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Assessing farmer behaviour as affected by policy and technological innovations: bio-economic farm models

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SEAMLESS integrated project aims at developing an integrated framework that allows ex-ante assessment of agricultural and environmental policies and technological innovations. The framework will have multi-scale capabilities ranging from field and farm to the EU25 and globe; it will be generic, modular and open and using state-of-the art software. The project is carried out by a consortium of 30 partners, led by Wageningen University (NL).

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Executive summary

A Bio-Economic Farm Model (BEFM) is defined as a model that links mathematical programming model formulations of farmers' resource management decisions, to biophysical models that describe production processes and the conditions of natural resources for the farm scale. Two important distinctions are made: 1. between positive and normative and 2. between empirical and mechanistic BEFMs. Positive approaches are approaches that try to model the actual behaviour of the farmer, while normative approaches are approaches that try to find the optimal solution to the problem of resource management and allocation. In this report the focus will solely be on mechanistic BEFMs. Mechanistic BEFMs are constructed according to an image the researcher has of the processes occurring in reality, while an empirical model translates the inputs into outputs on the basis of location specific data without explaining or formulating the underlying processes.

In this report a literature review has been carried out and about 180 references were collected and read, of which 70 ended up in this report. The mechanistic BEFMs are discussed on a number of aspects: suitability to policy evaluation and assessment of technological innovations, farmer decision making, the incorporation of time, production activities, comprehensiveness (how complete is the BEFM?), model evaluation (verifying the quality and robustness of the results of BEFMs) and transferability of the mechanistic BEFM to other locations. Finally, some useful complementarities to mechanistic BEFMs using other modelling approaches are discussed.

Specific part

1 Introduction

'Like a spouse, an FSR model takes some time to identify, takes even longer to comprehend, is surely complex but often instructive, and not exhaustively or exclusively, if treated with cautious respect, can serve intentions admirable.' (Anderson et al., 1985)

1.1 SEAMLESS

SEAMLESS is a research project commissioned by the European Commission which involves 31 universities, research institutes and small enterprises and is coordinated by Wageningen University. The project will 'develop an integrated and operational framework (SEAMLESS-IF), which integrates approaches from economic, environmental and social sciences to enable assessment of the impact of policy and behavioural changes and innovations in agriculture and agro forestry' (SEAMLESS, 2004). Furthermore, 'SEAMLESS-IF aims at rapidly becoming essential for integrated assessment of agricultural systems in the context of agro-ecological innovations, rural development, sustainability, agricultural policy reform, EU enlargement and world trade liberalization' (SEAMLESS, 2004).

SEAMLESS consists of 8 Work Packages. Work Package 3 'quantitative tools and models' aims 'to develop quantitative procedures and tools needed within SEAMLESS for ex-ante impact assessment of policy measures in terms of sustainability and multifunctionality at multiple scales' (SEAMLESS, 2004). To dive further into the SEAMLESS project, Task 3.3 of Work Package 3 consists of the development of a Farm Systems Simulator (FSSIM). FSSIM models farmer decision making on the farm level determined by certain production technologies and constrained by biophysical and socio-economic constraints with the aim to evaluate alternative policies and technological innovations. The main components of FSSIM are:

- An objective function that represents farmer's behaviour and goals in particular concerning risk.
- Integration takes place between the bio-physical processes and economic decisions.

One generic template for FSSIM for the entire EU will be constructed. Within this generic template different approaches can be implemented to deal with climate variability, different farming sectors and different socio-economic conditions across the EU.

Within FSSIM the agricultural activities will be coupled to the economic performance of the farm, on the basis of which the farmer bases his decision making. The farmer is assumed to 'maximize a utility function based on expected profit and risk, given relative prices, resource endowments, resource constraints, environmental regulations, payments and taxes' (SEAMLESS, 2004).

1.2 Bio Economic Farm Models

FSSIM will be a Bio-Economic Farm Model (BEFM). A Bio-Economic Model is defined as a model that links mathematical programming model formulations of farmers' resource management decisions, to biophysical models that describe production processes and the conditions of natural resources (Barbier and Bergeron, 1999). A Bio-Economic Farm Model is a bio-economic model for the farm scale; bio-economic models can also be made at regional, sector, watershed, national or continental scales.

1.2.1 Positive versus Normative approaches

Different approaches exist for modelling at farm level. BEFMs are normally subdivided in the Positive and Normative approaches (Flichman, 2004; Oude Lansink, 2004). Positive approaches are defined by Flichman and Jacquet (2003) as approaches that try to model the actual behaviour of the farmer, while normative approaches are approaches that try to find the optimal solution to the problem of resource management and allocation (Flichman and Jacquet, 2003) or in other words, resource allocation is strictly based on 'best technical means' (De Wit, 1992). Positive approaches are descriptive, describing what happens in reality and trying to understand it (Louhichi et al., 1999).

The distinction between normative and positive approaches will come to the fore during the discussion of mechanistic models at several occasions. A choice between the two approaches is not made as the aim of SEAMLESS is essentially an aim in line with both the positive approach (the model should model actual farmer behaviour), but also with the normative approach (the model should offer efficient and effective policy options). The challenge will be to come as close as possible to actual farmer behaviour, to make the model as positive as possible, while at the same time for some elements a more normative approach will be needed. For example, also alternative technologies and long time scales will be incorporated, which is more common in normative approaches.

1.2.2 Mechanistic versus empirical models

The distinction positive/normative tells something about what the model is being used for. Another distinction can be made according to the type of model: empirical versus mechanistic models. Empirical models are constructed from the data that are incorporated in them, while mechanistic models are build on a certain image the researcher has of the processes occurring in reality (Pandey and Hardaker, 1995). In other words, empirical models try to find relationships in the observed data that are not known *ex ante*, while a mechanistic model is built on already existing theory and knowledge (Austin et al., 1998). Empirical models are used for the description or explanation of the current situation (Ruben et al., 1998). With a mechanistic model the researcher verifies if his[1] understanding of reality is correct, and if so he tries to explain how reality functions (Pandey and Hardaker, 1995). Empirical models are more suited for positive approaches, while mechanistic models are more suited for normative approaches. However, this does not mean that a mechanistic model cannot be positive or that an empirical model cannot be normative.

For empirical models econometric modelling is often used, while for mechanistic models mathematical models or optimization models (such as Linear Programming (LP) Models (MGLP, Dynamic LP etc)) are frequently used. Positive Mathematical Programming (PMP) (Howitt, 1995) is a special case of a mechanistic BEFM, as it is built to calibrate exactly on base year data. Econometric models are statistical representations of farm-level systems, often estimated as systems of equations for input demand and output supply (Weersink et al., 2004). The empirical BEFMs have advantages, but major drawbacks as well which make them unsuitable to serve as a basis of FSSIM:

[1] 'his' could equally be 'her,' just as 'he' could equally be 'she,' which should be kept in mind when reading the rest of the report.

- The models require a lot of information: series of consistent and comparable observations are needed, which are often lacking, for example for the environmental effects of agriculture (Pacini, 2003; chp.7). Mechanistic BEFMs are more flexible in their data needs, and can thus more easily be adapted to the data available, as they can function well with small data sets (Howitt, 1995). As SEAMLESS aims to develop a FSSIM, which can be applied throughout Europe, this could impose large data problems.
- In empirical models prediction of future changes is mostly based on extrapolation of historical time-series. Therefore, it is difficult to include alternative technological options (Ruben et al., 1998; Falconer and Hodge, 2000; Flichman and Jacquet, 2003) or predictions of farmers reaction to changes in new policy and regulations (Flichman and Jacquet, 2003). Also, the aim of SEAMLESS is not only to predict, but also to explore (Van Ittersum et al., 1998), which is difficult with methods based on extrapolation (Hengsdijk and van Ittersum, 2002) as these methods are unable to adequately capture technical opportunities and the synergy of agronomic production factors at the basis of the biophysical processes. This is caused by a reliance on past and present performance (Hengsdijk and van Ittersum, 2002).

Advantages of empirical models are:

- An advantage is that provided the information is available the models can be easily aggregated to higher levels (Weersink et al., 2004)
- Empirical models calibrate themselves on data when they are constructed, while mechanistic models need validation.
- Econometric modelling is that variability among farms is captured in far more detail (Pacini, 2003; chp.7), as the econometric models are based on a series of consistent and comparable observations.

However, given the drawbacks and consequent unsuitability of empirical BEFMs for the development of FSSIM, in this report only mechanistic BEFMs will be discussed in depth. Empirical models might be mentioned, but an in depth discussion of these models is not provided. Thus, for FSSIM mechanistic models will be used in a positive approach, while it is more common to use empirical models for positive approaches (PMP is an exception). This poses some interesting questions as to how to do this, as will be encountered further on in the discussion.

1.2.3 Mechanistic Bio-Economic Farm Models: an introduction

Mechanistic models are used for the evaluation of possible changes in land use under different sets of technological and socio-economic conditions (Ruben et al., 1998). This evaluation of possible changes in land use can both be an exploration of land use potential in the long run as well as short- and medium term simulation of adjustment of land use under alternative conditions (Ruben et al., 1998).

Mechanistic Bio-Economic Farm Models (BEFMs) usually consist out of three modules (Ruben et al., 1998):

- An agro-ecological simulation model for agricultural activities that generates a wide range of input-output coefficients based on current and alternative activities.
- Farm Household Models that specify the underlying behavioural relations regarding farm household resource allocation and consumption priorities.
- Mathematical programming procedures as a method for the appraisal of farm household response to policy instruments.

Often, when mechanistic models are used, Linear Programming (LP) or some derivative of LP is used. Ten Berge et al. (2000) offer a good explanation of the structure of a Linear Programming model for farm analysis: Linear programming represents the farm as a linear combination of so called ‘activities’. An activity (Ten Berge et al., 2000) is a coherent set of operations (also called ‘production technology’) with corresponding inputs and outputs, resulting in e.g. the delivery of a marketable product, the restoration of soil fertility, or the production of feedstuffs for on-farm use. An activity is characterised by a set of coefficients (Technical Coefficients or input-output coefficients) that express the activity’s contribution to the realisation of user defined goals (or objective in modelling terms) (Ten Berge et al., 2000). The biophysical and economic rules that determine the transformation of inputs to outputs for a given activity are generally non-linear (Ten Berge et al., 2000). The definition of activities must therefore, ideally, be such that all non-linearities are embedded in the values of the input-output coefficients (or Technical Coefficients (TCs)). Technical Coefficient Generators (TCGs) (Ten Berge et al., 2000; Ruben and van Ruijven, 2001; Hengsdijk and van Ittersum, 2002) can then be defined as algorithms to translate data information into coefficients that represent the input and output coefficients for each discrete activity. Output levels might be realised with different levels of inputs, for example, substituting labour use by pesticides. Different activities have to be defined to model these different input levels to reach a certain output level (Ten Berge et al., 2000). As inputs are limited resources, constraints to the activities are defined, which represent the minimum or maximum amount of a certain input that can be used. This system of activities and constraints is then optimised for some objective function, reflecting a user specified goal, for example profit. A standard mathematical formulation of a LP model is:

Max (or Min) $[w = c'x]$

Subject to $ax \leq b$

$x \geq 0$

where w is the objective function: a linear function of the n production activities (x) and their respective contributions (c – coefficients) to the objective. $ax \leq b$ represents the m linear constraints with the right hand side b. a is an $m \times n$ matrix with TCs.

In an important aspect that has a large influence on the model structure of a BEFM is the incorporation of time. Time can be accounted for within a year or cropping season and over the years in BEFMs. A static model does not explicitly take account of time, while a dynamic model explicitly takes account of time (Blanco Fonseca and Flichman, 2002). With each time period added, the BEFM logically becomes larger as the model should have some model structure capable of dealing with this new time period or should be re-run for the time period. This will be further discussed in Section 4.3.

If empirical and mechanistic models are built to analyse the same problem, the results of these models can differ to some extent. For example, Wossink and Renkema (1994) found that a levy of 25 guilders was needed to reduce pesticide use based on a mechanistic approach, while a study based on econometric time series analysis indicated a levy of 100 guilders. According to Wossink and Renkema (1994) this was caused by the mechanistic approach including technical innovations and assuming instantaneous adjustments, while the econometric approach took the adjustments from historical time series. Here a problem of the mechanistic approach is encountered: instantaneous adjustments, which in reality never happen. The econometric approach can only consider the variation that already existed in the past (Flichman, 2004).

If mechanistic models will be used to develop the FSSIM in SEAMLESS, it will be worthwhile to make an inventory of potential problems, shortcomings and strengths in earlier applications of mechanistic BEFMs to analyse policy questions and the diffusion of technological innovations. More importantly, methods should be found to make these mechanistic models as positive as possible in their approach.

1.3 A History of Bio Economic Modelling

Bio-economic modelling is a type of Farming Systems Research. Through the 1980s and 1990s many different bio-economic models have been constructed in different places around the world. In Australia at the University of Western Australia MIDAS was constructed by a group of researchers headed by David Panell, who also wrote some methodological articles on different aspects of bio-economic modelling (Pannell, 1997; Pannell et al., 2000). At the same time in several places in Europe BEFMs were made, for example in France at the Institute Agronomique de Montpellier (Boussemart et al., 1996; Louhichi et al., 1999; Flichman and Jacquet, 2003) and INRA and in the Netherlands at Wageningen University. In Wageningen a lot of work has been done on the pollution and environmental policy aspects of BEFMs (Wossink et al., 1992; Berentsen and Giesen, 1995; Pacini, 2003). Also some research was carried out with respect to the biophysical aspects of mechanistic BEFMs and the normative use of BEFMs to support innovation of farms (Van Ittersum and Rabbinge, 1997; Rossing et al., 1997; Ten Berge et al., 2000; Dogliotti, et al., 2003). A group of researchers in Germany created the model MODAM, a multi-objective decision support tool for agro-ecosystem management (see Meyer-Aurich et al., 1998; Zander and Kächele, 1999). In North England the model Farm-adapt was made, that could also incorporate the biodiversity aspects (Gibbons et al., 2005; Ramsden et al. 1999; Oglethorpe, 1999). In Norway a large group of researchers worked together to create the model ECECMOD (Vatn et al., 1997), just as in Denmark, where the model FASSET was created (Berntsen et al., 2003). Lastly, some applications were found from researchers localised in the United States, an example of which is Barbier and Bergeron (1999) and Apland (1993).

2 Research objective and questions

This report provides an overview of potential problems, shortcomings and strengths of earlier applications of mechanistic BEFMs to analyse policy questions and the diffusion of technological innovations. Special emphasis will be on the model structure and the modelling solutions applied to solve the main problems of mechanistic BEFMs. The following aspects are taken into account:

- Farmer goals. Farmer goals are modelled in the objective function of the BEFMs. What goals determine farmer behaviour? How are these goals modelled? How can these mechanistic BEFMs be more positive in their approach?
- Production and conservation activities of farmers. What the farmer does or can do on his farm is modelled via activities in mechanistic BEFMs. How are these activities normally specified? How are potentially new activities for the future modelled?
- Resource availability and external pressures on the farm. Resource availability and external pressures are modelled by constraints in the BEFMs. These constraints limit the amount of scarce resources a farm can use based on its resource endowment or limit the production of outputs based on policy restrictions. How have these constraints been defined? Do the constraints influence the modelling approach chosen?

In a second part of the report, Chapter 5, an ideal 'summary' model structure is defined based on the insights gained from the overview of problems, shortcomings and strengths, using the innovative solutions applied in other model studies.

3 Methodology

The methodology used in this report is a literature review of the relevant past applications of mechanistic BEFMs and textbooks relevant to some aspects of mechanistic BEFMs. About 180 references were collected and read, of which about 70 ended up in this report. These 70 articles were more frequently quoted than the other articles or offered a clear methodological approach. The other references were less frequently quoted and incorporated less new aspects, and were often describing practical applications of BEFMs, with a focus on the numerical results. For the in-depth study of these references unfortunately no time was left. The references that ended up in this report were scored on a long list of criteria (see Appendix 1) to provide a useful summary of the article and to find which aspects of the mechanistic BEFM were explicitly modelled and which aspects were left out. It could be worthwhile to add also the other references currently not incorporated.

Out of these 70 references there were 37 model studies. The other 33 references were theoretical articles, literature reviews or text books. On several occasions in this report the number of model studies that mention a certain aspect of a BEFM is given. The total number of model studies on these occasions is not always equal to 37, as with some model studies it is not exactly clear what is being done or as some aspects are not relevant in certain model studies.

In Table 1 below an overview is given of useful definitions, discussed in the next sections of this report.

Tabel 1: An overview of definitions used in this report

Concept	**Definition**
Bio Economic Farm Model (BEFM)	A farm level model that links mathematical programming model formulations of farmers' resource management decisions, to biophysical models that describe production processes and the conditions of natural resources (Barbier and Bergeron, 1999)
Normative approach	Approaches that try to find the optimal solution to the problem of resource management and allocation (Flichman and Jacquet, 2003)
Positive approach	Approaches that try to model the actual behaviour of the farmer (Flichman and Jacquet, 2003)
Mechanistic model	Models that are built according to a certain image the researcher has of the processes and relationships occurring in reality (Pandey and Hardaker, 1995)
Empirical model	Models that are used to describe or explain the current situation (Ruben et al., 1998) and that were relationships are uncovered based on the observed data incorporated in the model.
Objective function	A function with which the realisation of a user defined goal can be optimised (Ten Berge et al., 2000)
Activities	A coherent set of operations (also called 'production technology') with corresponding inputs and outputs, resulting in e.g. the delivery of a marketable product, the restoration of soil fertility, or the production of feedstuffs for on-farm use (Ten Berge et al., 2000)

Table 1 (Continued): An overview of useful definitions used in this report

Concept	Definition
Technical Coefficients (TCs)	Coefficients describing the inputs needed to achieve one unit of output or according to (Ten Berge et al., 2000) the activity's contribution to the realisation of user defined goals (or objective in modelling terms)
Constraints	the minimum or maximum amount of a certain input that can be used
Alternatives	New activities, not yet used in reality: often technological innovations or newly developed cropping and husbandry practices
Indicators	A measure of the side effects of agricultural production (often environmental effects).
Response Multipliers (RMs)	Change in objective function due to parametric changes (for example, input prices)
Elasticities	Measures of the percentage change in a model variable divided by the percentage change in a model parameter (Pannell, 1997)
(Non-embedded) risk	Variability the decision maker faces due to uncertain yield and price levels beyond control of the decision maker
Embedded Risk	This occurs when some decisions depend on earlier decisions and on the outcomes of some uncertain events (Hardaker et al., 1997; chp.9). The decision maker has the opportunity to exercise some control by sequential decision making (Dorward, 1999)
States of nature	Different conditions that can occur in reality all with a certain probability.
Sequential decision making	During the cropping season the decision maker takes sequential decisions as more information comes available.
Recursive model	When a model is run period after period and each period starts with the end values of the last period, recursive modelling is being used (Wallace and Moss, 2002)
Inter-temporal model	Inter-temporal models are models that optimize over the whole time period.
Dynamic recursive model	Running the model year after year (with each years starting values are the end values of the year before) while optimizing over the whole period (Louhichi et al., 1999)
Generic model	Model that can be easily transferred between geographic locations
Specific model	Model that is specific for one geographic location and cannot be transferred.
Robustness	The extent to which a model responds to changes in parameters. A robust model is insensitive to changes in parameters.

4 Results/discussion

4.1 Strengths and weaknesses of mechanistic BEFMs

The scope of this Chapter 4 'Results/Discussion' is an in-depth discussion of mechanistic BEFMs (which are more commonly used in normative approaches). Before to start an in-depth discussion, the advantages and disadvantages of mechanistic BEFMs are listed.

Advantages of mechanistic BEFMs are:

1. Mechanistic BEFMs appear through constrained optimisation to match the reality of small farmers, striving, with limited resources, to improve their lot (Anderson et al., 1985).
2. Mechanistic BEFMs are relatively easy to learn and work with (Anderson et al., 1985)
3. Mechanistic BEFMs are less demanding concerning the availability of aggregate data than econometric models in evaluation of policy options at sector or regional level (Berger, 2001)
4. Many activities and restrictions can be considered simultaneously (for example: detailed agronomic information on technologies and information on the generation of externalities.) (Wossink et al., 1992; Pacini, 2003; Weersink et al., 2004). For example, the production of externalities is modelled through explicit relations (TCs), just as the production of outputs (Flichman and Jacquet, 2003)
5. Mechanistic BEFMs can be robust (Berger, 2001), in that they can be insensitive to changes in parameters (Pannell, 1997)
6. An explicit and efficient optimum seeking-procedure is provided (Wossink et al., 1992; Weersink et al., 2004), based on clear but simplistic rules of decision behaviour (Zander, 2005)
7. Once formulated, the effects of changing parameters can easily be calculated (Wossink et al., 1992) (through sensitivity analysis) and the effects of singular parameters can be considered (Flichman and Jacquet, 2003), for example the changes in production techniques due to changes in economic parameters like prices (Flichman and Jacquet, 2003).
8. New production techniques can be incorporated easily by means of additional activities (Wossink et al., 1992). These new production techniques can thus be evaluated, without implementing them in reality (Flichman and Jacquet, 2003).

9. Not only the economic costs and benefits of pollution and pollution abatement are considered, but also the degrees of pollution and pollutants in the environment (Flichman and Jacquet, 2003). Non convexities of production and pollution can be taken into account (Flichman and Jacquet, 2003) (see Section 4.4). With non-convexities is meant that the response curves of income or pollution levels to certain inputs might not always be convex in their shape due to farmers switching between production technologies with changing input levels and the changes between limiting factors in production.

Disadvantages of mechanistic BEFMs are:

1. The strong underlying assumptions of infinite divisibility of resources (for example land) and activities and single valued coefficients (Anderson et al., 1985). Single valued coefficients means that the technical coefficients (TCs) take one value and are not a function that can take several values.
2. Optimal adaptation of the farm to changing technology or changing circumstances given the degrees of freedom in the model. In practice, optimal adaptation can be hindered

(Wossink and Renkema, 1994; Berentsen, 2003). An example of this hindrance is the allotment of land on the farm.

3. The absence of a detailed specification of the decision making procedures at the producers' level (Ruben et al., 1998).
4. Neglect of other objectives than profit maximization (Ruben et al., 1998). However, this is not always true as can be read in Section 4.3
5. The assumption of perfect markets (Ruben et al., 1998) in aggregation of BEFMs to higher levels, meaning that market modules within the (aggregated) models function with the assumption of market clearance and a perfect price formation on the basis of market clearance, while in reality markets hardly ever function perfectly and are sometimes underdeveloped. However, transaction costs can be taken into account to some extent by adding them to the costs of the activities.
6. They do not explicitly capture the interaction between actors (equivalent to the assumption that there are no such transaction and information costs) (Berger, 2001), both in the aggregation of BEFMs to higher levels and in the farm level model for interactions between farm family members.
7. They do not fully take into account the spatial dimension of agricultural activities (and thus neglect the role of internal transport costs and the physical immobility of land) (Berger, 2001)
8. Factor substitution is not modelled by a continuous production function. This leads to scale effects being disregarded. Factor substitution is the substitution of one production factor by another production factor, for example in harvesting a field of wheat different ratios of manual labour and machinery can be used, dependent on the relative prices of both manual labour and machinery. (Kruseman and Bade, 1998) succeeded in modelling factor substitution to some extent by making use of a wide range of point estimates that represent small, linear segments of a continuous function. (Kruseman and Bade, 1998)

Often mechanistic BEFMs are used in a normative approach, for example Pacini (2003), Ten Berge et al. (2000), Wossink et al. (1992), Berntsen et al. (2003) and Berentsen (2003). In this report the challenge is to depart to some extent from the normative approach and come to a positive approach, as the results of the model should reflect what could happen in reality. To do this, a central feature of the normative approach has to be taken care of. BEFMs based on a normative approach are termed 'normative' as they are setting a 'norm.' The 'norm' is calculated as the optimal allocation and management of resources (Flichman and Jacquet, 2003). Farmers often do not succeed to manage the farm according to model outcomes (the norm) due to various reasons (like imperfect information, risk aversion, management quality and skills) (Falconer and Hodge, 2000; Calker et al., 2004). Normative economic models calculate the economic consequences based on what farmers ought to do in order to optimise profits (Berntsen et al., 2003). The data used in models reinforce this normative character as they are often not measured, but established on the basis of literature (Calker et al., 2004) or expert judgement.

Another important aspect in the construction of any BEFM is time. Farm decision makers take decisions over longer time periods that have a strong effect on farm development and realization of farmer goals (strategic decision making). These strategic decisions can be part of a BEFM, but makes the model larger and more complex. Next to the long-term decision making of the farmer, also many biophysical processes have an important time-effect, like nutrient flows. Lastly, within one growing period or year time can play a role through weather and price variability and the responses of farmers to this variability. The importance of time in BEFMs will be further extensively discussed in Section 4.3.

Aims, with which BEFMs are made, are discussed in the next section of this chapter: to evaluate policies or give some insights in the consequences of technological innovations.

Section 4.3 deals with the difficult question of making mechanistic model more positive, e.g. how can a mechanistic model simulate actual farmer behaviour closely? In the subsequent Section 4.4 one strength of BEFMs is further discussed, i.e. their ability to model the biophysical relations and how this translates into income. Section 4.5 'Comprehensiveness' deals with the inherent difficulty in all modelling approaches: 'did we really model all the important factors? Often BEFMs have been made for specific circumstances in a specific locality, which makes their use rather limited, so in Section 4.6 the transferability of models from one location to another will be discussed. Section 4.7 discusses how the researcher can assess the quality of his model: model evaluation. Section 4.8 highlights some other modelling approaches and additions to BEFMs, which might be useful for aggregation to higher levels or incorporation of new aspects of reality into BEFMs.

4.2 Suitability to policy evaluation and to assessment of technological innovation

'Given the budget associated with the CAP, ex ante policy evaluation would seem to be justification enough to develop this type of model' (Edwards-Jones and McGregor, 1994).

4.2.1 Introduction

As expressed by Edwards-Jones and McGregor (1994) 'the utility of a series of whole farm models for the European situation would be substantial, particularly in the *ex ante* policy evaluation and marketing of on-farm technology.' The BEFMs can be subdivided in a few broad classes based on what they are used for:

- Short term assessments on the suitability of an innovation: static models focusing on one technology, exogenous input/output prices, assessing whether a technology will be viable financially and will have positive environmental effects, for example Abadi Ghadim (2000)
- Efforts to highlight methodological aspects of mechanistic BEFMs and improve the method; for example Apland (1993)
- Prediction or exploration of the effects of changing policies on agriculture. For example, Pacini (2003) and Berentsen and Giesen (1994)

As the objective of SEAMLESS is 'to enable assessment of the impact of policy and behavioural changes and innovations in agriculture and agro forestry' (SEAMLESS, 2004), SEAMLESS belongs to the latter class of predicting or exploring the effects of changing policies and innovations. SEAMLESS incorporates the first class of models for short term assessments on the suitability of an innovation. Up to now, no BEFMs have been found with the same objective as SEAMLESS: modelling effects of policy changes and innovations at an aggregate level over a large period of time.

In 1994 Wossink and Renkema (1994) noted that 'relationships and trends are more important than the absolute figures.' However, at the moment mechanistic BEFMs are able to produce figures[2] useful for the (*ex ante*) evaluation of policies and assessment of technological innovation as is shown by Donaldson et al. (1995), Vatn et al. (2003), Louhichi et al. (1999) and Deybe and Flichman (1991). Characteristics that make these BEFMs suitable to these ends are:

- The potential to identify 'the possible trade-offs between economic and environmental objectives' (Ruben et al., 1998).
- The inclusion of important aspects disregarded in the policy making process, for example the holistic approach and environmental effects on lower spatial scales (Pacini, 2003; chp. 7).
- The ability to replicate methods for the determination of environmental performances for a vast range of spatial conditions and farming practices (Pacini, 2003; chp. 7).
- The ability to supply information to improve the efficiency of agri-environment schemes and to determine the corresponding payments to compensate farmers (Pacini, 2003; chp. 5).

[2] Logically there is some discussion on the quality of these figures, whether they are 'absolute' as Wossink and Renkema (1994) hoped for, or the probability of a change from the base scenario according to some trend line as suggested by Zander, (2005).

- The flexibility of the model in its data use. Data availability to adapt the model to different regions can be checked and if available implemented (Pacini, 2003; chp. 7).

Based on these characteristics it is concluded that a mechanistic bio-economic farm model permits the (*ex ante*) assessment of technological innovations and the (*ex ante*) evaluation of policies over a range of different geographic and climatic circumstances. Thus, it can be assessed whether these technological innovations and polices lead to the desired adjustments in terms of farm incomes, environmental effects and farm practices on farm and regional level. In the next sections the use of mechanistic BEFMs in evaluation of policies and assessment of technological innovation will be further discussed.

4.2.2 Suitability to policy evaluation

Farm-level models have to meet certain requirements in order to be useful to policy makers. Firstly, policy makers require site specific information on the relationships between alternative production practices and environmental quality to formulate the appropriate course of action (Weersink et al., 2004). Secondly, the BEFMs must integrate efforts from several scientific disciplines to a greater degree than is common for farm-level models (Weersink et al., 2004). Thirdly, it must be possible to scale up the results of the BEFMs to regional, sectoral and national level and the BEFM should thus easily fit into a representative/typical farms for the region. These requirements can be taken into account in the model construction of a BEFM. However, next to these requirements there are some more complex challenges as will be explained in the next paragraphs.

It is important to consider how farmers might *actually* respond in reaction to policy changes (Falconer and Hodge, 2000). Thus, in order to successfully evaluate policies it is important, firstly, to consider the differences of theoretical predictions of response and the actual responses (Falconer and Hodge, 2000) and secondly, to draw practical policy implications from these differences. In building a mechanistic model, ideally one would want to make the gap between these theoretical predictions of response and the actual response as small as possible, so that the model provides good predictions of what will actually happen. This requires the BEFM to become as positive as possible with regards to farmer behaviour. Comparing model predictions of farmer behaviour in the past to actual farmer behaviour in response to policies is a vital step in the development of any model for the prediction of farmer behaviour in the future (see further Section 4.7 Evaluation). Here a tension exists with the use of the same mechanistic BEFM for long term explorations of what can potentially happen in the future. These long term explorations are somewhat in between a pure positive and a pure normative approach as they indicate what is potentially possible, but should also indicate what happens in reality to arrive at this point. It thus is important to be flexible in model design, so that the model can both predict what will happen in reality in the short and medium term, but also what could potentially happen in the future given certain developments and what trends differing from the base-line scenario might be.

A limitation of BEFMs in the evaluation of policies is that policies like education and information (that are difficult to quantify in financial terms) are almost impossible to incorporate (Falconer and Hodge, 2000). BEFMs can evaluate policies based on assumed market conditions, production limitations or financial incentives (price support, quotas, import-levies, export subsidies, income support, cross-compliance policies and agri-environment schemes). It should be made clear to the policy maker that policies difficult to quantify in financial terms can not be directly modelled in a BEFM, but need to be captured by complementary approaches. It depends on the type of policy how policies can be modelled. Production quota or input limitations can be modelled by constraints and voluntary uptake of agri-environment schemes can be modelled by adding extra activities.

Policy instruments vary in their effectiveness to achieve certain desired results. This effectiveness depends also on the implementation level of the policy instrument, for example the height of a pesticide tax. As described in Falconer and Hodge (2001) below certain critical levels of policy instrument no change in the farm plan as compared to the base situation is achieved. Next to this, there are upper limits to the levels of policy instruments as at some point farmers will just go out of farming, because of too negative effects on income. Between these critical levels and upper limits of policy instruments, the policy instruments are effective. For evaluating policies, it is important to model these ranges, as this provides useful information to the policy maker.

A challenge exists in the comparison of effectiveness of different policy instruments. For example, Berentsen and Giesen (1994) investigated the effects of potential environmental policies on nitrogen losses on Dutch dairy farms and hold: 'A comparison of policies is difficult. Because it is to be expected that marginal costs increase with the amount of reduction of N losses (as cheap measures are followed by more expensive measures), a condition for a good comparison should be that the policies to be compared should lead to more or less the same reduction in N losses.' The same conclusion in a similar study was drawn by Berntsen et al. (2003). This problem in the comparison of policies is caused by the optimization procedure of BEFMs. A sensitivity analysis should be able to provide useful insights with regards to the comparison of policies results of for example; the degree of reduction in N losses (see Section 4.7 Evaluation).

In using mechanistic BEFM for policy evaluation one has to be aware of the above mentioned challenges and limitations:

1. the challenge to make the models as positive as possible in the predictions of actual farmer behaviour
2. limitation to take account of policies, that are difficult to quantify in financial terms (for example education and information)
3. challenge to compare different policies in achieving the same levels of effects
4. the challenge to uncover the limited ranges in which policy instruments function properly

If these challenges are overcome, mechanistic BEFM can yield an interesting insight in the impacts of policies. How these challenges can be faced will be explained in other sections of this report.

4.2.3 Deciding on (technological) innovations

Technological innovations are often modelled as new activities with improved resource efficiency. The construction of new activities is further explained in the Section 4.4 Production activities. BEFMs address the process of adoption of innovations as an adjustment of crop, livestock and technology choice in response to changing economic conditions that enable improvement of farm household welfare within the boundaries of resource availability (Ruben et al., 1998). This procedure only points to the necessary conditions for adoption, while sufficient conditions for adoption still have to be identified (Ruben et al., 1998). This means that an adoption has to be completely understood by the farmer and has to be compatible with his current farm machinery (= necessary conditions), while a farmer will decide to adopt when the adoption has certain positive effects (for example improvement in farm income and reduction in farm labour use) (= sufficient conditions). Farmer behaviour with regard to innovations will probably be somewhere in between the following extremes: innovative farmers adjusting smoothly to exogenous technical changes or conservative farmers who are reluctant to innovate and refuse technology adoption (Berger, 2001).

Farmers will not be able to reach the optimal production organisation calculated by a BEFM, because their capacity and willingness to achieve the optimal production organisation limits them (Wossink and Renkema, 1994). Here a problem is encountered with most current mechanistic BEFMs. As soon as a technological innovation becomes available to the model, it is instantaneously used as it is a better option than existing technologies as noted by Wossink and Renkema (1994). This problem of instantaneous adjustment has to be tackled, as otherwise mechanistic BEFMs will produce results that never will be observed in reality. The challenge is to make BEFMs as 'positive' as possible in that they model actual farmer behaviour *vis-à-vis* technological innovations. This could be done by incorporating the process of diffusion of an innovation and consequent adoption of an innovation by the individual farmer into a mechanistic BEFM.

By studying theories on the diffusion of innovations some useful insights can be gained in actual farmer behaviour vis-à-vis technological innovations. The diffusion of an innovation depends on the one hand on the nature of the innovation itself, and on the other hand, on the attitude of the farmers (Wossink and Renkema, 1994). The farmer can be conceptualised as an 'adaptive man' (developed by Cyert and March (1963) in Wossink and Renkema (1994)): the individual farmer tries to adapt the existing farm organisation to the changing environment in the light of his goals and objectives. Thus, farmer attitude is dependent on his goals and objectives and on social interaction within the family and between families/social groups. Goals and objectives, social interaction within the family and between families/social groups should be part of a mechanistic BEFM aiming to come close to actual farmer behaviour. An extensive discussion of farmer' goals and motivations is given in Section 4.3, while social interaction within the farm family is discussed in Section 4.5.2. Lastly, social interaction between farm families and social groups is beyond the scope of this report; however some remarks are given in Section 4.8.2.

The adoption of an innovation is not only dependent on the farmer attitude, but also on the nature of the innovation (as discussed above). The nature of an innovation is given by the potential gains of the innovation (see Section 4.4), the amount of investment needed (see Section 4.3.6) and the practicalities of the adoption. Whether a farmer begins using a technological innovation depends also on whether the farmer thinks it is practical (as in technically feasible) to do so. An example of this is highlighted by Apland (1993), Aubry and Chatelin (1997) and White et al. (2005): farmer time allocation. Depending on the available machinery, the amount of cropped land, the crops and the (expected) weather conditions the farmer makes a cultivation plan and has certain work peaks (Aubry and Chatelin, 1997). He estimates the length of time periods in which he can carry out his cultivations. His estimations depend on his behaviour versus risk: a risk averse farmer will estimate the length of time periods more conservatively. A farmer might thus not adopt an innovation if in practice it is infeasible to carry out the work in a certain time period.

Farmer time allocation can be modelled in several ways. A concept used by some authors (Apland, 1993; Ramsden et al., 1999) is field days (defined as time available for the completion of field operations). Apland (1993) investigates the importance of field days in economic models of crop farms. He divides the year into several periods, each containing a number of field days in which cultivations takes place. The amount of time available depends on the number of field days in a period, the number of farm workers and the weather. Apland (1993) concludes that a model not taking into account field days might overstate the contribution of additional land to profit and understates the contribution to variance of profit. A similar approach is used by Ramsden et al. (1999), who links available field days and machinery to field operation requirements. Field days can be nicely modelled in the structure of activities and constraints as done by Ramsden et al. (1999). The German Association for Technology and Structures in Agriculture (KTBL) provides for this purpose the number of available field days specific for half-monthly periods, climate zones and soil types in Germany (see http://www.ktbl.de/englisch.htm).

To gain *ex ante* insight into the effect of farmer time allocation on the adoption of different technological innovations, White et al. (2005) developed a measure, Returns to Opportunity-Costed Labour (RTOCL). RTOCL acknowledges and provides an accounting for the farm labour trade-offs that arise from adopting a technology. It is conceptualized that the value of labour changes during the growing season dependent on labour demands (White et al., 2005). So during peak-seasons of labour the opportunity costs of labour are higher than outside these peak-seasons. In order for a technological innovation to be adopted during these peak-seasons its benefits have to outweigh the labour opportunity costs. RTOCL requires a first model run to determine the shadow prices of labour and these shadow prices are used to calculate RTOCL. Thus RTOCL only provide insights when the model has been used.

In conclusion, in modelling technological innovations it is once again important to come as close as possible to actual farmer behaviour by considering farmer attitudes (based on his goals and objectives and social interaction) and the practical issues constraining adoption (such as time availability).

4.2.4 Presenting results

Policy makers want certain information from applications of mechanistic Bio-Economic Farm Models. Dependent on the interests of policy makers, mechanistic BEFMs should produce different kinds of information (or results). The interest can be in the changes of an objective function (for example farm income), the environmental effects of agricultural practices, changes in agricultural production and practices and macro-economic effects on market prices or other regions. The presentation of these results can be done in different ways depending on the interest of policy makers. Means of presentation of results are:

- Response multipliers
- Indicators
- Elasticities
- Trade off curves

They will be shortly discussed in the next paragraphs, and then a more theoretical approach will be taken towards the explanation of trade-off curves.

For quantifying the relative effects of policies or of changing market conditions on welfare or other variables Response Multipliers (RMs) can be used (Kruseman and Bade, 1998; Ruben and van Ruijven, 2001). RMs are defined as the relative change in the objective variable (for example farm income) caused by discrete parametric changes of an instrument variable (for example input prices or resource constraints) (Kruseman and Bade, 1998). A RM can be understood as an elasticity that measures the relative change in an objective function.

Price elasticities give an estimation of farmer responses to policies based on economic (dis)incentives (Falconer and Hodge, 2000). Price elasticities indicate to what extent the producer will respond to changes in relative prices[3]. If a certain input has a low price elasticity, the producer will continue using that input even if the price increases dramatically. Care has to be taken in the process of model construction and calculation of price elasticities (Falconer and Hodge, 2000) for the following reasons:

[3] Elasticities are (in mathematical terms) are measures of the percentage change in a model variable divided by the percentage change in a model parameter (Pannell, 1997)

- Elasticity estimation (in relation to policy instruments) assumes that farmers were producing efficiently prior to the price change due to policy changes. Otherwise, farmers in response to a policy change would reduce inefficient input usage, without experiencing negative income effects or other negative effects on their farm structure. Then the simulated results of the BEFM would not agree with observed farmer behaviour in reaction to a certain policy change.
- The estimated elasticity might be lower as in reality (because the model has more alternatives it can choose from and adapt) or higher than in reality (because the model reacts stronger to price changes). Thus, potentially large differences between actual responses and model predictions exist (as always).

Pacini (2003; chp.5) and Zander and Kächele (1999) used environmental indicators to model the effects of agricultural practices. To see whether specific policy objectives could potentially be met, these environmental indicators could then be constrained by including Environmental Sustainability Thresholds (ESTs). Desirable characteristics of an indicator include high uncertainty about its level prior to measurement, low uncertainty about its links to production practices and low cost accurate measurements (Weersink et al., 2004). Different environmental indicators should be chosen for different research questions and in different regions (or ecosystems) and it is of crucial importance to choose the correct environmental indicators for each region and research question (Meyer-Aurich et al., 1998). Some further comments are made on the selection of indicators in Section 4.5.3.

Scenarios and sensitivity analysis on the values of two different objectives (or indicators)[4] produce trade-off curves. Trade-offs between two conflicting objectives show how much of one objective has to be sacrificed to more fully realise the other objective (Rossing et al., 1997; Zander and Kächele, 1999; Ten Berge et al., 2000). Weersink et al. (2004) and Zander and Kächele (1999) advocate the use of trade-off curves to present results of BEFMs as these trade-off curves permit a comparison of the relevant environmental indicators for a certain farm and the on-farm losses in income. The trade-offs between the various dimensions of sustainability are transparent and decision makers can place alternative weights on those dimensions determining the appropriate balance between the health of the environment and the farm economy (Weersink et al., 2004). The slope of the trade-off curve represents the opportunity costs of environmental regulations in terms of reduced farm income (if an environmental objective is set out against farm income).

The trade-off function between two objectives generated by maximising the use of limited resources can be assumed to be identical to the production possibility[5] or to the supply function (Assfalg and Werner (1992) in Zander and Kächele, (1999)). Given stakeholder preferences for the two objectives, the indifference curve[6] can be added as shown in Figure 1. The intersection of the production possibility function and indifference curve describes the market equilibrium. However, this means that stakeholders can agree on a common indifference curve through a process of bargaining. As there are multiple objectives, different trade-off curves can be made, which can all in turn be confronted with indifference curves. All in all, this becomes a complicated process of bargaining and of constructing trade-off curves, requiring a lot of information. A sensitivity analysis of the different trade-off curves

[4] Objectives can be in the objective function, but also in the constraints or can be displayed as indicators. Indicators can also enter in the objective function

[5] Production possibility function is a function describing what can be maximally produced by the varying levels of two production factors, for example land and labour.

[6] An indifference curve is an asymptotic curve, along which the total utility of the consumer does not change for different ratios of two products (in this case, objectives.)

can provide useful insights with regards to the maximum objective achievement possible under given conditions, thus defining the boundaries of the multidimensional solution space (Zander and Kächele, 1999).

Falconer and Hodge (2001) describe two other representation methods to present trade-offs between multiple objectives with different policy instruments (and different application levels of policy instruments):

1. Frontier analysis: visual presentation of the trade-offs between different objectives under different policy instruments, according to an economic dominance criterion. The economic dominance criterion entails that a farm plan arising under a given policy scenario is dominant when no other plan can obtain the same or lower level of an indicator with the same or greater returns. This farm plan could then be said to be Pareto-efficient as no other farm plan leading to an improvement of one of the objective values is possible.
2. Cost-effectiveness index (CE) of two policies: a summary index giving the 'elasticity' of trade-offs between farm income and relevant indicators under different policy instruments. CE is percentage change in a relevant indicator level divided by the percentage change in farm income. A CE of 1 means that the relevant indicator changes 1% in any direction, while also farm income changes 1%. The higher the CE, the more effective policy is. It has its problems in interpretation and construction, but it can be useful to compare different policies.

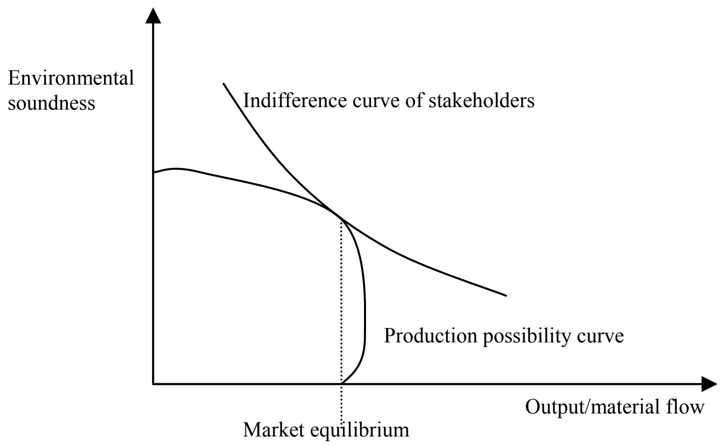

Figure 1 Transformation curve (=identical to trade-off curve between two objectives) and indifference curve of consumers, with at the intersection market equilibrium (Zander and Kächele, 1999)

4.3 Farmer decision making

'If FSR (Farming Systems Research) is not 'major-crop' biased, the farmer of relevance in many cases will be a woman. Since the preferences of women are likely to be different from men, omission of the women's viewpoint is likely to lead to misspecified models.' (Anderson et al., 1985)

'It is sobering to reflect that even the concept of 'optimising' whole-farm organisation is not understood in the context of a farm household. Rather, trivial surrogates have been used for the complex value sets involved (for example, risk aversion) when it is known that these are either insufficient or misleading.' (Dent, 1990)

This Section discusses two related questions: how to model farmer decision making? How to model his decision making over time? In the discussion about decision making in time also some other temporal effects are incorporated. Section 4.3.1 tries to 'define' decision making, while Section 4.3.2 discusses non-embedded risk and how this can be made part of the model. Section 4.3.3, 4.3.4, 4.3.5 and 4.3.6 are closely related and discuss relationships between time, farmer decision making and model construction. Finally, Section 4.3.7 explains how multiple objectives can be incorporated in the BEFM.

4.3.1 Defining decision making

The role of research is to understand the cognitive structures and the decision rules which govern family farmer decision making (Beranger and Vissac, 1994). Personal, family and farm business objectives and attitudes are not independent of each other and need to be considered together and farmers' behaviour reflects a combination of personality factors as well as lifestyle and economic objectives (Wallace and Moss, 2002). However, scientists do not hold a consensus on how to model farmer decision making and its importance to results of models. For example, Berger (2001) argues that the predictive capacity of bio-economic models will be mainly restricted by their inherent assumptions with regard to human decision-making rather than by ecological parameters.

Most studies that have modelled farmer decision-making have assumed that farmers maximise profit and have thereby ignored the reality that decisions of farmers are normally motivated by multiple, often conflicting, objectives of which profit maximisation is only one (Wallace and Moss, 2002). Instead of maximising profit farmers may want to minimise borrowing or maximise net worth of their farm or maximise cash accumulation or sustain family consumption. There exist important trade-offs between these goals, which influence the decision-making by the farmer, as Wallace and Moss (2002) showed by investigating these different strategies of farmers. Another conceptualization of differences between farmers with regard to their objectives and attitudes is offered by Van der Ploeg (1994b) with his farmer styles theory. Beaudeau et al. (1996) subdivided farmers in different styles according to their objectives, motivations, mentality and farm characteristics. For example, Van der Ploeg (1994a) identified the following styles: calculating, organizing, active skilled and holistic style. Decision-making procedures are based on subjective prices and alternative opportunities that may differ among households (based on availability of resources, access to markets, institutional arrangements and household objectives (Kruseman and Bade, 1998) and according to bargaining procedures within the households (Ruben et al., 1998). If a farmer is assumed to be rational profit-maximiser, his production decisions are influenced mainly by the relative prices of inputs and products (Falconer and Hodge, 2000).

For realistic modelling not only the multiple objectives should be incorporated, but also the changing objectives over time. Farm family objectives change, as the farm family goes through a process of generation, maturation, decline and regeneration (Wossink and Renkema, 1994; Wallace and Moss, 2002). Also the decisions of the farm family have a different time span; they take operational decisions on the day to day work, sequential decisions within a growing season or year in response to weather and price variability and strategic decisions for directing investments or developing the farm over the years. Then there is the issue of risk, of responding to uncertain events and maybe minimizing the probability of adverse states. In the subsequent paragraphs of this Section risk, decision making through time and multiple objectives are discussed.

4.3.2 (Non embedded) Risk and uncertainty

'Too often, models are built with cavalier assumptions of certainty.' (Hardaker et al., 1997)

A farmer faces risk and uncertainty about the economic consequences of his actions due to his limited ability to predict things such as weather, prices and biological responses to different farming practices (Pannell et al., 2000). A distinction is often made between embedded and non-embedded risk (Dorward, 1999). Non-embedded risk is related to the uncertain yield and price levels beyond control of the decision maker. In the case of embedded risk the decision maker has the opportunity to exercise some control by sequential decision making (Dorward, 1999), as embedded risk occurs when some decisions depend on earlier decisions and on the outcomes of some uncertain events (Hardaker et al., 1997). By sequential decision making the farmer can adjust his activities as more information on uncertain events comes available during the cropping season. Sequential decision making and embedded risk is further explained and discussed in Section 4.3.5. This Section further discusses non-embedded risk.

Whether non-embedded risk (or just called risk in the remainder of this section) should be incorporated in farm level models is a subject of debate. (Pannell et al., 2000) argues that the main issue for most farmers is how to respond tactically and dynamically to unfolding opportunities or threats to generate additional income or to avoid income losses (responding to embedded risk). Pannell et al. (2000) argue that is often not worthwhile to model risk, as:

- It is relatively less important in determining optimal strategies than the correct representation of underlying technical relationships.
- The difference in the value of the objective function for recommended strategies from models that do and do not represent risk aversion is, in most cases, extremely small. Pannell et al. (2000) found that income was only reduced to a small extent with a large reduction in income variance (= risk).

It depends on the objective of the study (assisting farmer decision making, policy evaluation or evaluation of current and future land use), study region and on the financial and time resources available within the research project (Pannell et al., 2000) whether risk should thus be incorporated or not.

However, the farm activities selected by a model are dependent on whether or not risk is incorporated (Pannell et al., 2000). This is demonstrated by Oglethorpe (1995): farmers were able to minimise income variance with only small reductions in farm income. But, farm intensity would be greatly reduced with slight decreases in income if farmers were assumed to maximise income while minimising income variance simultaneously instead of only maximising income. So if one is interested in modelling farmers' response to change and the consequent environmental effects of their practices, it might be useful to include risk in the model. However, it still depends on whether the model does or does not benefit more from improving the incorporation of other factors affecting model outcome than risk (Pannell et al., 2000).

It is often supposed that farmers diversify their farms to avoid risk. However, there might be other reasons why farmers diversify (Pannell et al., 2000):

- Non-uniformity of resource quality
- Resource constraints (for example limits on machinery or labour in certain periods)
- Complementary or positive interactions between enterprises.

Mathematical programming models for non-embedded risk are called Risk Programming Models by Hardaker et al. (1997). Models not incorporating risk are called deterministic models. These are often smaller and easier to test. An overview of risk programming models is given by Weersink et al. (2004) and Hardaker et al. (1997):

- Modelling farm diversification: If one is able to model the above mentioned reasons for farm diversification in a BEFM, risk reduction is automatically taken into account. Sensitivity analysis can be used to assess the effect of risk in deterministic models (Pannell et al., 2000).
- Quadratic Risk Programming (QRP) (Hardaker et al., 1997): an approach in which quadratic variance is minimized subject to a parametric linear constraint on expected income. Quadratic variance is the variance and co-variance of returns (= total revenues minus costs) of the activities. The assumptions which have to be fulfilled, before one can use QRP are rather strong: the distribution of total net revenue is normal or the farmer's utility function is quadratic (meaning that the utility function is not increasing at all points and implies increasing absolute risk aversion.)
- Minimisation of Total Absolute Deviations (MOTAD) or Target-MOTAD: a technique of quadratic programming. The quadratic variance constraint of QRP is replaced by a constraint on the mean absolute deviation of net income. First deviations for several states are calculated, and then the total mean deviation is calculated. This total mean deviation is constrained. In subsequent optimization rounds the constraint on the total mean deviation is increasingly tightened unttil no more solutions of interest are found. Target MOTAD (Tauer, 1983) contains, instead of a constraint on mean absolute deviation of net income, a constraint on the deviation from a target income. Advantage of target MOTAD is that the solutions are second degree stochastically dominant and efficient for risk-averse decision makers. A problem of Target MOTAD with respect to recursive models is that Target MOTAD would set a constraint on the summation of deviations from the target income over all the years, thus allowing the deviation and consequently the degree of risk aversion to vary over the years (Donaldson et al., 1995). Oglethorpe (1995) used a MOTAD, combined with an objective function of expected utility, in which expected farm income was adjusted for risk aversion. Risk aversion was interpreted as avoidance of variance in income.
- Donaldson et al. (1995) developed an objective function incorporating risk suited to recursive dynamic models. This objective function maximises the expected income minus a risk aversion coefficient times the sum of negative deviations from a target income (as in Target MOTAD). The sum of negative deviations and the expected income are determined endogenously in the model, but the risk aversion coefficient is determined exogenously. This works out mathematically as (Flichman, 2004):
  $\text{Max } U = E - \varphi\, \sigma_{Rnm}$
  with U as expected utility, E as expected revenue, φ as a exogenously determined risk aversion coefficient and σ_{Rnm} as the standard deviation of revenue according to states of nature (n) and market (m).

- Direct maximization of expected utility: this can only be used when the subjective utility function of the decision maker is known and the decision maker is risk averse. Thus, it is difficult with groups of decision makers as they all must be interviewed to obtain their subjective utility function. This problem with groups can be solved by using a Utility Efficient programming approach.
- Utility efficient programming (UE): the expected utility of the decision maker is maximised subject to some measure of risk aversion (r_a). Different formulations of the utility function can be used to model this.

Next to modelling risk directly in the objective function, risk needs also to be modelled by the incorporation of several states of nature. This is done on the basis of the calculations of returns of activities across possible states of nature. Possible states of nature signify here different conditions that might occur in reality. For each of these different conditions the expected total returns are calculated, which can then be compared to check what it would mean if different conditions occur. This does not account for any non-risk neutral behaviour of the farmer (Pannell et al., 2000). States of nature can be constructed in many different ways, for example by calculating an average and then defining a negative and a positive state of nature as a positive or negative standard deviation from this average for a parameter. Alternatively, the states of nature can be a negative and a positive extreme condition that could occur.

An example of this incorporation of risk in the activities is given by Apland (1993), who introduces three discrete price and yield states of nature and uses expected net revenue as an objective function. The objective function coefficients are the probabilities of the associated price/yield state. These price and yield states are determined by planting and harvesting dates (farmer's attitude towards planting and harvesting reflect their risk behaviour).

In line with Pannell et al. (2000) it is concluded that modelling non-embedded risk does not have a top-priority to include it in the model. It is more important to model embedded risk and the technical relations properly. However, there is the issue of the structure of farm activities changing once risk is incorporated as demonstrated by Oglethorpe (1995) and also admitted by Pannell et al. (2000). Risk is thus important in policy evaluations in which the effects of changes in farmer behaviour on the environment or change in production structure of the farm are of interest. As for the modelling approach, the models based on utility maximization are clearly superior to the models based on deviations in maximum income, as models based on utility maximization are closer to reality. They are also data and labour intensive.

4.3.3 Accounting for time

This Section introduces how BEFMs can be constructed that model over more time periods, either within one year (by subdividing the year in time periods) or over the years (by making every year one time period). When a BEFM takes account of time, it is said to be dynamic. Most BEFMs are static: an annual model of production is developed where the results reflect activities of a representative farm operation for a representative farm (Weersink et al., 2004). The static BEFM can only monitor the effect on yields of adverse environmental effects on the longer term (like soil organic matter depletion) without actually modelling the long term adverse effects. Also the static BEFM leaves out the sequential decision making by farmers during the year (the lack of full knowledge of weather conditions during the year leading to sub optimal results) and the strategic decision making by farmers over many years (whether or not to build a new shed or incorporate a new enterprise in the farm system). In subsequent Sections 4.3.5 and 4.3.6 first modelling with more time periods in one year will be discussed and modelling over more years. Section 4.3.5 discusses sequential decision making (or embedded risk), which means that the BEFM allows for within the year decision making. With sequential decision making the decision maker can adapt his decisions made at the start of the growing season. Section 4.3.6 shows how models can be adapted to incorporate more years. This allows for the incorporation of strategic decision making by the farmers, weather variability and the effects of adverse environmental practices. But before to discuss how models can be made dynamic, first static models will be explored a bit further and some methodological issues will be highlighted.

Static models can incorporate some temporal effects by the structure of the constraints and activities in the model (Pacini, 2003; chp.7), for example modelling crop rotations instead of individual crops (Dogliotti et al., 2003). Rotations of annual crops can be considered a type of perennial system with a mixture of agricultural uses of which the outputs may consists of multiple harvested products (Hengsdijk and van Ittersum, 2002). Interactions among successive crops with respect to soil nutrients, plague organisms etc. can be explicitly accounted for (Hengsdijk and van Ittersum, 2002). The number of potential crop rotations increases rapidly, with the number of crops considered and the sequence of the crops within the rotation. To select a suitable set of alternatives, Dogliotti et al. (2003) developed a ROTAT, a tool to generate a set of potential crop rotations based on agro-ecological rules. Also static models can monitor what the environmental effects are of a certain practices. For example static models can indicate what the decrease in soil organic matter is due to certain crops (without modelling the complete soil organic matter dynamics).

Incorporating time adds to the complexity of models and it thus depends on the objectives of the study whether authors do this or not (Weersink et al., 2004). Dynamic models are models incorporating time scales. Out of 37 models studies considered, 28 used static models and 9 dynamic models. However, different approaches exist to making models dynamic. For example Berntsen et al. (2003) used a static linear programming model coupled to a dynamic biophysical model that was being run year after year. Pfister et al. (2004) used a dynamic model that was run for one year only, but at a resolution down to one day. Here a subdivision of dynamic models introduced by Blanco Fonseca and Flichman (2002) will be used to avoid confusion (See Figure 2):

- Recursive models: When a model is run period after period and each period starts with the end values of the last period, recursive modelling is being used (Wallace and Moss, 2002). Optimization is carried for each of the individual years that are modelled.
- Inter-temporal models: models that optimize an objective function over the whole time period and that allow for inter-temporal trade-offs between the time periods. For example, an objective function maximizes farm income over the whole time period, while considering the relative preference for current income with respect to future income (by a discount rate) and the inter-temporal allocation of resources (by a set of constraints) (Pandey and Hardaker, 1995).
- Dynamic recursive models: Running the model year after year (with each years starting values are the end values of the year before) while optimizing over the whole period (Louhichi et al., 1999). An example of a dynamic model is used by Barbier and Bergeron (1999). Their model maximises aggregate utility over a five-year planning horizon (dynamic element), while the results of the first year of the planning horizon become the starting values for the following five-year planning horizon and this is done for twenty years in total (recursive element).

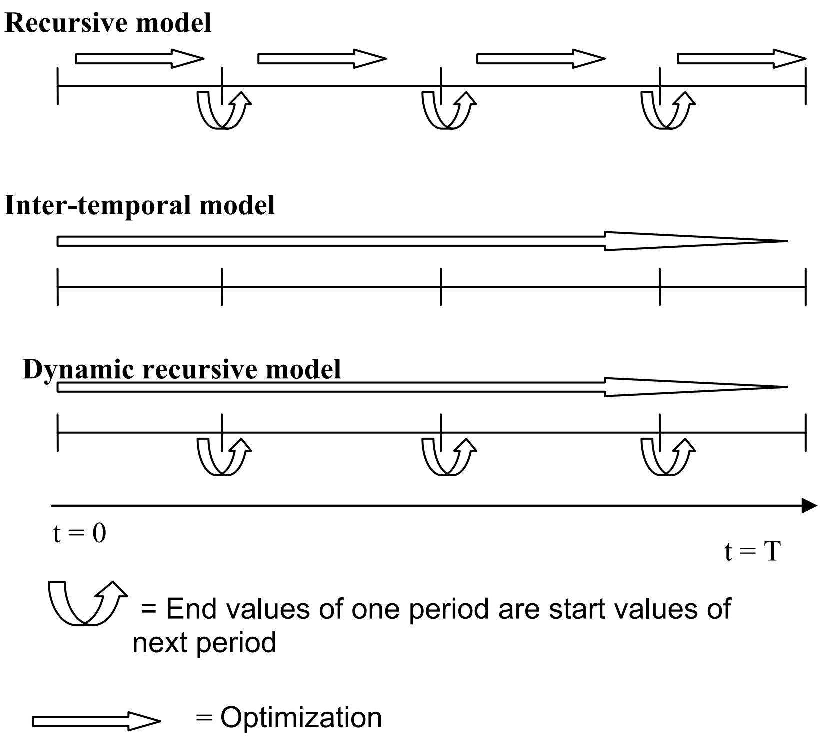

Figure 2: Differences between the different types of dynamic models

Although recursive modelling might be a good procedure to make models more dynamic, Wallace and Moss (2002) signal that optimum decisions are determined on the basis of a single period planning horizon (only current expectations are used). To overcome this limitation, Wallace and Moss (2002) embedded a finite multi-period planning horizon within the recursive model structure. This multi-period planning horizon was based on market and price expectations forecasted into the future, thus still enabling imperfect foresight, feedback and revision over time. Modelling market and price expectations can be done in various ways. For example, expected prices (Wallace and Moss, 2002) can be calculated using an adaptive expectations framework, which means that prices are calculated as the weighted average of past actual prices. Alternatively econometric models might be used to predict price and market development in the short run (by forecasting and extrapolation).

Talking about years might be confusing in this context, as sometimes a year comprises more cropping seasons or perennial crops are used which are there for many years once planted, or cows are present which grow over many years. Instead of ‘year’, it might be better to use ‘time period,’ in which time period is an amount of time at the start of which the decision-maker makes certain decisions having an effect on the outcomes at the end or in which a certain crop grows and is harvested or on which the financial year is based. However, talking about time periods would probably only confuse things more, as no one really knows how long a time period is.

A problem with integration of economic and agronomic/ecological models comes here to the fore. The natural sciences have a tradition with resolution at least down to the level of days, while economic analyses operate most often at the level of years (Vatn et al., 2003). For a successful integration of economic and agronomic/ecological models one of the two approaches has to be explicitly chosen and the model adapted accordingly.

Making models dynamic is not as easy as it sounds, unfortunately. Dynamic models increase rapidly in size and complexity and it can be difficult to let the models take account of all the dynamic issues (strategic decision making, weather variability, sequential decision making). With each time period added, the model structure doubles in size and the possible outcomes the model can return vastly increase. If also uncertainty and expected returns are added instead of certainty and fixed returns the model size increases again. If within the year decision making (sequential decision making) with many alternatives and decision options are incorporated, the model again doubles in size. At some point in this process, the modeller might just get lost in his model structure or it takes a lot of time and data to get the model running and produce some interesting results. Thus, the modeller should carefully guard this balance between model complexity, data needs, time availability and proximity to reality modelled by the BEFM.

4.3.4 General description of a dynamic model

A mathematical description of a general dynamic model is given by Hardaker et al. (1997):

- T is the number of time periods over which decisions are taken and one time period is t.
- X_t: At each time period, the condition of the system is described by a vector of variables X_t.
- Transformation function τ_t: The changes of the system between two time periods are given by a transformation function τ_t.
- a_t is a vector of the decisions taken by the decision maker in time period t.
- Each time period yields certain returns r_t. Total returns over the summation of all time periods is R_t.

In a stochastic model the returns during a time period and the transformation function is subject to uncertain effects k_t with probability $P_t(k_t)$ of occurring. An objective function for a stochastic model than becomes:

$$\text{Max } V_1(X_1) = g[E[r_1(X_1, a_1, k_1)], E[r_2(X_2, a_2, k_2)], \ldots , E[r_T(X_T, a_T, k_T)]]$$

With:

$V_1(X_1)$ = the overall expected return over T time periods.

$E[r_t(X_t, a_t, k_t)] = \sum_k P_t(k_t)\ r_t\ (X_t,a_t,k_t)$ = the expected returns in one time period t as the probability weighted average of r_t.

$X_{t+1} = \tau_t(X_t,a_t,k_t)$ = transformation function from time period t to t+1.

$r_t = r_t(X_t,a_t,k_t)$ = stochastic time period return.

If k_t is left out (no uncertain effects are taking place), than the above functions are equal to the functions for a multi-period problem under certainty.

Multi-period decision problems are often visualized by decision trees (Hardaker et al., 1997). From left to right the ‘tree’ branches off for each decision the decision maker takes, so if for a certain decision a with two potential outcomes (for example to harvest or not to harvest), the tree branches off in two directions. If a large number of periods are considered and a large number of decisions, these trees tend to get ‘bushy messes’ (Hardaker et al., 1997) of many decisions, branches and potential outcomes. If also uncertainty (each decision can have several uncertain outcomes) is added, the decision tree gets even bigger. An obvious problem exists here: the larger the number of outcomes and time periods, the larger the decision tree gets and the larger and more complicated the model gets. The model becomes also more intensive in terms of data needs, meaning that more data is needed as more time periods and uncertain outcomes are considered. This poses a practical obstacle in the design of dynamic BEFMs.

The overall expected return over T time periods ($V_1(X_1)$; above) is not unambiguously defined in real terms (Hardaker et al., 1997). The overall expected return can take several forms: discounted net present value (PV), Expected PV, Utility or Expected Utility. Utility functions can take several forms, incorporating the net present value, risk aversion or any aversion from variance in income. Hardaker et al. (1997) argue that the assumption of a perfect or near perfect capital market is important for the choice of the type of function for overall expected return. If the assumption of a (near) perfect capital market can be maintained, the time preferences of decision makers can be assumed to be objective (e.g. following some general rule). If the assumption of a (near) perfect capital market cannot be maintained, subjective time preference has to be taken into account, meaning that the decision maker will have preferences for a certain amount of cash at a certain moment in or during a certain time period. Unfortunately, in reality capital markets are not perfect or near perfect, especially with regards to borrowing of farmers and individuals. However, objective functions with regards to expected utility and time preferences are difficult to construct and data and time intensive. Thus, often strong assumptions have to be made on capital markets and subsequent time preferences.

4.3.5 Sequential farmer decision making

Sequential decision making is the reaction of the farmer during the cropping season to variability in climatic and socio-economic conditions. Decisions on crop choice and technology are of a sequential nature, e.g. within a selected cropping pattern there still exist considerable degrees of freedom with respect to factor intensity (Ruben et al., 1998). This leads to sequential decision making and embedded risk[7] by the farmer as conceptualised in Figure 3. Pannell et al. (2000) argue that incorporating sequential and strategic farmer decision making is more important than incorporating risk. Deybe and Flichman (1991) mention another aspect that might play a role in sequential decision making of the farmer, which is short term capital availability. They further comment that this is difficult to incorporate, but important as it determines the adoption of technological innovations and full use of resources.

Any important decision taken today will have consequences that extend into the future and that require further choices to be taken later (Hardaker et al., 1997) as conceptualized in Figure 3 for one growing season. In Figure 3 it can be seen that different considerations for the farmer are important at different moments in time. Any modelling approach based on just one of these considerations is likely to miss important aspects of farmer decision making and thus leading to the wrong results. For example, any approach optimising cropping mix on the basis of profit maximization will lead to results not observed in reality. Farmers at the start of the cropping season are not sure about prices received at the end of the cropping season and profit maximization might not be an important objective in the first place (maybe farm growth is more important).

[7] A subdivision is made in two types of risk, non-embedded risk and embedded risk (see also section 5.3.2. risk and uncertainty). Embedded risk is risk that the farmer can respond to by sequential decision making, thus making adjustments to his farming practices within the cropping season (Dorward, 1999)

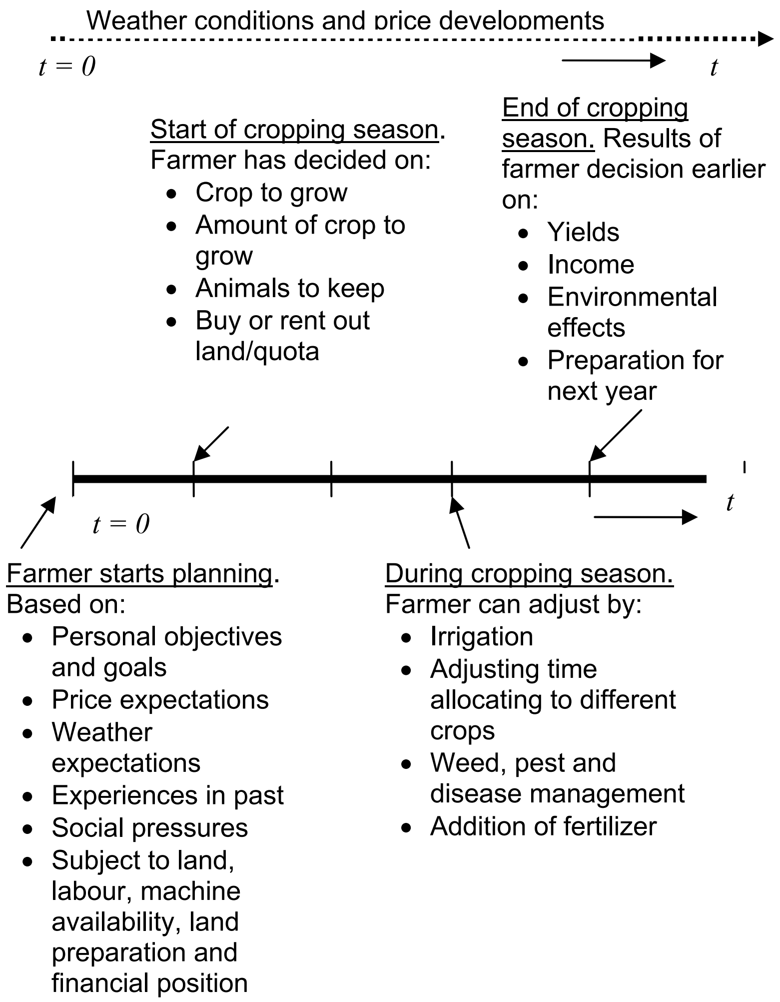

Figure 3: A conceptualization of farmer sequential decision making during the growing season

Dorward and Parton (1997) give four necessary conditions that must hold, if modelling of sequential decision making and embedded risk is to be warranted and worthwhile in a particular situation:

- there is uncertainty regarding quantities or prices of outputs or inputs
- there are opportunities for making tactical responses to unfolding information as it becomes available during a season
- uncertainty and tactical responses to uncertainty affect scarce resources
- there are limited opportunities for using markets to maintain resources (especially labour and capital) to the farm in sufficient quantities and at sufficiently low cost to allow a fixed pre-seasonal plan to be profitably implemented

Furthermore Dorward (1999) suggests that modelling embedded risk and sequential decision making may not be extremely relevant in cases in which farmers have access to effective capital and other input markets (like labour) as these farmers will be able to maintain ‘ideal’ production activities by hiring in resources from outside the farm in case of unfavourable conditions occurring. Modelling embedded risk and sequential decision making will thus be relevant in the case in which farmers do not have good access to these resource markets (Hardaker et al., 1997). Pfister et al. (2004) modelled resource decisions of poor farmers in Nicaragua with a one year model and a time resolution down to the level of days. They argue that it is vital to consider time aspects for resource-poor farmers to understand their decisions (which at first might seem disadvantageous). These farmer decisions can be understood if the seasonal variations and oscillations in labour availability, fertilizer application and credit availability can be understood.

The construction and calculation of models incorporating embedded risk and sequential decision making by the farmer are data and labour intensive, so the extra effort and costs should be worthwhile (Dorward, 1999). These models are so data and labour intensive, because the size of a sequential decision problem increases rapidly (Hardaker et al., 1997):

- when the number of periods in the sequential decision making process increases;
- when the number of choice options at each decision increases;
- when the number of possible outcomes at the end of each period increases.

To make the models not over-intensive for data and labour, the modeller should try to limit the number of time periods, the number of choice options and the number of possible outcomes.

Whether or not to model sequential decision making, thus depends primarily on the influence sequential decision making can have on model results: can it help the farmer to maintain his income? Will it influence the structure of the activities on the farm? What are the options the farmer has at hand in responding (access to labour and land markets)? If one assesses on the basis of these questions, that sequential decision making can have an important effect on model results and one has the data and labour resources available, then sequential decision making should be taken into account.

Once established that one wants to model embedded risk, there are different methods to do this:

- Dent (1990) proposes the use of expert systems, which is a computer structure incorporating expert human reasoning which will reach the same conclusions as a human expert would when working with identical data. An expert system attempts to formulate the rules by which experts proceed in decision making situations (Dent, 1990). Expert systems are also mentioned in the context of modelling the social milieu of the farmer in Section 4.4.2.
- Discrete Stochastic Programming (DSP) in which the year is divided in several time periods and in each time period several states of nature are possible according to decisions taken at the beginning of the time period and according to uncertain events. A simple mathematical formulation of two period DSP model is given by Hardaker et al. (1997):
  Max E[Income] = p_t Income(z_{2t})
  Subject to: $A_1x_1 \leq b_1$
  $L_{1t}x_1 + A_{2t}x_{2t} \leq b_{2t}$
  $C_{2t}x_{2t} - I_{2t}z_{2t} = f_{2t}$
  and $x_1, x_2 \geq 0, t = 1, \ldots, T$
  Where subscripts 1 and 2 indicate first- and second-stages; the subscript t indicates the state of nature; p_t are vector are 1 by s vectors of joint probabilities of activity net revenue outcomes given that state of nature t has occurred; L_{1t} is a set of s matrices linking first- and second-stage activities; C_{2t} is a matrix of activity net returns at the end of the second time period.
  The more periods and states of nature are added, the more complex DSP models become and the larger the models get. Hardaker et al. (1997) conclude that DSP models are able to model risks in both Technical Coefficients and constraints, thus reflecting embedded risk. Furthermore they add that if DSP is being used it is usually relatively trivial to

extend the DSP model to include non-embedded risk, even if risk aversion is important.

An application of a two time period DSP is described by Vatn et al. (2003), who come up with the following procedure with two time periods to link sequential decision making to year-to-year weather variability. Firstly, the researcher models the expected developments of natural processes of importance for farmers' choices and decisions made by the farmer on the basis of these expected developments. (For example the farmer at the beginning of the cropping season expects average year weather conditions (Vatn et al., 1997)). Secondly, the agronomic/ecological models can be run with the farmers' decisions and the actual developments of natural processes giving the actual outcomes. At the start of the second time period, the farmer has different expectations based on the weather so far, so again his decisions can be modelled on the basis of expected developments and the actual developments are modelled in a consecutive second step. In this second time period the farmer might or might not choose for certain actions (like irrigation or a second round of fertilization). A model thus takes sequential decision making into account by using observed weather data and estimating farmers' weather expectations at different moments in the cropping season.

- Semi-sequential Programming (SSP) is a simpler form of DSP (description based on Dorward (1999)). Instead of several time periods in one year, some adverse states of nature are defined over the entire year. Activities in these adverse states of nature are constrained activities (less yield and lower input use) as compared to activities in favourable states and borrowing in the favourable states is constrained borrowing as compared to the borrowing in adverse states (when adverse conditions occur, farmer needs to borrow more). The activities in the adverse states of nature are a core set of 'safety activities' while other activities can be formulated as incremental improvements from these safety activities. Dorward (1999) concludes that the DSP approach yields better results as the SSP approach, because resources can be reallocated between activities (instead of withdrawal of resources in case of adverse states of nature) and because of more flexible capital structure of the model (savings can be made in favourable states of nature).

Although taking into account sequential decision making can bring model more closely to what actually happens in reality, it is data and time demanding to construct such models. Also, as noted by Hardaker et al. (1997), these models tend to become complex easily. This limits their usefulness in reality, especially if the researcher aims to develop a simple model with low data needs.

4.3.6 Modelling over several years

By modelling over several years, strategic decisions by the farmer, long term effects of practices with adverse environmental effects and weather variability can be taken into account. Firstly strategic decision making, long term effects of practices with adverse environmental effects and weather variability will be shortly explained and secondly some dynamic models will be further explained.

Strategic decision making are the decisions affecting the farm system over the long term. According to several authors (Csaki, 1977; Hardaker et al., 1997; Wallace and Moss, 2002) it is of vital importance for the performance of the farm system for the farmer to get these decisions right. These decisions are usually the 'big' investment decisions. As investment usually yield returns over many time-periods and have a large effect on the performance of farm systems, they need to be taken account in a model trying to explore options for the future. As demonstrated also by Wallace and Moss (2002) for farmers it is important to get the strategic decisions right that influence the attainment of their long term objectives like minimising borrowings or sustaining farm growth. Following Csaki (1977) investment is dependent on the availability of investments (dependent on the capital market and the capital position of the farm) and the need to invest. Part of the profit can be re-invested into the farm (Csaki, 1977) and investments contribute to the fixed costs of the farm. Once the investments are made, these fixed costs have to be paid and a farmer cannot easily move away from his investments. Return on investments can be assessed in a dynamic model at the end of the whole time period. In assessing different alternative activities, the investments needed for these alternatives have to be considered over the time period in which this investment is paid back as only in this way the optimal activities can be found. For example, if a farmer decides to grow an alternative crop, he might need to buy harvesting machinery, which requires a serious investment. In the short run it might seem advantageous for the farmer to make this investment as his income will be higher, however, there might be losses (due to prices going down as farmers adopt the technology) at the end of the pay-back period leading to less favourable returns on investment. An investment in other machinery could have more favourable returns on investment. Investment in machinery and buildings should be modelled with integer variables (e.g. 0, 1, 2 tractors) and not with real variables (Thompson, 1982). The incorporation of real and integer variables in one model is called mixed integer programming (Thompson, 1982).

Long term effects of practices with adverse environmental effects are related to problems of erosion, eutrophication, soil organic matter depletion, pesticide accumulation etc. These long term effects can lead to yield decreases after several years together with all sorts of environmental problems. By running the BEFM over several years with biophysical models that are able to model the relevant agronomic, environmental and ecological processes, these long term effects can be detected. ‘User cost’ is the amount of income forgone in the future due to unsustainable practices that reduce the future output of the agro-ecosystem (Pandey and Hardaker, 1995).

Agronomic performance and environmental effects are highly dependent on weather conditions during the year (Calker et al., 2004). Modelling with average weather data ignores this dependence and thus makes models less sensitive to extreme results. Also, modelling with average data assumes risk neutrality (Thompson, 1982), as natural variation is the source of risk and uncertainty. Gibbons et al. (2005) succeeded to model temporal variability (e.g. weather) by running the model with observed data of a time period of 10 years. They conclude that not in all the years the required reductions (in nitrate loss) could be attained and thus weather variability should be taken into account (especially rainfall). Gutierrez-Aleman et al. (1986) modelled ‘good’ and ‘bad’ years in terms of rainfall by adding or subtracting half standard deviation to the average rainfall levels. They found that higher variability in farm income was caused by variation in weather conditions than by changes in levels of technical efficiencies of sheep and goat production. Another option to model weather variability is to include three type of years (wet, dry and average) and link a probability to their occurrence as described by Donaldson et al. (1995).

Wossink and Renkema (1994) modelled the development of the family farm limited by behavioural constraints over time. Wossink and Renkema (1994) did this by coupling a farm continuation model and an innovation adoption module to their LP model of Dutch arable farms (they decided to leave out family consumption, as this was found to be constant over time for Dutch farming families.). Within the model the continuation of the farm or the adoption of an innovation was dependent on the age of the farmer, the size of the farm and the amount of information a farmer has about an innovation.

Hardaker et al. (1997) identifies three dynamic modelling methods for taking account of time over a period of several years:

- Deterministic/stochastic dynamic programming (DDP/SDP): a mathematical optimization technique for solving multi-decision problems, developed by Bellman (1957) (in Hardaker et al. (1997)).
  - The objective function of the DDP is:
    $\text{Max } V_1(X_1) = g[\, r_1(X_1, a_1), r_2(X_2, a_2), \ldots , r_T(X_T, a_T)]$
    It is difficult to optimize this objective function simultaneously, Bellman (1957) (in Hardaker et al. (1997)) 'decomposed' the objective function into T one time period optimizations. The objective function then becomes:
    $\text{Max}_{at}\, V_t(X_t) = g_t\, [[r_t(X_t, a_t)], V_{t+1}(X_{t+1})]$ for t= T-1, … , 1
    This is only possible if Bellman's principal of optimality is met (Hardaker et al., 1997): an optimal decision at any stage can be found provided that all subsequent decisions with regards to the state resulting form that decision are also optimal.
  - The objective function of SDP is:
    $\text{Max } V_1(X_1) = g[E[r_1(X_1, a_1, k_1)], E[r_2(X_2, a_2, k_2)], \ldots , E[r_T(X_T, a_T, k_T)]]$
    Which can also be decomposed, however this decomposition is not give here.
- Dynamic probabilistic simulation: this technique can used if the interest is not in the optimization over the total number of time periods, but in the development of a stochastic process over time, especially a Markov-chain, for example the spread of a certain crop. A Markov-chain is characterised by the fact that the condition of the system in t = j does not depend on the time periods the system passed through in the time periods before t = j. The transformation function than describes the probability that the system will be in a certain condition if the system moves from time period i to j. The dynamic probabilistic simulation thus moves forward from one time period to the next and each time the system conditions can change subject to certain probabilities.
- Monte Carlo simulation: the behaviour of the system is modelled time period after time period. The transformation from one time period to the next is based on a random draw from a probability distribution and on the decision taken. This process is run repetitively with several iterations for the whole number of time periods. After a large number of iterations the outcome of the simulation and the sampled values become distributed in a similar way as the probability distribution from which the draws are made.

There is a strong correspondence between the type of objective function chosen (see Section 5.3) and whether or not the model is made dynamic. The objective function chosen determines to some extent approach taken to make a model more dynamic. DSP and SSP approaches are relatively simple and do need much iteration or probability distributions and they offer a mechanistic functioning of the dynamic model. Recursive dynamic modelling seems the most appropriate model type, as recursive and inter-temporal models tend to leave out either the optimization over the whole period or the decision making on the basis of years.

4.3.7 Multi Criteria Decision Making

'A rather common attitude among agricultural and natural resource analysts, especially economists, towards Multi Criteria Decision Making (MCDM) methods can be summarized as: Why bother with new approaches?' (Dent and Jones, 1993)

'After all, as some authors have pointed out, the choice of a particular MCDM approach is in itself an MCDM problem!' (Rehman and Romero, 1993)

Multi Criteria Decision Making (MCDM) refers to a collection of different approaches to take more than one objective into account (Rehman and Romero, 1993). An overview of MCDM approaches is provided by Rehman and Romero (1993). The MCDM models either incorporate the multiple objectives in the objective function or optimise one objective, while taking the other objectives as constraints or optimizing farm profit, while taking the other objectives as externalities of the maximization of profit. A short description of the most frequently used approaches is given below:

- Multiple Goal Linear Programming approach (MGLP). The MGLP procedure consists of a number of optimisation rounds, in each of which all the goals are optimised one by one, while the constraints on the other goals are increasingly tightened (Zander and Kächele, 1999; Ten Berge et al., 2000). After a number of optimisation rounds a Pareto efficient solution can be found, in which an increase of the achievement of one goal leads to the decrease of the achievement of another goal (Rehman and Romero, 1993; Louhichi et al., 1999).
- Weighted Goal Programming (WGP): more objectives can be optimized simultaneously through the specification of targets for each objective, with the overall objective to minimize deviations from those targets (Wallace and Moss, 2002; Weersink et al., 2004), for example MOTAD (Minimisation of Total Absolute Deviations; see Section 4.3.2) (Oglethorpe, 1995). A sample structure of a WGP is given by Wallace and Moss (2002):

  Minimise $L = w^{-`} d^{-} + w^{+`} d^{+}$
  Subject to: $ax \leq b$
  $hx + d^{-} - d^{+} = G$
  $x, d^{-}, d^{+} \geq 0$
  $d^{-`} d^{+} = 0$

  Where w^{-} and w^{+} are vectors of p weights, d^{-} and d^{+} are vectors of p under- and over-achievements, and G is the vector of objectives target levels g_k for the p decision criteria (objectives). H is the p × n matrix of coefficients relating the decision variables, x_j to the objective targets. $ax \leq b$ represents the usual set of resource or production constraints.
  A compromise set of solutions is a set of solutions which are closest to the ideal solution of one of the objectives (Louhichi et al., 1999). WGP is based on a Simonian 'satisficing' (Simon, 1955, 1957, in Rehman and Romero (1993)) instead of an 'optimising' approach, as the decision-makers set targets for their objectives, which need to be satisfied (Rehman and Romero, 1993; Wallace and Moss, 2002).
  One weakness of WGP is the nature of the objective function. If the weights w_i are interpreted as measures of the relative preferences attached to each goal by the decision-maker, then the objective function represents an additive utility function (Wallace and Moss, 2002). To estimate this utility function for each individual decision maker would be a lot of work and very costly. Thus the objective function is a compromise to achieve an approximation of the goal structure of the decision maker (Wallace and Moss, 2002).
- Lexicographic Goal Programming (LGP) is a form of WGP, but instead of the weights being relative as in WGP the weights are absolute or pre-emptive. These absolute weights are achieved through a prioritization of the goals (Rehman and Romero, 1993). In the optimization the high priority goals are resolved before the low priority goals are considered (Rehman and Romero, 1993). An example of LGP is Dorward (1999)
- Modelling environmental effects more as externalities, rather than as objectives in themselves. (This resembles MGLP; only with MGLP the externalities can be included one by one in the objective function in subsequent optimizations). Pacini (2003; chp. 7) instead chose to use the regular profit maximising assumption, as in his model environmental benefits arise as joint-outputs from agriculture and as he uses a specific structure of abatement technologies. The same is done in the MODAM model developed by Zander and Kächele (1999). An example of a mathematical formulation is (Schuler and Kachele, 2003; Meyer-Aurich):

Max Farm Gross Margin $= \sum_{j=1}^{n} c_j x_j$

Subject to: $\sum_{j=1}^{n} a_{ij} x_j \le b_i$

and $\sum_{k=1}^{n} d_{kj} x_j \le e_k$; $x_j \ge 0; i = 1, ..., m; j = 1, ..., n; k = 1, ..., o$

with c_j gross margins of the production activity *j,* x_j is the quantity of productions activity j, a_{ij} is the amount of input i necessary for each production activity, b_i is the total available quantity of input, d_{kj} is the environmental impact k of the production activities j measured with an agri-environmental indicator and e_k is the maximum tolerable value for the environmental impact k. This maximum tolerable value e should be established by society. The abatement costs of the farm are then the costs, or loss in income to achieve this maximum tolerable value (Meyer-Aurich, 2005).

- Near Optimal Linear Programming (NOLP; Jeffrey et al., 1992; Weersink et al., 2004): an applied modelling approach producing solutions that are not optimal respect to any one objective, but instead are somewhat or 'nearly' optimal for all objectives.
- Compromise Programming (Yu (1973) and Zeleny (1973) in Rehman and Romero (1993)). In Compromise Programming first an Ideal Point is defined as the optimum value of different objectives given the constraints of the model and the preference of the decision maker (Weights elicited from the decision maker). Then, the efficient solution closest to this Ideal Point is the best compromise solution. A set of solutions within a certain 'distance' from the ideal point is the compromise set. Compromise Programming is first using a weighted approach to establish the Ideal Point and then nearly-ideal solutions to come close to this Ideal Point. It can thus be understood as a combination of Weighted Goal Programming and Nearly Optimal Linear Programming, both of which are discussed above.
- Multi-attribute Utility Functions (MAUT) (Keeney and Raiffa, 1976 in Rehman and Romero (1993) is an approach in which a multi-attribute utility function is assumed for the decision maker or elicited from the decision maker, which can then be used to order a set of finite alternative solutions to the multi-objective problem. Several problems exist with this approach. One problem is the assumption of preferential independence (meaning that the decision maker does not have a preference of one alternative to go together with another alternative) (Rehman and Romero, 1993). Another problem is estimating the separate utility functions for each objective and then attaching weights and scales to them in the additive utility function (Rehman and Romero, 1993).
- Outranking (Strassert and Prato, 2002) is a procedure of several steps in which potential activities are compared in their achievement of several objectives. One activity outranks another activity for one objective if its objective value is higher. By building up an outranking matrix, all activities can be compared for the number of times they outrank other activities and a set of nearly optimal activities can be selected. An ultimate decision of the optimal activity is consequently based on priorities of the decision maker in comparing the different nearly optimal activities

An important difference between MGLP and WGP (and LGP) is that the objectives in WGP (and LGP) all have to be in the same units as they are aggregated and one single optimization is run, while in MGLP the objectives can be in different units as the trade-offs between the objectives are of interest (Van Ittersum, 2004). Another difference is that in the case of

MGLP the stakeholders decide the levels of the constraints, while in GP targets and weights for the different objectives are established by the stakeholders.

The choice of an MCDM model depends first of all if either a normative or a positive approach is used. A MGLP is better suited for a normative approach as it can potentially happen if different objectives are achieved, while WGP suits a positive approach better as it uses a weighting and the same units are added to objectives and it can be seen how much of each objective will be realised in reality. Rehman and Romero (1993) conclude that it is depends on the number of objectives and the constraint set whether to choose for WGP or MGLP. MGLP works well with two or three objectives and a relatively simple constraint set, while WGP can better be used with many objectives and a large number of constraints and decision variables. NOLP in turn is not dependent on pre-defined values by the stakeholders, but the stakeholders can afterwards assess trade-off curves of different sustainability indicators (Weersink et al., 2004).

The choice of the MCDM model thus depends on the objectives of the study. If one is working with stakeholder groups each prioritizing different objectives, MGLP might be the suitable approach. WGP and LGP might also be useful with several stakeholder groups, but also with one decision maker who can give his weights. The problem remains of getting everything in the same units. The approach by modelling of environmental objectives as externalities seems closest to what is actually happening in society and might thus be more suitable to discuss trade offs with policy makers. Multi-Attribute Utility Functions and Outranking approaches are rather time and resource demanding, and have some associated methodological problems.

4.3.8 Application of the different approaches

In the 33 model studies incorporated here, different objective functions were used in line with the different approaches described above. 19 studies used a simple measure of profit (income, net revenue etc) maximization, 3 studies used a measure of profit maximization minus some risk factor, 3 studies used an objective function that maximized utility, 6 applied a MCDM approach and 2 incorporated strategic objectives into the objective function. Logically, it depends on the objective of the modelling study and whether a normative or a positive approach is taken, which objective function is used. Generally speaking, there seems to be potential for the improvement of the objective function with regard to risk and strategic objectives the farmer might have.

4.4 Production activities

As defined in Section 1.2.3 a production activity (Ten Berge et al., 2000) is a coherent set of operations (also called 'production technology') with corresponding inputs and outputs, resulting in e.g. the delivery of a marketable product, the restoration of soil fertility, or the production of feedstuffs for on-farm use. An activity is characterised by a set of coefficients (Technical Coefficients or input-output coefficients) that express the activity's contribution to the realisation of user defined goals (or objective in modelling terms) (Ten Berge et al., 2000)

4.4.1 Constructing activities

In the construction of production activities, three steps have to be taken: construction of all currently used activities and alternative activities to be modelled, design of the production technologies (related to for example conventional or integrated or organic production technology) and the estimation of Technical Coefficients for the activities. These steps, however, are usually intertwined to a large extent and can not be fully separated. With the goal-oriented approach, Hengsdijk and van Ittersum (2002) developed a conceptual approach to the design of a manageable set of alternative land use systems. The goal-oriented approach describes the application of the three steps mentioned above to the process of designing suitable activities for future-oriented studies:

1. goal-oriented identification and design of land use systems: output-oriented approach of estimating the inputs needed to achieve a certain output.
2. quantification of biophysical production possibilities: estimation of production possibilities based on knowledge of the underlying processes for each of the combinations between physical environment and crop or animal type.
3. defining the optimal mix of inputs required to realize production possibilities: 'the art of finding the technically optimal combination of inputs to realize particular target outputs, which is often called the best technical means' (Hengsdijk en Van Ittersum, 2002).

An important decision in the construction of activities is whether to choose a input-oriented or an output oriented approach. In the input oriented approach outputs are calculated from the amounts of inputs used, while in the output-oriented approach the inputs are derived from the level of outputs aimed for, often at a high resource use efficiency (in line with the goal oriented approach). In the subsequent Section 4.4.2 the output oriented approach (target oriented approach) will be further discussed. In models that should closely simulate actual farmer behaviour (positive approach) an input oriented approach is more likely, as then the estimated outputs can be easily compared to observed data on outputs.

Production activities might be modelled at different levels, for example at crop, rotation, herd or livestock unit-level. It depends on the objectives of the study, on the specialisation of the modeller and on the level on which the rest is of the BEFM is constructed, which level is preferable. Potential advantages of modelling at rotation and herd level are that:

- at the rotation and herd level interactions between crops and age classes of animals do not have to be considered in the BEFM. These interactions are accounted for by the construction of the rotations and herd structure. Preferably the initial conditions (for example soil nitrogen) at the start of the time-period (for example rotation) are equal or worse to the conditions at the end (Hengsdijk and Van Ittersum, 2003). Otherwise, the natural resources of the farm are slowly used without replacing them and this is not adequate to sustain production. For example soil mining could occur, leading to decreasing yields. Here, a potential tension between the static nature of many BEFMs and reality is encountered. In reality, farmers might choose unsustainable practices. So by modelling at herd or rotational level temporal effects can be taken into account in a static model (see further Section 4.3.3). The activities should finally include also practices judged as agronomical unsustainable, which however could turn out to be superior from an economic point of view.

- modelling at the rotation and herd level usually leads to a simpler structure of the BEFM as interactions across crops and animals do not need to be modelled via the LP model. For example, when modelling at the crop level the BEFM could design all kinds of crop rotations and the BEFM should filter out infeasible crop rotations through constraints. When modelling at the rotation level the BEFM stays simpler as the choice is made from a set of feasible rotations (because the researcher can exclude rotations that are not feasible in agronomic terms *a priori*).

In the model studies reviewed, modelling at crop and livestock unit was more popular than modelling at rotation level, of the 27 models reviewed 17 were at crop and livestock unit level, while 10 were at herd and rotation level. Often the studies at crop and livestock unit level used agro-ecological simulation models. These agro-ecological simulation models can also be used with crop rotations, but then an intermediate tool has to be used to construct the crop rotations (see Section 4.4.4).

Production activities in BEFM are quantified by Technical Coefficients (TCs; also input-output coefficients), which state the amount of inputs needed to achieve certain outputs and the consequent environmental effects. TCs are discrete estimates, meaning that they are point-estimates relating fixed amount of inputs to fixed amount of outputs, for example if a farmer gives 100 kg of N fertilizer per hectare and irrigates 2 times, the yield will be 6 tonnes per hectare and a 10 kg per hectare of N will be leached. In the estimation of TCs, the modeller is not interested if the use of an additional 10 kg of N fertilizer per hectare would lead to 6.3 tonnes of yield. Theoretically, instead of TCs continuous production functions could be used, which describe the non-linear relation between output and certain levels of one input. Through the use of TCs synergy effects between inputs and outputs can be taken into account and so one can avoid problems of linearity of LP.

Next to synergistic effects, TCs take account of the non-convexities of production and pollution as explained by Flichman and Jacquet (2003). If a single crop is considered and one input, the response curve of crop yield (and thus the response curve of the income) to an increase in the use of the input is convex. However, if several inputs and crops are considered together with several production technologies, the response curve of income and pollution levels can be non-convex. This can be explained by changes in the use of production factors and technologies (Flichman and Jacquet, 2003). For example, at low levels of nitrogen input a farmer might plant a variety A which produces well at low nitrogen levels. When the farmer raises his nitrogen input (due to declining prices), he changes from variety A to variety B, which uses nitrogen more efficiently and has higher levels of production. Thus the increase of costs for extra nitrogen input is more than off-set by an increase in yield leading to a net increase in income, and to a non-convexity in the response curve of income to input use (See figure 3). Also, due to a higher nitrogen use efficiency variety B might lead to a lower level of nitrogen leaching as variety A, thus creating another non-convexity.

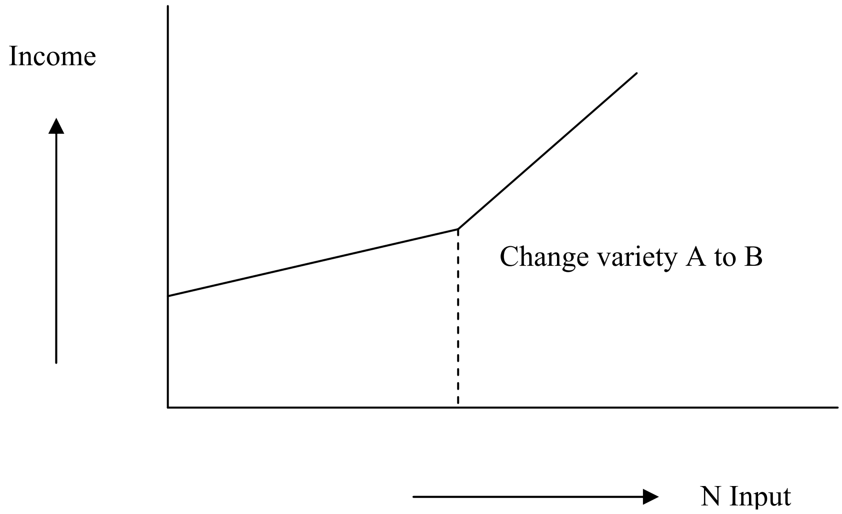

Figure 3: a non-convexity between output (income) and input (N input)

Non-convexities need to be included in any BEFM as they reflect the change from one production activity to another production activity and the interactions between inputs. With interactions between inputs is meant that different inputs become yield restricting; Input increases of one input will first trigger a yield increase, but beyond certain input levels further yield increases will not occur as another input has become restricting (De Wit, 1992).

Once one has decided at what level the activities will be modelled (crop, herd etc), one can start actually quantifying the activities and deciding which alternative activities need to be incorporated.

4.4.2 Technological innovations and alternative cropping and husbandry techniques

Activities which are not currently used, but might be a suitable alternative for the future are titled 'alternative' in the rest of this report. These alternatives are often technological innovations or newly developed cropping and husbandry practices.

Specific alternatives can be evaluated in a mechanistic BEFM. Whether or not the BEFM incorporates the alternatives in its optimum farm plan, is an evaluation of the suitability of the alternatives. However, in exploring what are potential options for the future, one cannot just include some specific alternatives. Then, a 'very' large number of alternatives need to be included, as this is the only way that BEFMs can find any potential cropping and husbandry techniques not yet conceived in practice (Ten Berge et al., 2000) and as input substitution possibilities can be incorporated in the different alternatives (Falconer and Hodge, 2000). For input substitution it is important that the alternatives are sufficiently 'different,' thereby allowing input substitution of, for example, different pesticides (Falconer and Hodge, 2000). Two types of inputs can be distinguished: primary inputs, which have an essential role in the growth and development of plants and animals (for instance, water and nutrients) and secondary inputs that have different roles (primarily facilitating) in the production process and can (to a certain extent) be mutually substituted based on the required objectives (Hengsdijk and van Ittersum, 2002). According to Hengsdijk and van Ittersum (2002) alternatives have to meet two conditions: they must be possible from a biophysical point of view and feasible from a technical point of view (although they may not be feasible at the moment). Their economic and environmental feasibility will be evaluated in the farm models.

The complete set of alternatives must comprise a variety of contrasting alternatives allowing to realize the different objectives (Hengsdijk and van Ittersum, 2002).

TCs for the alternatives also need to be assessed. Some of these alternatives have not been used in reality and no data are available on the Technical Coefficients. Thus, these have to be estimated by the researchers and different approaches of estimating these can be taken. Again a subdivision can be made between a normative and a positive approach in the estimation of the technical coefficients for alternatives. The normative approach is based on what is technically possible if all conditions are ideal; while the positive approach tries to model what would actually happen in reality. Two examples of normative approaches are discussed in the literature:

1. The Target Oriented Approach. In the target oriented-approach the production target is set by choice of the most limiting factor (based on an *ex ante* assessment of the socio-economic and bio-physical context; for example, water limited yield) and of the objectives and then the set of inputs to realize this target is defined (Bessembinder et al., 2000; Ten Berge et al., 2000; Hengsdijk and van Ittersum, 2002; Dogliotti et al., 2004; Van Ittersum, 2004). The target oriented approach is based on the observation that numerous combinations of inputs are possible to realize a given output, but that an efficient set of inputs can only be identified if the required objectives are explicit (Hengsdijk and van Ittersum, 2002). The target-oriented approach results in inputs being used with the highest technical efficiency according to the available knowledge and techniques and production being on the technically feasible production frontier (Ramsden et al., 1999). Production is then only limited by biophysical constraints, while social constraints are left out (Bessembinder et al., 2000). Social constraints are determined by society, for example the knowledge the farmers have, unemployment rate, or a certain dietary pattern. The target-oriented approach is a future-oriented approach (Hengsdijk and van Ittersum, 2002).
2. Meta-modelling. In order to develop a procedure of generating TCs based on continuous production functions Ruben and van Ruijven (2001) analysed a set of agro-ecological technical input-output coefficients (obtained from an agro-ecological simulation model) with regression techniques (a meta-regression model) to define continuous production functions. These continuous production functions can then be used in the optimization model. This procedure is called meta-modelling and has the following advantages according to Ruben and van Ruijven (2001):

   - Meta-modelling is meant to simplify the outcomes of simulation models with the objective of gaining better insight into the critical relationships within the simulation procedures.
   - Meta-models are used for the validation and verification of the robustness of simulations models
   - Meta-models are much smaller in size and can be used to replace the original simulation model in subsequent analyses.
   - The estimated functions still include all points of technical efficiency, but enable a more detailed analysis of the marginal effects.

   Disadvantages to this procedure (Ruben and van Ruijven, 2001) exist as (i) problems of over- or underestimation frequently appear, (ii) as it is difficult to model joint outputs in the meta-model (e.g. yields and nutrient balances), (iii) as the validity of the meta model depends on the correctness of the agro-ecological simulation model on which it is based (a model of a model), (iv) as there are rather limited possibilities to evaluate the robustness of meta models and (v) as it is difficult to assess multi-input/multi-product problems.

Ruben and van Ruijven (2001) compared their Response Multipliers (RMs) of the BEFM obtained via a meta-modelling procedure with the Response Multipliers obtained via a procedure based on agro-ecological simulation models (Kruseman and Bade, 1998). The RMs of Ruben and van Ruijven (2001) are well below the RMs of Kruseman and Bade (1998), because agro-ecological simulation models overestimate the farm household response due to the discrete nature of technical input-output options and the non-linear nature of the meta-modelling specification gives rise to smaller adjustments in line with the marginality principle(Ruben and van Ruijven, 2001).

Problem with the above normative approaches is that one is not sure that the technological innovation or alternative activity will really perform up to the level estimated by the researcher. Of course, the assumption that technological innovations will be used to their maximum efficiency is a strong one and this probably will never happen in reality as there is always something hindering optimal resource use. If one is interested in what might really happen in reality, a positive approach has to be used. Unfortunately, a discussion in the literature of a positive approach in the estimation of TCs for new activities is lacking. A useful concept in this context related to crop yield is hierarchical production levels (Van Ittersum and Rabbinge, 1997): the potential yield level (yield limited by growth defining factors (light, temperature)) limited yield (yield limited by growth limiting factors (water and nutrients)) and the actual yield (yield limited by growth reducing factors (pests and diseases)). The normative approach towards the estimation of TCs could be at the ‘potential’ or ‘limited’ yield level, while the positive approach tries to estimate the ‘actual’ yield levels.

In conclusion, it is important that the researcher is aware of the limitations of the data and approach he chooses for quantifying the alternatives. If his interest is in discovering what is possible in the long term, then he can use a more normative approach based on technical feasibility. However, if his interest is in what are good alternatives for use in the near future given the current situation, then he will have to use a more positive approach and try to use estimates for his TCs that are close to the ‘actual’ performance in reality. He always needs to be aware of the potential gap that exists between the model outcomes and reality with regards to for example yield levels and adoption percentages of alternatives.

4.4.3 Estimating TCs

For current activities TCs can be based on observed data from farms, surveys or national statistics agencies. This depends on the similarity of circumstances, in which the observed data were measured and to which the BEFM should apply. If a reseacher is constructing a BEFM for an existing farm, he might use estimates of TCs in observed data from previous years for that farm. If no data are available in the desired detail, experts with good knowledge of input and output relations in the study area (e.g. farmer or scientists with long term experimental and on farm experience) can be asked for their estimates of TCs (as done by Zander and Kächele (1999)).

In order to construct TCs for alternatives, researchers might do a literature search and find information or might ask experts for their judgement. Alternatively, he can use advanced statistical methods extrapolate TC values for alternative activities from current activities. Another approach is to let agro-ecological simulation models estimate the TCs. Ruben and van Ruijven (2001) sum up the advantages of the use of agro-ecological simulations models:

- They are based on a detailed understanding of how production conditions and farming practices influence yield levels.
- They explicitly address interactions between cropping and livestock activities.
- They provide clear insight into the locally relevant limiting factors for increasing yields or reducing nutrient balances

Agro-ecological models make use of the mathematical representation of processes, which are the laws of nature (Flichman and Jacquet, 2003). These models also take the effects of cultivation, of crop rotations and on ecosystems into account (Flichman and Jacquet, 2003). Agro-ecological simulation models take account of synergy effects that exist between input use, soil management practices and soil characteristics (Ruben and van Ruijven, 2001).

4.4.4 Number of activities

Immense numbers of activities can potentially be incorporated, for example over 100,000 crop rotations can be generated if 15 potential crops can be grown on a certain farm. The number of activities is commonly reduced to a feasible number based on expert judgement. This dependence on expert judgement poses the risk of missing out on activities that experts could not think of or would disapprove of (because activities are considered agronomically inferior, while possibly being economically superior), thus limiting the solution space and feeding arbitrariness (Dogliotti et al., 2003). This risk is also noted by Hengsdijk and van Ittersum (2002), who found that many land use studies hardly discuss the underlying data and concepts used for the description of activities and choices concerning the type of activities that are considered are not made explicit. To counter this risk, Dogliotti et al. (2003) developed a tool (ROTAT) to generate all possible activities (e.g. crop rotations) and then reduce them to a feasible number of activities by the use of filters. These filters represent expert knowledge, agronomic and sociological theory and facts.

A wide range of alternative activities can be incorporated, however continuous production functions are not used for the analysis of the choice among current activities and alternatives (Ruben et al., 1998). This might make it difficult to find sub-optimal or second best solutions (but optimal from the point of view of the farmer) as the activities related to this sub-optimal or second best solution are just not among the alternative activities incorporated by the researcher in the BEFM. This is a danger a researcher has to be aware of when building his BEFM and an extensive sensitivity analysis on the activities should be able to find these effects.

The limitations of missing out suitable alternatives due to expert judgement and missing out suitable second-best optima can both be accounted for in the construction of the model. By incorporating more activities, which also have non-maximum output levels and which are less input intensive, second-best optima might be found. The selection of the activities from all possible activities should in turn be based on agro-ecological principles to avoid arbitrariness.

4.5 Comprehensiveness

'That so much is appreciated and quantified about the physiology of a crop plant and so little about the social system in which it is but one of many sub-systems seems to be contrary to systems thinking.' (Dent, 1990)

4.5.1 Holistic approach

Many of environmental-economic modelling studies that advocate a systems approach lack a holistic interpretation of the farm ecosystem (Pacini, 2003; chp. 5). Pacini (2003; chp. 5) further adds: 'the omission of information on many environmental aspects can lead to serious misjudgements in the multi-objective policy-making process and conflicts between different government programmes or regulations.' A point here raised by Pacini (2003) is that the aspects included in a BEFM should be in line with the objective of the BEFM. If a researcher wants to contribute to the multi-objective policy making process, than he should make sure all objectives are adequately modelled. Here, a problem is encountered as a farm is organised differently than science: in a farm the social, economic, agronomic, environmental and institutional aspects are fully integrated and dependent on each other. Contrarily in science these aspects are divided and studied from a disciplinary perspective. A BEFM that is weak in one of these disciplines is likely to lead to wrong results.

Constructing a BEFM thus requires integrating scientists from different backgrounds in an inter/multi/trans-disciplinary set up. A major difficulty is ensuring consistency of data between disciplines, as different disciplines tend to use different spatial and temporal units of analysis (Flichman and Jacquet, 2003; Weersink et al., 2004). In the model studies here reviewed in some cases it was obvious that the researcher modelled one aspect of the model more in depth (his specialisation) than other aspects of the model, which were less his specialisation. For example, Dogliotti et al. (2003) focused on the development of a tool for modelling crop rotations (taking a bio-physical interest), while Wallace and Moss (2002) modelled five different objective functions of farmers (taking a socio-economic interest). Some examples exist where the integration between disciplines was tried, for example Donaldson et al. (1995) (who coupled EPIC (an agro-ecologic simulation model) to a dynamic recursive LP model) and Vatn et al. (1997) and Vatn et al. (2003) (who developed the model framework ECECMOD, consisting of a set of sub models for generating information for the farm model). Of course, this also depends on the aim of the study.

As BEFMs should be constructed in a multi-disciplinary team of scientist, the tasks different disciplines should carry out can be divided. According to Anderson et al. (1985) the socio-economists tasks compromise:

1. The social milieu in which farm decisions are made
2. The institutional setting and policy environment in which farming is conducted, including details on land tenure, credit and taxation.
3. The economic environment of farms including long-term market prospects for inputs and outputs and, most importantly, understanding of the opportunity costs and transactions costs faced by farmers
4. The attitudes, aspirations and personal constraints of farmers, including their desire or otherwise for change, for leisure, for education, for different foods and so on, and their human and other capital.

Of the four above mentioned socio-economic activities the third task is discussed to some extent in Section 4.3 on farmer decision making and the second task is discussed by constraints and the structure of activities in a BEFM. However, the other two tasks (number one and four) have not been encountered explicitly in literature. These tasks involve modelling the sociological issues and the interactions of the farmer with other groups. Berger (2001) tried to model transaction costs and the influence of the other farmers on a farmer to some extent, but does not go as far as to include the entire social milieu or personal preferences of the farmer for one task or the other. Some comments on the first and fourth task are provided in Section 4.5.2 on decision making within farm families.

Next to the socio-economists, contributions should come from agronomists, ecologists and livestock specialists. The importance of the agronomists, ecologists and livestock specialists is underlined by Belcher et al. (2004), who conclude that: 'The economic and environmental sustainability of the system is dependent on the biophysical constraints which determine the management options that are technically, agronomically and economically viable.' The tasks of the agronomist, ecologist and livestock specialist include:

1. modelling the responses of crop yields and animal production to changes in input
2. modelling the effects of agricultural practices on the biotic and abiotic environment
3. modelling the long term dynamics of soil fertility (for example soil organic matter, soil nitrogen) and the influence of weather variability
4. modelling the interaction and exchanges between farm enterprises (livestock and crops, crops and agro-forestry, different crop enterprises)

Some research has been done on almost all of these tasks and these are discussed in other sections of this report. Task 1 is partly discussed in Section 4.4; task 2 in Section 4.5.3; task 3 in Section 4.3.3 and task 4 in Section 4.4.

To facilitate working together with different disciplines, it is useful to work in a modular structure, as each discipline can construct one module. Other advantages of working in a modular structure are:

- that the non-separability between production and consumption decisions (Ruben et al., 1998; Ruben and van Ruijven, 2001) can be adequately modelled;
- that the sequential character of farm household production decisions are taken into account, as the modular structure permits the integration of information from different disciplines (Kruseman and Bade, 1998);
- that the BEFMs are more suitable for use in different locations (Ruben et al., 1998);
- that modelling procedures are kept transparent and data requirements can be better controlled (Anderson et al., 1985; Kruseman and Bade, 1998);
- that the separate validation and improvement of modules (Zander and Kächele, 1999) is possible.

Table 2 indicates which aspects of reality have been often incorporated (in the activities or constraints) and which aspects have been hardly ever incorporated in 36 model studies reviewed in this report. Clearly it depends on the objective of the research what is incorporated and what not. However, some aspects are more popular than other aspects, for example nitrogen is often incorporated, but more efforts could be made to incorporate transport, pests and diseases, off- and non-farm income, soil fertility as a constraint, soil organic matter, and biodiversity and nature, which have all been incorporated less than 10 times. In the following discussion some of these aspects will be further explored.

The construction of a BEFM has to be done in a multidisciplinary environment, with each discipline contributing its modules and working together on the integration between the modules. From the description of the tasks above, it is concluded that mainly the social and sociological aspect is lacking from the BEFM. In the next section a short discussion is provided to underline the importance of the social aspect and to explain shortly one potential type of model. In subsequent sections other aspects important for the comprehensiveness of a model are discussed, such as spatial heterogeneity and the new functions of agriculture. In the last section of this paragraph, the difficult balance between comprehensiveness and model development is shortly explained.

Table 2: Different aspects of a mechanistic BEFM and the number of model studies that incorporated it. (* = mainly nitrogen; ** = linked to rotational constraint)

	Aspects	number of studies
Activities	soil type/soil depth	14
	climate variability	10
	Soil Organic Matter	5
	Nitrogen balance	20
	Phosphorus balance	9
	Potassium balance	6
	Emissions	10
	Erosion	9
	Run off/leaching	15
	Biodiversity and nature	6
	Farmer time allocation	16
	capital availability	18
	off- and non-farm income	4
	input prices	30
Constraints	water supply	10
	nutrient availability	12*
	Slope	1
	soil fertility	5
	rotational constraints	19
	pest and diseases	6**
	transport	4
	labour/planning	16
	capital availability	11
	machinery availability	20
	regulations/laws and subsidy schemes	11
	Emissions	2
	Run off/leaching	4
	Erosion	1
	Use of inputs	8
	Production quotas	9

4.5.2 Social milieu of the farmer: farm families

The farmer often does not decide alone on how to react to policy and a potential technological innovation: he is influenced by his social milieu (Anderson et al., 1985). Maybe the most important elements of this social milieu are the other members of the farm family and farm families living in the neighbourhood. A similar observation is made by Wossink et al. (1992): 'For realistic modelling different categories of family farms are to be distinguished with regard to their financial and technical status.' But not only the economic background of the farm families is important, also social parameters like attitudes, values, traditions, peer group pressure and culture should be included (Dent, 1990). Ruben et al. (1998) argues that intra-household interactions need to be part of BEFM, as individual household members have different priorities, as access to resource is dependent on gender and age and as labour productivity is determined by the internal distribution of food (not an issue in temperate regions, but more in tropics). This is also underlined by Edwards-Jones and McGregor (1994) who state that the major obstacle in the development of whole farm models for European agriculture might be our ignorance of the fundamental processes on-going within the farm household.

Intra-farm household interactions should be incorporated in the objective function of a BEFM, however, so far no literature was found where it was tried to incorporate these intra farm household interactions. Potentially suitable objective function are an additive utility function, which adds up the utility functions of the individual household members or a constrained objective function which is constrained by certain basic goals other family members have that are entered as constraints (for example, family members each want to have their own riding horse on a dairy farm). Another option for the incorporation of intra-household interactions in a mechanistic BEFM is the inclusion of expert system instead of the objective function. Expert systems are computer programs based on artificial intelligence that try to simulate the decision making process of human experts (in this case, the farmer and other family members) (Dent, 1990; Edwards-Jones and McGregor, 1994). An expert system consists out of a set of IF/THEN rules, thus forming a computational description of human decision making. Generic descriptions for groups of farmers have to be made according to farmer typology, as not a specific expert system can be made for each farmer (Edwards-Jones and McGregor, 1994). Even these expert system models can learn from each other, thus creating parent and child-systems. An application of such an approach was found in Berger (2001), who developed an approach based on Multi Agent Systems and Cellular Automata to model these effects. (For a further discussion of MAS see Section 4.8).

4.5.3 Environmental effects

Environmental impacts are a result of agricultural practices (Oglethorpe and Sanderson, 1999; Flichman and Jacquet, 2003; Pacini, 2003; chp.5). This is also termed 'joint production' of agricultural outputs and environmental effects (Falconer and Hodge, 2001). A comprehensive BEFM should incorporate those environmental effects, which are relevant in a certain environment and have a clear relation to agricultural practices. Thus, in assessing if policies are effective in achieving certain environmental objectives, the changes in agricultural practices should be modelled. For example, Meyer-Aurich et al. (1998) developed environmental indicators for the abundance of amphibians and partridges as these species were relevant for the case study area and the agricultural practices had a clear effect on their habitat. There are less location specific environmental indicators such as soil erosion or N-leaching, which are used, for example by Meyer-Aurich et al. (1998), Berentsen (2003) and Pacini (2003; chp.3). A complete BEFM should account for the heterogeneity in space and time of environmental effects (Falconer and Hodge, 2000).

Most often these environmental effects are modelled through indicators. There are different ways to construct indicators. An indicator can be some variable in the model (for example, farm income), but it can also be compiled through the combination of several variables in the model. For example, the herbaceous plant biodiversity indicator was based on species cover of different species and field sizes (Pacini, 2003). Alternatively an indicator can be constructed in a procedure of scoring and weighting of sub-indicators to capture the effects of different types of the same input (for example pesticides). This type of indicator construction takes account of the problem that the practices and the environmental effects of these practices are very heterogeneous (Falconer and Hodge, 2001). For example, Falconer and

Hodge (2001) discusses this in relation to pesticide inputs: 'the diversity of pesticide inputs and their effects means there are no clear targets against which environmental quality improvements might be measured.' Falconer and Hodge (2001) constructed an indicator for pesticides based on 9 characteristics of those pesticides. For these 9 characteristics information was available on the label. Logically, often the indicator has to be measured by data collection in reality to provide insight into the current level of the indicator.

Comprehensive frameworks exist that enable the derivation and selection of a complete and meaningful set of indicators for a certain location, for example the Environmental Accounting Information System (EAIS) developed by Pacini (2003; chp.3). Indicator selection is done by considering the environmental effects at different levels within the farm: site, field and farm. For each of these levels relevant set of indicators can be compiled. From this set of relevant indicators, the most useful indicators in terms of objective of the study, worst environmental effects and data availability can be selected. Data availability is important to consider as there is a danger of severe data needs, consequent high costs of data collection and data maintenance work needed to supply these data (Pacini, 2003; chp.7), which could limit a successful construction of the model.

Environmental effects can also be modelled in other ways than via just environmental indicators. As mentioned by Zander and Kächele (1999) the different skills of the farmer to manage the environment and minimise the adverse environmental effects or the farmers awareness to environmental risks can be incorporated in the model. The environmental awareness of the farmer to environmental risk can be a part of a multiple goal objective function, as it is then assumed, for instance, that farmers not only maximise profit, but also minimise N-surplus on the fields. The skills of farmers to manage the environment in a none damaging way can be modelled in the structure of the activities. More environmentally friendly and efficient activities could be added if the farmer seems to have the right skills to adopt those. A difficult issue to tackle in this context is the difference between the farmers. One farmer might be aware and skilful to manage the environmental resources in the 'correct' way, his neighbour might not be at all skilful and aware.

When taking account of environmental goods, the models are usually supply-based, as noted by Oglethorpe and Sanderson (1999). The costs of the supply of an environmental good are known, which are the income losses of the farmer. What the public is willing to pay (by taxation) for this supply is not incorporated. Related is the absence (Meyer-Aurich, 2005) of a concrete estimation of off-farm costs of, for example, soil loss discussed in the public, thus optimal reduction in soil erosion is difficult to assess. A market module for environmental goods could be an elegant solution. The modelling system developed by Zander and Kächele (1999) supplies information on ecological and economic costs and benefits of agricultural practices with respect to socio-economic conditions by providing a complete set of trade-off curves (combined with sensitivity analysis) for all the different objectives taken into account in the MGLP model, like is done by Rossing et al. (1997) and Ten Berge et al. (2000).

In conclusion, indicators are a potent way to model the environmental effects as an outcome of agricultural practices. A shortcoming of an indicator is related to its nature: it is an aggregation over time and space, so extreme effects occurring in a specific field at a specific time are aggregated out as discussed in the next section. Two powerful extensions of a BEFM would the incorporation of potential environmental friendly behaviour of a farmer in the objective function and an estimation of the demand for environmental goods instead of only calculating the costs of supplying them.

4.5.4 Spatial heterogeneity

Farms mostly consist of a number of fields characterised by specific hydrological, soil and weather conditions (Zander and Kächele, 1999). However, these specific conditions are often not incorporated in the BEFM. Production decisions are usually taken at farm level, while the impacts of these decisions can occur at all levels. Impacts at higher levels need to considered when scaling up a model, and impacts at lower levels (field or site) should be included in a BEFM as noted by Pacini (2003), Vatn et al. (2003) and Zander and Kächele (1999). So if these impacts differ, climatic and soil heterogeneity should be taken into account (Weersink et al., 2004). A way to present the spatial effects is by coupling the BEFM to GIS and generating a map with land uses or other results of interest (Zander and Kächele, 1999).

Another spatial interaction that is not incorporated is the influence of a field on its neighbouring field. Input-output relationships of agricultural systems should be defined as a function of output of soil and hydrological processes of adjacent agricultural systems (Hengsdijk and Van Ittersum, 2002). For example in the case of erosion or run off, there is an input into adjacent agricultural or non-agricultural systems. According to Hengsdijk and Van Ittersum (2002), these spatial interactions are hardly ever taken into account as they are dependent on land allocation. Thus, ideally land allocation and these spatial interactions should be modelled iteratively or simultaneously.

To take account of spatial heterogeneity, Vatn et al. (2003) introduces the idea of partitioning, which is structuring and simplifying existing variation in space and time into partitions that are considered homogenous. These partitions are organised in a hierarchy, and the different processes involved are modelled at the relevant level. Units at each level are divided according to partition criteria, which ensure that the partition is homogenous. For each of the partitions a set of activities can be constructed, which are relevant for those specific circumstances. Exchanges between partitions could then reflect the exchanges between spatial units.

Spatial heterogeneity can be incorporated in LP models by including extra constraints on which activities can be used on which spatial units, however it is likely to make the LP model slightly more elaborate and complicated.

4.5.5 Incorporating the new functions of agriculture

Next to the traditional provision of food and fibres, agriculture is producing other goods and services for society (EU, 1999; Feinerman and Komen, 2003). This is often termed multi-functionality, although the meaning of the concept is highly contested. New functions according to the European Union (EU, 1999) are the preservation, management and enhancement of the rural landscape, the protection of the environment and the contribution to the viability of rural areas. More practical examples of these other goods and services are farm-based recreation and landscape activities (for example, farm shops, farm parks, farm trials, rooms for rent, camping, agri-environment schemes, increased biodiversity) or the production of regional and 'environmentally friendly' products (which are labelled accordingly) (Feinerman and Komen, 2003). These new functions of agriculture should be incorporated in any BEFM if one wants to come close to what is actually happening in agriculture, and given the importance attached to these new functions by policy makers in the EU. Some of these new functions can be modelled by including extra activities a farmer might incorporate in his farm, if he has time left according to the model (for example, a camping-activity). So the extra activity has a low priority as first the normal farm activities should be carried out. These activities reflecting the new functions can then make a contribution towards farm income. On a regional basis a market module could limit the total number of certain activities (for example, 10 farm campings in one region). The production of regional or 'environmentally friendly' products could be incorporated by the introduction of two parameter levels for price. The choice of the parameter level then depends on the attainment of certain constraints required for the regional produce or 'environmentally friendly' label.

To enable integrated inclusion of the effects of new functions of agriculture these will also need to be quantified. For some functions this is quite simple, like the generation of extra income by the uptake of for example, farm shops. However, the production of 'rural landscape' and 'protection of the environment' is far more difficult. Environmental effects and environmental protection can be quantified with indicators as explained in Section 4.5.3. Production of the 'rural landscape' can be understood as the provision of a pleasant landscape and maintenance of biodiversity. Biodiversity can be measured with indicators, for example crop diversity indicator or a livestock diversity indicator or herbaceous plant biodiversity indicator (all Pacini (2003; chp.3)) or a wild plant indicator or partridge indicator or amphibians indicator (Meyer-Aurich et al., 1998). Although this sounds all straightforward and appealing, according to Zander and Kächele (1999) the problem with these biotic indicators is that it is generally difficult to identify valid general indicators with respect to the type and/or number of species or the number of individuals of one species that are present in a landscape. A potential solution is offered by Geertsema (2002), who constructed an ecological simulation model to model population dynamics of plants in landscapes as affected by a number of variables as habitat quality, spatial composition of the habitat, local populations present, seed bank dynamics etc. This ecological simulation model is made at field level, but a simpler more general form could be incorporated into a BEFM as a separate module. Another potential solution is offered by Van Wenum (2002), who estimated the economic value of biodiversity with the aid of a yardstick for biodiversity and constructed a wildlife production function. This wildlife production function translates inputs such as management and soil conditions to output of wildlife (in relevant units).This wildlife production function could be used for a BEFM to estimate relevant TCs.

Biodiversity itself can be seen as an indicator for measuring the quality of the landscape. Other indicators are presence, size and amount of landscape elements like fields, hedges, pools, wetlands etc. Two problems are that the history of the landscape determines to some extent also its quality and that the quality (or pleasantness) of the landscape is largely subjective. Thus, in constructing a landscape indicator first its users (or landscape experts) should be interviewed for their opinion and in a second step this information can be combined with other indicators for example bio-diversity indicators and the history of the landscape to derive the indicator. For a discussion of landscape indicators and how landscape is influenced by agriculture, see Hendriks et al. (2000). A general problem with both landscape and biodiversity indicators is that these are only relevant when also spatial heterogeneity is modelled, which is explained in Section 4.5.4.

BEFMs are suitable to model the new functions of agriculture. For some functions this might be more difficult than for other functions. Particularly difficult to assess are the achievement of a pleasant landscape and the effects of changed agricultural practices on biodiversity. Some potential assessment tools have been indicated, but a more extensive literature search and testing of the tools is needed.

4.5.6 A complete BEFM vs a timely delivery?

Although the focus of this Section is comprehensiveness of BEFMs, this treatise itself probably does not comprehend everything that can be achieved in a complete BEFM. In the previous sections some suggestions are made for aspects that could be incorporated in a BEFM, which have so far only received limited attention. However, the more complete the model gets, the more data are needed, the more expensive it becomes and the more time it takes to develop the model. A danger exists that 'the system under study may have been significantly perturbed before useful results are obtained.' (Anderson et al., 1985). A criterion formulated by Thompson (1982) can help during the model construction: 'the data requirements of any model must not be greater than the data that can be assembled with the resources available.' Thus there is a precarious balance between comprehensiveness of the model, data needs and time needed. Logically, when incorporating a new aspect as described in the sections above this will take more time then incorporating aspects, which have been incorporated many times before. This does not mean that these new aspects should not be incorporated. For example, the lack of a sociological approach in a BEFM might limit the ability of a BEFM to simulate closely to actual producer behaviour and the selection of indicators for environmental effects depends on the questions the policy makers have. Thus, the challenge for the modeller is to balance his time, data needs and model performance and be aware of the aspects he is missing out.

4.6 Transferability of the model

If the structure of a Bio-Economic Farm Model is flexible enough, it can be applied to various locations. There is a trade-off between precision and applicability. The more precise a BEFM is, the more difficult it is to apply it to other locations than the location it was made for. A BEFM that is easy to transfer between locations is called generic. A specific BEFM is thus defined as a BEFM that can only be used in a specific location to which it is adapted. The importance of the development of generic BEFMs is underlined by Belcher et al. (2004), who aimed to create a relatively simple model that provides information on general system dynamics, as they felt that 'models already exist that can provide high levels of precision simulating economic and environmental systems.' Whether a specific or general BEFM is made depends on the objectives of the modeller, as reflected also by Thompson (1982), who intended to make a model of easily manageable size. Thus some authors stressed the importance of making generic BEFMs, a clear explanation of what makes a generic model is lacking.

An example of a BEFM that has been applied to different conditions is the model MODAM developed by Zander and Kächele (1999), which has been applied to different circumstances (for example Meyer-Aurich (2005) and Kachele and Dabbert (2002)) and is made to be flexible according to Zander and Kächele (1999). To make it flexible Zander and Kächele (1999) did not model MODAM at a low spatial scale and used expert knowledge to estimate the Technical Coefficients. This was done to keep the data needs low as the danger is that data are needed, which are not available. Clearly, the advantage of using expert knowledge is that there are always experts who can estimate model parameters; however, the model thus becomes dependent on this expert knowledge, in-transparent and difficult to repeat. Also, the expert knowledge should be reliable. Maybe instead of relying on expert judgement, the approach followed by Meyer-Aurich et al. (1998) is better. The model developed by Meyer-Aurich et al. (1998) (some predecessor of MODAM) can be easily adapted to other regions and different goal functions, because some of the data are generally available (site specific parameters on soil maps) and only data on farm structure and potential yields need to be surveyed. One could argue about the relative ease and costs of carrying out a survey to get this farm-related data.

Apart from the data needs the size and structure of a model can limit its transferability. Large models, for which the researcher needs a lot of time to understand the model structure and adapt the model structure to the relevant circumstances, are difficult to transfer. A simple, small, easily manageable model with a clear model structure is probably easier to transfer. To date, no criteria with regards to size, model structure and easy of use exist. An extensive sensitivity analysis could help to make models smaller and easier to use with lower data needs, as parts of the models or parameters that do not influence model results (but only add to its complexity) can be detected and taken out. This resizing of the model requires more time of the modeller.

It is concluded that one of the most important requirements for the transferability of a BEFM is low data needs as the lack of data on environmental effects of farming practices (Pacini, 2003; Chp.7) and on technical input-output coefficients (Ruben and van Ruijven, 2001) can be a serious problem in model construction. A modular structure should be used for a generic BEFM as this allows ease of adaptation and extension of the model with modules relevant to other locations. For example, Zander and Kächele (1999) designed MODAM as a set of hierarchically linked modules. A last important requirement for transferability of a BEFM is robustness (insensitivity to changes in model parameters).

4.7 Evaluation

'It is important to distinguish between the image of reality in our minds and the mathematical model we construct as an abstract of the perceived reality.' (Zander and Kächele, 1999)

'If a model is to be used for system design, and if anyone is to have confidence in the results, model validation is vital' (Pandey and Hardaker, 1995)

4.7.1 Definition

A broad definition of model evaluation is given by Jansen (1997): the major method of showing the reliability of a model for a purpose. In modelling complex natural and agronomic systems the model evaluation confines itself to inspect the appropriateness of the model to the limited end in view (Jansen, 1997). Four methods for testing a model on its quality are given by Ignizio (1982) in Dorward (1999):

1. Logical consistency in model construction, which means (Jansen, 1997):
   - the model is correctly derived from the assumptions formulated;
   - dimensions and units are compatible;
   - mass is conserved;
   - parameters and variables lie within their natural ranges.
2. Reliability of the data on which the model was based.
3. Logical consistency or model responses to simple stimuli (weak form of sensitivity analysis).
4. The correspondence of model outputs to measured or surveyed data.

In the next sections the third and fourth method will be further discussed. The first method has already been explained and basically means a thorough examination of the BEFM and its results. The second method is obvious: can the data be trusted?

Model evaluation is often confused with model calibration. Model calibration is fitting of the parameters in the model equations such that the model simulations match observed data (Pfister et al., 2004). This is done with empirical models as one is fitting model behaviour on actual behaviour observed in the data. Empirical models are 'black box' models that do not explain the processes underlying the data, so they should be able to reproduce the inputs in the results. Calibrated models can be validated by comparing a fresh set of data to the predictions of the model. Alternatively, one observation of the data set used for calibration can be left out and one can assess whether the model come closes to this observation left out during calibration (Jansen, 1997).

4.7.2 Correspondence analysis with reality

According to Gutierrez-Aleman et al. (1986) 'the assumptions, structure, and data upon which the model is based must approximate reality to the extent that results bear a close resemblance to the actual farm conditions represented by the model.' This statement basically translates as 'the model and its outcomes should correspond closely to reality.' The most straightforward way and probably the most thorough method of model evaluation is carried out by Vatn et al. (2003) and Thompson (1982) and means comparing the model outcomes with observed data collected of farms or by statistical agencies. Vatn et al. (2003) compared the model outcomes of ECECMOD with many different observed data sets on farm incomes, on tillage practices, on pollution figures etc.

In verifying model outcomes of the BEFM against actual farming practice a gap might exist (Wossink et al., 1992). The size of this gap gives an indication of the ability of the model to come close to reality (Thompson, 1982). Four reasons can cause this gap (Wossink et al., 1992): difference in knowledge (between researcher and farmer), difference in inputs, difference of evaluation of risks and difference in the optimization objective. This gap can be minimized by making the model more specific and comprehensive and hence complex. A trade-off between simplicity and greater accuracy exists (Thompson, 1982), meaning that it takes more time to make the model come closer to reality and the model can probably not easily be transferred to other locations.

Of the 34 BEFMs reviewed 15 carried out some form of comparison with observed data from reality. Seven worked with sensitivity analysis (see subsequent Section) and twelve did not explicitly mention carrying out either of them. Vatn et al. (2003), Thompson (1982) and Deybe and Flichman (1991) describe the comparison between their results and data from reality, while others only shortly mentioned it and did not discuss its results. For a BEFM in a positive approach one is required to carry out this correspondence analysis with data from reality, as otherwise one cannot be sure that the model bears any resemblance with reality. Many (12+) of the model studies here reviewed described their model results number by number, relating the numbers the model produced back to its assumptions, but did not mention how robust their results were to changes in parameters or how close their base run actually was to reality. This is a shame as the interest of the reader is often not in the absolute numbers produced, but more in the ranges in which the model functions properly and the more general quality of the model.

4.7.3 Sensitivity analysis

'In principle, sensitivity analysis is a simple idea: change the model and observe its behaviour.' (Pannell, 1997)

Sensitivity analysis is a method of validating a BEFM, in that it tests the robustness of the model. Pannell (1997) holds that a sensitivity analysis should be an integral part of any methodology generating solutions (e.g. outcomes of optimizations), because only results of the sensitivity analysis indicate the status of the solution and as parameter values are almost always uncertain. Uses of sensitivity analysis thus are:

- Testing the robustness of the model: A model is robust for a certain model parameter if it results do not change or only very little with large changes in parameter values (Pannell, 1997; Pfister et al., 2004).
- Indicating which coefficients or variables most strongly affect the behaviour of the whole system. These coefficients or variables should be estimated with special care (Zander and Kächele, 1999).
- Providing an analysis of the quality of the results of the BEFM. To judge the quality of the results the uncertainty of the outcomes should be quantified (Ten Berge et al., 2000). Especially in explorative BEFMs the uncertainty can be high due to the large number of variables and coefficients involved (Ten Berge et al., 2000).
- Detecting needs for future research (Zander and Kächele, 1999).

Even if the model is robust and the quality of the simulated results high, it still does not mean that the model structure itself is correct (Pannell, 1997). Sensitivity of an LP programming model to parameter values represents a special case according to Makowski et al. (2001) and Rossing et al. (1997) as uncertainty may have little effect on the realisation of objectives, but leads to very different optimal production systems in terms of structure. A good background article on the application of sensitivity analysis to normative economic models is offered by

Pannell (1997). In theory, sensitivity analysis could go on indefinitely, but in practice beforehand it should be decided when the sensitivity analysis is stopped (Jansen, 1997).

In carrying out a sensitivity analysis several parts of the BEFM can be varied: the contribution of an activity to the objective function, the objective function itself, a constraint, the number of constraints (adding more or removing a few), the number of activities and parameter values (of the TCs) (Pannell, 1997). One parameter value can be changed at a time (partial analysis), but also more parameters together. Sometimes correlations between parameters might play a role, meaning that if one parameter takes a different value, another correlated parameter is also likely to change, leading to different model outcomes (Pannell, 1997). Examples of standard partial sensitivity analysis are shadow prices (= the increase in the objective function due to one unit more of the binding constraint), Right Hand Side ranging (= calculating the changes in the objective function and shadow prices due to changes in constraints), Cost Coefficient ranging (= calculating the range in which the coefficients in the objective function lead to successful optimization) and Reduced Costs (De Ridder et al., 2003).

It might not always be useful to carry out a complete sensitivity analysis on all model parameters. An important first step in any sensitivity analysis is the selection of a number of parameters or sets of parameter values to which the model is responsive and whose values are uncertain (Pannell, 1997). In carrying out a sensitivity analysis a lot of information might be generated by modelling all the possible changes in input values of coefficients and exogenous variables (complete factorial design) (Pannell, 1997). Linking a database to the model (Abadi Ghadim, 2000) might be a good way to store and summarize all this information in tabular or graphical form.

There are different ways of presenting results of a sensitivity analysis to decision makers or policy makers. Several methods are described by Pannell (1997): a spider diagram (= changes of several parameters on one model variable in one graph), diagram showing the change of one parameter on several variables, series of tables/graphs for changes of more than one model parameter, slopes (rates of change of a model outcome as a result of changes in a model parameter), elasticities, sensitivity indices, break-even values, comparison of constrained and unconstrained solutions (in line with MGLP; see Section 4.3.7) and probabilities. While most presentation methods are relatively easy to understand, some will need some explanation:

- A sensitivity index is a number calculated by a defined procedure which gives information about the relative sensitivity of results to different parameters of the model (Pannell, 1997).
- Break-even values give the change of parameter value needed for the optimal solution to change in a certain way (Pannell, 1997) (which is about equivalent to Reduced Costs).
- Probability: quantifying the probabilities of certain model outcomes within the sensitivity analysis (Pannell, 1997).

Sensitivity analysis is also sometimes called error propagation (Pfister et al., 2004). Error propagation calculates the results of an error in the parameter value on the results, which is one aspect of a sensitivity analysis. The effect on the results of this potential error indicates the quality of the model. Through distributions and probabilities of errors in parameter values, the uncertainty in model outcomes can be calculated (De Ridder et al., 2003). If this uncertainty is low, an error in the specification of one of the parameter values is relatively small. It is of course easy to understand that in modelling a researcher would like small effect of errors for highly uncertain parameter estimates and large effects of errors of extremely certain parameter estimates. Instead of modelling the result of an error in one of the parameters, also errors in all parameters can modelled simultaneously, thereby estimating the uncertainty of the simulated results. Uncertainty is the deviation in a percentage of the simulated results from the base value.

As mentioned in Section 4.7.2 sensitivity analysis is only carried out by 8 out of the 34 model studies reviewed here. In the review of the model studies it was felt that useful information related to model quality and performance was missed, because of this lack of sensitivity analysis and correspondence analysis with reality. Often, the absolute numbers produced in some runs with the models are discussed at length and nothing is said about the quality and robustness of the results. Just as correspondence analysis with reality a sensitivity analysis can yield many useful insights into the quality and robustness of the BEFM and the relative changes of the objective function and farm plan. On the basis of their usefulness is it concluded that a sensitivity analysis and a correspondence analysis with reality should be an integral part of any BEFM construction.

4.8 Other modelling approaches

In this section some modelling approaches are discussed, which can be used in conjunction with mechanistic BEFMs, thereby improving the performance of the modelling system.

4.8.1 Upscaling across hierarchical levels: how to do this?

Upscaling a mechanistic BEFM from the farm level to other higher hierarchical levels is not trivial. Most BEFMs made in the past are essentially partial equilibrium, in that only a small proportion of the total population of farms of a certain type is subject to policy implementation (Falconer and Hodge, 2000) and will change its practices accordingly. If the total population of farms is considered, macro-economic effects start to play a role. This means that output and input prices can change in the model as macro-economic changes in supply and demand will have an effect on these prices. So far, many BEFMs only consider the supply side of agricultural production and do not take the demand side and the presence of imperfect markets into account (Ruben et al., 1998). Ruben et al. (1998) identifies two methods of taking possible price changes at higher integration levels into account:

- Determining market clearing conditions endogenously for regionally tradable commodities. The adjusted prices can then be used in subsequent iterations to identify changes in farm level response.
- Using the results of separate Farm Households Models (FHMs) for a subsequent partial analysis of relevant markets at the regional level.

Heterogeneity both within a farm and between farms makes the process of upscaling more complex (Weersink et al., 2004). A potential way to scale up is by identifying and modelling 'typical' farm types for a certain region (or other hierarchical levels). An example is identifying 'typical' farms is given by Zander and Kächele (1999). The typical farm types can be differentiated on the basis of soil type, ecological characteristics, type of production, legal form, size class and production potential of the farm sites (Zander and Kächele, 1999). These representative farm types can then be aggregated up for a certain region.

4.8.2 Multi Agent Systems (MAS)

One type of interaction hardly ever taking into account in mathematical programming models, which is especially important in upscaling to higher levels is the exchange of information about new technologies or policies (Berger, 2001). A 'critical mass' of convinced users must be reached before an innovation will spread. To account for these sort of effects, Berger (2001) combines Multi Agent Systems (MAS; = computer systems composed of autonomous entities or agents which have only limited knowledge and information processing capacities) together with Cellular Automata (CA; to model the agents' interactions in the physical or social space. Distance between agents influences their interactions) in a recursive linear programming model. The approach by Berger (2001) enables the use of computer simulations with human like agents in order to study how an aggregation of individuals leads to complex macro behaviour. Berger (2001) is interested in analysing the path of agricultural development without imposing the final outcome, defining constituent parts of an agricultural region and establishing some rules concerning their dynamics.

An advantage of the use of MAS (Berger, 2001) is the possibility to incorporate land and water markets (locally defined resources) with an endogenous price formation. Cellular Automata account for the spatial dynamics of farm development as farms are competing with their neighbours for land and water allocation and as internal transport costs limit farm growth (Berger, 2001). Next to this, cellular automata account for variability in soil properties and distance to infrastructure or suitable water for irrigation.

The Multi Agent Systems can be incorporated instead of the objective function in a mechanistic BEFM, however some problems exist as for each decision maker (or farm) a separate BEFM has to be made, which is a rather laborious work and which requires the availability of large amounts of data on the individual farms. Also, it is difficult to construct 'typical' agent systems for the 'typical' farm used for upscaling. These drawbacks of MAS apply more to larger scale studies covering large regions and MAS might be more suitable to case studies incorporating a low number of farms and with financial resources to collect the relevant data.

5 Towards an 'ideal' model

'We suggest a scheme of the real world (including a farming system under study and the rest of reality), which is separate from the farming systems researchers' world (including its assumptions, concepts, models, insights and conclusions) by a 'threshold of relevance'. The necessary condition for crossing this threshold is an artistic achievement of acceptability and accuracy in the modelling of the system under study.' (Anderson et al., 1985)

5.1 Construction of mechanistic BEFMs

This Chapter provides a synthesis of Chapter 5 as it is tried to develop an ideal mechanistic bio-economic farm model (if such a model exists at all) and supplements Chapter 5 on some important aspects as some items related to model design are not discussed in Chapter 5. Of course, it maybe is impossible to design an ideal mechanistic BEFM in reality as model design depends on the objectives of the study, on the data availability, on the resources available (both time and money) and on earlier experiences with mechanistic BEFMs. In this report no reality of limited time, knowledge, experience and resources is present that limits the ideal model the researcher would like to construct. From this perspective the following discussion tries to hint how different aspects of reality can be modelled, what aspects of reality can be left out and what aspects of reality, which are currently not modelled that deserve more attention. Hopefully, researchers constructing their 'ideal' bio-economic farm model can obtain some useful insights from this discussion. In this first section some general aspects related to the whole BEFM will be discussed, followed by three sections that discuss the different parts of a bio-economic farm model. These different parts are the objective functions, activities and constraints. The last Section 5.5 underlines the importance of not stopping, when the model produces results, but also analyse these results on their quality.

Before starting to model the researcher should look closely to his research questions and decide which approach he has to use: positive or normative. His decision regarding a positive or a normative approach has large implications for the way the BEFM can be constructed. For example, a normative model can use a more simple objective function and can be run easily for long time horizons. A positive model must come close to actual farmer behaviour and should have a more elaborate objective function. Quite likely, it is most valid for a short to medium term time scale as uncertainty about actual responses increase with longer time scales. In several Sections of Chapter 5 it has been shown that the distinction between positive and normative can have strong effects on model construction (See for example Section 5.4.3 for construction of activities).

In this report mechanistic bio-economic farm models are reviewed. However, there is a problem here as noted by Vatn et al. (2003): a systematic discussion in the literature about the way the integration between economic and environmental models should be done is lacking. Vatn et al. (2003) is one of the only authors who discuss the integration explicitly. Most titles of articles comprise something like 'bio-economic' or 'ecological-economic' or 'combining the environmental and economic,' but hardly ever it is explained what makes the integration successful. Sometimes ecological or agronomic aspects are only calculated before the economic model, thus creating a sequential modelling. For example, Donaldson et al. (1995) first calculated TCs with a crop growth model (EPIC), and then incorporated these results in an LP model (which calculates the optimization in economic terms). One advantage according to them is that by using the crop growth model separately from the LP model the technical production function is separated from price effects in resource allocation and a better understanding of the impact of changes in relative output prices alone could be gained. it is recognised that in this kind of 'bio-economic' model agronomic decisions have an effect on economic outcomes, but it is not fully known how socio-economic decisions influence agronomic decisions as illustrated in the Figure 4 below.

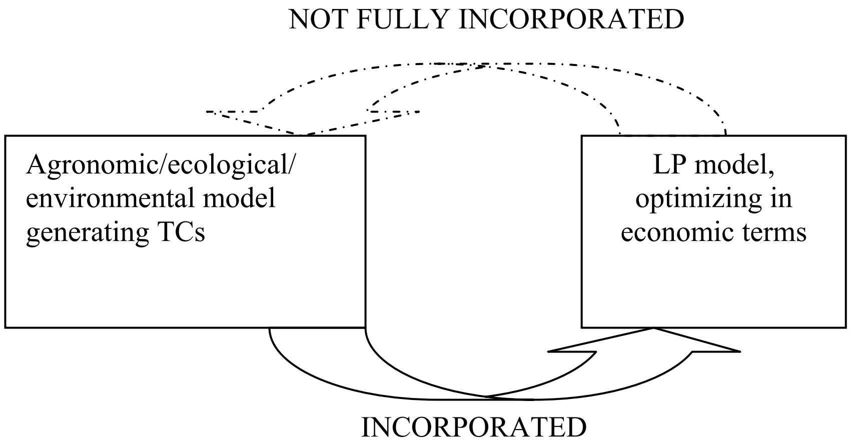

Figure 4: Feedbacks between the linear programming optimization model and the agronomic/ecological/environmental model

For an integration to be successful, integration has to take place on three aspects (Vatn et al., 2003): integrating across scales (both in time and space; see Section 4.5.4 and 4.3.3), integrating across disciplines (combining analysis of natural processes with an economic decision framework; see Section 4.3.5) and integrating across processes characterized by complex interactions and feedbacks. Integration across processes is related to the way in which the modelling is carried out. Ideally, one would like to model all processes explicitly and simultaneously (Vatn et al., 2003). This is not possible due to limited understanding of some processes, danger of in-transparent modelling and creating over-complex models (Vatn et al., 2003). Vatn et al. (2003) solved this tension by a mechanistic modelling of the basic processes and next the obtained results were corrected (using correction factors) for effects of a more second nature.

Thus, the integration of ecological/agronomic/environmental and economic aspects should be explicitly discussed and the researcher should make sure that he takes all relevant interactions and feedbacks between the economic and ecological systems into account. If he misses out on some of the interactions and feedbacks, his model might lead to wrong results. The three aspects over which integration should take place according to Vatn et al. (2003) provide a guideline to carry out the integration of ecological/agronomic/environmental and economic models. Thus, in model construction before starting to model the researcher should make explicit which interactions and feedbacks are important, which knowledge he has (and which knowledge he is lacking from other disciplines) and what are the relevant time scales to model on in relation to the research question.

It is important to think in an early stage of model construction on how widely applicable one wants the BEFM to be: a specific model for the application in a case-study or a generic model transferable for use to other locations. A transferable BEFM should have low data needs, robust, easy to adapt and extent and an accessible model structure (so that also other researchers can easily get into the model; preferably by modelling it in a modular structure).

So once the researcher has clear ideas with regards to the approach he wants to use (positive or normative) and to the integration of economical and agronomic/ecological/environmental aspects, and he is aware of the practical limitations due to data availability, availability of disciplinary knowledge and time availability and he has decided if he wants the model to be generic or specific, he can start to consider the separate elements of the model: the objective function, the activities and the constraints.

5.2 Objectives

Optimization in a mechanistic BEFM takes place on the basis of the objectives incorporated in the objective function. It depends on whether the model serves a positive or normative purpose, which objectives must be incorporated. For a normative approach a researcher can often use simpler objective functions as for a positive approach as the positive approach has to model what decision makers would actually do, while the normative approach can show through which set of activities the maximum achievement of a certain objective can be attained or how alternative objectives affect the optimum system configuration. The main focus here will be on the positive approach as it requires more complex objective functions.

If only one objective is incorporated in the objective function, that particular objective determines the activities selected by the model before any of the constraints are binding. When one of the constraints is binding and if additional units of that constraint come available, the model would choose those activities that offer the highest 'return' per extra unit of the binding constraint. For example, if profit is maximised, logically the activities with the highest financial returns will be chosen by the model: the model will choose as much of the activity with the highest financial return, then the second highest, etc, till all available labour is used (e.g. one of the constraints becomes binding). If one additional unit of labour comes available, the model will choose that activity that gives the highest returns in terms of labour. Before any of the constraints are binding it is assumed that financial return of activities determines farmer decision making. Logically, this is an over-simplification as farmers might have many other objectives (see Section 4.3), which can also be dependent on time, like paying of their loans or accumulating cash for their pension (Wallace and Moss, 2002). These changing objectives over time should be incorporated in the objective function, especially because these objectives might be conflicting with each other. A certain practice might yield a profit, but if it undermines the farm capital position farmers will not chose the strategy. Here off- or non-farm income might play a crucial role as farmers with such extra income, do not necessarily need to make a profit and can easily pay of loans, as discussed by Wallace and Moss (2002). For them, other objectives related to farming are more important, like lifestyle or living on the countryside.

A relatively easy addition to the objective function that can improve its ability to model actual farmer behaviour is the minimization of income variance (together with the maximization of expected income). This is described in Section 5.3.2. This objective function is said to take account of non-embedded risk, as non-embedded risk leads to variance in income (which is minimized). An exogenous risk aversion coefficient can be added, however this introduces a whole debate about which level this risk aversion coefficient should realistically take (and methods should be found to find a realistic value). The objective function incorporating non-embedded risk in this way, leads to good results as shown by Oglethorpe (1995) and Pannell et al. (2000) and it had a clear effect on the farm activities selected by the farm model. The objective function (consisting of profit maximization, risk aversion coefficient and minimization of income variance) is sometimes said to maximise expected utility, however this seems arguable as utility is not as narrowly defined as simultaneous maximization of income and minimization of income variance with some risk aversion coefficient. Some objectives functions based on utility functions obtained from decision makers exist and using utility here could create confusion. These utility based methods can take account of risk and personal goals and objectives of the farmer; however they are rather complicated and require either large data collection efforts or exogenous determination of some parameter. Also, by putting more effort in the correct modelling of activities and technical relations non-embedded risk can be taken into account, for example adding less risky activities to the model, which provide a stable (but maybe moderate) income to the farmer as noted by Pannell et al. (2000). Pannell et al. (2000) found that the reductions in farm income were relatively small (giving a nearly optimal solution), with the incorporation of risk and minimization of income variance.

A further extension of the objective function can be the inclusion of sequential decision making (= farmer response to embedded risk) by dividing up the year in several time periods. This has clear drawbacks in terms of data needs and complexity of the LP model, as both increase exponentially with the inclusion of more time periods. As argued by Dorward (1999) these extra efforts should be worthwhile. The incorporation also depends of the access to resources (capital and labour) farmers have, and the incorporation of sequential decision making is thus especially important if the farmers have poor access to functioning resource markets according to Dorward (1999). Thus, the researcher should decide whether his farmers have good access to resources or not and can use this as a guideline to decide whether or not to incorporate sequential decision making.

Up to now, in literature the focus has been on both types of risk mentioned above and not so much on the other goals and objectives farmers might have (both financial and personal) and the social interactions that influence the decision making process by the actor. Wallace and Moss (2002) give an example of how other financial goals and objectives can be incorporated. For the personal goals and objectives and social interactions there still remains some work to be done. It is concluded that researchers should focus less on risk and more on other aspects of farmer decision making like personal goals and objectives and social interactions. Risk has the problem that it is difficult to quantify, that farmer response to risk is not as straightforward as minimization of income variance and that access to resource markets is more important than embedded risk. To ensure more realistic and less theoretical objective functions, it might be useful to construct an easy measure of objective function quality that should always be checked when model results are produced: correspondence with reality (see Section 4.7.2).

Making the BEFM dynamic has implications for the whole model structure, but most of all for the objective function as not only the current returns should be optimised, but the returns over the whole time period included in the model. A dynamic recursive model is most advanced and most logical to use of all the dynamic models, as inter-temporal and recursive models tend to leave things out. An obvious problem with dynamic approaches is complexity and data needs as argued in Section 4.3.3. The more time periods are added, the larger the model gets and the more data it needs. Of course, it depends on for what purpose the model is used, but it might be important to include all the temporal effects (like investment decisions, long term soil fertility etc) for a realistic positive approach. Unfortunately, it is not known what the influence of long term temporal effects is on model results.

5.3 Activities

Activities tell what the farmer can do on his farm. The choice and construction of the activities depends partly on the approach taken: positive or normative. In positive approaches the researcher tries to find what the input-output relations are at the moment, while in normative approaches the researcher tries to model what input-output relations are potentially possible in the future or how a technological innovation potentially performs. With a normative approach the researcher has to keep in mind and inform the decision makers, that there might exist a gap between the levels ‘predicted’ by the model and what is currently observed in the field. For example, the researcher has almost always to make some assumptions with respect to the TCs of a technological innovation (when incorporating it in the model), as it is not currently used. If this technological innovation does not perform much better in the model than the current activities, then probably in reality it will perform at the same or lower level than the current activities, because of the uncertainty of the assumptions made for the TCs.

As explained in Section 4.4.1 the construction of activities consists out of three steps:

1. construction of all currently used activities and alternative activities to be modelled
2. design of the production technologies (related to for example conventional or integrated or organic production technology)
3. the estimation of Technical Coefficients for the activities

Below all three steps will be shortly discussed. In the first step (construction of all currently used activities and alternative activities) 'all' means all feasible activities. The researcher should try to incorporate as many activities as possible and ideally follow the approach taken by Dogliotti et al. (2003), who constructed all possible activities and used a tool based on agro-ecological principles to select the feasible activities. Also, the inclusion of sub-optimal activities can help to find activities that farmers might choose in reality, because these activities have some advantage, not perceived by the modeller. Selections always have a certain degree of arbitrariness in them, in that they always leave out certain aspects and incorporate others. For the researcher it is important to be explicit about the aspects left out and included during his selection.

The second step of the design of the production technologies has till now not been elaborately discussed. Most models mention the inclusion of different production technologies, for example 'organic' versus 'conventional' or 'environmentally friendly' versus 'base.' Often the model is run twice for the different production technologies, each time with a different set of activities adapted to the production technology. For a farmer, such a change in production technology would mean a radical change affecting the entire set up of his farm. A gradual change that might take place in reality (for instance, a farmer chooses one environmentally friendly activity and then another one, till his entire farm consists of environmentally friendly activities) is excluded by re-running the model for different production technologies with different sets of activities. It is possible to allow for a gradual change of production technology in a mechanistic BEFM. The activity description could also contain a variable on the production technology, whereby output and thus profit are dependent on the production technology used according to Pacini (2003; chp. 6). Thus, the farmer might choose one by one activities that belong to the 'new' production technology due to his changing objectives, external pressures (policies) or adoptions of innovations (Pacini, 2003; chp.6). The farmer could thus gradually change his production technology. By including a variable on the production technology, it is decided endogenously, which production technology is more suitable given objectives and pressures, and not exogenously (by re-running the model with different sets of activities). This is especially relevant when the researcher wants to model the change of farmers to more environmentally friendly activities or production technologies and is using a positive approach.

The third step in the construction of activities is the estimation of TCs or determining the input-output relationships. It depends on the local conditions and on the objectives of the study which inputs and outputs are included. Outputs can be physical yields, side products (like straw), environmental effects, social status (like owning many animals) or knowledge (the more often a farmer uses a certain activity, the more useful knowledge on that activity he gets). Environmental outputs can be captured by indicators for the effects relevant for that case study area. Some more widely applicable indicators exist like nitrogen leaching or ammonium volatilization. The determination of the important inputs for a certain model is a more difficult process: a simple option is only nitrogen fertilizer and water availability and a more complex option is soil organic nitrogen (which is in turn determined by nitrogen fertilizer, nitrogen leaching, nitrogen coming available from fixed soil nitrogen, nitrogen input from nitrogen fixing crops, etc (for example Berntsen et al. (2003)), water availability, availability of other nutrients and presence of suitable farm implements. It depends on the objectives of the study and the approach (normative or positive), how far the researchers should go in modelling the various inputs. That the way of modelling the inputs limits the usefulness of the results is demonstrated by Meyer-Aurich et al. (1998), who wanted to model nitrate leaching variability. The nitrate leaching variability was low, as it was mainly caused by variation in water holding capacity of the soil. Nitrate fertilizer had little effect on the nitrate leaching variability and the nitrate surplus as nitrate fertilizer was dependent on yield levels and as always balanced inputs of nitrate fertilizer were used to achieve certain yield levels.

Often agro-ecological simulations models can help to model the relevant input-output relations, especially in biophysical terms. However, these models often lack the capacity to model the socio-economic inputs as accurately as the biophysical inputs (see also Section 5.1). Examples of aspects that are often not included in the biophysical models are farmer time allocation during the year, investments for different activities and pests and diseases. These aspects have to be incorporated in the construction of the activities. Some of these aspects (for example investment) might be important to include as part of the objective function that is maximised, so that the selection of activities during the optimization will also happen on this basis. Other socio-economic aspects that could thus be incorporated are the risk associated with certain crops (or maybe better the susceptibility to output variance of activities) or the knowledge needed to carry out certain activities (especially relevant in relation to technological innovations).

Two aspects that have a high potential to be included and are somewhat linked are spatial heterogeneity and multifunctionality (or new functions of agriculture). There are quite many different new functions of agriculture, most of which are easy to incorporate as is demonstrated in Section 4.5.5. A nice landscape, biodiversity and nature conservation (activities) are probably more difficult to include as the outputs are spatially dependent and rather uncertain, but there are some opportunities for indicator development. Spatial heterogeneity becomes more and more important due to the interest in location specific environmental effects (for example nature) and the influences of spatial units on each other (for example spread of pests and diseases and erosion). Mechanistic BEFMs are well able to take account of this spatial heterogeneity it only requires dividing the farm up in homogenous fields or parts with each their own activities and exchanges. The mechanistic BEFM becomes larger and more laborious.

Lastly, there is a tension between what actually happens in current activities and how the researcher constructs activities in his model. When the researcher constructs activities in his model, all the inputs are replaced after use by new inputs and the activities are constructed such that they can go on for ever. A farmer might not do this, for example he might give too little of some nutrient, thereby allowing the nutrient concentration to decrease in his soil, with adverse effects only occurring over 25 years. Thereby, these current practices of the farmer appear better (financially) than they are, because an input is left out. However, these inputs can be monitored, for example the mechanistic BEFM can give some results describing the decreases in soil fertility due to certain activities. A researcher constructing a static model has a problem, as he has to assess also of the effects of activities on the longer term in order to judge whether a technological innovation is really such a good technological innovation as it appears in the model. In a positive approach the researcher has to come close to what farmers are actually doing, even if the activities of the farmers are not sustainable and not using all the inputs that should be used.

5.4 Constraints

Constraints represent the resource endowments of the farms (land availability, rotational constraints, labour availability (or farmer time), machine availability, nutrient availability, capital availability for investments and purchases, water availability, etc) and give the restrictions imposed on the farm by exogenous factors. A useful division of constraints into three categories is given by Thompson (1982):

- real constraints: limits on the fixed factors of production, land area available and the fertility of the soil, for example total land availability, soil nutrient availability, water availability and rotational constraints;
- artificial constraints: limits due to policy restrictions;
- accounting constraints: constraints aimed at balancing the demand for each input with the supply of inputs and costs in the input supply activities.

Again it depends on the objectives of the study and on the local situation which constraints should be taken into account. Sometimes constraints can be interchangeable with objectives, for example in an MGLP model, which is particularly useful in normative studies.

5.5 Post-model analysis

Model construction does not stop once the model runs successfully and some results are produced. Some authors (For example Berentsen (2003)) do not mention anything about the quality of their results and about the relative proximity to observed, while other authors conclude that the model is functioning well, however do not discuss the quality of the results. For example, Zander and Kächele (1999) hold that ‘MODAM allows the depiction of economic and ecological spatial problems at variable scales,’ but does not mention if MODAM depicts these economic and ecological problems correctly. Through model evaluation useful insights can be gained, with regards to the quality of the BEFM, the sensitivity of the results to parameter changes and the correspondence of model results to reality. Also, a discussion of the results of model evaluation can be much more informative than the description of absolute numbers the BEFM produces.

Another exercise that can provide useful insights is running the model with actual weather data over more years to see what extreme weather effects can do to model outcomes. Several sources (for example, Gibbons et al. (2005) found this had an influence and should therefore be incorporated.

6 Conclusions

- The balance between modelling purpose, model complexity, data availability and timely delivery should be carefully considered in the process of construction of a mechanistic BEFM. It is important to prioritize on the basis of this balance what should be modelled and what can be left out before actually starting to model.
- The purpose of the BEFM determines the approach, either positive or normative. The construction of positive and normative models differs in some important respects, but a positive model can be adapted to answer normative questions, while it is difficult to use a normative model to answer positive questions.
- A truly integrated BEFM has a two way correspondence between the economic and the biophysical part, which means that not only the economic model is dependent on the calculations of the biophysical model, but that the biophysical model is also dependent on the optimization of the economic model. In future research suitable methods should be developed to ensure a proper integration and a clear explanation of the integration within a mechanistic BEFM should be provided.
- Only 7 (21%) out of 33 reviewed models included a sensitivity analysis and only 14 (42%) out of 33 compared the model outcomes with observed data. As sensitivity analysis and correspondence with reality analysis can give many useful insights with regards to the quality and robustness of results of a mechanistic BEFM, these should be an integral part of any BEFM construction.
- Some important aspects have so far generally been left out in the construction of mechanistic BEFMs like investment decisions, social interactions, personal goals and objectives of the farmer and temporal effects of soil fertility. These could have potentially large effects on the simulated results of a BEFM and could improve the ability of mechanistic BEFM to come closer to actual farmer behaviour (e.g. be more positive). The importance of these aspects should be investigated in future research.
- In the past mainly for each purpose or application a specific model has been made, although a minority of authors made reference to the potential transferability of their model. Generic models have to meet certain requirements with regards to data needs, robustness and model structure, however there seem to be good opportunities if the data needs are kept low and dependent on generally available data.

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Appendix 1: Criteria for analyzing the literature

1) Whole farm model? Yes/no
   a) If a farm model is made, what type of farm
   b) What zone? Temperate regions vs. Tropics.
2) Is aggregation tried to higher levels like region or industry? Are the models made with the intention to aggregate them to regional or sector level?
3) For policy making or assisting decision making by the farmer?
4) Is the main interest describing reality and understanding reality or predicting what might happen in the future?
5) Type of model:
   a) Positive models: Econometric or PMP
   b) Normative models: MGLP, Dynamic LP, MCDM,
   c) Mathematical mechanistic models: agronomic/crop simulation model
6) Objective function:
   a) Profit maximization?
   b) Maximization of utility?
   c) Taking into account risk?
   d) Amount of objectives taken into account?
   e) Does the objective function used match reality? Eg. Lead to the desired results?
7) Activities:
   a) How are activities/technical coefficients quantified? (using statistics, expert knowledge, survey information, crop simulation models)
   b) At which hierarchical level are the activities modelled? (for example, field or rotation level/Herd or livestock unit level).
   c) All aspects/enterprises of the farm modelled with the same accuracy?
   d) Are only currently used activities taken into account or also alternatives for the future?
   e) Do soil type/slope/SOM/soil depth influence the activities used on a certain soil?
   f) Exchanges between farm enterprises?
   g) How is climate/weather variability taken into account?
   h) Is Organic Matter Content taken into account? (Endogenous or exogenous)?
   i) Is N taken into account? (Endogenous or exogenous)?
   j) Is Soil P taken into account? (Endogenous or exogenous)?
   k) Is Soil K taken into account? (Endogenous or exogenous)?
   l) Are emissions taken into account?
   m) Is erosion taken into account? (Endogenous or exogenous)?
   n) Is run-off/leaching taken into account?
   o) Is biodiversity taken into account? (Endogenous or exogenous)?
   p) Is effect on nature taken into account?
   q) Is farmer time allocation taken into account? (Endogenous or exogenous)?
   r) Are capital availabiltiy and investments taken into account?
   s) Related to the above two points: Incorporating off- and non-farm income (different capital endowments of farms)?

t) Are input prices (fertilizer/concentrates) taken into account? (Endogenous or exogenous)?

8) Constraints:
   a) Which types of constraints are mainly taken into account (all types/ economic /agronomic/environmental)?
   b) Is water supply taken into account as a constraint?
   c) Is nutrient availability taken into account as a constraint?
   d) Is the inclination of a slope taken into account as a constraint?
   e) Is soil fertility taken into account as a constraint?
   f) Are there rotational constraints?
   g) Are there any weed/pest/disease constraints?
   h) Are there any transport constraints?
   i) Are there labour/farmer planning constraints?
   j) Are there capital constraints?
   k) Is the available machinery taken into account as a constraint?
   l) Is consumer/market demand taken into account as a constraint?
   m) Are regulations/laws specifically taken into account?
   n) Are subsidy schemes taken into account? (Endogenous or exogenous)?
   o) Are market prices taken into account? (Endogenous or exogenous)?
   p) Are there constraints on:
      i) Emissions?
      ii) Run-off/leaching?
      iii) Erosion?
      iv) Use of inputs?
      v) Amount of animals/production quotas?
9) Is model validation and calibration carried out?
   a) If so, how close are the model outcomes to the data against which it is validated?
10) Can the model be easily transferred to other locations?
11) General comments/conclusion on the model