 3: East), the second number indicates the position from north to south. For the location of the special sub-zone 3.0 there is an exception as it overlaps with the sub-zones 3.1 and 3.2. In Table 6.1 the annual rainfall, which increases from north to south, is also indicated, although in a crude manner.

Table 6.2 Division (%) of the areas of the sub-zones for the administrative regions; areas are in 100 km²

regions	sub-zone															area
	1.1	1.2	1.3	2.1	2.2	2.3	2.4	3.0	3.1	3.2	3.3	3.4	3.5	3.6	3.7	in zone
Kayes	99	98	97	2	5	3	0	0	0	0	0	0	0	0	0	777
Koulikoro	1	2	3	64	54	67	96	0	0	0	0	0	0	4	2	545
Tombouctou	0	0	0	2	0	0	0	99	38	34	6	0	0	0	0	834
Gao	0	0	0	0	0	0	0	0	62	63	0	0	0	0	0	877
Mopti	0	0	0	0	7	0	0	1	0	3	92	92	28	0	0	777
Ségou	0	0	0	32	34	30	4	0	0	0	2	8	72	93	6	609
Sikasso	0	0	0	0	0	0	0	0	0	0	0	0	0	3	92	142
area	242	257	274	214	202	215	136	311	633	766	372	356	239	194	148	4559
% of total	5.3	5.6	6.0	4.7	4.4	4.7	3.0	6.8	13.9	16.8	8.2	7.8	5.2	6.3	3.2	100

Table 6.2 contains the areas of the sub-zones and the division of the areas into administrative regions.

6.2.3. The resources per sub-zone

In this Section the resources of the 15 *sub-zones* are described, after which the *sub-zones* are characterized. For all sub-zones, a characterization of the soil types is given. The resources will be described according to: the areas for each soil type, the population and labor availability, the wood resources, animals and water resources. The results are presented in Table 6.3. In the Table the average rainfall for the sub-zones is also given. Information concerning the areas, population, labor availability and water availability are used in the Multiple Goal Linear Programming Model. Certain types of information, notably that for animal husbandry, the production of wood is not used in the model, but is used to compare results of the model with the present situation.

Soil classification and the areas for the sub-zone

Of most of the soils of Mali an inventory has been made by the Projet Inventaire de Resources Terrestres (PIRT) and the description of the soil types in the zone largely based on the three main documents of the PIRT project, namely: the atlas, the technical report and the annexes. (PIRT, 1983a, b, c). However, the North-East part of the zone was not included in the inventory of the PIRT. For this part the Carte Mondiale des Sols de la FAO/UNESCO (FAO/Unesco, 1973) was used.

In the classification of the PIRT 68 units of soil/vegetation are distinguished. For the objectives of this study, the level of detail of the PIRT study is not necessary because many of the distinctions that were made are not stable. For the exploration of possibilities for sustainable agricultural production it is necessary to make use of stable characteristics. The characteristics that were utilized are: the texture, the soil depth, the presence of gravel, and the water permeability determine in general manner the availability of water in the soil for crop cultivation.

With the aid of the 68 units of soil/vegetation of the PIRT a regrouping was done into 16 types of soil (PSS) that can support a vegetation, and two other soil types that do not support vegetation (rocks or soil submerged with water). The following main types of soil were distinguished:

The soils of type EC (sols d'ecoulement) can be inundated. They correspond to some of the TI-soils (Terrains inondées) in the PIRT (1983) classification.

Superficial soils (SU) are shallow soils that belong to the TR group of soils according to the PIRT. They are distinguished from the gravely soils, which are also superficial, by their absence of gravel. The soil type SU contains the PIRT soil types with codes TR-5 and TR-6. TR-3 is put in a sub-category SU_inc because it has a strong inclination.

Gravely soils are soils that contain relatively much gravel, and they belong to the TC and TR class according to the PIRT classification.. A distinction between the soil types is made based on soil depth. Hence there is a soil type GR (average depth: 44 cm) and a very shallow soil type `GR_su' (average depth: 18 cm).

The other soil types, which don't have special characteristics like the first 3, are classified according to texture. The main classes are: sand (SA), loamy sand, (sable limoneux, SALI), sandy loam (limon sableux LISA), loam (limon, LILI) and clayy loam (limon argileux LIAR).

Sand (SA): Sandy soils have a grossly sandy texture.

Loamy sand (SALI) are also sandy, but with a finer structure

Sandy loam (LISA) is the most frequent soil type in the zone. A distinction is made on the basis of the texture of the top layer between LISA_f (fine) and LISA_g (gross).

The loam (LILI) soils form a small group that we have separated from the clayy loam (LIAR) not only because of a lower clay content but also of the difference in position in the toposequence. Loamy soils are situated on the slope, and they therefore have a high risk of run-off.

The clayy-loam soils (LIAR) receive run-off water and are composed of heavier soils.

Unsuitable soils, and soils permanently under water. These soils cannot be used for crop production.

Population and labor

The quantitative description of the population was used to arrive for the estimation of the requirements for different production processes the labor availability in each of the sub-zones. The presented information is on the basis of the second general population census and the Habitat of Mali (DNSI, 1991d), where the population is given by sub-district. Next for each sub-district the fraction of its area that falls in the given sub-zone. The assumption was made that the allocation of population is proportional to the area of the sub-zone. The density is then derived and is also presented in Table 6.3. The table shows the population density that was found and the highest population densities are found in the south-east sub-zones, which are sub-zones 2.4, 3.4, 3.5, 3.6 and 3.7.

The availability of labor depends on the proportion of the population that is active. This proportion was estimated at 55 % and this was based on Veeneklaas *et al* (1991). The estimated population growth was estimated at 2 % per year (Sissoko *et al*, 1995).

Rainfall

The description of the rainfall situation for each of the different sub-zones is done on the basis of data collected by 40 rainfall stations in Mali. This information was obtained from the Direction Nationale de la Météorologie.du Mali. This information concerns daily rainfall data that was measured during the period 1961 - 1990. The average annual rainfall was estimated for each sub-zone making use of the rainfall data that was obtained from each of the rainfall stations in the sub-zones and, in certain cases, use of rainfall stations that were situated near to the sub-zones. When observing the table one can see that rainfall increases when going from the north to the south.

Table 6.3 Resources of the sudano-sahelian zone

	sub-zone																zone
	1.1	1.2	1.3	2.1	2.2	2.3	2.4	3.0	3.1	3.2	3.3	3.4	3.5	3.6	3.7		
general characteristics																	
rainfall (mm/yr)	473	621	741	396	445	550	741	188	155	250	385	451	585	585	877		
area (1000 km^2)	23	25	27	26	22	20	14	30	62	75	35	34	25	18	15		452

population 1987 (1000 hab)	286	315	157	127	159	174	302	300	291	203	333	821	741	544	388	5142
density (hab/km^2)	12.3	12.7	5.8	4.9	7.3	8.5	22.2	9.9	4.7	2.7	9.4	24.0	29.6	29.8	25.9	11.4
number of animals (1000 TLU)	234	171	99	74	86	159	151	201	205	288	330	464	474	352	277	3567
animal density (TLU/ km^2)	10.1	6.9	3.6	2.9	4.0	7.8	11.1	6.7	3.3	3.9	9.3	13.5	18.9	19.3	18.5	7.9
area <6 km of a PWP * (%)	66	60	38	43	49	69	96	51	19	18	47	83	91	94	93	
area <15 km of a PWP (%)	99	95	78	81	96	95	100	74	51	43	81	97	100	100	100	
wood production (1000 m3/ yr)	9.0	14.4	23.0	6.9	7.2	11.5	11.8	0.1	0.0	0.0	4.1	12.9	11.6	14.9	15.0	142.3
distribution of total area among soil types (%)																
EC	2.2	7.6	2.4	1.0	2.2	1.2	3.8	10.4	0.0	0.2	10.4	18.4	18.7	11.3	5.4	5.8
GR	14.2	22.2	38.0	5.5	6.8	29.7	45.9	2.8	2.9	4.0	16.6	12.3	8.7	21.5	24.5	13.3
GR_su	0.0	0.0	4.4	0.0	0.0	3.3	10.3	0.0	0.0	0.0	0.0	0.0	5.1	16.3	30.6	2.7
LIAR	2.4	7.0	0.0	0.0	9.3	0.6	0.0	0.0	0.8	0.4	0.9	2.7	10.9	17.3	23.5	3.6
LILI	11.8	22.7	25.0	2.7	4.0	5.0	26.5	2.3	4.1	2.1	6.2	1.7	8.2	9.7	11.4	7.6
LISA_f	16.1	11.7	10.2	29.6	9.4	20.8	10.1	12.3	16.2	15.5	10.1	13.9	23.0	14.4	2.9	14.9
LISA_g	22.4	9.5	1.1	24.7	39.4	25.8	2.1	20.5	16.4	10.6	6.5	14.8	8.5	1.5	0.0	13.8
SA	0.0	0.0	0.0	0.0	0.0	0.0	0.0	18.9	26.5	39.0	1.8	0.0	0.0	0.0	0.0	11.3
SALI	5.8	0.0	0.0	36.2	24.4	10.6	0.0	17.4	0.1	0.0	18.8	5.5	3.8	0.0	0.0	7.3
SU	17.3	10.6	8.4	0.3	0.0	0.9	0.0	0.3	5.6	8.1	9.5	3.1	0.0	0.0	0.0	5.1
SU_inc	6.7	7.5	4.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0

inundated	0.0	0.0	0.0	0.0	4.4	0.0	1.3	10.7	2.0	0.5	13.6	23.3	9.9	7.0	0.0	5.2
unsuitable	1.1	1.2	6.1	0.0	0.0	2.0	0.0	4.5	25.5	19.4	5.7	4.2	3.2	0.8	1.6	8.6
TLU repartitioning (%)																
cattle	73.5	79.6	84.1	67.8	71.1	65.2	70.8	54.7	44.7	48.3	70.8	67.6	71.4	73.9	85.3	68.3
sheep	6.2	4.4	4.1	8.6	8.3	10.4	7.0	13.3	14.6	13.3	8.9	11.4	9.7	8.6	6.5	9.5
goats	7.4	5.2	5.7	9.8	8.7	13.2	9.9	17.9	19.8	20.7	14.1	12.9	10.7	10.0	4.0	11.8
others	13.0	10.8	6.0	13.8	11.9	11.1	12.4	14.1	20.9	17.7	6.2	8.1	8.2	7.5	4.2	10.3

* PWP = Permanent Water Point

N.B: For the calculation of the numbre of TLU the conversion given by [Breman & De Ridder (1991, page 456)](#) is used:

1 TLU = 1,5 cattle = 10 sheep = 12 goats = 2 donkeys =1 horse = 0,8 camel.

Water resources

In the sudano-sahelian zone of Mali, the water resources are divers, there are natural water resources: rivers, (Niger, Senegal, Bani) which are permanent, traditional water wells and modern hydro-electric infrastructure (pumps and dams).

For an estimate of the area that is available to cropping activities, the positions of the traditional and modern hydrological facilities was established and hence the availability of water in the different sub-zones. The assumption was made that the maximum distance that could be used for the cultivation of crops was a distance of 6 km around a permanent water point, either modern or traditional, see (19..). So a circle of 6 km was drawn around a permanent water point. The part of land that is not covered by the circles of 6 km was estimated. This part is an indication of the fraction of land that cannot be used for wood plantation purposes.

A similar kind of estimate is made for the fraction of land that cannot be used for pasture in the dry season due to a shortage of water. The limit for this type of activity is a circle of 15 km from the water point.

As is the case for wood, water is also considered as a constraint because it is limited. The utilization of land for animal husbandry or crops is limited for the zones because the availability is limited.

The hypothesis is used that crop activities are not practiced in a region further away than 6 km from a permanent water point and in the dry season the animal husbandry activities are not possible in a region further away than 15 km from a permanent water point. Therefore for the modeling work the areas that are outside the mentioned regions cannot be used for crop or animal husbandry activities.

Ruminants

The actual herds in the sub-zones are estimated on the basis of regional statistics of l'OMBEVI (1992) and

assumed that the division of the herd is proportional to the area of a regions of the different sub-zones. The results, expressed in total *TLU* (tropical livestock unit) for the sub-zone and the *TLU km⁻¹* are presented in Table 6.3. For the calculation of the number of TLU the conversion rates given by Breman & De Ridder (1991, page 456) are used: 1 TLU = 1,5 cattle = 10 sheep = 12 goat = 2 donkey =1 horse = 0,8 camel. At the most there are three types of animals that are taken into account in the group `other ` of the table. The animal density varies from 3 to 20 TLU km⁻¹ . The fraction of cattle in the total number of animals, which is for most of the sub-zones around 75 %, is lower in sub-zones with low rainfall (3.0, 3.1, and 3.2).

Woody plants

The resource of woody plants in the sudano-sahelian zone are estimated on the basis of the information that is provided by the Projet Inventaire des Ressources Ligneuses (PIRL). The global overview is given, in Table 6.3 a presentation is given of the annual actual production of wood, and this is given with the aid of an estimate of the annual growth in m^3 ha^{-1} yr^{-1}. In addition the estimate of the production of wood per habitant is added.

Characterization of the sub-zones

Sub-zone 2.1 :
is situated at the extreme north of the Koulikoro and Ségou region with an area of 25.828 km^2 and an average annual rainfall of 396 mm/yr. The main agro-ecological zone is Ouagadougou in the natural region of HODH, which covers 93 % of the total area of the sub-zone. The dominant soil types are loamy sands (36 %), coarse sandy loams (25 %) and fine sandy loams (22 %).

Sub-zone 2.2 :
It is located in the region of Koulikoro and a little bit in the region of Ségou, the area is 21.752 km^2 and the an average annual rainfall is 445 mm/yr.

The main agro-ecological zones are: the Delta Mort Occidental in the central delta of the Niger river, in such a way that the Bas Kaarta and Tyermandali are situated in the HODH. The dominant soil types are coarse sandy loams (LISA_g) and loamy sand (SALI).

Sub-zone 2.3 :
Is situated in the center of the Kouliloro region with an area of 20.465 km^2 and an average annual rainfall of 550 mm/yr. The main agro-ecological zones are the Tyemandali in the HODH and the Bélédougou in the Plateau Mandingue. The principle soil types are gravely (GR), coarse sandy loams (LISA_g), clay loam (LIAR).

Sub-zone 2.4:
Is located to the south of the Koulikoro region with an area of 13.616 km^2 and an average rainfall of 741 mm/an. The Wénia and the Bélédougou are the dominant agro-ecological zones, situated on the

Mandingue plateau. The Moyen Bani Niger is situated in the central delta of the Niger river represents only 5 % of this sub-zone. The main soil types are gravely, loam, fine sandy loam.

Sub-zone 3.0 :

Is situated in the south west of the Tombouctou region with an area of 30.128 km^2 and an average annual rainfall of 188 mm/yr. The agro-ecological zones that are dominant in this sub-zone are the Daounas situated in the HODH and is situated around the Central delta of the river Niger. The main soil types are clay loam (LIAR), coarse sandy loam (LISA_g), loamy sand (SALI) and sand (SA).

Sub-zone 3.1 :

Is situated in the west of the Tombouctou region and is in the Gao region, with an area of 38.156 km^2 and an average annual rainfall of 155 mm/yr. the main agro-ecological zone is Minkiri situated in l'Aklé Azaouad hence for the Ganderas and the Tin bilal is situated in the Gourma, so that l'Abourak is situated in the Tilemsi

Sub-zone 3.2 :

Is situated in the south of the Tombouctou region and the Gao, with an area of 44.850 km^2 and an average annual rainfall of 250 mm/yr. The dominant agro-ecological zone is Tillit (61 %) and Tin bilal (18 %) situated in the Gourma, in such a way that l'Abourak (12 %) is situated in the Tilemsi. Sand is the main soil type, in addition to fine sandy loam and gravely. The soil type INAPT (rock) is less important in this sub-zone with 19 % of the total area.

Sub-zone 3.3 :

Is situated in the south of the Mopti region, with an area of 35.427 km^2 and an average annual rainfall of 385 mm/yr. The main agro-ecological zones are the Dyondé on the Bandiagara-Hombori plateau, the Mondoro in the Gondo-Mondoro, such that the Delta Vif, the Delta Mort occidental and the the surrounding zone are in the natural region of the Central Delta of the River Niger. The dominant soil types are gravely soils, clay loam, loamy sand and inundated clay.

Sub-zone 3.4 :

Is situated in the center of the Mopti region and reaches in the west in the extreme East of the region the district of Ségou (Cercle de Macina). The sub-zone covers a region of 34.229 km^2 with an average annual rainfall of 451 mm/yr. The main agro-ecological zones in this sub-zone are: the Haut plateau Dogon, the Delta vif, the western Delta and the Séno. The dominant soil types are clay soils gravely soils, sandy loams and fine loamy sands.

Sub-zone 3.5 :

Is located in the north of the region of Ségou and part of the extreme south the region of Mopti (Cercle de Djenné) with an area of 25.059 km^2 and an average annual rainfall of 585 mm/yr. The main agro-ecological zones are the Moyen Bani Niger, the Bas plateau Bobo and the plaine du Sourou. The main soil types are fine loamy sands and loamy clay soils.

Sub-zone 3.6 :

Is situated in the extreme south of the Ségou region with an area of 18.276 km^2 and an average annual rainfall of 747 mm/yr. The predominant agro-ecological zone is the Falo situated on the Koutiala plateau, which covers 66 % of the total area of the zone. As is the case for the Moyen Bani Niger, the Bas Plateau Bobo and the Moyen Bani Occidental, the main types of soil are fine loamy sands, gravely soils, superficial gravely soils and clay loams.

Sub-zone 3.7 :

Is situated on the extreme north of the Sikasso region and borders the Soudano-Sahelian zone. It is covered by the Yorosse district as well as the district of Koutiala (which is the object for the case study). The area is 14.990 km^2 with an average annual rainfall of 877 mm/yr. The agro-ecological zones of this sub-zone are the Moyen Bani Oriental which represents 74 % of the area of the sub-zone, the Falo, (24 %) and the Kénédougou (2 %) which is located on the Koutiala plateau.

6.2.4. Resources of the Koutiala district

The Koutiala district is situated between 12deg. 24' latitude north and 5deg. 28' longitude west and is part of the 3rd administrative region of Mali, commonly called South Mali. It borders to the north and north west to the districts of San and Bla (the region of Ségou), at the south to the district of Sikasso and Burkina Faso, to the east to the district of Yorosso and to the west to the district of Diola. The area is not very mountainous, and is 9100 km^2. The area is divided into administrative units: one overall unit and 6 sub-district the central sub-district, M'Pessoba, Zangasso, Molobala, Kouniana, and Konséguela. The climate is of the type Soudano-Sahelian in the north and sudanian in the south with only one rainy season. The average annual temperature is 30 degrees approximately (Sivakumar *et al*, 1984). The rainy season is from May to October, and the number of rainy days varies from 38 to 72 (CMDT, 1987-1993). The average annual rainfall is 980 mm (Sivakumar *et al* .,1984). Table 6.4 gives the rainfall for the period 1986 to 1992.

Table 6.4 Rainfall (mm) and number of rainy days per year in the Koutiala district

station	Koutiala		M'pessoba		Molobala		Zebala	
year	mm	days	mm	days	mm	days	mm	days
1986	835	63	1043	50	901	52	855	56
1987	704	68	846	50	715	48	712	44
1988	893	71	773	51	1015	66	857	50
1989	633	64	688	49	740	49	865	53
1990	913	67	618	41	732	60	471	38
1991	843	67	688	54	795	55	767	52
1992	671	72	621	53	649	62	770	56

The population of the region is 286.244 habitants (BCR, 1991) with an average density of 24 hbts/km^{-2}. The population, which mainly comprises of ethnic groups such as the Minianka, Bobo and Dionka who mainly take part in agro-pastoral activities. The division of the population per sub-district is given in Table 6.5. Note that the division is not homogenous in the district with the relative density low in the Konséguéla sub-district compared to the others. The growth of the population in the district is 3.3 % per year, whereas nationally this is 1.9 %. The population comprises 78 % which is rural and mainly works in the primary sector. An estimation of the population per age group indicates that 55 %, 5 % and 40 % respectively are younger than 18, between 18 and 21, and finally 21 years and older. The population is relatively young.

Table 6.5 Population statistics for the Koutiala district in 1987

sub-districts	area (km^2)	population (n)	density (n km^{-2})	growth rate (% an^{-1})	villages (n)
Koutiala*	1375	104661	76.1	+3.8	51
Konséguela	2045	27069	13.2	+3.1	33
Kouniana	1800	35420	19.7	+2.7	35
Molobala	1435	34303	23.9	+3.4	25
M'pessoba	1210	59825	49.4	+2.8	55
Zangasso	1235	24966	20.2	+3.5	32
district	9100	286244	31.5	+3.3	231

Source: BCR (1991)

Table 6.6 The main soil types in the Koutiala district

code	soil type	km^2	%
EC	ecoulement (run-on)	296	3
GR	gravillonnaire (gravely)	1918	21
GR_su	gravillonnaire superficiel	3721	41
LIAR	limon-argileux (clay-loam)	2430	27
LILI	limon-limoneux (loam)	428	5
LISA_f	limon-sableux fin (loamy sand)	282	3

The main types of soils that are important in the district of Koutiala are presented in Table 6.6. A characterization of the soils is given in section 6.2.3. More than 60 % of the district is occupied by soils little suitable for agriculture (GR and GR_su). It is noteworthy that in agriculture more and more is being invested in livestock. The importance given to the herds in a production systems of a zone is explained by

the fact that the herd is an generally an investment and saving. For others, the animal husbandry activities are complementary to the cropping activities in such a way that use is made of traction power, the manure and the use of by-products. This is especially the case for the concentration of herds in the sectors where the human density is high and the pressure for space for living and crops is very high (CMDT, 1993)

Table 6.7 Number of animals in Koutiala (1992-93)

sector	cattle	sheep/goat	donkeys	horses	pigs
Koutiala	80073	53631	5062	83	1817
M'pessoba	47929	32118	5754	35	1184
Molobala	42759	19734	2659	48	5006
Zebala	42696	42856	3047	167	1433
district	213457	148339	16522	333	9440

Source: Rapport CMDT, 1992/1993

Table 6.8 Characterization and importance of farm types in the Koutiala district

type	characterization	number	(%)
A	with equipment and herd	9092	46
B	with equipment, no herd	7905	40
C	able to borrow equipment	2383	12
D	no equipment	401	2
total		19781	100

Source : Estimations based on the Annuaire Statistique CMDT (1994) - Resultats de l'enquête agricole permanente 1993/1994.

6.2.5. The socio-economic and institutional environment of Koutiala

The institutional environment of the Koutiala district is rich with the presence of different development structures and organization from the development world. The Malian Company for the Development of Textiles (CMDT) is the main development structure and covers the district. The livestock sector is charged with training of the livestock owners as far as improvement of feed quality and animal health is concerned. The forestry department is charged with the policing of the forests and organization of the population and material exploitation of the forests. A number of other development agencies exist that are not mentioned here.

The main credit structures in the district are: the CMDT and the Banque Nationale de Développement Agricole which allocate the credit to the organizations for the purchase of equipment and inputs. In the

domain of the mobilization of rural savings there is the savings bank and the rural credit called `Kafo Jigenè'. Other structures for rural credit banking are also present, such as Banque Malienne de Développement et la Banque Internationale de l'Afrique de l'Ouest.

There exist many rural markets in the district that constitute the place where outputs are sold (cattle, agricultural products) and the place to purchase outputs. The most important markets in the district are Koutiala (Commune), Molobala, M'Pessoba, N'Togonasso and Sadiola. For cattle N'Togonasso is the important market in the district and this is also the community market for small ruminants. The commercial transactions for the markets are not only limited for animals but also concern agricultural products from the district of Koutiala which is a zone where millet, sorghum and maize are produced.

The rural development of Koutiala is generally is a far more advanced state when it is compared to the other zones of Mali. There exist many organizations that play an important role in the stocking of inputs and the selling of products. The village association is a transitory structure towards the `Ton Villageois', a pre-cooperative structure. In the district of Koutiala there existed in 1994, 20 Tons villageois and 345 AV (CLD; 1994. PP 9). There are 6 central cooperatives for stocking and commercialization in the district and the other cooperatives many other cooperatives such as a Coopérative des éleveurs de Welingana; la Coopérative des éleveurs de M'Pessoba ; la Coopérative agro-pastorale de Koutiala la Coopérative agricole de N'Togonasso; la Coopérative des anciens combattants et victime de guerre; la Coopérative des transporteurs routiers de Koutiala; la Coopérative des maraîchers et planteurs de Koutiala; la Coopérative des riziculteurs de Koutiala. So in total there are 14 cooperative societies in the district (Source CAC, Koutiala, Décembre 1993). There is also a syndicate for the cotton producers and staple crops (SYCOV) which has another structure in the interest group and defends the interests of the peasants in the district.

In 1994 there were ten milk producing groups who delivered their milk to the milk factory (Dembélé, 1995). The group of milk producers are in Wolodougou, Signè, Sirakélé II, N'Goukan, Ouendjina II, Kaniko I, Kaniko II, Namposséla, Shikolomba, et de la Commune de Koutiala.

The land property rights in Mali are dominated by a coexistence of tradition and by the law. Traditionally, access to land was obtained through the `right of the axe', by fire and by heritage. (Maiga *et al*., 1994). About 90 % of the land is managed this way. Decisions about the right to cultivate land are made in the villages. The law recognizes the traditional rights as long as the State does not need the land for own purposes.

It should be noted that a legal code for the use of pastures, even if it were elaborated is hardly known or not applied. The use of pastures is free for everyone.

6.3. Agricultural production activities

6.3.1. Introduction

For the exploration and analysis of the possibilities for the sustainable use of resources of a region with a

Multiple Goal Linear Programming (MGLP) model one needs a quantitative description of the various ways in which the resources can be used productively, in other words the `production activities'. These production activities are well-defined and quantified means of agricultural production in which a unique combination of inputs result in a unique mixture of agricultural output. The inputs include e.g. the amount of land, labor requirements to carry out field operations, animal traction, fertilizer and manure. Outputs of crop activities can include the yield of the main product, crop residues and possible environmental side-effects such as soil losses due to erosion. For livestock activities inputs include the quality and quantity of feed, labor and capital, while the outputs include live weight (meat), milk, manure and traction. See for a more elaborate description of the production activities used in the MGLP model Quak *et al.*, 1996 and Bakker *et al.*, 1996.

The quality and quantity of the natural resource base determines the boundary conditions of agricultural development. The yields of crop activities are e.g. a function of a combination of crop characteristics, soil properties, and climate. They determine the production potential of crops. In the description of crop activities the so-called `target-oriented' approach is applied: First the production (output) is determined, based on the quality and quantity of the natural resource base and subsequently, the requirements (inputs) to realize that production (Van Duivenbooden *et al.*, 1991). In par. 6.3.2 this approach is illustrated on the basis of input-output matrices of five sorghum activities.

Because the PSS project aims at the exploration of *sustainable* development options for the soudano sahelian region, it is obvious that factors affecting agro-ecological sustainability are taken into account in the definition of crop activities. Agro-ecological sustainability in this respect means that yields are not jeopardized in the long run. Current production in the soudano sahelian region is characterized by a depletion of soil organic matter and nutrients, and soil losses due to erosion resulting in reduced yields (Van Keulen & Breman, 1990). In the applied MGLP model, agro-ecological sustainability is operationalized in terms of a balanced organic matter and nutrient supply, and a limited soil erosion. It is assumed that the annual losses of soil organic matter due to decomposition are replenished with crop residues, manure, or the organic matter produced during a fallow period. The macro nutrients (N, P and K) withdrawn from the system due to the removal of consumable products and/or crop residues and inevitable losses (leaching, de-nitrification, and volatilization) are replenished with nutrients in crop residues and manure, fertilizers and the annual supply from natural resources (deposition, nutrient fixing micro-organisms, and weathering). Moreover, the crop activities are defined in such a way that the soil erosion does not exceed a certain `tolerated' soil loss per ha per year. The `tolerated' soil loss is a threshold value based on PIRT (1983b) that may not be exceeded and varies between 2 and 10 ton/ha, depending on the soil type. Erosion is described on basis of the Universal Soil Loss Equation (USLE) developed by Wischmeier& Smith (1960) and which has been calibrated for West-African conditions by Roose (1977). Soil erosion can be reduced by construction of stone bunds requiring labor and capital. At erosion susceptible soils stone bunds must be applied at shorter distances than less susceptible soils to meet the `tolerated' annual soil loss. The consequences of this requirement are reflected in the labor and capital inputs of crop activities.

The integration of arable cropping systems and livestock has been identified as one of the key elements for agricultural development in the soudano sahelian region of Mali (Breman, 1990). Integration of both

activities can be mutually beneficial. Crop activities can produce high quality fodder crops (e.g. cow pea) or crop residues (straw) which can be applied in livestock activities to increase meat and milk production, while manure can be used in arable cropping systems to replenish soil organic matter and nutrients. The interaction between in-and outputs of cropping systems and livestock is simplified illustrated in Figure 6.3. Both compete for the same resource base (land, water, labor and capital), produce final products to satisfy national or individual goals (grains, cotton, meat and milk) and intermediate products (crop residues and manure) which are used as inputs in mutual activities.

Figure 6.5 Relational diagram of crop and livestock activities, presenting their competition for resources and their complementarity through the use of the other's by-products.

To sketch the full scope of choices involved in the use of intermediate products various transformation activities have been defined. Each option has its advantages and disadvantages in terms of nutrient losses, labor requirements, and contribution to the replenishment of the soil organic matter and nutrient resources. The transformation activities do not directly result in final products used to satisfy human demands but are applied to transfer intermediate products produced by one activity (output) to other activities (input). This distinction is artificial, but from a viewpoint of the MGLP-model required to reduce the size of the model. The output of these transformation activities supplies two type of pools, the crop residue/forage pool or the organic matter/nutrient pool as illustrated in Figure 6.6. Both type of pools exists at the farm and field level. Three types of activity produce final consumable products and intermediate products: crop activity, livestock herd activity, and livestock fattening activity. Two activities produce only intermediate products: rangeland activity and fallowing. Six activities are used to transform or transport intermediate products: (i) mulching activity in which crop residues are used as mulch reducing soil erosion and supplying soil organic matter stocks, (ii) plowing activity in which crop residues and manure are plowed under to maintain soil organic matter stocks, (iii) burning activity in which crop residues are burned at the field to facilitate plowing and to recover rapidly their nutrients, (iv) compost activity in which crop residues and manure are mixed at the farm making advantage of the N-fixing capacity of straw, (v) crop residue transport from the field to the farm allowing to feed crop residues at the stable, and (vi) transport of organic matter; with this activity organic matter and nutrients are transported from the farm to the field to supply soil organic matter and nutrient stocks. Additionally, fertilizer and feed supplements can be purchased to supply the organic matter/nutrient and residue/fodder pools. The way in which these activities are related is presented in Figure 6.6 which constitutes hence a relational diagram for the defined types of activity. The crop activities are described in section 6.3.2. The livestock activities for herds and the fattening activities are described in section 6.3.3. Other types of activity in the diagram area treated in section 6.3.4. The characteristics of the types of activity (definition criteria, units and input-output relations) in Figure 6.6 are summarized in Table 6.9.

The intermediate products, crop residues and manure, or in more general terms organic matter sources (including their nutrients) play a crucial role in the integration of the cropping and livestock systems and in the objectives of the project to analyze and explore the possibilities for sustainable agricultural development in the sudano-sahelian region.

Because the quality of organic matter differs among organic matter sources and therefore their capacity to maintain the soil organic matter content, the various organic matter sources are expressed in standard organic matter (Matière Organique Standard MOST). One unit of MOST (UMO) is defined as the quantity organic matter (of a given quality) that can maintain 1 % organic matter in the first 20 cm of a clay soil on one hectare during on e day of optimal micro biological activity. Three variables are necessary to calculate the MOST input of a crop activity (in terms of UMO's per ha) required to maintain the soil organic matter content:

1. A target organic matter content of the upper soil layer which has to be maintained,

2. The number of days with optimal microbial activity which is for rain fed crops a fraction (0.4) of the length of the growing season and for inundated crops one tenth of the inundated period,

3. The texture of the soil. Fresh organic matter is protected against decomposition by means of binding to clay particles (Verberne *et al.*, 1990). The higher the clay content of a soil the more fresh organic matter is required to maintain the target soil organic matter content. The MOST requirement for a sandy soil is 1.6 times as high as for a clay soil.

The value of organic matter sources in terms of MOST depends on the content of fibers (lignin, cellulose) of the product. A relation between the fiber content and the amount of organic material to attain 1 UMO is derived from the dynamic soil organic matter model developed by Verberne *et al.* (1990). The value of most crop residues in terms of MOST corresponds for example with 0.04 UMO kg^{-1}.

To maintain 1.5 % organic matter content in a clay soil in a zone with a rainy season of 120 days, one needs an annual input of $1.5 * 120 * 0.4 = 72$ UMO ha^{-1}. If this input comes solely from crop residues, one needs $72/0.04 = 1800$ kg ha^{-1} y^{-1} of crop residues. For a sandy soil 1.6 times as much crop residues are required.

Figure 6.6 Relational diagram of the activities with respect to their production and use of organic matter and nutrients, both at the field and at the farm.

Table 6.9 Definition of activities, their inputs and outputs and the units in which these are expressed

activities	definition criteria	inputs	unit	outputs	unit
crop	sub-zone	land	ha	main product (field)	kg ha^{-1}
	climate	capital	F cfa ha^{-1}	residue/fodder (field)	kg ha^{-1}
	soil type	labor	md ha^{-1}	MOST (field)	UMO ha^{-1}
	crop	MOST (field)	UMO ha^{-1}	NPK (field)	kg ha^{-1}

	production level	NPK (field)	kg ha^{-1}	nitrogen binding capacity	kg N kg^{-1}
	crop residue use	draught animal	anim.day ha^{-1}		residue
	soil conservation measures				
herd livestock	selling strategy	fodder (field)	F cfa ha^{-1}	milk and meat	kg TLU^{-1}
	production level	fodder (farm)	md ha^{-1}	MOST (field&farm	UMO ha^{-1}
		capital	kg	NPK (field&farm)	kg ha^{-1}
		labor	kg	draught animal	TLU
livestock fattening	age	fodder (farm)	kg	meat	kg TLU^{-1}
	production level	capital	F cfa ha^{-1}	MOST (farm)	UMO ha^{-1}
		labor	md ha^{-1}	NPK (farm)	kg ha^{-1}
fallow	sub-zone	land	ha	MOST (field)	UMO ha^{-1}
	soil type			NPK (field)	kg ha^{-1}
rangeland	sub-zone	land	ha	fodder (field)	kg ha^{-1}
	climate			wood	m^{-3} ha^{-1}
	soil type				
	season of grazing				
crop residue burning	sub-zone	residue (field)	kg	NPK (field)	kg kg^{-1}
	soil type	labor	md ha^{-1}		
	crop				
crop residue plowing	climate	residue (field)	kg	MOST (field)	UMO kg^{-1}
	soil type	labor	md kg^{-1}	NPK (field)	kg kg^{-1}
	crop	capital	F cfa kg^{-1}		
		draught animal	anim.day kg^{-1}		
crop residue	sub-zone	residue (field)	kg ha^{-1}	MOST (field)	UMO ha^{-1}

mulching	climate	labor	md ha^{-1}	NPK (field)	kg ha^{-1}
	soil type				
	crop				
	production level				
compost making	sub-zone	residue (farm)	kg	MOST (farm)	UMO kg^{-1}
	crop	labor	md kg^{-1}	NPK (farm)	kg kg^{-1}
				nitrogen binding capacity	kg N kg^{-1} residue
transport of crop	sub-zone	residue	kg	residue/fodder (farm)	kg
residue to the farm	soil type	labor	md kg^{-1}		
	crop	capital	F cfa kg^{-1}		
	transport mode				
transport of organic	climate	MOST (farm)	UMO	MOST (field)	UMO
matter to the field	soil type	NPK (farm)	kg UMO^{-1}	NPK (field)	kg UMO^{-1}
	transport mode	capital	F cfa UMO^{-1}		
		labor	md UMO^{-1}		
buying fertilizer		capital	F cfa kg^{-1}	NPK (field)	kg
buying supplements		capital	F cfa kg^{-1}	fodder (farm)	kg

6.3.2. Crop activities

6.3.2.1. Definition criteria

If one wants to consider a specific activity, it is necessary to know the characteristics of that activity. These characteristics, often called « definition criteria », describe on the one hand the environment (rainfall, soil type) in which the activity is carried out, and on the other hand the techniques used to execute the activity (production level, erosion measures, selling strategy). The definition criteria for the crop activities (rain fed and inundated) are given in Table 6.10. For inundated crop activities the criteria of measures for water conservation and soil conservation are not applied. These crop activities are therefore defined on the basis of six criteria. For each definition criteria a set of variables is defined which

can be combined with each variable form another criteria.

Table 6.10 Criteria and variables of rain fed and inundated crop activities. See text for explanation of abbreviations

sub-zone	rainfall	soil type	crop	production level	crop residue use	measures soil conservation
SZ_11	dry	EC	*andropogon*	extensive	mulching	flat
SZ_12	normal	GR	*andropogon* (re-growth)	semi-extensive	other	ridges
SZ_13		GR_su	peanut	semi-intensive	plowing	tied ridges
SZ_21		LIAR	'bourgou'	intensive	burning	
SZ_22		LILI	cotton		grazing	
SZ_23		LISA_f	maize		forage (farm)	
SZ_24		LISA_g	millet		forage (field)	
SZ-30		SA	cowpea			
SZ_31		SALI	cowpea for forage			
SZ_32		SU	irrigated rice (canals)			
SZ_33		SU_inc	irrigated rice (pump)			
SZ_34		IN_H1	controlled inundated rice			
SZ_35		IN_H2	controlled inundated rice			
SZ_36		IN_H3	sorghum			
SZ_37		IN_H4	sorghum of the river delta			
		IN_H5				
		IN_H6				
		IN_H7				

Sub-zone
The Soudano sahelian region is divided into 15 sub-zones which are relatively homogeneous regarding soil and climate characteristics. Moreover, administrative boundaries are taken into account to simplify the collection of statistical data. The 15 sub-zones are oriented in the west east direction, because rainfall, one of the most important climatic factors, changes mostly in the north-south direction (from 300 to 900 mm). See section 6.2 for a sketched map of the Sudano-sahelian region and the location of the sub-zones.

Rainfall
The climate of the sub-zone gives the environment for vegetative growth. For each sub-zone it is characterized in terms of radiation, rainfall (number of rainy days, average rainfall per decade), potential

evapotranspiration and et vapor pressure deficit, on the basis of climatic data for 30 years (1961 - 1990) of the `Direction Nationale de la Meteorologie'. These data are used per decade. A separation has been made between dry, normal and humid years. A dry year represents the 20 % (=6) driest years, while a humid year represents the 20 % (=6) wettest years. A normal year represents the remaining 60 % (18) years of the 1961-1990 period.

Soil type

The soil is a resource that should be apt to temporarily store water and nutrients in order to give crops, trees and grass the possibility to grow. For the sudano-sahelian zone of Mali 18 soil types have been distinguished, using as criteria the possibility to be inundated, soil depth, presence of gravel, and texture. Soil characteristics are derived from PIRT (1986a, b,c) and are described in more detail in section 6.2.

Crop

Crop characteristics used to quantify the production potential of the fifteen distinguished crops include the minimum and maximum growth cycle, length of development stages, parameters defining the partitioning of biomass over crop parts, nutrient contents, and crop specific parameters used to estimate the water-limited production according to Tanner & Sinclair (1983). Crop specific information is derived from Van Duivenbooden *et al.* (1991), Van Duivenbooden (1992), Purseglove (1974, 1975) and Penning de Vries & Djitèye (1982).

Production level

Four target production levels are distinguished: extensive, semi-extensive, semi-intensive and intensive. They differ in yield, level of mechanization, nutrient efficiency and the occurrence of a fallow period. It is assumed that at he highest production level (indicated with `intensive') the yield of a rain fed crop activity can reach 80 % of the yield limited by water availability. It is assumed that an additional 20 % of the yields is lost by diseases and pests. At a low production level, the yield is determined mainly by nutrient availability, which is derived from Penning de Vries & Djitèye (1982). Use of animal traction at field preparation gives 20 % higher yields than at the lowest production level (Van Duivenbooden *et al.*, 1991). Between this production level and the intensive production level an intermediate level (semi-intensive) is fixed. The production level also defines which operations are carried out, what kind of equipment is used, whether animal traction is applied and the labor requirements. It is assumed that at the more intensive (= higher) production levels more animal traction is applied. Moreover, it is assumed that at the less intensive production levels nutrient losses are larger due to less favorable growing conditions. A fallow period for the extensive production levels is defined as an additional organic matter source to maintain the soil organic matter content.

Use of crop residues

This criteria determines how crop residues are used. Six crop residue uses are defined: (i) plowing the crop residues into the soil to supply the soil organic matter resources, (ii) mulching to reduce soil erosion and to supply soil organic matter resources, (iii) burned at the field, (iv) transport of crop residues to the farm where they can be used as forage in livestock rearing or for compost making (v) fabrication of compost, or (vi) crop residues can be grazed directly by cattle or small ruminants Formally, in the crop activity, there is only a choice between mulching and other. In the MGLP model, the residues that were

not used for mulching, can be used for the other 5 types of activity (plowing, grazing, etc.)

Table 6.11 Some examples of in- and output coefficients for sorghum activities in sub-zone SZ_37 (Koutiala) under normal rainfall conditions

definition criterion	unit	values for the definition criteria				
soil type		LIAR	LIAR	LIAR	GR	GR
crop		sorghum	sorghum	sorghum	sorghum	sorghum
production level		semi-intensive	semi-int.	semi-ext.	semi-int	semi-int
crop residue use		other*)	other*)	other*)	other*)	mulching
conservation measures		flat	tied ridg.	tied ridg.	tied ridg.	tied ridg.
outputs:						
main product	kg ha^{-1}	2475	3065	1039	2003	2003
residue (field)	kg ha^{-1}	4339	5370	2420	3514	0
MOST (farm)	UMO ha^{-1}	41	50	22	33	33
N (farm)	kg ha^{-1}	2	2	1	2	2
P (farm)	kg ha^{-1}	0	0	0	0	0
K (farm)	kg ha^{-1}	8	10	4	6	6
nitrogen binding capacity	kg ha^{-1}	5	6	2	4	4
inputs:						
MOST	UMO ha^{-1}	117	146	152	131	5
N	kg ha^{-1}	94	138	69	161	152
P	kg ha^{-1}	5	6	2	4	3
K	kg ha^{-1}	53	81	37	105	78
labor:						
1. spread of organic matter	md ha^{-1}	2	2	1	1	10
2. preparation	md ha^{-1}	10	21	19	20	20
3. semis	md ha^{-1}	2	6	5	5	5
4. maintenance-1	md ha^{-1}	15	20	20	20	20
5. maintenance-2	md ha^{-1}	27	31	18	26	26
6. harvest	md ha^{-1}	26	32	14	22	22
7. hors harvest	md ha^{-1}	2	2	1	1	1

8. rest	md ha^{-1}	55	30	13	26	33
draught animals	ad ha^{-1}	19.3	9.6	8	9.1	9.1
monetary input	F cfa ha^{-1}	30170	9802	5010	8640	7260

*) means that crop residues can be used for plowing into the field, for burning, for transport to the farm, or for grazing

Measures of conservation of water and soil
Three cultivation techniques are distinguished that influence run-off: flat, ridges and tied ridges, of which the latter two are applied to reduce run-off. The conservation measures affect water infiltration and therefore the water-limited production potential of crops. Moreover, these cultivation techniques affect soil erosion.

Theoretically, the 15 sub-zones, 2 rainfall-year types, 18 soil types, 15 crops, 4 production levels, 2 crop residue uses and 3 conservation measures can be combined, resulting in different crop activities. However, not all combinations are feasible. Some combinations of sub-zones and crops are for instance infeasible due to the limited availability of water for crop growth in certain sub-zones, inundated crops are only grown at inundated soils and not all crops are combined with each production level, residue use or conservation measure. For the feasible combinations in-and outputs are quantified. The inputs include MOST, N, P and K, labor, draught animals and capital. The outputs include the main product, the residue, and the remainder of the main product after threshing. This remainder contains MOST, N, P K and represents also a nitrogen binding capacity, when mixed with dung. In Table 6.11 five examples are shown of sorghum activities which differ in soil type, production level, residue use and conservation measures.

As described in the introduction section 6.3.1 the crop activities are defined in a target oriented way, i.e. first the yields (outputs) are determined and subsequently the requirements (inputs). This approach can be illustrated on the basis of the sorghum activities shown in Table 6.11. First the water-limited production is estimated based on the available amount of water. Rainfall (distribution), soil characteristics and conservation measures determine the run-off and the infiltrated water which is reduced with losses due to evaporation and percolation. On basis of the available water, crop specific parameters and the vapor pressure deficit the total biomass is estimated with the method described by Tanner & Sinclair (1983). The biomass is corrected assuming inevitable losses due to sub-optimal water supply at the start and end of the growing season, and diseases and plagues. Using crop specific partitioning ratios the biomass is distributed over the crop parts, grains, ear, leaves, stems et roots. The output includes the grains, the residue (leaves and stems) while the ears are transformed into the output MOST. Based on the nutrient content of the ears the amount of N, P and K can be estimated as a separate output shown in Table 6.11. The nitrogen binding capacity quantifies the amount of N that can be immobilized by the relatively N poor ear parts. This output can be used by to immobilize urine N if compost is used to be mixed with dung.

Subsequently, the inputs are calculated. The requirements of organic matter in terms of MOST are described in paragraph 6.3.1. The MOST input is required to maintain the soil organic matter content at a

target organic matter level. It is noticed that these target levels are higher than the current soil organic matter contents (see section 6.2). A similar requirement has to be met for the nutrients N, P and K for which the annual withdrawal should be compensated by natural and external resources. Therefore, the quantity of nutrients is calculated which is taken up by the crop and removed from the field plus the losses caused by soil erosion. This amount of nutrients should be compensated by supply processes to guarantee a sustainable production system. The supply from natural resources includes several processes: wet and dry deposition, biological fixation, and inundated water. These components are subject to loss processes including denitrification, volatilization, leaching and erosion which are governed by rainfall, soil type, crop, production level, conservation measures and whether nutrients are derived from organic or inorganic material. It is e.g. assumed that nitrogen from organic material is subject to higher losses than nitrogen from (inorganic) fertilizers. The difference between the nutrient withdrawal and supply from natural resources allows to quantify a nutrient balance of the system. A deficient balance, i.e. the nutrient outflow exceeds the inflow, must be compensated by the supply of organic matter and/or fertilizers which are also subject to the same loss processes as nutrients from natural resources. Dividing the nutrient deficit by the complement of the loss fraction results in the fertilizer requirement of a particular crop activity.

Eight periods are defined in which various field operations have to be carried out requiring labor and draught animals. For these operations so-called task times are available defining the number of man-days and animal-team days required to complete an operation including the necessary traveling time (Van Duivenbooden *et al.*, 1991; PIRT 1983a,b,c; Van Heemst *et al.*, 1983). Some operations are a function of the yield level (e.g. harvesting), others a function of the area (e.g. plowing). Matching the available days in each period with the labor and animal traction requirements of the operations in each period allows to identify labor and animal traction peaks during the season. For reasons of simplicity only the total annual animal requirements are shown in Table 6.11.

The monetary inputs of crop activities include capital costs and `consumable' costs. The former includes the costs of animal traction (carts, donkeys), their implements (plow, sowing machines, etc.) and stones for stone bunds. The annual capital costs are based on the depreciation costs and maintenance costs. The `consumable' costs are the costs for seed and crop protection. The costs of fertilizer are not included in the crop activity, as the activity defines the amount of nutrients and organic matter that is lost from the soil. In the LP model it is calculated how to restore the nutrient balance: with nutrients and organic from the system or with the use of fertilizer.

6.3.3. Livestock activities

For a large part of the population in the sudano-sahelian zone livestock is the main livelihood. The low quality of fodder is one of the key problems the livestock sector faces. The quality and quantity of available fodder determines the potential livestock production. Integration of arable and livestock production systems as illustrated in Figure 6.5 can improve the fodder situation and thus animal productivity. The approach chosen to quantify livestock activities takes in an explicit way into account the regional feed availability and quality.

A livestock activity is defined as the specific combination of inputs (feed, labor and capital) resulting in a

unique set of outputs (meat or live weight, milk, manure and traction). Three animal species are defined for which in-and output matrices are determined and applied in the MGLP model: cattle, goats, and sheep. For reasons of simplicity the description of the animal activities in this section is restricted to that of cattle activities. The in-and output relations of the other animal species are principally in the same way derived. See Quak *et al*. (1996) for a more elaborate description of the cattle livestock activities.

Cattle is divided into two types of animals: (i) cattle that lives in *herds* and has a mixed production goal consisting of milk, live weight (meat) and traction (oxen); they are also called *dual-purpose animals*, and (ii) cattle reared individually for intensive meat production by means of *fattening*. Both types produce manure as a by-product and are related to each other because herd animals that are sold can be used for fattening. Figure 6.7 gives a schematic overview of the in-and outputs of the two cattle activities and their relationships. The feed for both types of animals are divided into 8 different quality classes (q1 to q8) and its availability for herd purpose animals in two seasons (dry and rainy season). Fattening is supposed to take place only in the dry season. The outputs of both cattle activities consists of meat and manure, plus milk and a fraction of animals suitable for traction (the latter only for the dual-purpose animals).

Figure 6.7 Inputs and outputs of livestock activities.

6.3.3.1. Livestock in herds

Starting point in modelling the herd structure is the assumption that an equilibrium cattle system is described, i.e. a system of which the in-and outputs are the same from year to year. To model the herd structure a distinction is made between female and male animals. Moreover, 11 age categories are defined, 0-1 year, 1-2 year, etc. up to the last category of 10-11 year. It is assumed that the maximum age at which animals are sold is 11 years. To regulate the herd structure selling strategies need to be specified. In the model a selling strategy refers to the age at which the males, reproductive females and the non-reproductive females are sold. If the selling strategy for male animals is e.g. 2, all male animals are supposed to be sold at the age of exactly two years. As the reproductive function of male animals in a herd theoretically can be accomplished by one animal, all male animals are assumed to be superfluous and, therefore, sold.

A distinction is made between 4 levels of production, corresponding to 4 levels of menu quality. The menu quality is expressed in the fraction of energy intake needed for maintaining an animal at its actual weight. A quality of 1.10 means therefore that the quality of the menu offered to an animal is such that the animal would take in 1.1 times its maintenance requirement. This means that around 9 % (1/1.1) of the feed can be used for production. The higher the menu quality the higher the productivity of animals.

For a given menu quality, the difference between the three objectives milk, meat and traction is obtained by different choices for the selling strategy. Three selling strategies are considered. If the main of production is milk, then all calves that are not needed for the maintenance of the herd at the same number should be sold as soon as possible, which, in the model, is after 12 months. For the case of meat, the non-reproductive calves remain in the herd until they are 2 years (females) or 3 years (males) in order to gain weight before being sold. The last strategy, the sale of males at the age of 8 years, and females at the age

of 1 year, serves to maximize the fraction of males of over 3 years of age in the herd. it is this fraction that can be used as draught animal for the crop activities.

Thus, 12 herd cattle activities are defined, combining 4 menu qualities with 3 selling strategies. The defined activities yield different production levels for meat, milk and traction. (Table 6.12). Besides, there is also a type of output that consists of animals that can be used for fattening, when they have not yet reached their full adult weight. (see also 6.3.3.3).

Table 6.12 Definitions and productivity of cattle herd activities

Activity	menu quality	production goal	live weight (kg animal^{-1} yr.$^{-1}$)	milk (kg animal^{-1} yr.$^{-1}$)	draught animals (animal animal^{-1} yr.$^{-1}$)
1	1.05	milk	25	62	0.00
2	1.05	meat	27	55	0.00
3	1.05	traction	29	46	0.07
4	1.10	milk	35	117	0.00
5	1.10	meat	38	99	0.00
6	1.10	traction	40	79	0.08
7	1.15	milk	44	176	0.00
8	1.15	meat	48	144	0.00
9	1.15	traction	52	118	0.09
10	1.20	milk	50	212	0.00
11	1.20	meat	55	172	0.00
12	1.20	traction	59	141	0.09

6.3.3.2. Feed quality and quantification of feed input

There are 8 feed quality categories using the same criterion as for menus, but applied to separate feeds. For example, with a feed with quality level 0,5 an animal could only fulfill 50 % of its maintenance requirement. If such a feed would be the only feed available, an animal could survive for a long time on it. Coupled to the quality is digestibility (Table 6.13). The table shows that digestibility is positively related to feed quality. The feeds distinguished in the model come from the rangelands, the crop activities and the purchase of cotton seed cake.

Table 6.13 Feed quality for the feeds used in the MGLP model

	quality	digestibility (%)	dry season feeds	rainy season feeds
1	0.25	35	rangeland grass N<4 g kg^{-1} DM	
2	0.50	40	rangeland grass N : 4-6 g kg^{-1} DM	
3	0.75	45	rangeland grass N : 6-8 g kg^{-1} DM, *Andropogon* millet, sorghum, maize straw	
4	1.00	50	rangeland grass N 8-10 g kg^{-1} DM, millet, sorghum, maize leaves, *Andropogon*, rice straw	
5	1.25	55	rangeland grass N : 10-13 g kg^{-1} DM, cowpea hay, peanut, treated rice	
6	1.50	60	rangeland grass N>13 g kg^{-1} DM `bourgou' ; *stylosanthes hamata*	rangeland grass N<16 g kg^{-1} DM
7	1.75	65		rangeland grass N 16-22 g kg^{-1} DM
8	1.00	70	cotton seed cake	rangeland grass N>22 g kg^{-1} DM

It is noticed that for livestock activities also the target-oriented approach is applied: For each herd activity the menu quality determines the production level. It also determines the average feed quality of the dry matter (DM), and its quantity. For each menu quality a number of `feed strategies' are defined with which the menu quality can be obtained. In the MGLP model it is determined which feed strategies are selected to attain the goals set. In Table 6.14 an example is given of one menu quality that can be obtained with different combinations of various feeds.

Table 6.14 Feed requirement by season (in kg DM) for various feed strategies, for a menu quality level of 1.10

feed strategies	feed requirement (kg animal^{-1})								
	rainy season	dry season by quality level							
		1	2	3	4	5	6	8	
25	522	196			890				
26	522	514				607			
27	522	704					445		
28	522	922						272	

29	522	257		822				
30	522	599				498		
31	522	770					342	
32	522	942						196
33	522			457	616			
34	522			799		280		
35	522			913			171	
36	522			1004				88

The monetary inputs and labor requirements for execution of the 12 herd activities are given in Table 6.15. Labor must be furnished throughout the year. To the labor requirements for herding time needed for milking is added. It has been estimated at 10 minutes per kg of milk. This number is based on the data presented by Van Duivenbooden & Gossèye (1990).

Table 6.15 Monetary and labor inputs (in 1000 F cfa animal $^{-1}$ yr.$^{-1}$ and (man animal^{-1}) by production level

production level (quality)	1.05	1.10	1.15	1.20
labor	0.015	0.025	0.03	0.035
monetary inputs	0	2	3	4

6.3.3.3. Fattening

The fattening activities are defined for the period December to May, period when animals in good shape are relatively rare, and prices on the market are good. The fattening activities therefore only use feed and labor in the dry season. The fattening takes place during 6 months at a stable. The latter implies that animals do not have access to natural rangelands. The feed sources that can be used are therefore only the agricultural by-products and the supplements that can be purchased (in the model the only supplement is cotton seed cake).

Six animal categories are considered for fattening, depending on their initial weight. The six categories are : young animals < 150 kg, males of 150-250 kg, females of 150-250 kg, males 250-350 kg, females of 250-350 kg, males of 350-450 kg.

Three menu quality levels are distinguished, corresponding to 1.25, 1.5 and 1.75 times the maintenance requirement. Thus 18 fattening activities are distinguished. They are presented in Table 6.16 together with their productivity (gain of weight) and their total digestible organic matter requirement. Again, the feed requirements can be met by means of various feed strategies. Of course, only feeds that are available in

the dry season can be used to fulfill the feed requirements for the fattening activities. The monetary inputs for the three menu quality levels 1.25, 1.5 and 1.75 are, respectively 2000, 4000 and 6000 F cfa animal^{-1}. These inputs cover the infrastructure and the veterinary care. Labor requirements are estimated at 0.05, 0.06 and 0.07 man animal^{-1}, for the three quality levels, respectively.

6.3.4. Transformation activities

The transformation activities support the crop and livestock activities by means of the production and transformation of by-products that they need. The transformation activities can be divided into activities (i) that produce intermediate products as major output (fallowing and rangeland activities), (ii) activities that transfer intermediate products produced by a certain activity to other activities (transport of crop residues from field to farm, organic matter transport from farm to field), (iii) activities that represent crop residue strategies (mulching, plodding activity, burning, compost making). These latter activities transfer MOST, crop residues and nutrients among the various activities that produce consumable products (crop and livestock activities) as illustrated in Figure 6.6. The definition criteria and the in-and outputs of these transformation activities are shown in Table 6.9.

Table 6.16 Definitions and productivity of fattening activities

Act.	menu quality	sex	initial weight (kg)	Intake (kg DOM)	weight gain (kg)
1	1.250	m/f	100	338	52
2	1.250	m	200	454	45
3	1.250	m	300	545	35
4	1.250	m	400	622	26
5	1.500	m/f	100	457	101
6	1.500	m	200	556	86
7	1.500	m	300	630	68
8	1.500	m	400	686	49
9	1.750	m/f	100	568	144
10	1.750	m	200	653	123
11	1.750	m	300	711	98
12	1.750	m	400	746	71
13	1.250	f	200	446	41
14	1.250	f	300	515	23
15	1.500	f	200	533	76
16	1.500	f	300	565	42

| 17 | 1.750 | f | 200 | 605 | 103 |
| 18 | 1.750 | f | 300 | 605 | 57 |

DOM= Digestible Organic Matter

6.3.4.1. Fallow activities

The fallow activities produce MOST and nutrients which can be used as input for crop activities. It is assumed that the biomass produced during a fallow year depend on the most limiting nutrient N, P or K. The availability of these nutrients is determined by the annual supply by natural resources (rainfall, microbial fixation, and weathering). With known minimum nutrient concentrations in fallow vegetation the organic matter production during a fallow year can be determined. However, in reality water will be the most limiting factor in many cases because the soils in the sudano-sahelian zone are to such an extent depleted and, therefore, degraded that run-off is the dominating process. In the model it is supposed that production takes place in a good production situation, that is, a situation where degradation of the land has not taken place.

It is assumed that the fallow vegetation is not grazed by livestock. In reality this would imply that labor and capital (fences) are required to protect the fallow vegetation. However, these requirements are not taken into account. Moreover, it is assumed that no biomass accumulation occurs over the years while in reality biomass production of fallow vegetation will increase due to a build up of natural resources (nutrients and organic matter in soils).

6.3.4.2. Rangeland activity

Rangeland activities produce different qualities of forage which are used as inputs for the livestock activities, and wood (from woody species) which can be used for cooking.

The method used to determine the forage production is based on the empirical model described by Breman & De Ridder (1991). They estimate for situations in which nitrogen is the most limiting growth factor the biomass production which can be exploited without damaging the production in the long run. The biomass production in this method depends on the nitrogen dynamics of the pasture system. The available nitrogen depends on the annual supply by natural resources (rainfall), the soil characteristics (texture, soil depth and position (slope, level) in the landscape) and a recovery rate of the woody species. The forage production is categorized in quality classes according to its nitrogen content and digestible organic matter content. These different quality classes are used in the feed rations described in par. 6.3.3.2.

6.3.4.3. Burning of residues

The burning of residues transform the residues produced by crop activities in nutritive elements that can then be used again by a crop activity.

Besides the residues themselves the only input is labor used to tear out the crop residues before burning

them in the field preparation period. The outputs are the nutritive elements P and K in the residues. It is assumed that the nitrogen is completely burnt. It is supposed that the carbon that remains after burning contributes only to restitution of the organic matter in the soil that has been decomposed.

6.3.4.4. Plowing crop residues into the soil

The plowing activities consists of plowing the crop residues into the soil and thus transforming the residues in MOST and nutritive elements. These activities can be carried out with crop residues from millet, sorghum, maize, cotton, cowpea, and peanut. The output of the plowing activities are therefore MOST and nutrients, and they can be used in the MGLP model to restore the organic matter and nutrient balances for the soil type on which the crop was grown.

The labor and animal traction inputs are used in the period. after the harvest, as it is supposed that during the 20 days after the harvest the soil is still wet enough to permit plowing. Monetary inputs are needed because of the use of the plow.

6.3.4.5. Mulching

The mulching activity is defined to serve two purposes: (i) to reduce soil erosion and (ii) to contribute to organic matter requirements of crop activities. The mulching activity transforms residues produced by crop activities in MOST and nutrients (N, P and K).

Mulching activities can only be realized with crop residues from millet, sorghum, maize and cotton. Moreover, crop residues from one crop activity can not be used by other crop activities.

The labor requirements of mulching activities are defined in the off-season in which they do not compete with field operations of activities.

6.3.4.6. Compost making

In making compost, crop residues transported to the farm are used in order to mix them with dung. The aim is to reduce nitrogen losses during the period of decomposition of the dung. The crop type determines the transformation into MOST, while the production of compost in the MGLP model is limited to the subs-zones in which the crop residues are produced.

Labor input is for the collection of cop residues and its placement in, e.g. the corral. The outputs are organic matter and nutritive elements contained in the residue and a capacity to bind nitrogen that would otherwise be lost from the dung through volatilization.

6.3.4.7. Crop residue transport from field to farm

The transport activities transfer the residues produced by the crop activities from the field to the farm,

where they can be used as forage or compost.

The transport mode, which is one of the definition criteria, can be either of two: by a donkey drawn cart or by the head, which is the traditional way. Labor is necessary for the transport by cart or using the head and capital for the depreciation of the cart and the donkeys. The output is the same crop residue, but no longer at the field but at the farm, usable for forage at the farm or for compost making.

6.3.4.8. Transport of organic matter from farm to field

These activities transport organic matter (including its nutrients) from the farm to the field. The organic matter, expressed in terms of MOST (standard organic matter units), is produced by crop activities, livestock activities (manure), and compost and compost making activities.

Two types of transport are defined, by head or by using a donkey cart. The other inputs are labor for the transport and the spreading of the organic matter on the field, and capital for depreciation of the donkey cart and the donkeys. The nutritive elements are transported with the organic matter. The output of the activity is the organic matter (expressed in MOST) transported to the field.

6.3.5. The technical coefficient generator (GCT) of the PSS project

6.3.5.1. Introduction

The following description of the Technical Coefficient Generator (fr. Générateur des Coefficient Techniques, GCT) of the PSS project should help the user to examine and to use the GCT. To introduce changes is more difficult, and may lead to problems in the functioning of the GCT. The GCT is a utility that can be used to estimate in a consistent fashion the outputs which require inputs for different types of agro-sylvo-pastoral activities. For the term `technical coefficients' to which we refer in the document quantified estimates are given for inputs and outputs. This term is an economist's term in which the social sciences are opposed to the other sciences, coined `technical' (e.g. agronomy, animal nutrition). As an aide to the science, the economist attempts to analyse a system and its effects on man. In our case this is done with the aid of a multiple goal linear programming model.

The GCT is developed making use of EXCEL (version 4), a product of Microsoft. For a illustration of the GCT basic knowledge of EXCEL is required (opening of files, changing a cell, entering a value in a cell, going through and examining a file with the aid of arrows, or a mouse, choosing options from the menu, etc.). To understand the formulas in detail, a thorough understanding of EXCEL is necessary, but this probably is not enough. How the formulas are used and their justification is presented in the research reports of the team responsible for systems modelling of the PSS project.

6.3.5.2. The type of activities

The GCT can be used for 18 types of activity each with their own code. The GCT of one type of activity furnishes a quantitative estimation of the production and of the inputs needed for the various activities of

that type. For information on the characterization for each type of activity and relationship between different types of activities, the reader is referred to the appropriate documents of the PSS project.

The activity types with their codes are:

code Type of activity
CUL: CULtures pluviales (rain fed cropping)
CIN: Cultures Inondées (inundated cropping)
PAT: PATurage (rangeland)
SYL: SYLviculture (wood plantation)
JAC: JAChère (fallowing)
FOC: FOurrage au Champ (crop residue use as forage)
BRU: Burning (BRUlage) of crop residues
ENF: Plowing (ENFouissement) of crop residues into the soil)
TRF: Transport of Residues to the Farm
FOF: crop residue used as FOrage at the Farm
LIT: compost (LITière) making by mixing crop residue with dung
TFC: Transport of manure (Fumier) from farm to field (Champ)
BOV: Elevage des BOVins en troupeau (cattle rearing in herds)
CAP: Elevage des CAPrins en troupeau (goat rearing in herds)
OV: Elevage des OVins en troupeau (sheep rearing in herds)
BL: Boeufs de Labour (draught animal training and feeding)
MB: Elevage d'eMBouche bovin (fattening of individual cattle)
SFT: Stratégies Fourragères (feed strategies for BOV, CAP et OV)
SFM: Stratégies Fourragères (feed strategies for fattening)
ENG: achat des ENGrais chimiques (application of fertilizer)

6.3.5.3. The main calculation files and help files

For each type of activity there is a main calculation file, with the name INEX_act.XLS, `act' will correspond to the code of the activity type. `INEX' is an abbreviation of the Inputs and OUTputs'. For example, for the activities placed in the file, the calculation principle is INEX_ENF.XLS. There are nine auxiliary files in which calculations are made that are common to a number of types of activity. In this way they reduce the size of the main calculation files. They are the following files:

BESMOEN.XLS: BESoin en Matière organique et engrais (organic matter and nutrient requirement, inlcuding fertilizer)
CLIMAT.XLS: Données sur le CLIMAT (climatic data)
CRUES.XLS: Hauteur des CRUES (data on the water level of the Niger river)
PRIXMAT.XLS: Data on prices (PRIX) of MATerials, donkeys, etc..
REND_NO.XLS: Yield (RENDement) and crop calendar in a Normal year
REND_SE.XLS: Yield (RENDement) and crop calendar in a dry (SEche) year
SUBSTRAT.XLS: Data on soil types (SUBSTRATs)

TT.XLS: Transport Times
VALDEBAS.XLS: Base values (VALeurs DE BASe) for crops

There are three help files. There are two files with the macros (procedures for the functions are written to be used), in which part of the calculation for certain types of activities is done. The other file contains the lists of values for certain parametres. This file (LIST_NOM.XLS) contains amongst others the list of the sub-zones, the list of soil types the list of intensity levels (see Table 6.10). In addition, file contains for each type of activity the list of files that is used for the calculations.

LIST_NOM.XLS: LIST of names (NOMs) and values of definition variables
F_MAX.XLM: Macro file, used for calculations of the productivity of rangelands
INTERPOL.XLM: Macro file with formulas for interpolation

6.3.5.4. Preparing and starting the GCT

Installing the GCT is done by copying all the files necessary in the sub-directory C:\PSS\GCT. The GCT can be used only within the spreadsheet EXCEL (version 4 or 5). After starting EXCEL, the Macro file GCT.XLM in the directory C:\PSS\GCT should be opened. It is then possible to execute one of three macros:

* ChoisirTypeDactivité (Choose the type of activity) After activating the macro a list of types of activity is presented from which one is to be selected. This enables one to examine the GCT files, the formulas that are used and the results for one activity.
* GénérerCoefficientsTechniques (Generate Technical coefficients) With this option the TC for a (large) number of activities can be calculated and stored on file. Again one has to choose first the type of activity
* ActInfo enables one to get INFOrmations concerning the TC generated for a certain activity type, and which is chosen first (the number of activities, the definition variables and the names and dimensions of the calculated variables).

After having activated one of the three macros a list of different activity types appears on the screen. One chooses using the mouse or the cursor and confirms the choice by pressing the <Enter> key.

6.3.5.5. Examining the calculation files and the data base

After the choice of the type of activity, all files needed for the calculation of the inputs and outputs for that type of activity are opened. The active file is the principal calculation file (with the name INEX_act. XLS, act referring to the type of activity). It is then possible to go through the various files, examine the type of calculations that are made, and the data and the formulas that are used.. Usually one only sees the calculated values on the screen, except for the active cell, of which it is possible to look at the formula used. It is therefore necessary to activate the cell for which one wants to know the formula that is used.

Definition of an activity
An activity of a certain type is defined for a combination of values of definition variables that characterize

the activity. For the crop activities, for example, the definition variables are, amongst others, the soil type, the sub-zone (which defines the climate), the crop and the intensity or production level. Each combination of definition variables defines an activity. It is this combination that is given as input for the calculation. All definition variables should have a value otherwise errors will be introduced in the calculation. Table 6.10 shows the definition variables for the crop activities.

How to change the definition variables
The definition variables can be manipulated by changing the values contained in the vector <input>. By activating the menu Formula-Goto or Edit-Goto and by choosing the name <input> from the list that is presented, one will know, in case of doubt, of which cells <input> is made up. After making changes in <input>, one presses F9 or chooses CalculateNow from the Tools-Option-Calculation or Options-Calculation menu. Then the definition variables (sub-zone, soil type, etc...) are calculated on the basis of the values in <input> and the lists contained in the file LIST_NOM.XLS. At the same time, all other cells are updated and the results of the calculations in all files can be examined.

The most important results are put together in a vector of the name <output>, that contains for the activity under consideration the outputs (e.g. the yield) and the inputs (labor and nutrient requirement, etc.).

6.3.5.6. Generating coefficients for a large number of activities

In the calculation files the results for only one activity can be examined at a time. For the generation and saving of a large number of activities another file is used with the name CT_act.XLS (`act' is the code of the type of activity that correspondents with the code in the file INEX_act.XLS). The series of activity definitions are saved in the file DEF_act.XLS.

On the basis of a series of activities (combinations of values of the definition variables) generation of the TC is done automatically. In this process the values of the definition variables (the vector<input>) and the values of the vector <output> are stored in the file CT_act.XLS. These are the technical coefficients that can be used in the MGLP model. If one would like to have other parts of the calculations as well, one would need to add them to the vector <output> in the INEX_act.XLS file.

How to run the GCT for a given type of activity
The way to calculate the data on inputs and outputs for many activities is started by execution of the macro *GénérerCoefficientsTechniques*. One then chooses the type of activity and the directory where one wants to store the files used in the MGLP model. Then, for each of the definition variables, all its possible values are presented.The user chooses the options that have to be included in the model. For example, for the crop activities, there is a menu for the sub-zones, the soils, the level of intensity, etc. Suppose the user wants to run a model for the sub-zone 1.3, then he chooses only that sub-zone out of the list of the 15 sub-zones presented. Among the soil types he also chooses the soil types that he wants to include in the model.

After the generation of the technical coefficients the file CT_act.XLS contains all the technical coefficients as well as some general statistics, such as the total number of combinations of the definition variables, the number of combinations for which calculations were done and the number of activities that

can be used in the MGLP model

(a) Technical requirements to use the macros (this part is not complete)

1. INEX_act.XLS
A variable with the defined with the name <input> , which refers to the values of the definition variables. Also, the variable <output> contains the resulting values (inputs and outputs for the activity). Finally, the variable `possibilité' is defined, and has a logical value (`true' or `false'). The variable indicates whether or not a combination of definition variables can be realized or not. For example, a combination may be impossible because the soil type and the crop are incompatible, or the combination of a crop and a sub-zone (climate) is incompatible, etc.

2. The file CTDEFact.XLS is included in the directory C:\PSS\GCT, and the first column corresponds to the vector <input> of INEX_act.XLS.

3. The directories available on disk should correspond to the list of directories stored in the vector < ctdirlist > in LIST_NOM.XLS (\pss\ct\sz_11, \pss\ct\sz_12, ...,\pss\ct\sz_37, \pss\ct\kout, \pss\ct\zone)

(b) Exercises for the Technical Coefficient Generator

0. Start the GCT (Start EXCEL and open the file GCT.XLM)

1. Look and go through the GCT. For all the exercises you are encouraged to go through the different files.

a Open the GCT f or cattle (bovins)
Which are the calculation files that are used?
In the file INEX_BOV.XLS:
At which feeding level is the actual activity
What is the gain in weight for a female of two years?
What is the size of the simulated herd and what is the fraction of males?

b Open the GCT for the production of compost (litière)
Which calculation files are used?
In the file INEX_LIT.XLS:
For which crops are residues used for compost in the present activity?
What is the crop residue quantity that can be crushed by 10 TLU in one night?
Does this quantity depend on the crop, according to the calcuations? Why (not)?

c Open the GCT for the production of rain fed crops and open also the file that generate the technical coefficients (CT_CUL.XLS).
Which are the files that are used for the calculations?
For which sub-zone is the activity presented? What is the average rainfall? What is the rainfall in a dry

year?

Where can the calculations of the crop yield (total biomass) be found?

2. Doing the calculations for a number of activities

a. Start the GCT for wood plantation (sylviculture).

Which calculation files are used?

Which are the monetary inputs that are required?

What is the effect of the area of a parcel?

3. Change the parameters and re-calculate

* Weight of the adult cattle (bovin)

* The area of a parcel for wood plantation (sylviculture)

What is the influence of monetary input?

4. Generate technical coefficients for the activities of one type

Generate the technical coefficients for the transportation of manure (Transport de fumier) in sub-zone 2.4 for 4 soil types in that zone; save the data for the MGLP model in the corresponding directory.

6.4. Restrictions

The restrictions in the model an be divided into two types: the technical restrictions and the restrictions that are concerned with the objective variables. The first type of restriction is almost always some form of balance that limits the use of resources or intermediary products to total availability. This type of restriction specifies hence always that the sum of total uses cannot exceed total availability:

Total use $\leq$ Total availability

A global view of the different types of technical restriction is given in Table 6.17. For each resource or intermediary product there is an indication where it comes from and which type of activity uses it. For the sources where it comes from there is a `+' sign and the activities for which they are used the sign `-` is used. For example, the harvested residues on the fields are directly used for by the crops. These residues are utilised for different types of activities that are mentioned in the tableau: Burned residues, worked-under residues, fodder and transport.

Each type of restriction given in the tableau corresponds with many restrictions in the model, because the resources and the intermediary products are subdivided. For example, the labor balance is required for each combination of a sub-zone and a period. For the model of the Sudano-Sahelian zone of Mali there are 15 sub-zones and 30 periods, so 450 (15*30) restrictions for labor are included in the model. For the model for the Koutiala district, which falls into one single climatic zone, and where there are 10 crops that

can be cultivated, there are therefore 10 balance restriction for crop residues at the farm in the model.

The land is sub-divided according to three criteria: the sub-zone, the soil type and the distance of a field from a permanent waterpoint. The last criterion is included for a better estimate of the land availability for agriculture. The hypothesis of Veeneklaas *et al*. (1991) was used which states that land outside the radius of 6 km from a permanent waterpoint cannot be used for crop production. And the land outside a radius of 15 km from a permanent water point cannot be used for grazing in the dry season. There are three types of restrictions: one for the total area, one for a radius of 15 km around a permanent water point and one for a radius of 6 km around a permanent water point. The areas are estimated for the sub-zones and are given in Section 6.2 for the resources.

The system used for the restriction techniques in the model are not completely described here. For example, for the yield of fodder for small ruminants in the model distinction is made between organic material and dry material. This distinction is not included in Table 6.17.

Table 6.17 List balances or technical restrictions of the MGLP model. For more explanation, see text

resource or intermediate product	subdivision according to		provenance (+) / utilization (-)
land	sub-zone	+	natural resource
	soil type	-	crop activities
	distance to permanent water point	-	activities of wood plantation
		-	fallowing
		-	rangeland
labor	sub-zone	+	population in the sub-zone
	period	+	labor of outside the sub-zone
		-	almost all types of activity
crop residues (field)	sub-zone	+	crop activities
	soil type	-	burning of residues
	crop	-	plowing/ mulching of residues
		-	forage in the field
		-	transport to the farm
crop residues (farm)	sub-zone	+	transport to the farm
	crop	-	forage at the farm
		-	compost

forage (total)	sub-zone	+	rangeland
	season	+	forage in the field (residues)
	quality	+	forage at the farm (residues)
		+	supplementing
		-	livestock activities
forage (farm, season dry)	sub-zone	+	forage at the farm (residues)
	quality	+	supplementing
		-	livestock activities
nutritive elements (field)	sub-zone	+	fertilizer use
	soil type	+	fallowing
	type of nutriment	+	burning of residues
		+	plowing/ mulching of residues
		+	livestock (manure during grazing in the field)
		+	transport of manure from farm to field
		-	activities of wood- or crop production
nutritive elements (farm)	sub-zone	+	manure gathered in corals or stables
	type of nutriment	+	compost produced at the farm
		-	transport of manure to the field
draught animals	sub-zone	+	cattle livestock in herds with
			training of draught animals of
		-	crop activities
		-	plowing of crop residues
fattening animals	sub-zone	+	cattle livestock in herds
	sex	-	livestock fattening
	initial weight		

6.5. Development objectives and the economic environment

Objectives

In the PSS project the development objectives that were included in the analysis with the MGLP model are sustainability (the organic material balance, and nutritive elements), elementary self-sufficiency (for a

normal year and for a dry year), the net revenue, the production of cereals, cotton, milk and meat, fodder security for ruminants (for a normal and a dry year). These are the attributes that were considered.

These productions and the net revenues are the objectives. The other attributes are given by the target values, and are included in the model as goals. The targets for the self-sufficiency are given in a similar fashion (Table 6.18). As far as sustainability is concerned, the goal is that the different balances should be in equilibrium.

The prices: relation between the production and the price

The prices of the external inputs (fertilizers and supplements) and of the final products are important coefficients in the model. The prices that were taken into consideration for the inputs and outputs were based on the levels in the Koutiala district and are given in Table 6.18. It is possible to analyse the effect of the price level on the results with the aid of a sensitivity analysis (see Section 6.8).

A problem with the use of fixed prices is hat it assumes that the price of a product does not depend on the quantity of the product. This may be realistic for the case of a peasant, but is not realistic when the production of a whole zone is considered. An effort was made to solve this problem. The way to solve this problem in the model is to include the relation between price and quantity for all agricultural production. Because this is very difficult, if not impossible, when constructing the MGLP model only for a few individual products price-quantity relations were included. As price elasticities for the demand were not available, the following approach was adopted.

The starting point is Tableau 6.18 where the base price of the inputs and the agricultural outputs are given and, for the products for whom the price depends on the production and the demand for consumption. The total production of a product is divided in 4 parts. The first part is the start starts at zero and the total requirement of the zone for consumption. In this part the production is valued at 100 % of the base price. The second part succeeds the first part and is also longer than the it. The third part follows the second and is also longer. The fourth and last part follows the third and continues to infinity.

The price of the product in the second part is 75 % of the price in the base, and in the third part it is 75 % of the price of the second part, the price in the fourth part is at the 75 % level of the third level. It can be seen that the production reaches a maximum in the first part, the price of the production in this part stays the same as the price in the base. In this case there is no longer only one price for the whole production, but it implies that the production value is a continuous function of production. The steps are presented in Figure 6.8.

Table 6.18 Price levels considered for the inputs and outputs and the consumption norms (in unit per person) and the 'normal' demand used for the price function

	price (F cfa)	unit	source (prix)	norm of consomm.	normal demand

outputs					
millet	47	kg	1	90	125
sorghum	36	kg	1	55	125
maize	35	kg	1	67	125
cowpea grains	75	kg		10	15
peanut grains	75	kg		12	15
rice	100	kg	1		125
cotton grains (1st quality)	125	kg	2		
milk	150	kg		9	40
meat (cattle)	325	kg live weight	3	12	18
wood for burning of	1500	m^3		0.75	
construction wood	3000	m^3		0.1	
inputs					
nitrogen (N)	360	kg pure element	4		
phosphor (P)	650	kg pure element	4		
potassium (K)	360	kg pure element	4		
cotton seed cake of	50	kg			
remunerated labor	600	man day			

Sources: 1: OPAM/SIM (1995) 3: Statistiques OMBEVI
2: Contrat-Plan CMDT-SYCOV 4: IFDC (1994)

Figure 6.8 *Relation between total production and the price.*

6.6. An example of an **MGLP model** for one climatic zone

6.7. Case study

As part of this course on land use analysis the course a case study will be developed. This will be done by

using the tools that were developed by the PSS project, namely, th etechnical coefficient generator.

The following steps are to be followed:

1. Select a zone in Mali

2. Define policy views and objectfunctions to be included in the case study.

3. Using the technical coefficient generator determine the input - output coefficients.

4. Determine and quantify the constraints.

5. Develop an IMGLP model in XPRESS.

6. Generate a number of land use scenarios.

7. Conduct sensitivity analysis with the model that was developed.

8. The results are presented in a report, which is presented and discussed in a plenary session.

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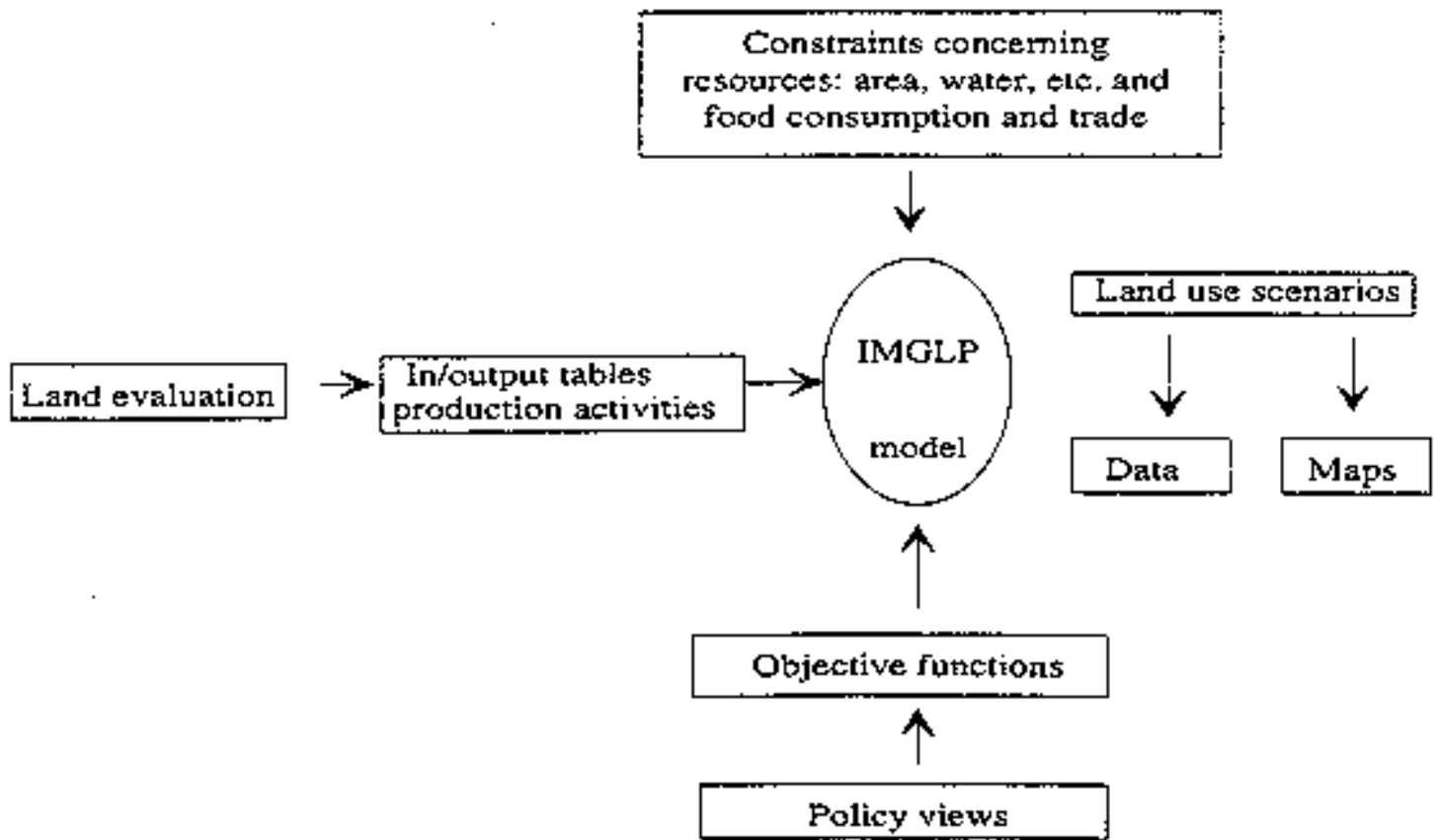
Figure 2.1   General methodology for explorative land use studies.
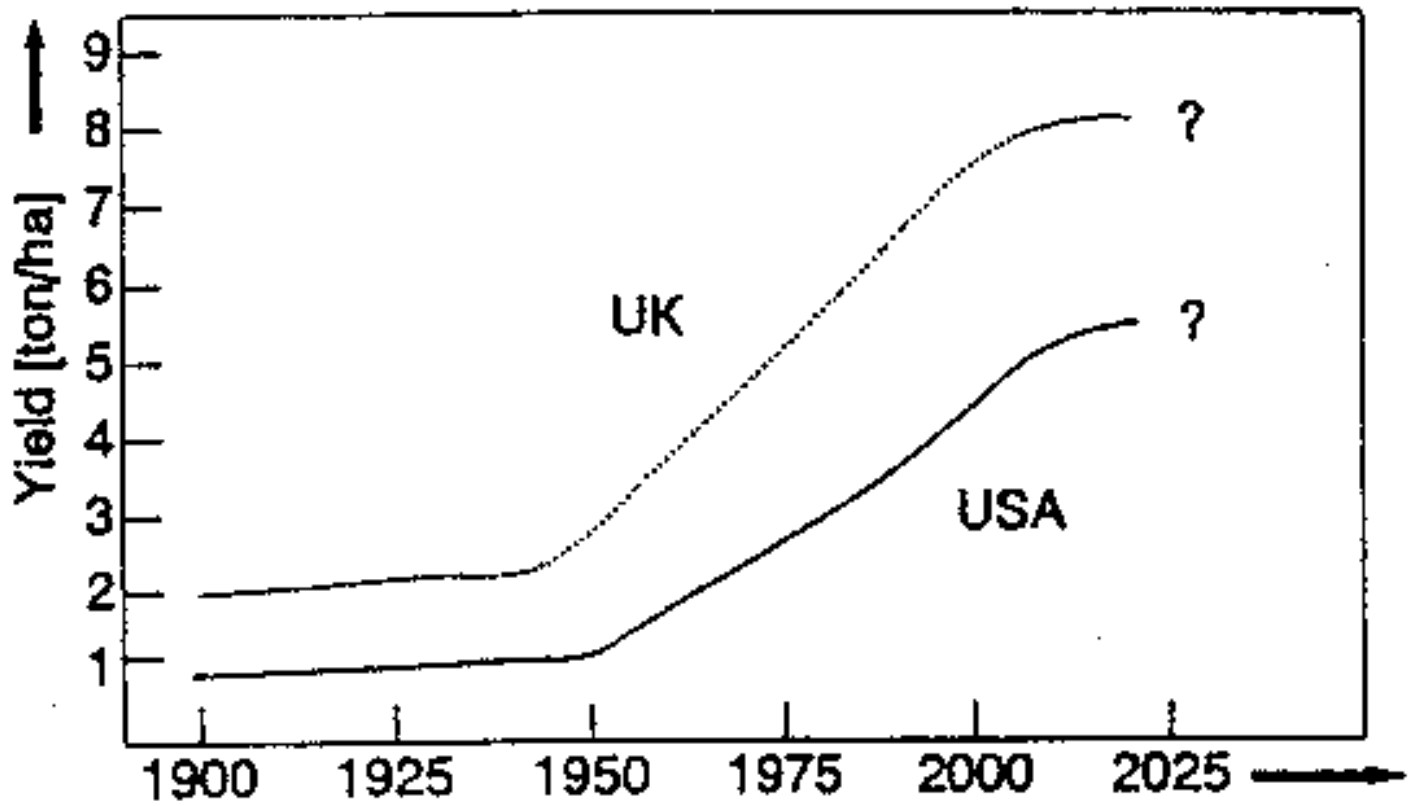
Figure 2.2 Development of soil productivity for wheat in the UK and the USA. Source:
Rabbinge & Van Latesteijn, 1992.
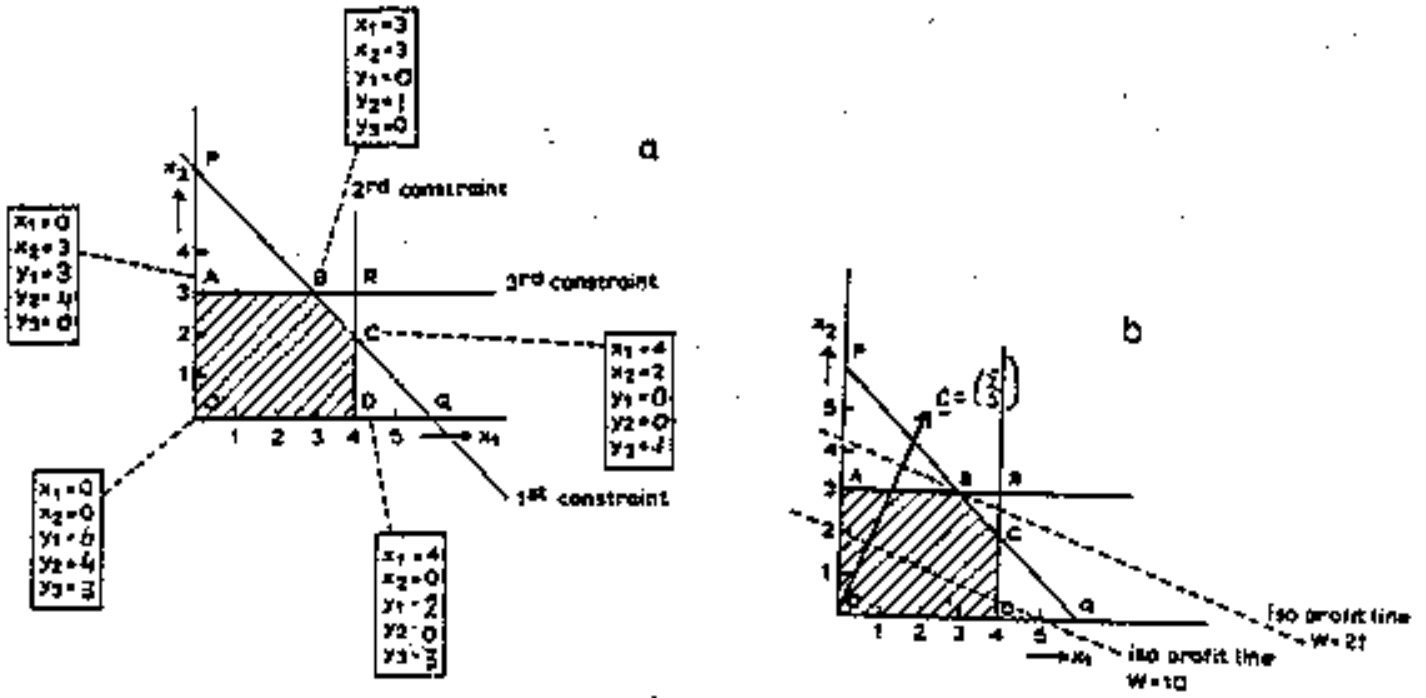
Figure 3.1 Graphic representation of a linear programming model. The solution space (shaded) and iso-profit lines (dashed lines) Source: Rossing, 1989.
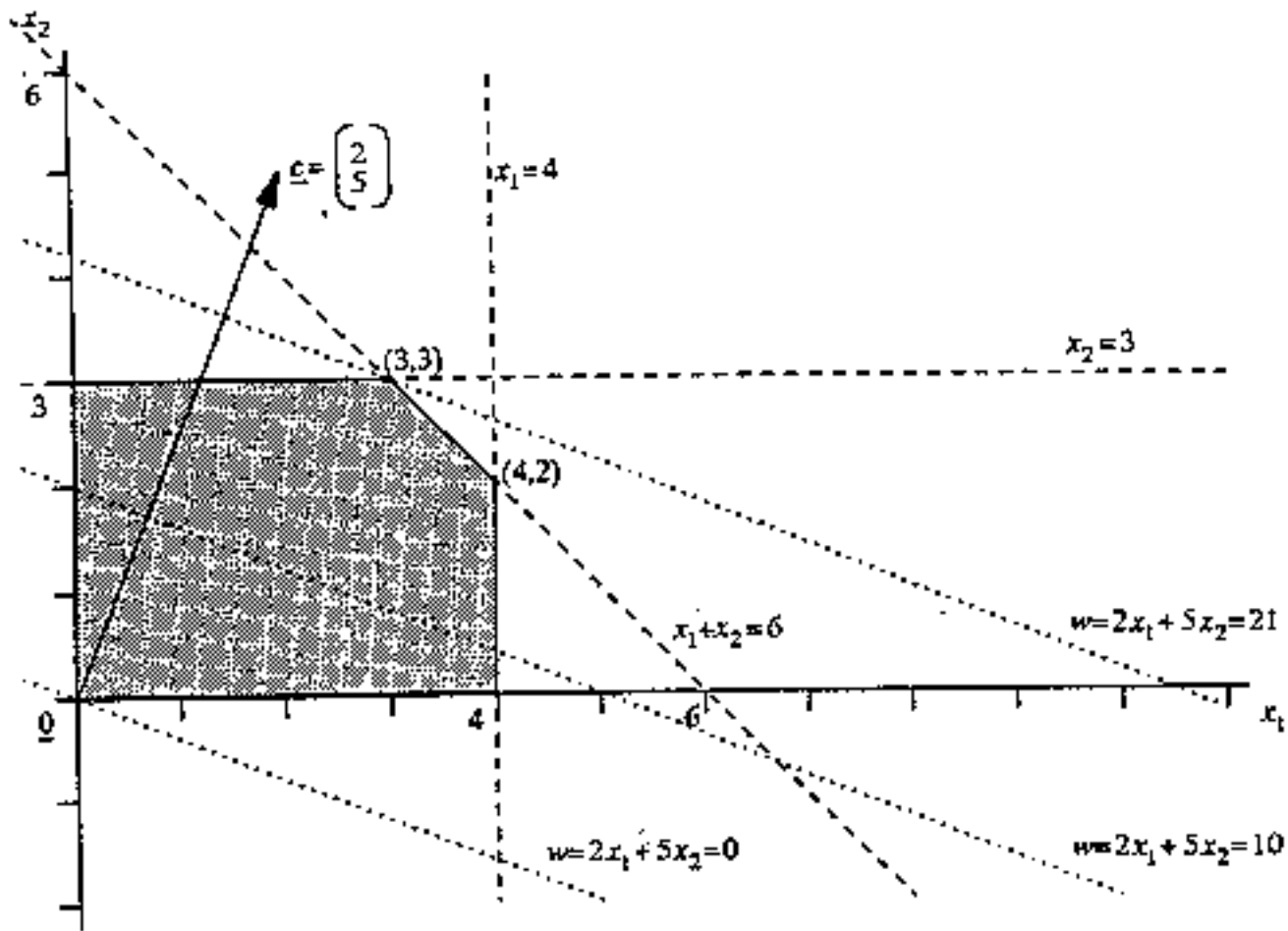
(a): Unique solution
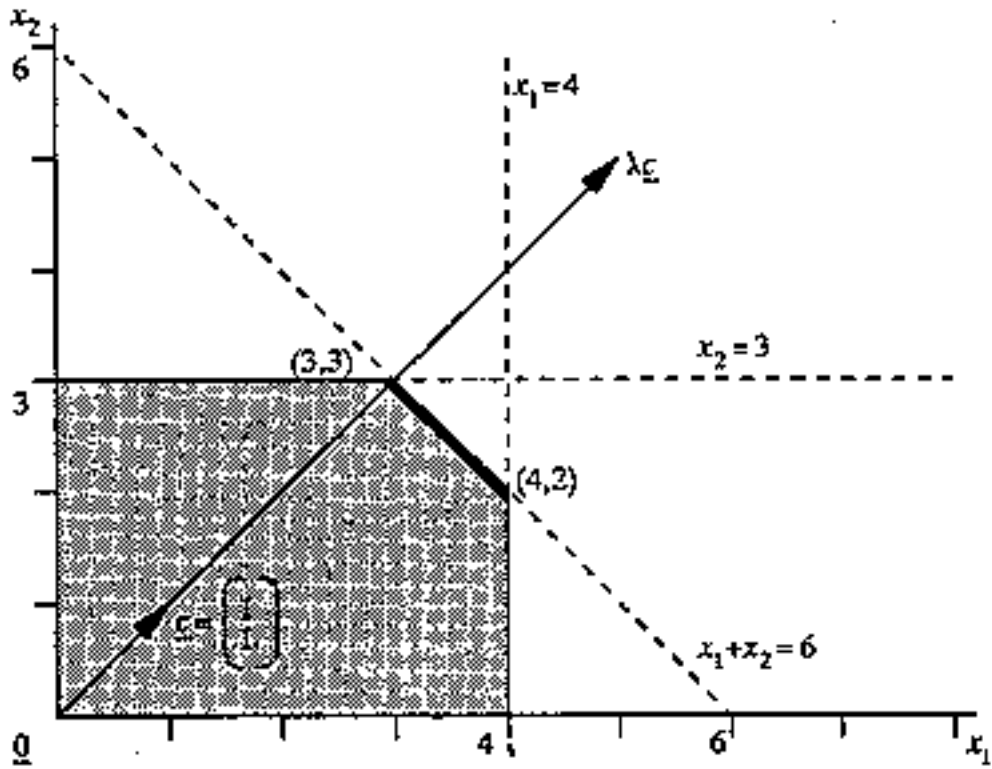
(b): Alternative solutions
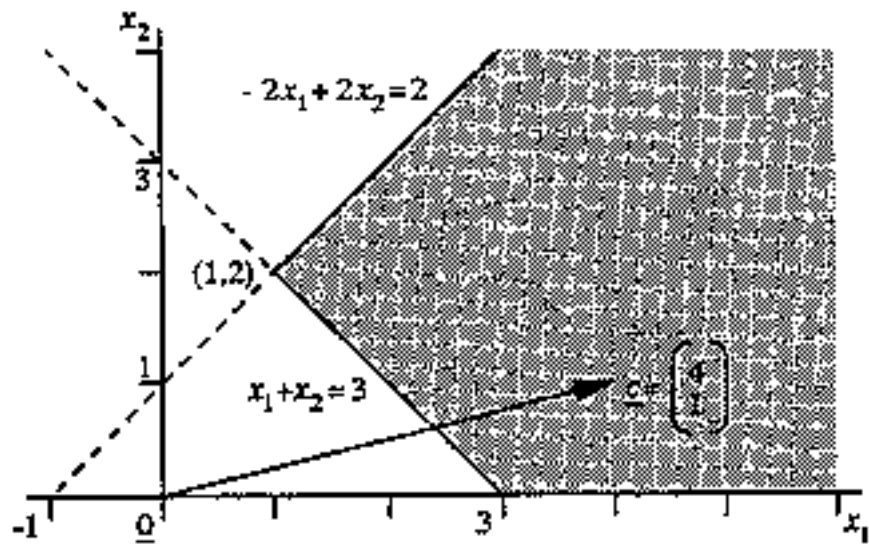
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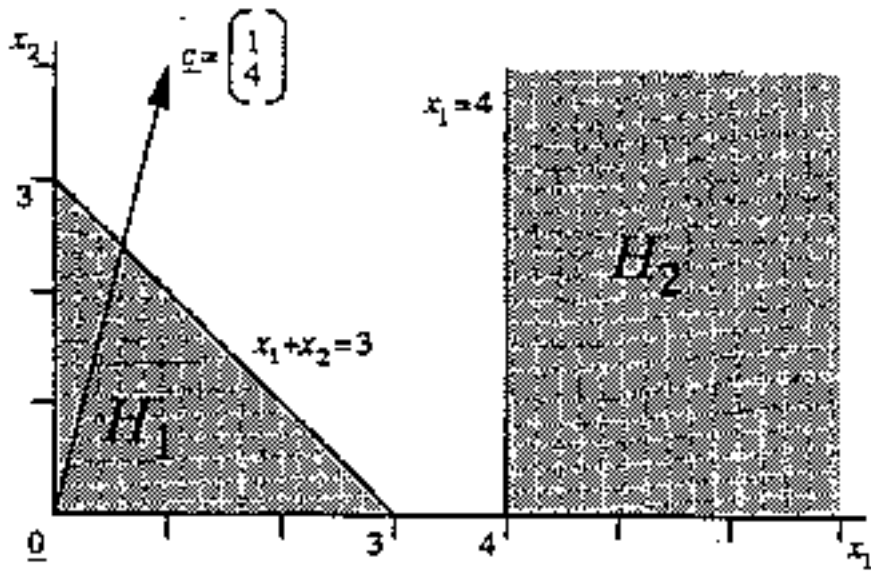
(d): No feasible solution
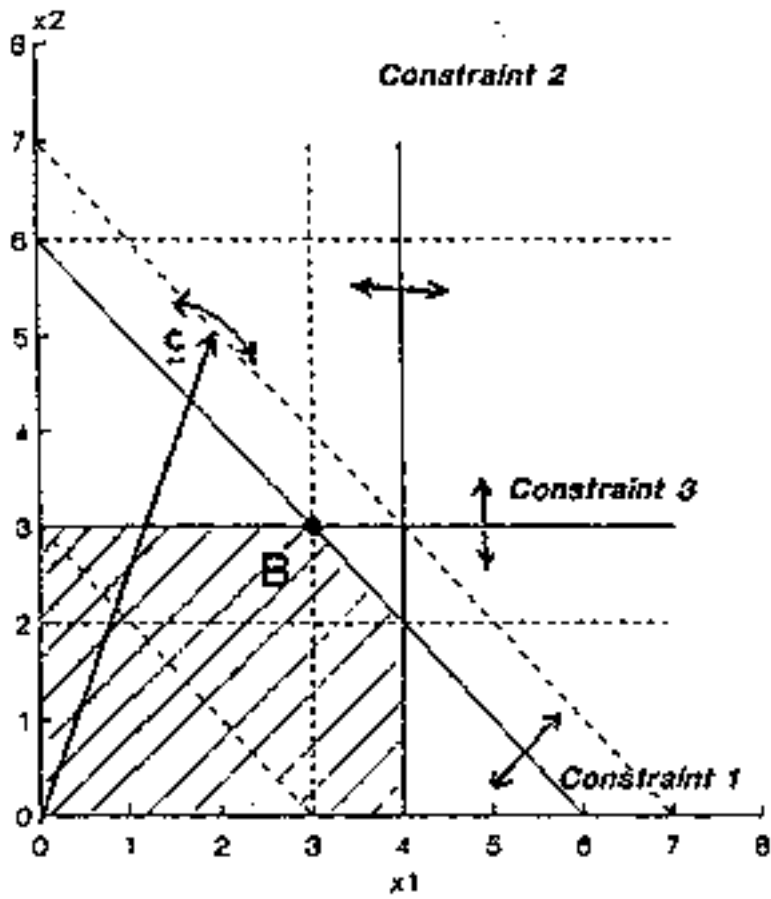
Figure 3.3   Sensitivity analysis of the optimal solution.
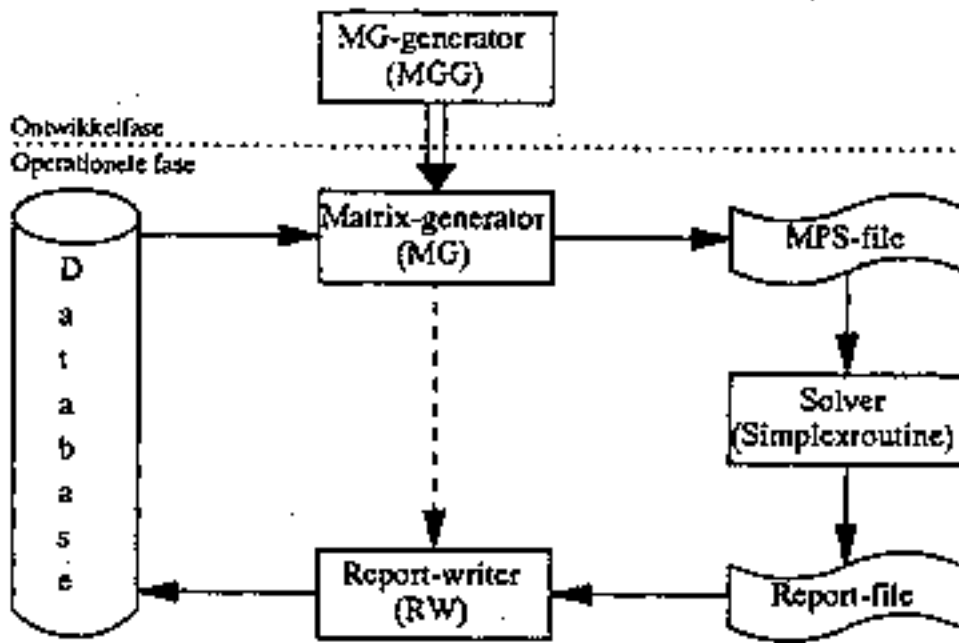
Figure 3.4   LP software. Source: Hendriks & Van Beek (1991).
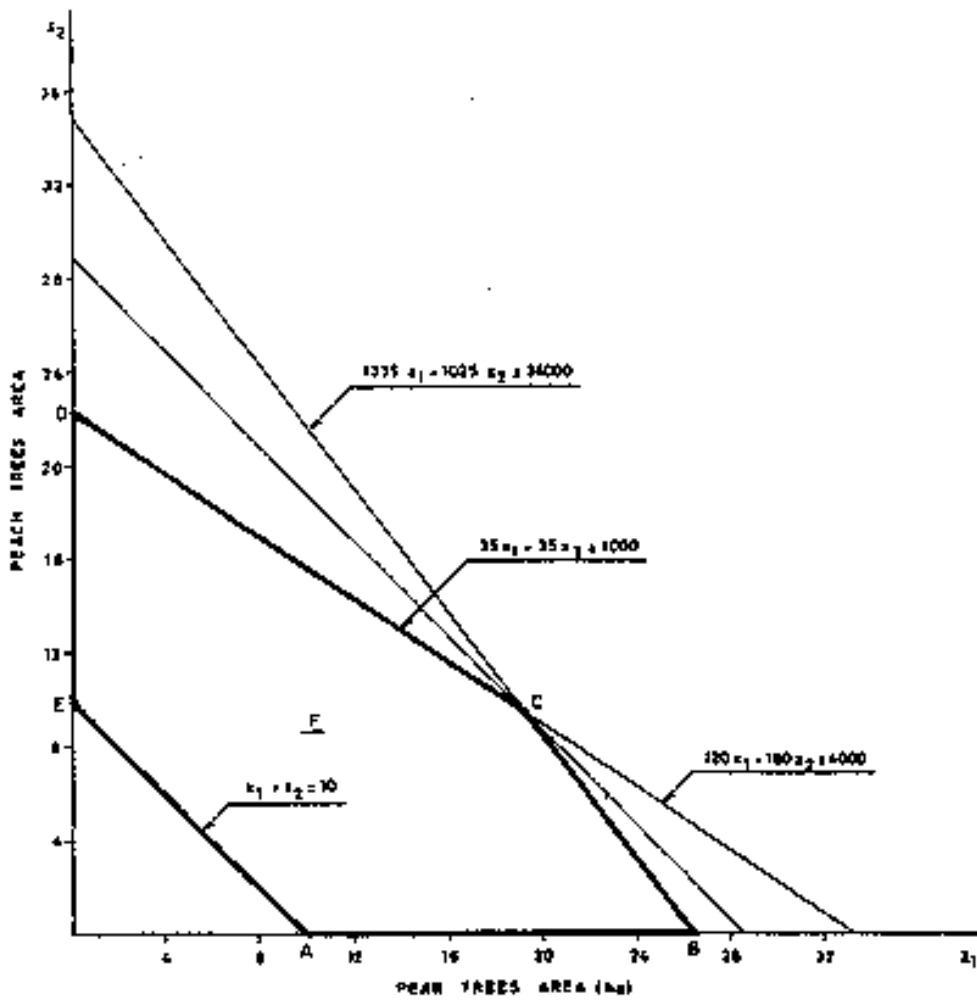
Figure 3.5 Feasible set in the decision variable space. Source: Romero & Rehman, 1989.
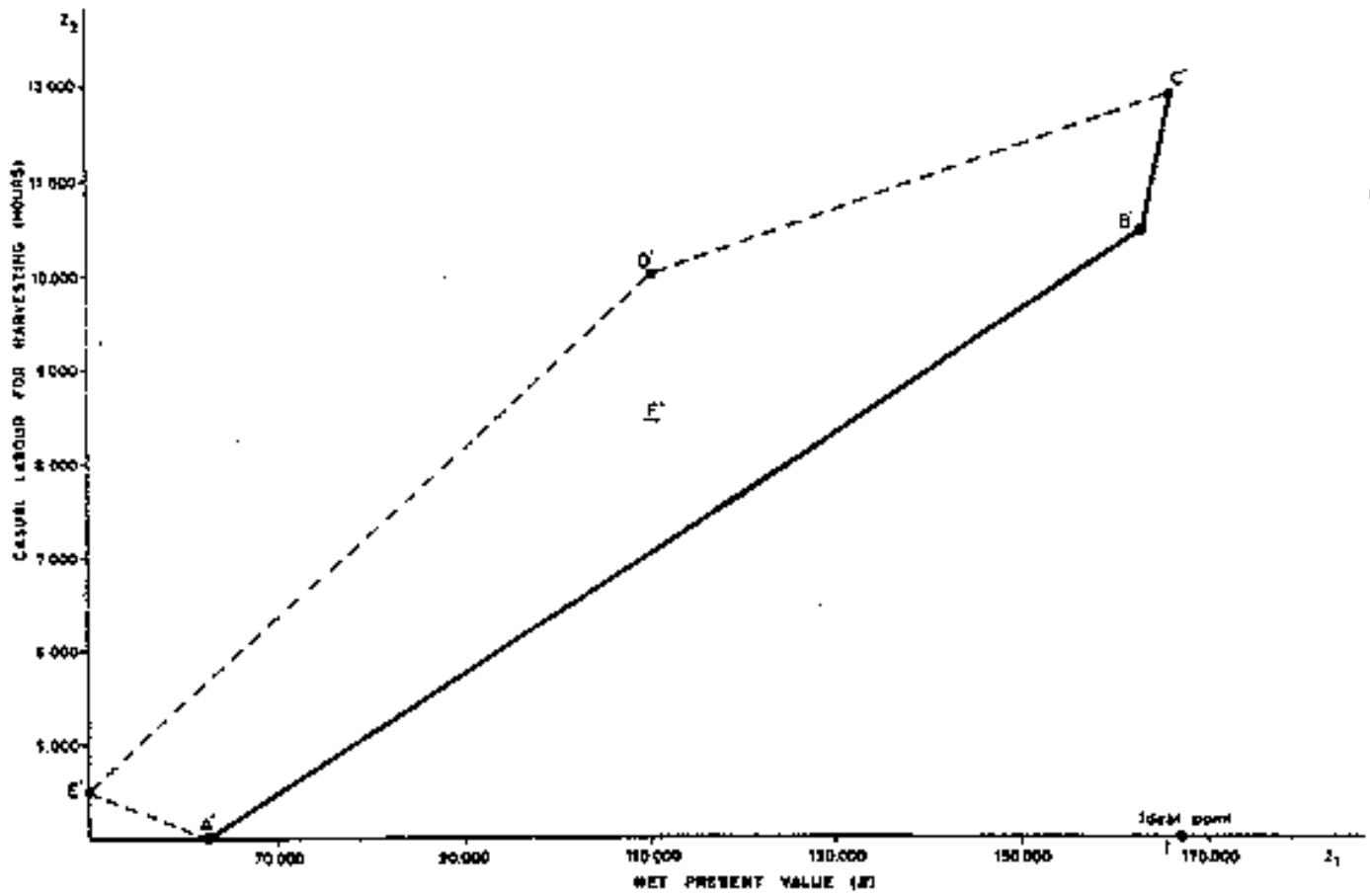
Figure 3.6 Image of the feasible set in the objective space. Source: Romero & Rehman, 1989.

http://library.wur.nl/way/catalogue/documents/Sahel/RAP31/R031_3_7.GIF
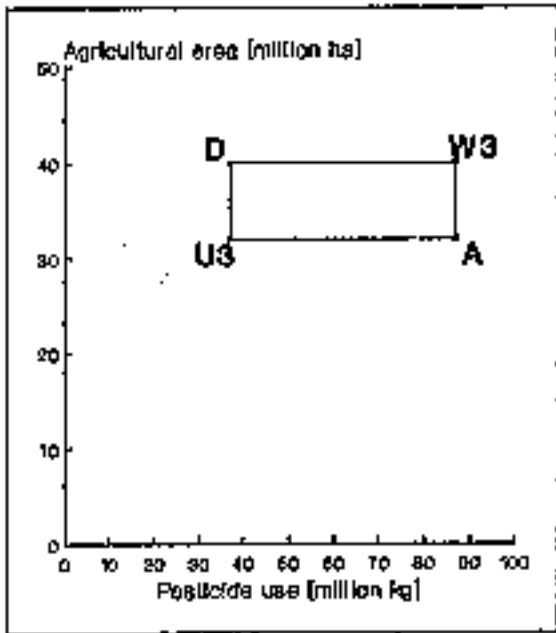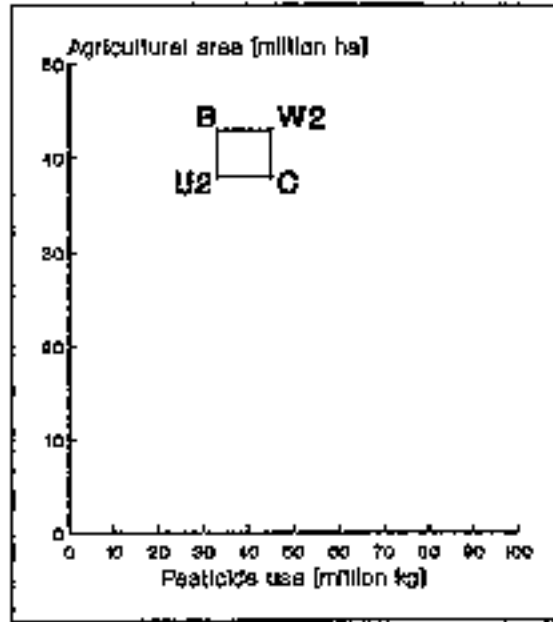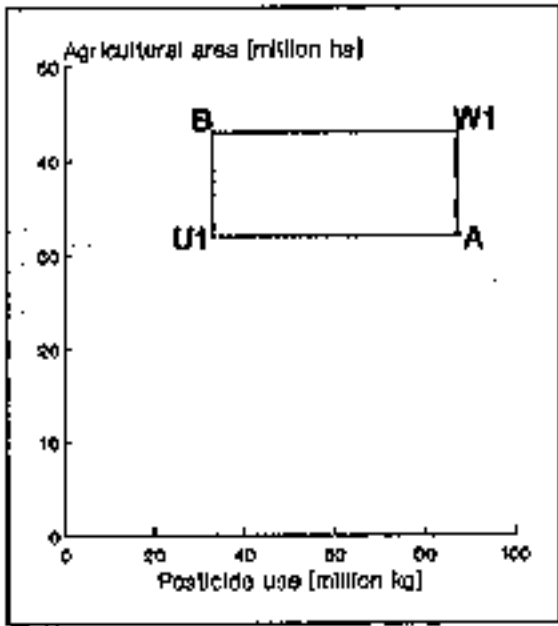
Figure 3.7   Graphical illustration of IMGLP procedure with two objective functions (i) minimization of the use of pesticides and (ii) minimization of the agricultural area. Source: Spharim et al. (1992).

Figure 4.1 The various aspects of the methodology for explorative land use studies.
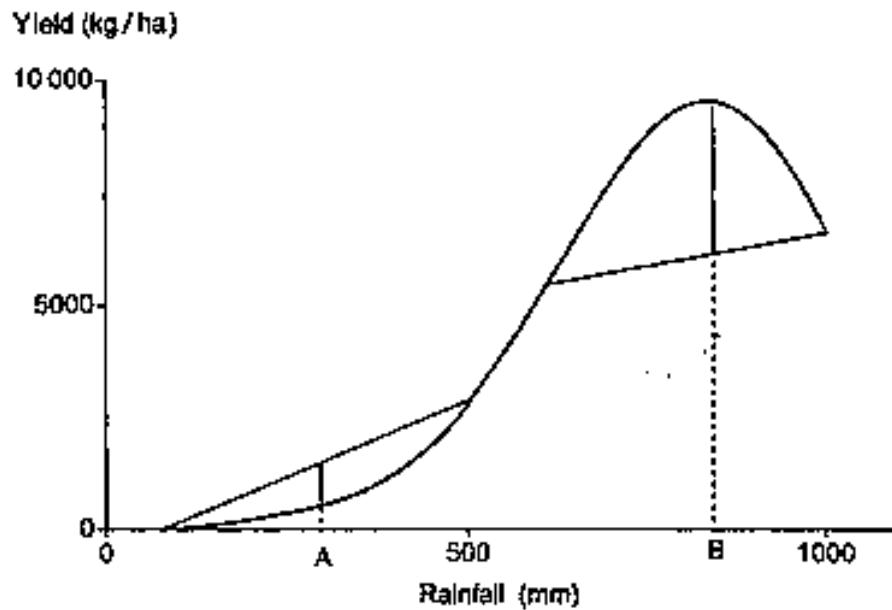
Yield (kg/ha)

Figure 4.2 The influence of averaging rainfall on its calculated yield response. The yield
is underestimated by averaging in the lower rainfall region (A) and
overestimated in the higher rainfall region (B) (De Wit & Van Keulen, 1987).

Figure 4.3 *Production situation, production levels and associated principal growth factors (Rabbinge et al., 1994b).*
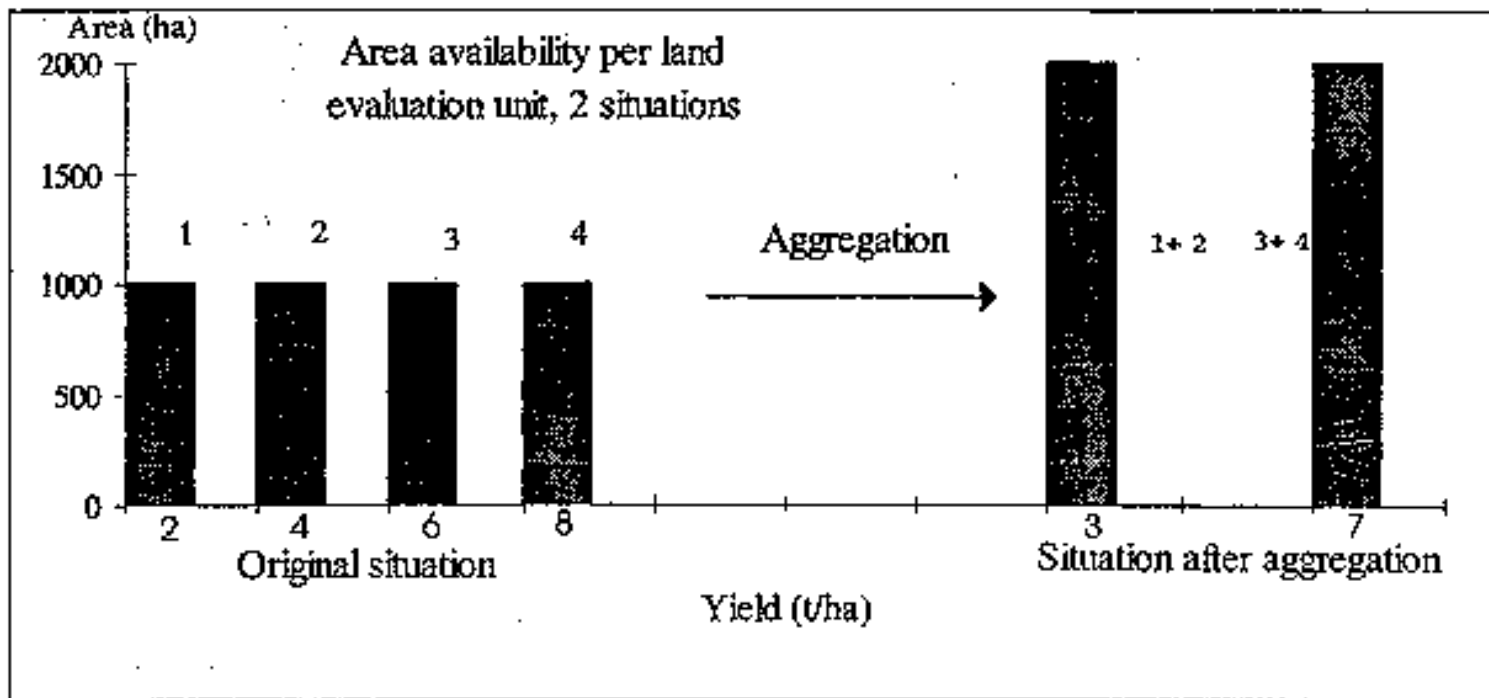
Figure 4.4 The effect of aggregation of four land evaluation units of each 1000 ha to two units of 2000 ha each on the minimum agricultural area required to produce 10000 ton wheat in the region (4000 ha total) (see text).
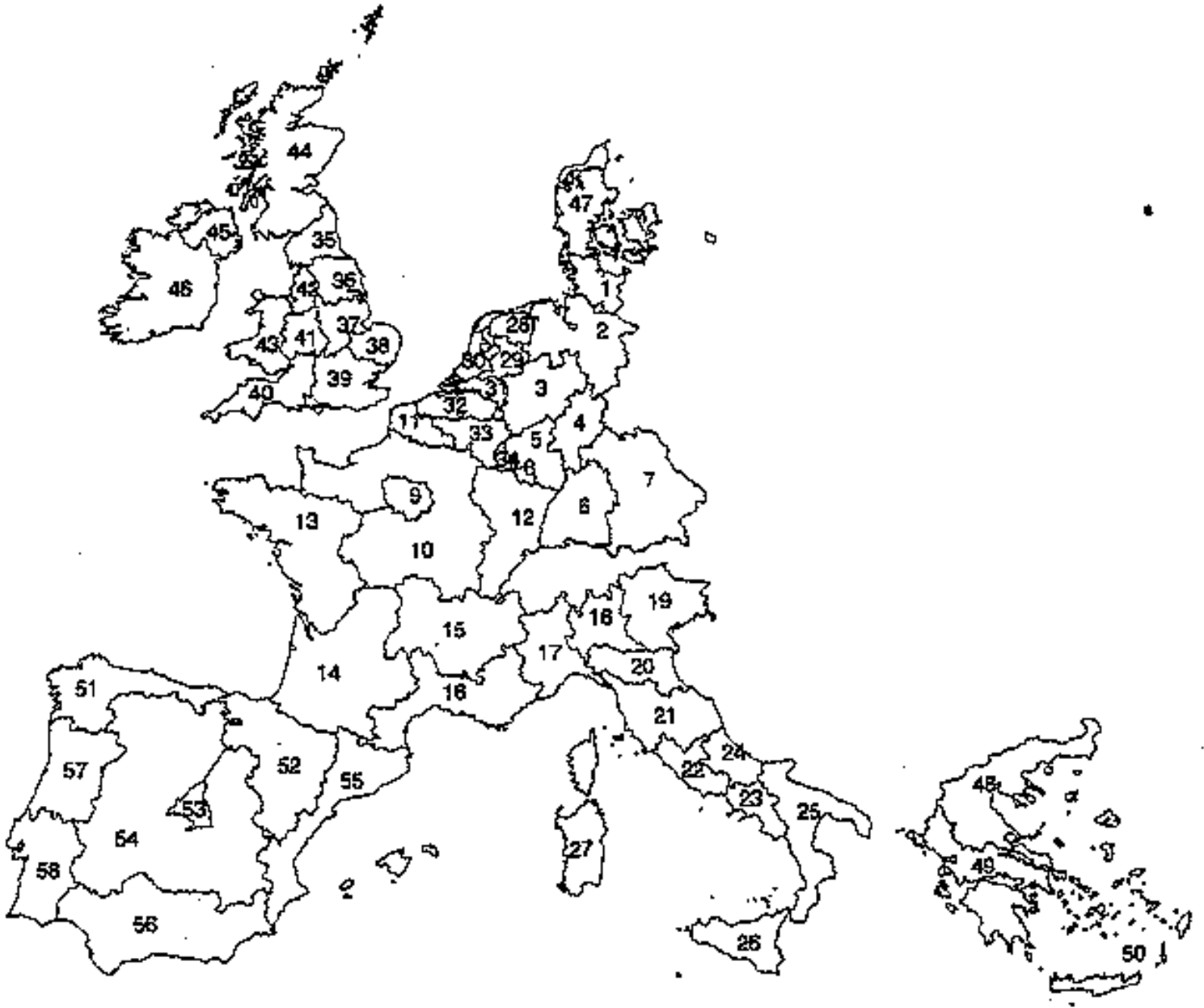
Figure 5.1   The political administrative units at NUTS-1 level in the EC.
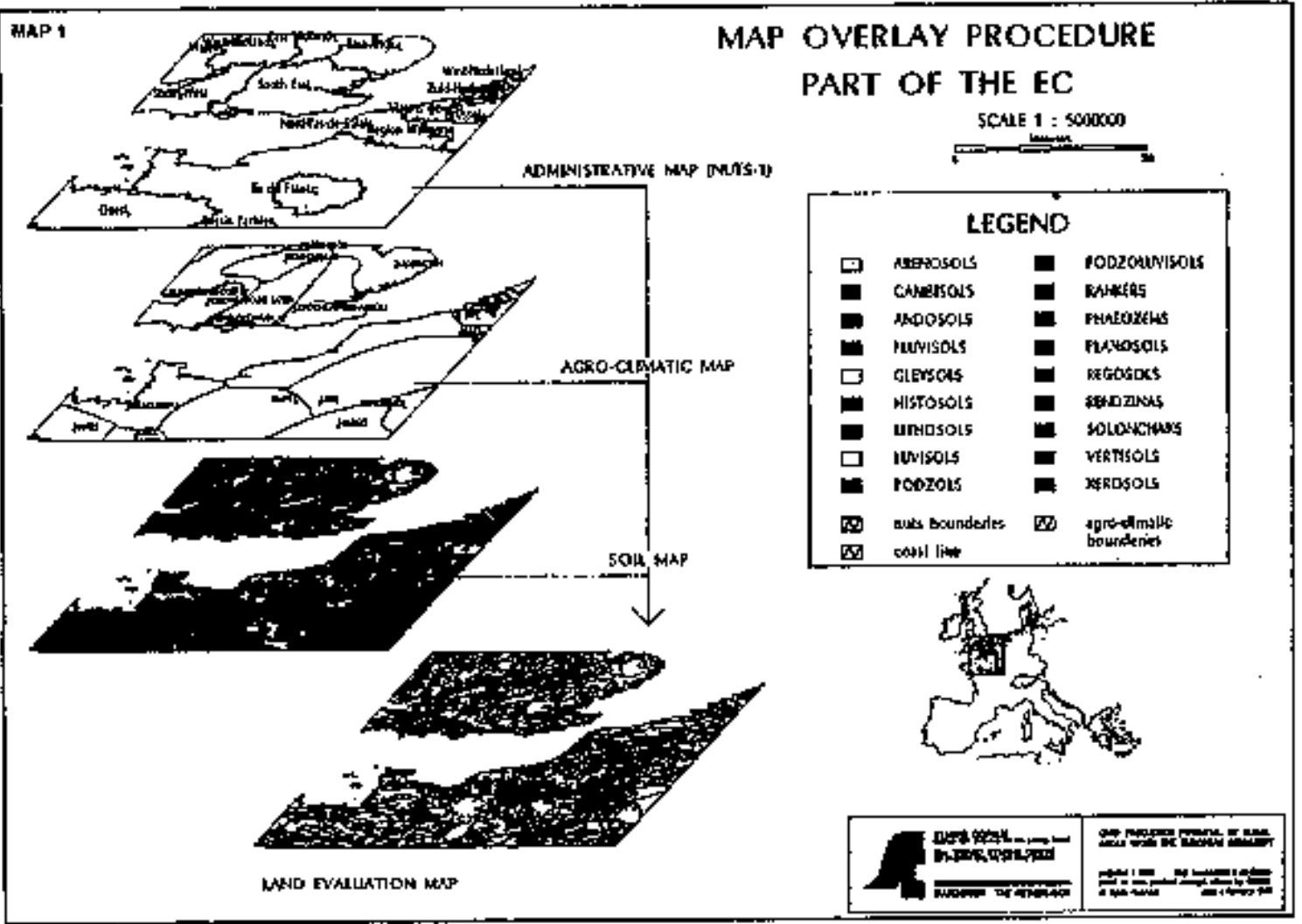
Figure 5.2   Example of an overlay of soil map, agro-climatic map and a map with the
NUTS-1 regions for a part of Europe.
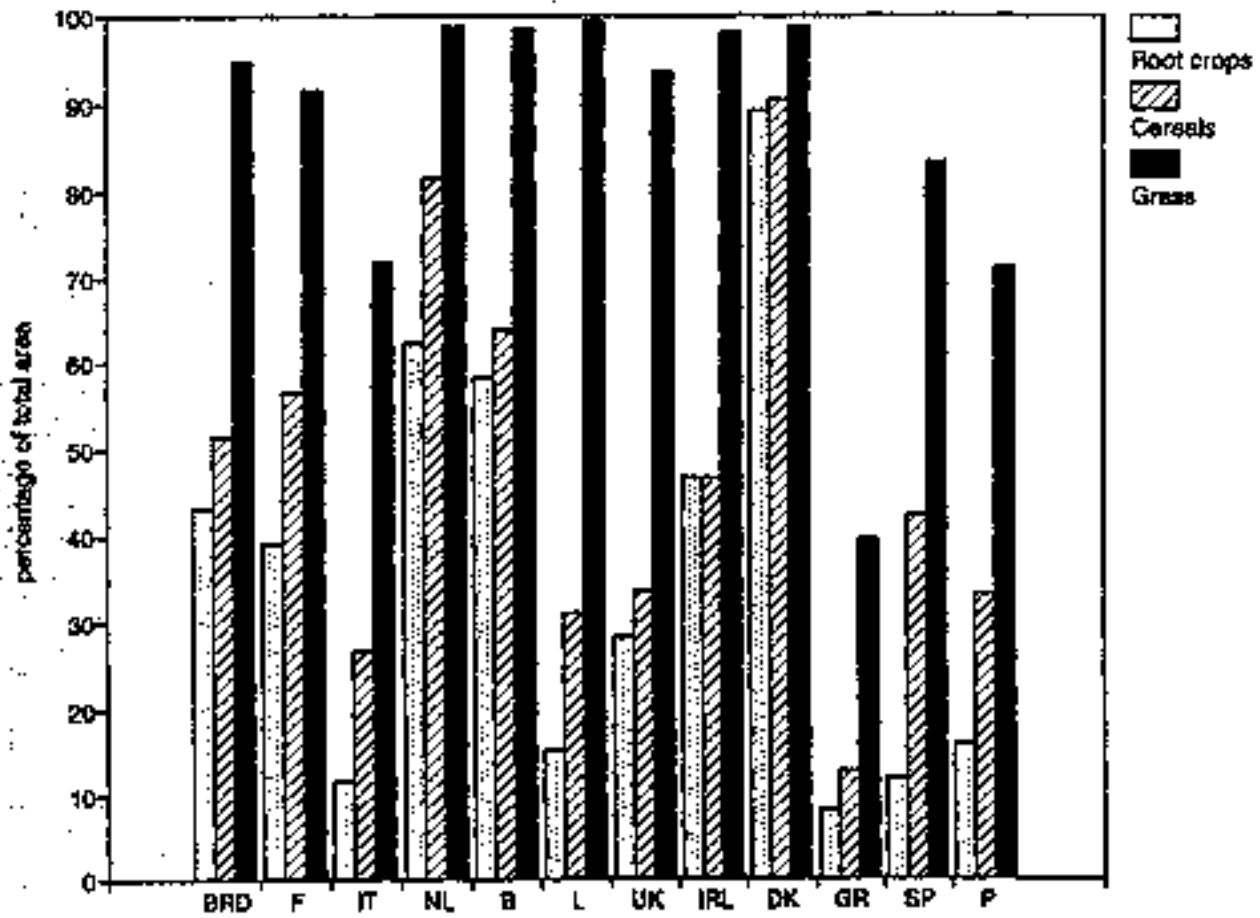
Figure 5.3 Percentage of agricultural area suitable for root crops, cereals and grass.
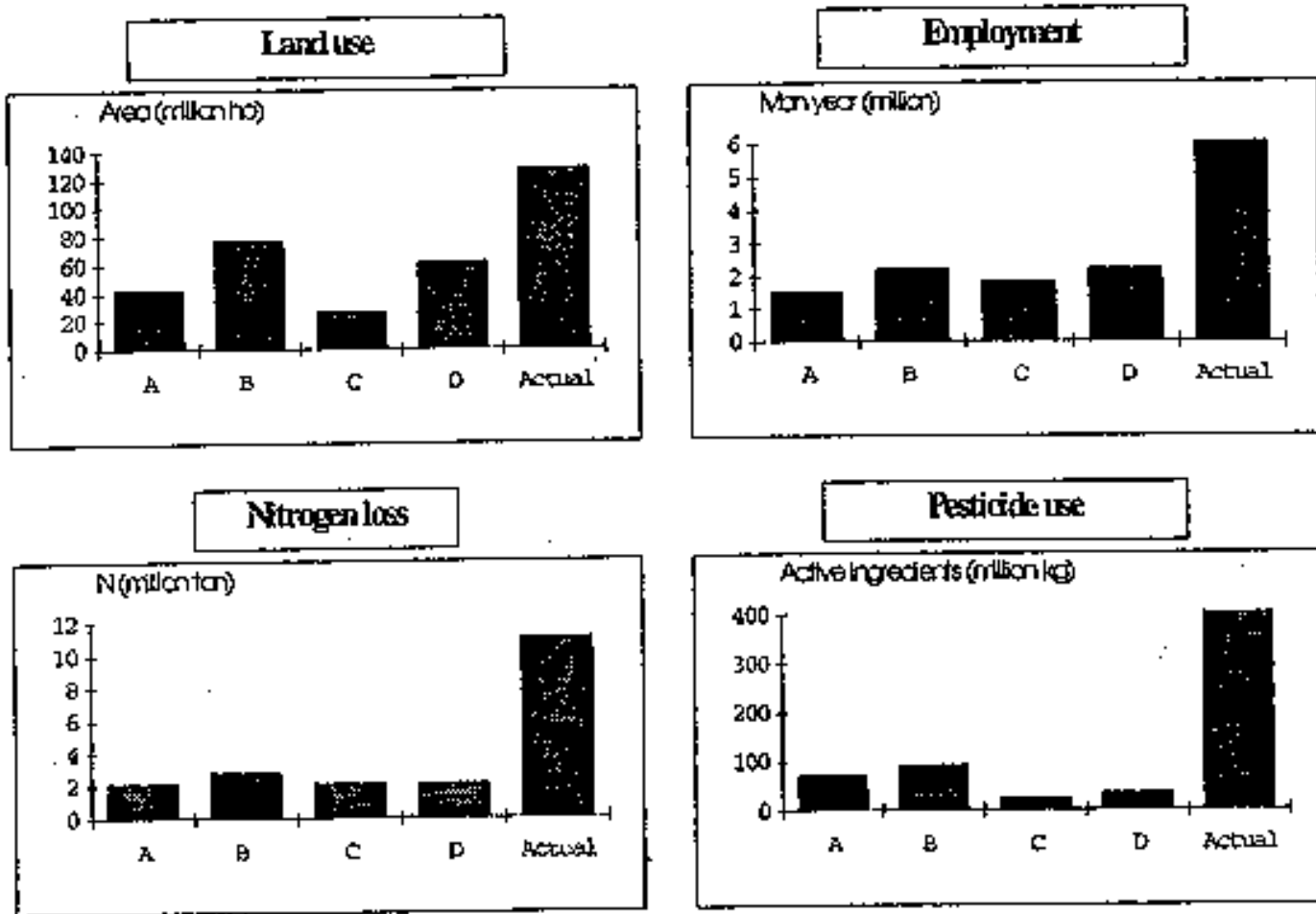
Figure 5.4 Agricultural land use, employment, nitrogen loss and pesticide use in the four scenarios and in the current situation (Van Latesteijn & Rabbinge, 1992).
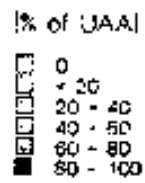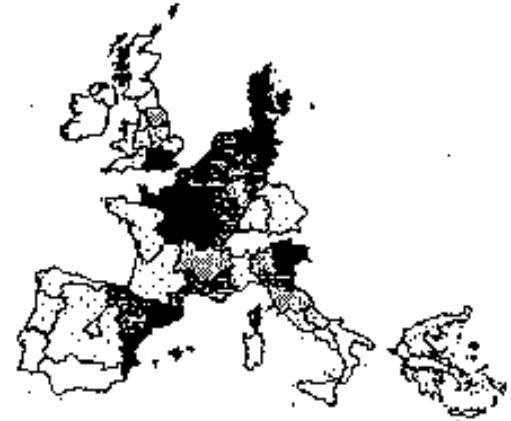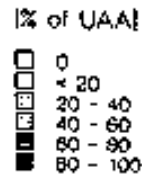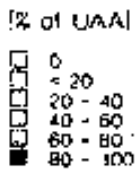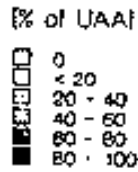
Figure 5.5   The allocation of cereal production (a, b) and grass production (c, d) in
Scenarios A (a, c) and B (b, d). The shading indicates the percentage of the
suitable area per region that is actually used. Rabbinge & Van Latesteijn,
(1992).
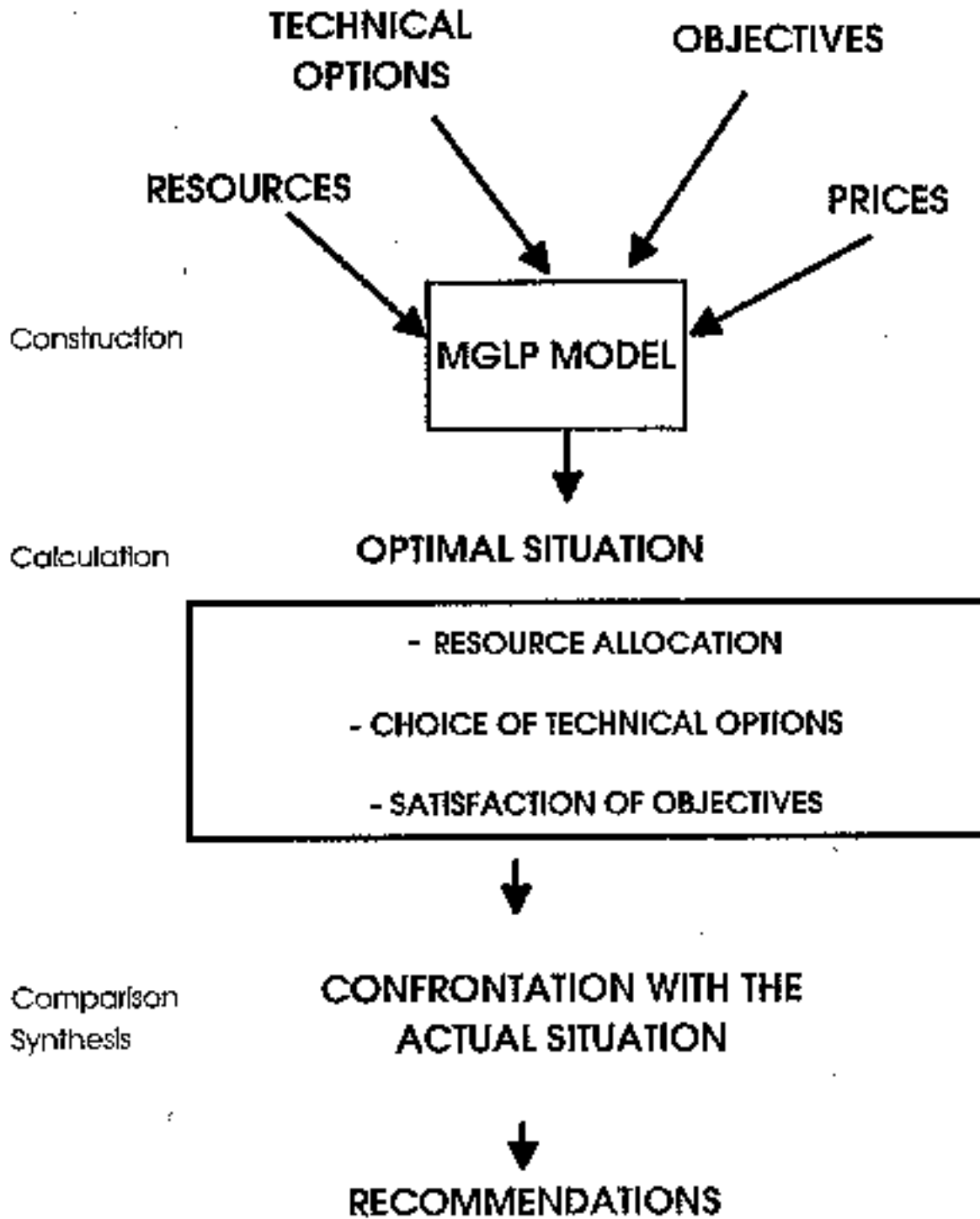
Figure 6.1 Phases in MGLP modeling.
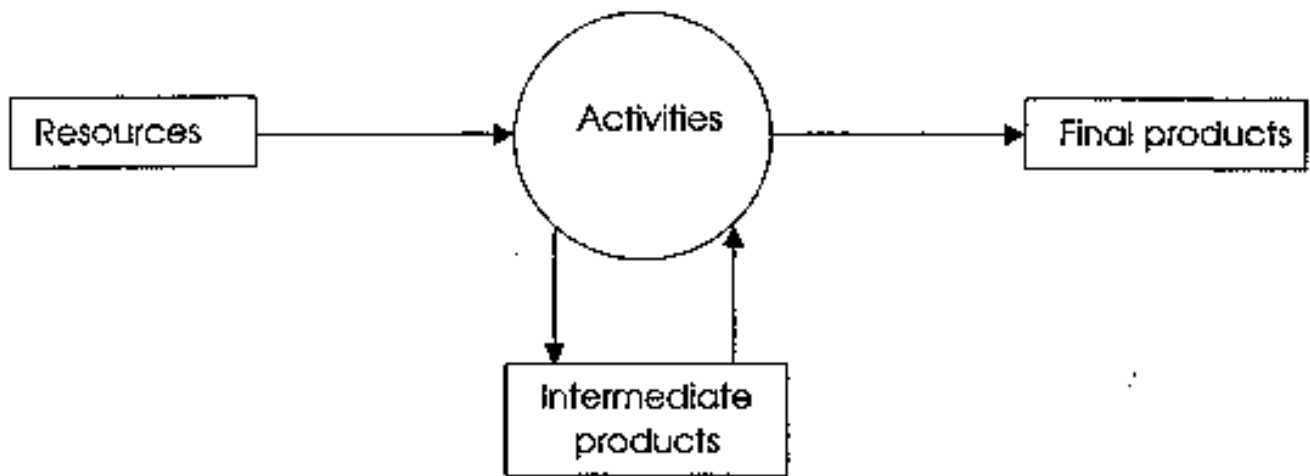
Figure 6.2   The production process of the activities.
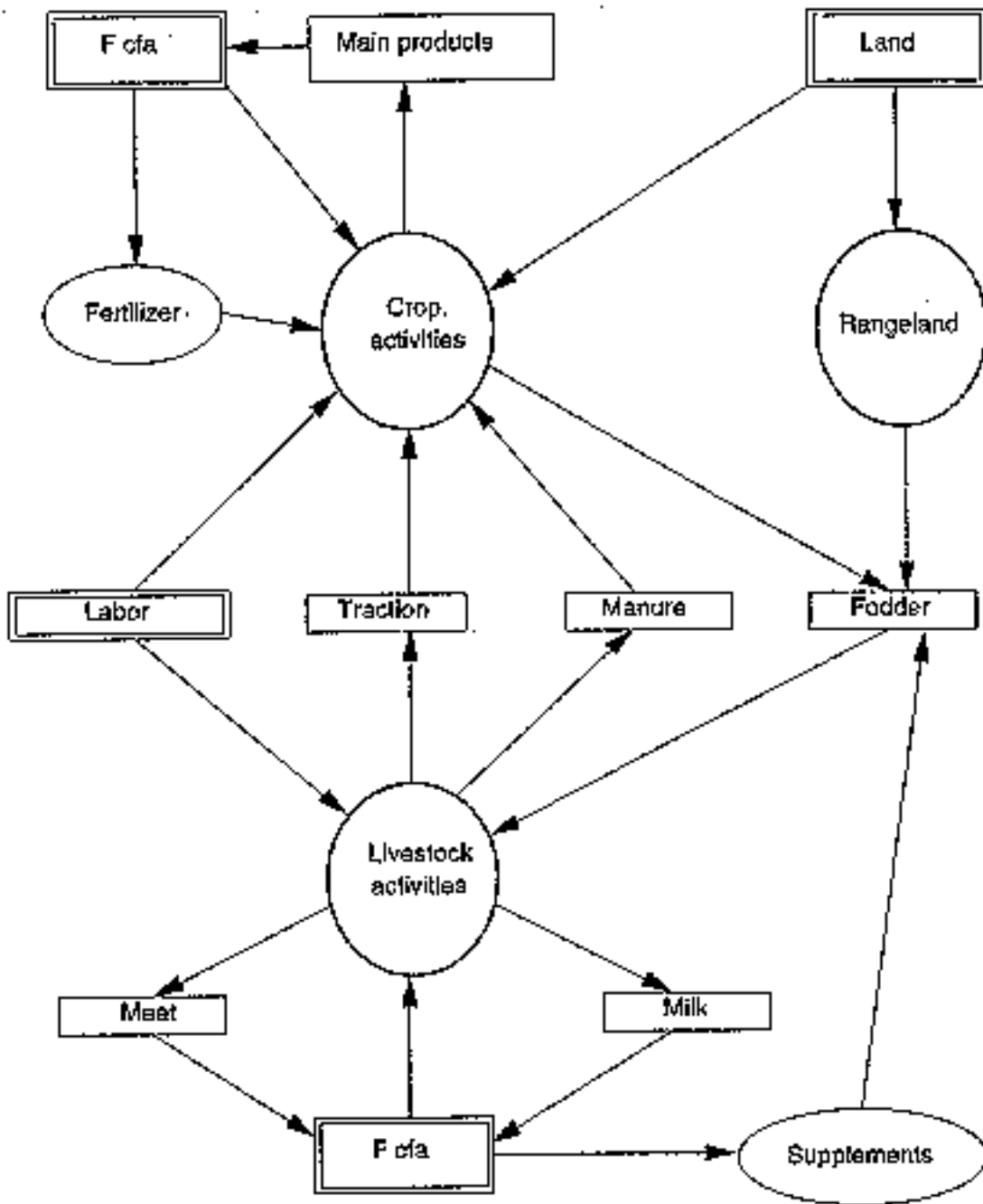
Circle: activities
Double rectangle : resources
Single rectangle: final or intermediate product

Figure 6.3 Relational diagram of the main components of the MGLP model.
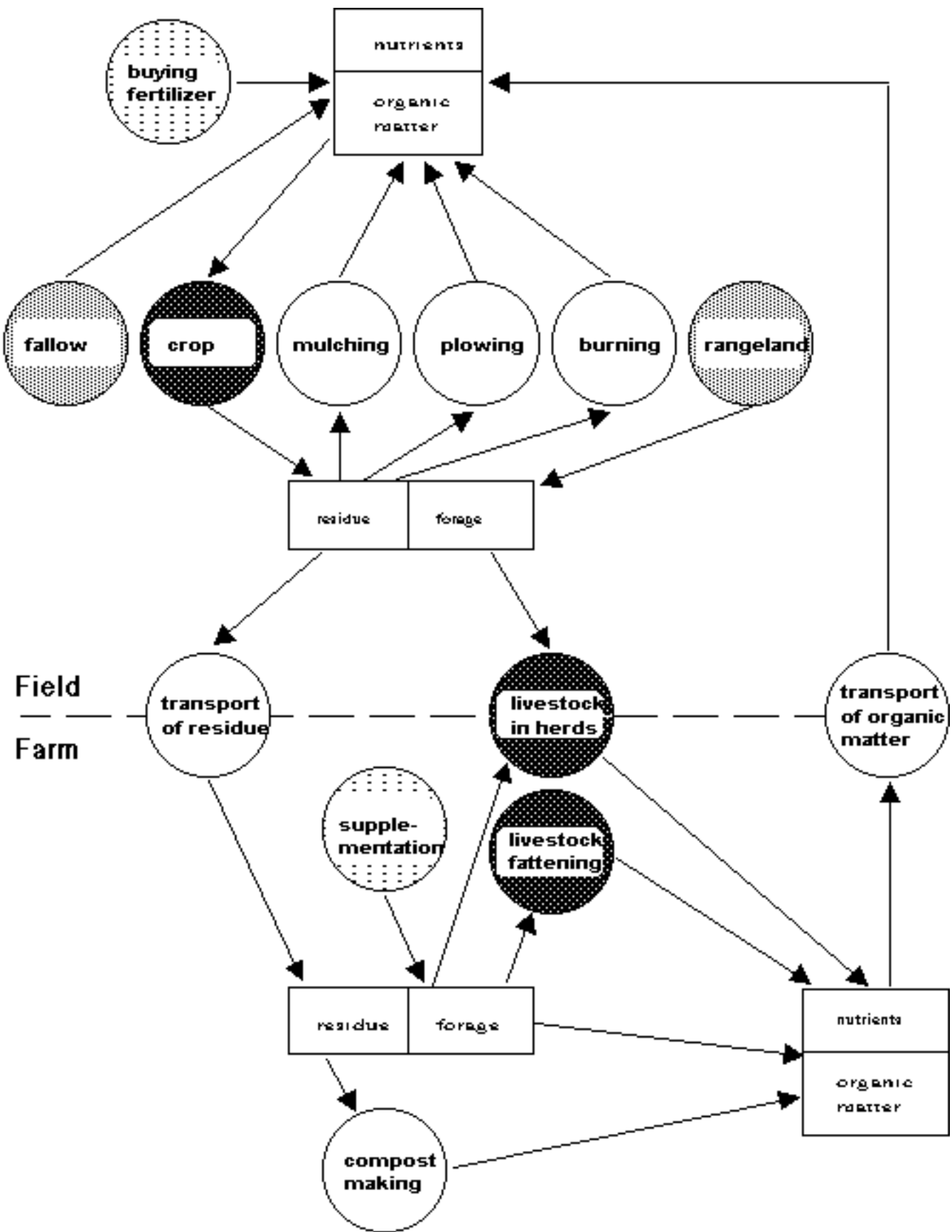
Figure 6.6 Diagramme relationnel des activités de production et de leurs sous-produits.
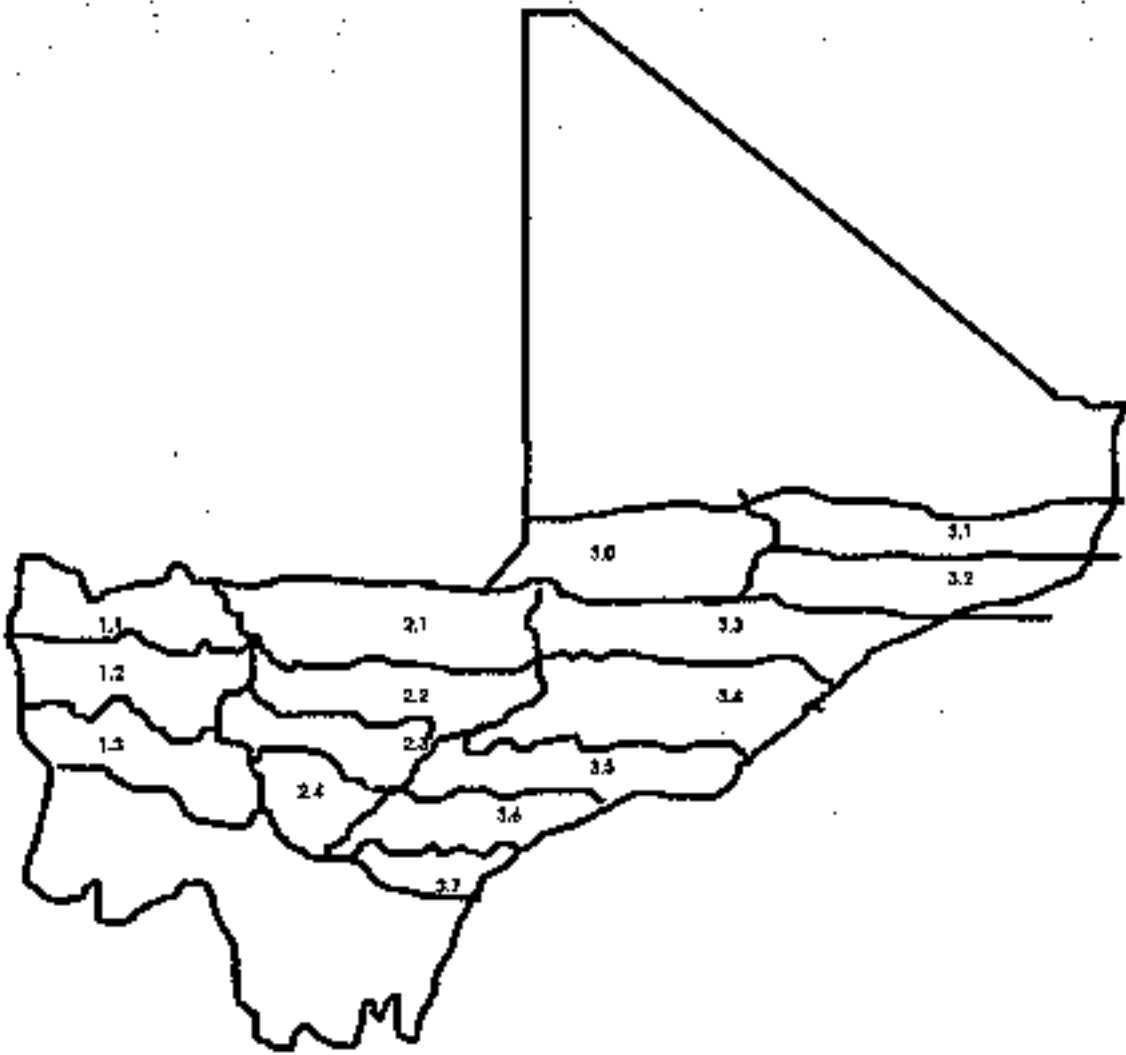
Figure 6.4 Zonation of the sudano sahelian zone by the PSS project.
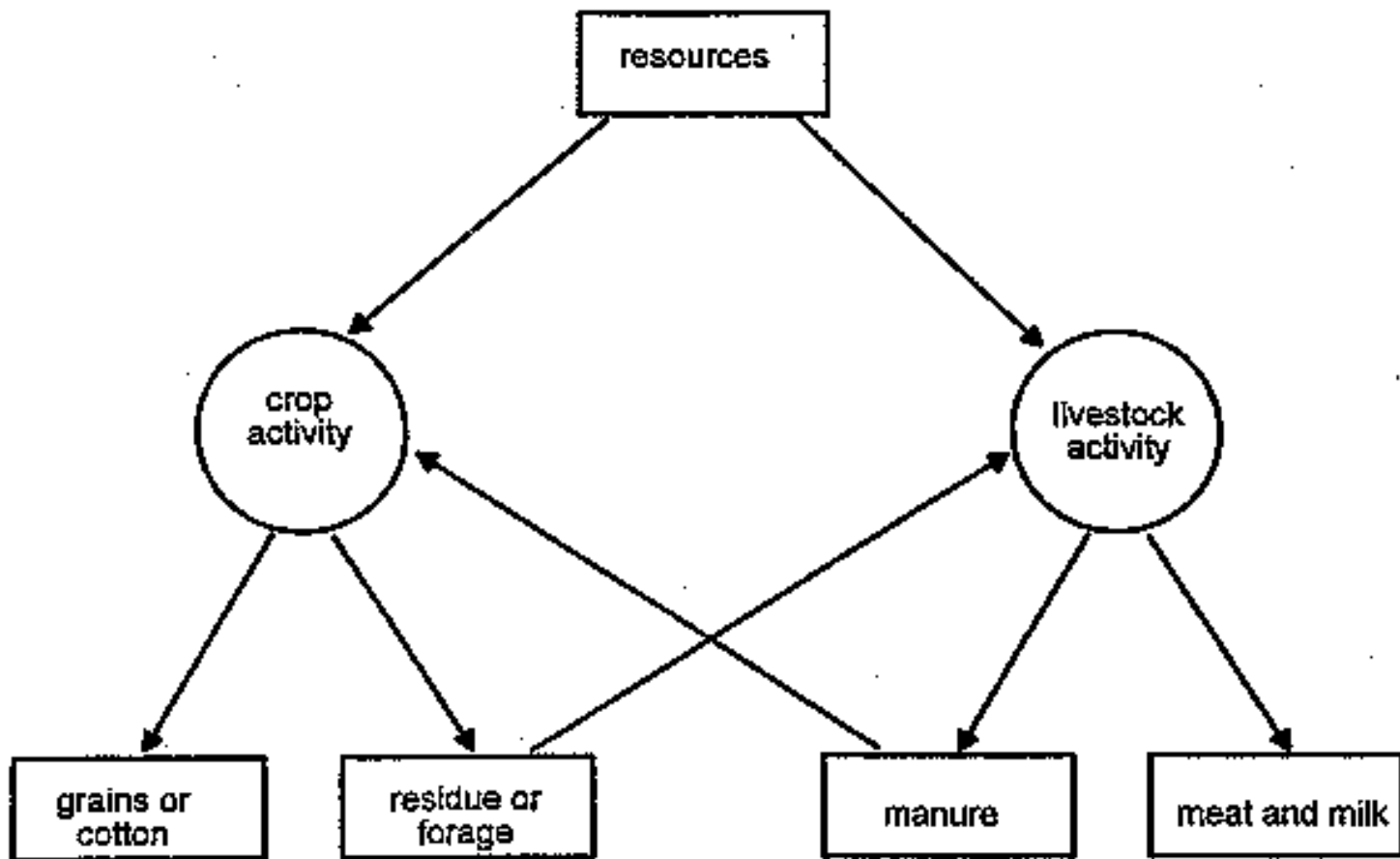
Figure 6.5 *Relational diagram of crop and livestock activities, presenting their competition for resources and their complementarity through the use of the other's by-products.*
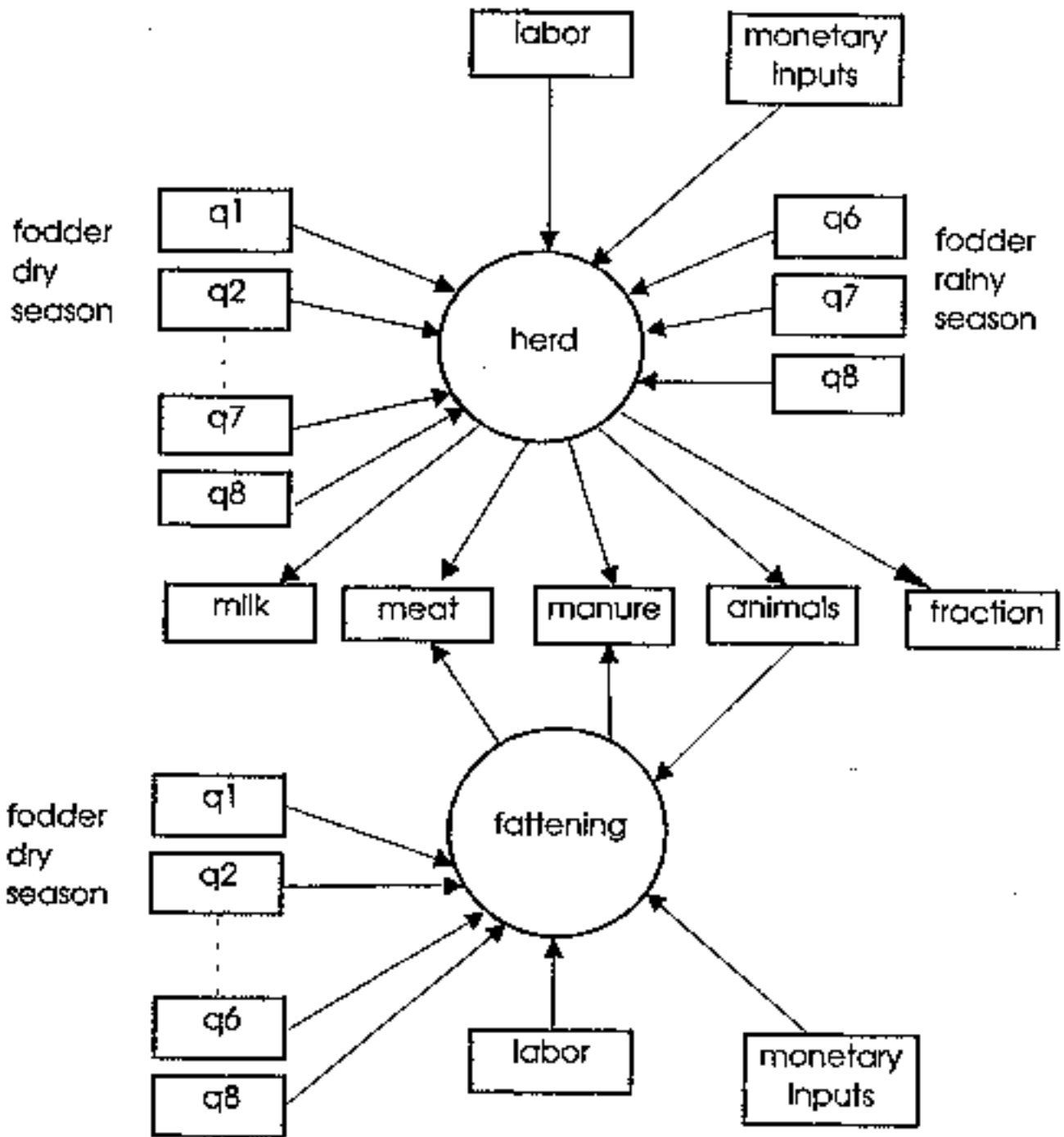
Figure 6.7 Inputs and outputs of livestock activities.