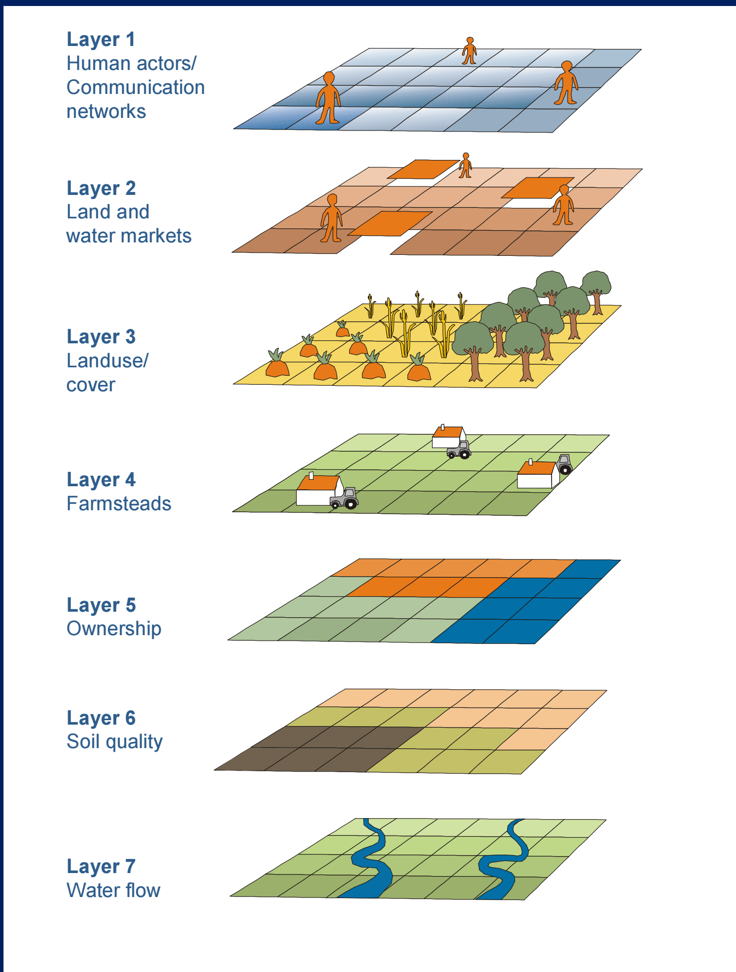
Mathematical Programming-based Multi-Agent Systems (MPMAS)



Technical model documentation
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This manual together with the software application and input files is available from: http://www.uni-hohenheim.de/mas/

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Contents

Glossary of terms

ECDF	Empirical Cumulative Distribution Functions
IBM-OSL	IBM Optimization Subroutine Library
MILP	Mixed Integer Linear Programming model
MPMAS	Mathematical Programming-based Multi-Agent Systems
NRU	Nutrient Response Unit. A type of soil classification used in the model.
SOS	Specially Ordered Sets
TSPC	Tropical Soil Productivity Calculator. A deterministic model simulating crop yields and soil fertility changes
VBA	Visual Basic for Applications

Abstract

MPMAS is a software application for simulating land use change in agriculture and forestry. It combined whole farm mathematical programming with various biophysical models simulating crop yields in a spatial setting. MPMAS has been applied to empirical research questions in Chile, Uganda, Ghana, Thailand, Vietnam, Ethiopia, and Germany. This manual provides technical details about using the model, it describes the structure and contents of the input and output files. It accompanies an example data set that is available online.

Introduction

MPMAS is a software application for simulating land use change in agriculture and forestry. MPMAS, which stands for mathematical programming-based multi-agent systems, combines economic models of farm household decision-making with a several biophysical models simulating the crop yield response to changes in the water supply and changes in available soil nutrients. The purpose of this manual is to give technical information about how the software functions and how to apply it to new empirical applications. The manual accompanies a default model application which users can download from http://www.uni-hohenheim.de/mas/.

The manual is structured as follows. This first section gives background information about MPMAS and an overview of empirical applications of the model. A subsequent section describes how the model should be installed and used on a desktop computer. We then describe the structure of the model and each of the input files. This is followed by a description of auxiliary workbooks that help users to analyze particular decision problems. The final section explains the contents of output files and how these can be analyzed.

Background information

MPMAS is part of a family of models called multi-agent systems models of land-use/cover change (MAS/LUCC). These models couple a cellular component representing a physical landscape with an agent-based component representing land-use decision-making (Parker *et al.* 2002). MAS/LUCC models have been applied in a wide range of settings (for overviews see Parker *et al.* 2003, Janssen 2002) yet have in common that agents are autonomous decision-makers who interact and communicate and make decisions that can alter the environment. Other MAS/LUCC applications have been implemented with software packages such as Cormas, NetLogo, RePast, and Swarm (Railsback *et al.* 2006). The main difference between MPMAS and these alternative packages is the use of whole farm mathematical programming to simulate land use decision-making. With this decision-making component MPMAS is firmly grounded in agricultural economics.

The philosophy of agent-based modeling has always been to replicate the complexity of human behavior with relatively simple rules of agent action and interaction. Theoretical applications often have only a couple of rules. More rules are, however, needed in applications to complex empirical situations in which many economic and environmental variables affect the decision-making, such as in land use decision-making. The question hence arises how simple rules need to be. Most applications have used relatively simple rules, also called heuristics, to represent the economic decision-making of agents. In Schreinemachers and Berger (2006) we argued that agents in most rule-based systems have limited heterogeneity and adaptive capacity. We therefore advocated giving agents goal-driven behavior, such as based on whole farm mathematical programming. This approach does not require the modeler to specify a complete set of rules, only objectives, a discrete set of alternative decisions, and a discrete set of resource and information constraints.

The use of mathematical programming (MP) has a long tradition in agricultural economics (Hazell and Norton 1986), and the precursors of today's agent-based models – so-called adaptive macro and micro systems – were implemented with MP (Day and Singh 1975). Examples of agent-based land use models using MP are Balmann (1997) and Happe et al. (2006) who analyzed structural change in German agriculture using the software AgriPoliS. Berger (2001) built on Balmann's model in an empirical application to Chile and used it to simulate water allocation and technology diffusion. Schreinemachers *et al.* (2007) extended the model in an empirical application to Uganda to simulate food security and soil fertility dynamics. Some of these applications are summarized in the following.

Empirical applications

This section shortly describes four recent applications of MPMAS to illustrate the functionality of the model. References are given that give additional information.

1. Irrigation water use in Chile

Research area:	Maule Basin, Chile; 4,300 km2; 3,592 farm households
Objective:	To develop a decision support tool for the local watershed management and to simulate the impact of various water-saving agricultural technologies on agricultural land use. The model includes two alternative biophysical models for simulating the irrigation water supply (WaSiM-ETH and Edic-cedec).
References:	Berger 2001, 2000

2. Soil fertility decline and poverty dynamics in southeast Uganda

Research area: Two villages, 12 km2, 520 farm households

Objective: Rapid population growth and unsustainable land use have depleted soil fertility and exert a downward pressure on crop yields in Uganda. Researchers have introduced high-yielding maize varieties to boost yields. The model was used to simulate the combined diffusion of improved maize varieties and short-term credit and assess the impact on poverty and soil fertility.

References: Schreinemachers *et al.* 2007, Schreinemachers 2006, Schreinemachers and Berger 2006

3. Land use change in northern Ghana

Research area: White Volta Basin; 3,779 km2; 34,691 farm households

Objective: To develop an MPMAS decision support tool, which is used (i) to analyze the farm level socio-economic constraints, and (ii) to analyze the distributional impacts of irrigation technologies on welfare of the farm households and water resource management in the Upper East Region of Ghana.

References: -

4. Land use change in a mountainous watershed in northern Thailand.

Research area: Mae Sa watershed area, 140 km2, 1,309 farm households

Objective: The watershed has seen rapid land use change as the relative profitability of fruit trees has declined and intensive agriculture of greenhouses has spread. The model was used to assess the impact of various innovations to make litchi trees more profitable and to project the diffusion of greenhouse agriculture under various conditions.

References: Schreinemachers *et al.* Submitted, Schreinemachers *et al.* Submitted, Schreinemachers *et al.* 2009

Table 1 compares the above four studies. It shows that the research areas range from a few square kilometers to large areas of thousands of square kilometers; and from a few hundred of agents to many thousands of agents. Additional applications are currently being developed to study sustainability of mountainous agriculture in northern Vietnam, and climate change in southern Germany.

Table 1 Empirical applications of MPMAS

	Application	No. of farm agents	Spatial dimension		Temporal dimension		Type of agriculture
			extent [km^2]	resolution [m]	duration [years]	time step [days]	
1	Chile, Maule Basin	3,592	5,300	100	20	30	Market-oriented and commercial
2	Ghana, White Volta Basin	34,691	3,779	100	15	30-365 *	Semi-subsistence; rice, millet, maize, onion and tomato
3	Uganda, Southeastern	520	12	71	16	30-365 *	Semi-subsistence; maize, cassava, bean and plantain
4	Thailand, northern uplands	1,309	140	40	15	30-365 *	Commercial fruit, vegetable and flower production

Note: * Components of the model have different time steps. The decision-making follows an annual sequence while land, labor, crop water requirements, irrigation water supply, and rainfall are specified on a monthly base.

Source: Berger and Schreinemachers In press

Use of the MPMAS software

MPMAS is available as a freeware software written in C++ that can be downloaded from http://www.uni-hohenheim.de/mas/. The software is a single executable file that does not need installation. Both a Windows and a UNIX version are available. The use of Unix OS is recommended as the program runs more stable on this operating system. We note that the MPMAS source code is not publicly available at the moment. Researchers who are interested in applying MPMAS and who need additional features not currently available in MPMAS can get in touch with us.

MPMAS uses optimization software, which needs installation. It currently uses the Optimization Subroutine Library (OSL) which gives a high performance on very large models and can handle many integers (Wilson and Rudin 1992). IBM, the producer of OSL, has stopped the development of its software and transferred the source code to an open source community (http://www.coin-or.org/resources.html). This new solver, called COIN, is currently being implemented to replace the OSL.

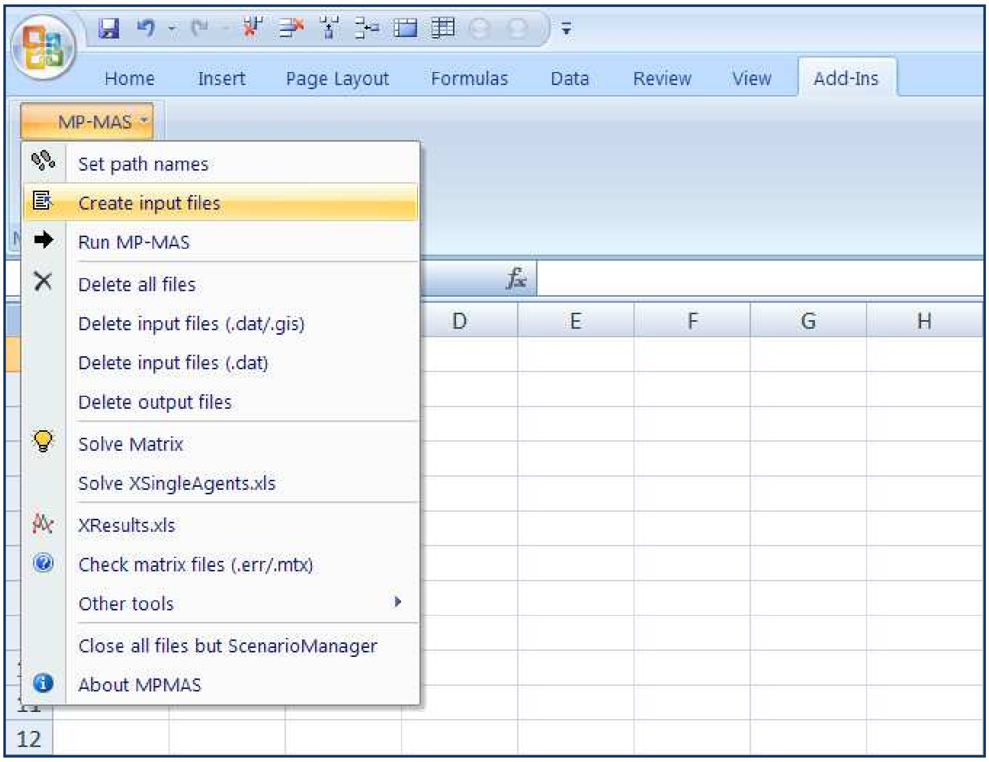
Software installation

To use MPMAS the user needs to do three things:

1. **Copy the default folder with input files to any location on the hard disk**. Under Windows we suggest copying it to the main directory (usually C:/). The folder contains the following subfolders:
   - input : contains ASCII input files
   - out : contains ASCII output files created when running the MPMAS model
   - Stata : contains Stata do-files for analyzing the model output
   - xlsInput : contains Microsoft Excel input files from which the ASCII input files in the subfolder "input" are created. This is explained in the following sections.
2. **Install an academic version of the Optimization Subroutine Library (OSL)**. This software is available from the MPMAS web site.
3. **Install the MPMAS Visual Basic Macro in MS Excel.** Visual Basic for Applications is used to create scenarios and create input files as explained in the following. The application works with both Microsoft Excel 2003 and 2007. The later version has the advantage that it the worksheets have more columns and rows: 16,384 columns and 1,048,576 rows (as compared to 256 columns and 65,536 rows in MS Excel 2003). This advantage is especially important for creating the MP matrix. In addition, the 2007 version saves workbooks more efficiently thereby reducing disk space. To install the add-in in MS Excel 2003, go to `Tools>Add-ins`. Click browse and find the location of `Mpmas.xla`. Select this file so that MPMAS appears in the list of Add-ins and make sure the checkbox is selected. The MPMAS add-in is now installed and any time you open Excel, the menu will appear as shown in Figure 1. In MS Office 2007 one can install the add-in through `Office button/Excel options/Add-Ins/Go`. To run macros, the security setting in Microsoft Excel (`Tools>Macros>Security` in MS Excel 2003 and `Office`

`button>Excel options>Trust Center>Trust Center Settings` in MS Excel 2007) should be set to medium or low so that macros are enabled when opening files. All VBA code is fully accessible by pressing ALT+F11 in MS Excel. The code is organized in modules that are explained in module m0.

Figure 1 MPMAS menu options in Microsoft Excel 2007



Windows Operating system

The OSL Library can be installed under Windows by double clicking the executable file `v3_winlib_aca.exe` which opens a graphical interface which guides through the installation. The regional settings in Microsoft Windows have to be set to English (US) when installing the OSL Library. Language settings can be changed through:

`Start/Control Panel/Regional and Language Options/Regional Options>`

After installation and a reboot of the PC, the regional settings can be changed back to any language. In addition, it has to be ensured that the environment variable points to the OSL Library. Check this through:

`Start>Control panel>System>Advanced>Environment Variables>`

If the OSL Library is installed normally (under Program Files) then the path should have the value:

`C:\Program Files\IbmOslV3Lib\osllib\lib`.

Unix operating system

The following procedure can be used to install the OSL under the Unix OS. Create a folder called "OSLLIB" (or any other name) on your Linux file system. Copy the file "v3_osllib_linux.tar" to this folder. Right-click your mouse and select "extract here". Then open the Terminal and type:

```
/OSLLIB/v3_osllib.tar_FILES ./install_osl osllib academic
```

Next, the operating system should be directed to the file **`libosl.so`**. This can either be accomplished by directing the path name to the correct location or by copying the file **`libosl.so`** to the folder **`/lib/`**

When using the tcsh (TENEX C-shell) the following will probably work: Type `echo $LD_LIBRARY_PATH` to find the current path to the library. If incorrect then first unset the path by typing: `unsetenv LD_LIBRARY_PATH.` Then set the path to the file `osllib.os`, for example:

```
Setenv LD_LIBRARY_PATH /fat/OSLLIB/v3_osllib.tar_FILES/osllib.tar_
FILES/osllib/lib
```

When using bash (Bourne Again SHell) one of the following two options will work:

Type `echo $PATH` to see if there is a path to `/usr/local/bin`. If not then open the `.bash_profile` file in your home directory and add the following lines:

```
PATH=$PATH:/usr/local/bin

export PATH
```

Then type `echo $LD_LIBRARY_PATH` to see if `/usr/local/lib` is now in your library loading path. If not then add the following lines to the `.bash_profile` file in your home directory:

```
LD_LIBRARY_PATH=$LD_LIBRARY_PATH:/usr/local/lib
export LD_LIBRARY_PATH
```

As an alternative, one can also locate the file `libosl.so` (the location depends where the tar-file was unzipped) and then simply copy this file to the library folder. For example, in Ubuntu Linux type: `sudo cp v3_osslib_linux/osllib/lib/libosl.so /lib/` in the terminal window (copy and paste in the Explorer will not work as the command needs the super user (sudo) prefix.

Using the model

Using MPMAS involves three basic steps of adjusting input files, running the MPMAS executable, and analyzing the model output as shown in Figure 2. These steps are continuously repeated during the process of building, testing, and using the model. This manual describes the contents of these input files in detail, so that users can make informed adjustments and create realistic scenarios.

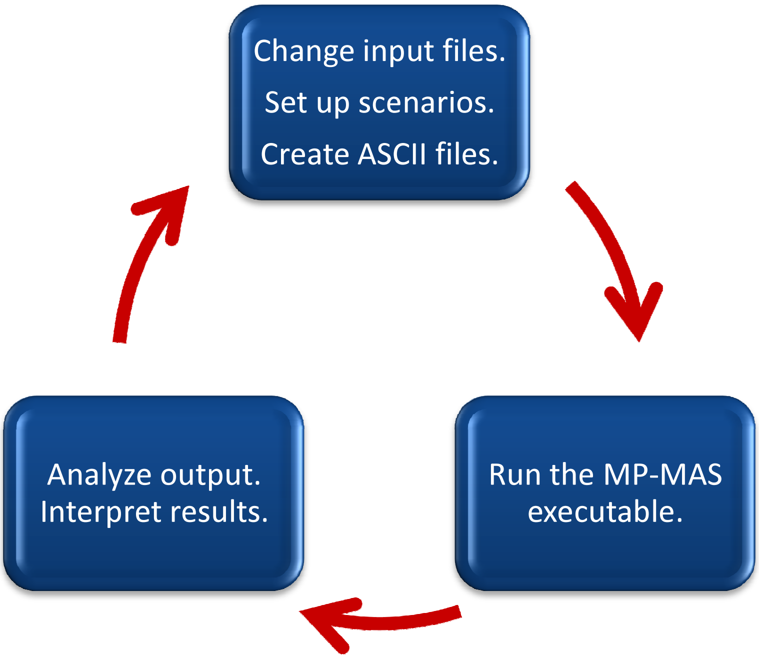


Figure 2 The MPMAS modeling process

To create a new empirical application of MPMAS we advise users to start with the Default file set and then to stepwise adjust this set to the own application while trying to run the model at each step.

For instance, the MP model can be gradually expanded to include more crop activities. Running the model after each significant change helps to locate possible errors more easily as the program's error calls can sometimes be cryptic and it is therefore difficult to pinpoint an error after making many changes at a time.

After ASCII input files have been created, which is explained below, the MPMAS executable can be called from an MSDOS command window under Windows or a Shell command window under Linux. We recommend using Linux as it runs more stable than the Windows operating system. Under both operating systems the command line has the following syntax:

```
[file path] [executable] -N[prefix] -O[input file path] -O[output file path] [options]
```

in which `[prefix]` is the name of the input files as given in ScenarioManager.xls. Note that Windows is case insensitive. The syntax part `[file path]` directs to the folder where the executable is located. If the current directory (`cd`) is set to the main folder containing the input files then no paths names do not need to be specified in the syntax as in the example shown in Figure 3.

MPMAS has no interactive interface—when running the model users can only see the progress in solving MP problems but cannot directly see or interpret simulation results. Figure 3 and Figure 4 show the computer screen that users will see in Microsoft Windows and Ubuntu Linux, respectively. The MPMAS saves all simulation results to ASCII text files, which then need be analyzed using statistical software.

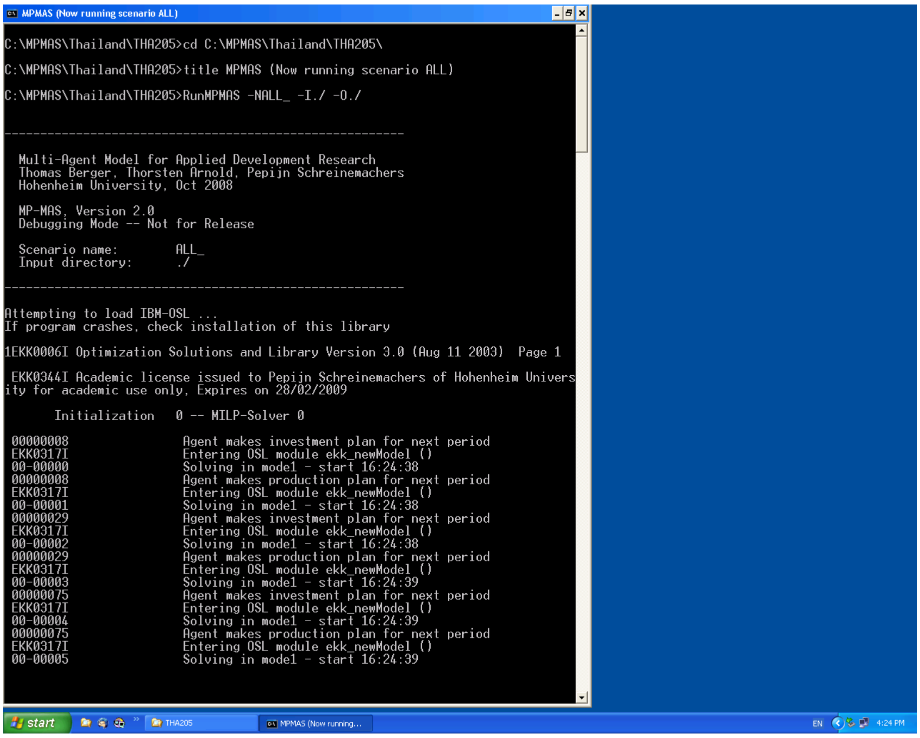


Figure 3 The MSDOS window showing command line and model run

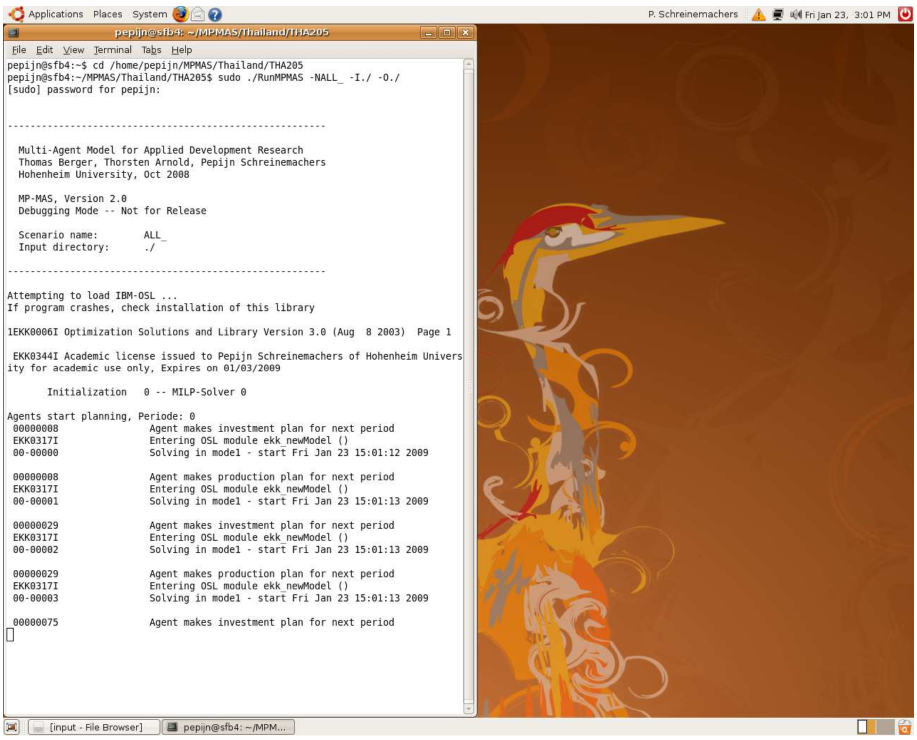


Figure 4 The Linux window showing command line and model run

Structure of the model

MPMAS works with a set of input files that are read and processed. It is hence different from many software applications in that the input data are not entered through specially designed graphical user interfaces but the user is more or less free to organize the own data.

Input files are written in Microsoft Excel workbooks and contain one or more worksheets with data and sheets for calculations and notes. The use of Excel workbooks has the advantage that most users are familiar with it. It is furthermore convenient as workbooks are easily linked and can contain separate sheets for calculations and documentation of the model. Comments, explanations, and whole calculations can thus be kept together with the final input data which greatly simplifies its use. The disadvantage is that `small changes can have big consequences'; that is, accidentally entering a value in the wrong place can make the program crash.

The general design of input files needs to follow some conventions that are explained in the following.

WORKSHEET NAMES: The name of each ASCII input file is derived from a prefix specified in ScenarioManager.xls and the name of the Excel worksheet. For example, if the prefix is set to "A" and the worksheet is named "MILP" then the input file will be called "A_MILP". The worksheet names can therefore not be changed.

ORDER OF THE WORKSHEETS: Excel file contain multiple worksheets. The number of worksheets converted to ASCII is set in the upper table in ScenarioManager.xls. If, say, two worksheets are to be converted then the workbook is opened and the first two sheets are taken. Worksheets with input data should therefore come first in the workbook while worksheets with calculations and notes should come at the end.

RED-COLORED CELLS: Excel input files need to be well documented by including sufficient explanation in the worksheets. When converting the Excel worksheets into ASCII these explanations need to be cleared. Red-colored cells in row 1 indicate that the column should be cleared while red-colored cells in column A indicate that the row should be cleared.

TEXT COLORS: Different text colors are used to make clear how the cell is calculated.

- Blue numbers contain a formula and refer to cells in the same workbook

- Red numbers contain a formula and refer to cells in other workbooks
- Pink numbers are changed by ScenarioManager.xls when converting files to ASCII
- Black numbers are normal cells without formulas

CELL NAMES: One of the advantages of using MS Excel is that workbooks can be linked. If workbooks are linked then a change of a cell value in one workbook automatically changes this same value in all other workbooks that are linked to this cell. However, using references such as "=BasicData!B2" has the weakness that if inserting new columns or rows then this reference is not updated in workbooks that are not currently open. This can be overcome by using textual cell names instead, e.g. give the cell B2 the name "Growth" using the Name Box feature of Excel.

The fourteen files in the default data set, listed in Table 2, include ScenarioManager.xls and 13 input files. ScenarioManager.xls is used to set up scenarios and to convert the input files to ASCII format. Each input file contains data for a specific component of the model with the exception of BasicData.xls which contains parameters used by multiple components. The number of input files can vary between applications as some components are optional.

The second file is the mathematical programming (MP) matrix (Matrix.xls), which simulates the decision-making of all agents. This file is central to MPMAS. The function of all other input files is to calculate parameters in this MP matrix. The remaining input files can be divided into three groups:

- First, input files that create the population of agents, including their resource endowments (Population.xls), their spatial attributes (Maps.xls), and their knowledge of and access to innovations (Network.xls).
- Second, input files containing parameters which are constant over the simulation run, including general parameters (BasicData.xls), crop water requirements (CropWat.xls), and the distribution of water rights over agents (WaterRights.xls).
- Third, input files that simulate dynamics over time: demographic changes in agents' household size and composition (Demography.xls), growth of trees and changes in input requirements (Perennials.xls), growth of animals and changes in yields and input requirements over time (Livestock.xls), changes in market prices (Market.xls), changes in the fertility of soils (Soils.xls), and finally, changes in the water supply (Routing.xls).

The general design of input files needs to follow some conventions that are explained in the following.

Table 2 Overview of the MPMAS input files

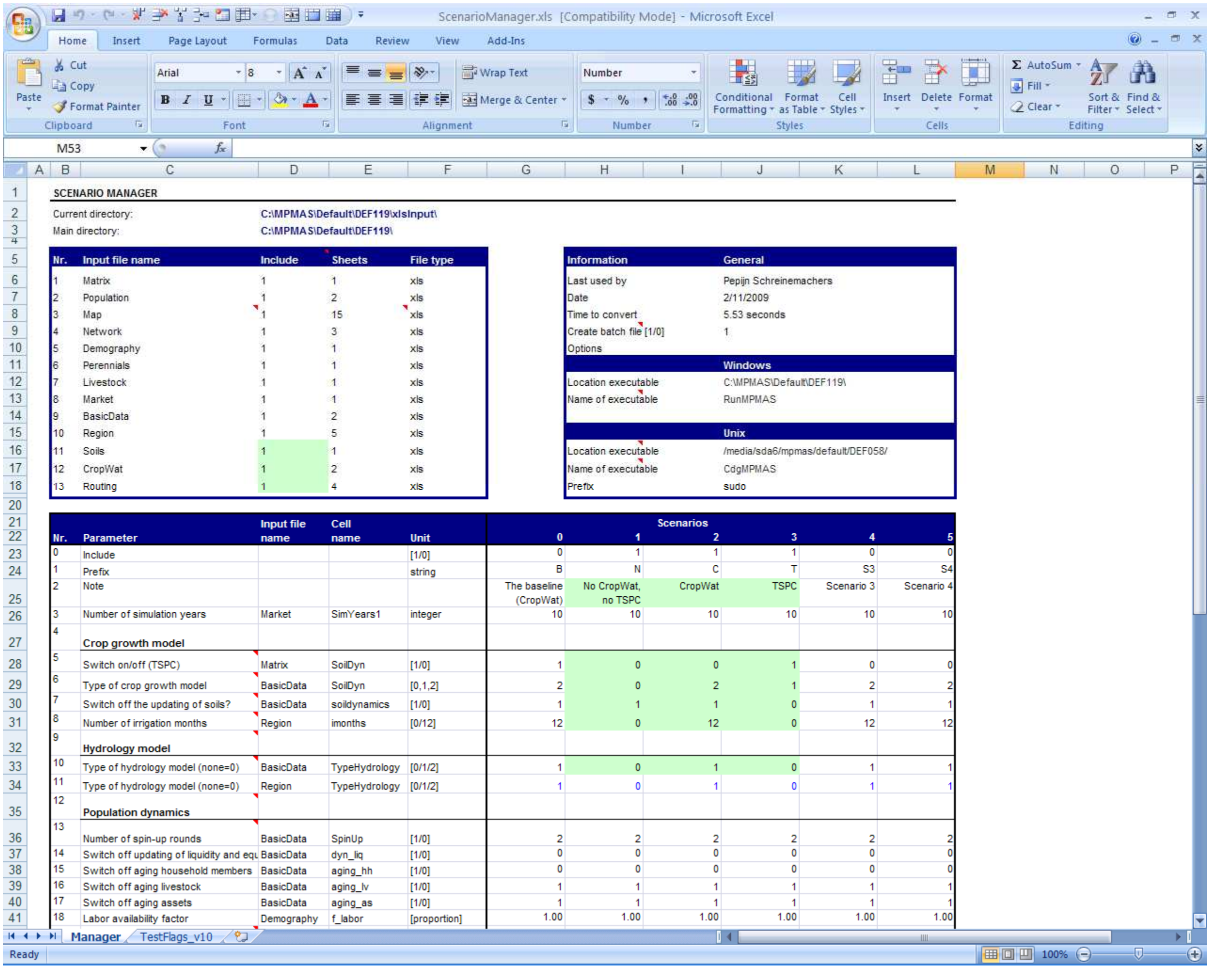
Input file	Optional	Contents	
ScenarioManager	No	To create input files and to manage simulation experiments	
Matrix	No	A generic MP tableau (Mixed Integer Linear Program or MILP) that simulates the decision-making of agents.	
Population	No	Generates agent populations (household members of various ages, farm assets, liquidity, and other agent characteristics)	Initial conditions
Map	No	All spatial information including the boundary of the watershed, location of agents and agricultural plots.	Initial conditions
Network	No	Defines networks of innovation diffusion and determines for each network the level of diffusion at the start of the simulation.	Initial conditions
BasicData	No	Basic parameter values used in several components of the model.	Constant parameters
CropWat	Yes	Monthly crop water requirement for each crop activity included in the MP tableau and the efficiency of various irrigation methods.	Constant parameters
WaterRights	Yes	Defines the distribution of water between agents (water rights).	Constant parameters
Routing	Yes	The amount of irrigation water and precipitation for each month and for each year in the simulation run.	Model dynamics
Perennials	Yes	Annual yields, variable inputs, and capital needs of perennial crops.	Model dynamics
Livestock	Yes	Annual yields, variable inputs, and capital needs of farm animals.	Model dynamics
Soils	Yes	Soil fertility dynamics and crop yield response to soil nutrients.	Model dynamics
Market	No	All price information in the objective function of the MP tableau: prices for buying agricultural inputs, farm gate selling prices, and the off-farm labor wage rate.	Model dynamics
Demography	No	The labor supply for each age of an agent household member and defines population dynamics such a the probability of dying and the probability of giving birth.	Model dynamics

MPMAS input files

ScenarioManager.xls: Managing input files and scenarios

Figure 5 shows a screenshot of ScenarioManager.xls. The workbook is used to change parameter values in the Excel input files and to convert them to ASCII. The top-left block specifies the name of the Excel input files; it has an option to include/exclude certain Excel workbooks, and it specifies for each workbook the number of worksheets to be converted to ASCII.

Figure 5 Screenshot of ScenarioManager.xls



SCENARIO MANAGER

Current directory: C:\MPMAS\Default\DEF119\xlsInput\

Main directory: C:\MPMAS\Default\DEF119\

Nr.	Input file name	Include	Sheets	File type
1	Matrix	1	1	xls
2	Population	1	2	xls
3	Map	1	15	xls
4	Network	1	3	xls
5	Demography	1	1	xls
6	Perennials	1	1	xls
7	Livestock	1	1	xls
8	Market	1	1	xls
9	BasicData	1	2	xls
10	Region	1	5	xls
11	Soils	1	1	xls
12	CropWat	1	2	xls
13	Routing	1	4	xls

Information	General
Last used by	Pepijn Schreinemachers
Date	2/11/2009
Time to convert	5.53 seconds
Create batch file [1/0]	1
Options	
	Windows
Location executable	C:\MPMAS\Default\DEF119\
Name of executable	RunMPMAS
	Unix
Location executable	/media/sda6/mpmas/default/DEF058/
Name of executable	CdgMPMAS
Prefix	sudo

Nr.	Parameter	Input file name	Cell name	Unit	Scenarios 0	1	2	3	4	5
0	Include			[1/0]	0	1	1	1	0	0
1	Prefix			string	B	N	C	T	S3	S4
2	Note				The baseline (CropWat)	No CropWat, no TSPC	CropWat	TSPC	Scenario 3	Scenario 4
3	Number of simulation years	Market	SimYears1	integer	10	10	10	10	10	10
4	**Crop growth model**									
5	Switch on/off (TSPC)	Matrix	SoilDyn	[1/0]	1	0	0	1	0	0
6	Type of crop growth model	BasicData	SoilDyn	[0,1,2]	2	0	2	1	2	2
7	Switch off the updating of soils?	BasicData	soildynamics	[1/0]	1	1	1	0	1	1
8	Number of irrigation months	Region	imonths	[0/12]	12	0	12	0	12	12
9	**Hydrology model**									
10	Type of hydrology model (none=0)	BasicData	TypeHydrology	[0/1/2]	1	0	1	0	1	1
11	Type of hydrology model (none=0)	Region	TypeHydrology	[0/1/2]	1	0	1	0	1	1
12	**Population dynamics**									
13	Number of spin-up rounds	BasicData	SpinUp	[1/0]	2	2	2	2	2	2
14	Switch off updating of liquidity and equ	BasicData	dyn_liq	[1/0]	0	0	0	0	0	0
15	Switch off aging household members	BasicData	aging_hh	[1/0]	0	0	0	0	0	0
16	Switch off aging livestock	BasicData	aging_lv	[1/0]	1	1	1	1	1	1
17	Switch off aging assets	BasicData	aging_as	[1/0]	1	1	1	1	1	1
18	Labor availability factor	Demography	f_labor	[proportion]	1.00	1.00	1.00	1.00	1.00	1.00

Manager TestFlags_v10

As its name suggests, ScenarioManager.xls, can be used to set up and run different scenarios. This is done in the lower table. Five scenarios are included in the Default data set but this can be expanded without change the VBA code. Scenarios are created by adding and/or changing parameters in this lower table. These parameters are only changed in the ASCII input files while the Excel input files remain unaffected. The VBA code loops through the workbooks in the upper table and for each workbook loops through the cell names in the lower table to find a matching cell name with a parameter to change. For instance, in row 3, a parameter is included for changing the number of simulation periods in Market.xls to 10 in the first scenario. When opening Market.xls, the VBA code searches for a cell name "SimYears" and changes its value to 10. An error message will appear on the screen if the cell name "SimYears" does not exist in Market.xls. Different scenarios can be set up by adding rows to the table and defining cell names and parameter values.

Matrix.xls: Agent decision-making

Matrix.xls contains the mathematical programming (MP) tableau, which is a mixed integer linear programming model (MILP). It optimizes the expected net household income, including the expected income from farm, non-farm, and off-farm labor and includes current as well as future expected income streams. A generic MP tableau is defined that can capture the activities and constraints of every agent. The MPMAS then changes the resource endowments (right-hand-side values) and switches on and off activities and constraints, to tailor each MP to a particular agent. Although all MPs are agent-specific, there is therefore no need to define each MP individually; the software handles this using data from all other files. For instance, prices are derived from Market.xls, initial resource endowments (right-hand-side values) come from Population.xls, input-output data for livestock and perennials come from Livestock.xls and Perennials.xls, while access to innovations comes from Network.xls. All input files contain information about where in the MP tableau values need to be calculated. The exact location in the matrix is specified using activity and constraint indices.

Matrix.xls includes twelve categories of data, numbered in column A and listed in Table 3 below.

Table 3 Data categories in the Matrix-file

Nr.	Name	Brief description
1	Parameters and coefficients	Information about the MP tableau, such as the number of activities and constraints and the location of certain activities.
2	Objective function coefficients	The price vector of the MP tableau. The VBA code generates this vector from the MP tableau.
3	Programming matrix	The specification of activities and constraints. No missing values are allowed, zeros need to be entered explicitly.
4	Fixed/independent constraints	Fixed/independent constraints can be included, for instance if a right-hand-side value should always take a value 10.
5	Binary for disinvestments	These coefficients specifically relate to the three-step-consumption model (see Market.xls) and should be left blank if this model is not used.
6	Fixing of columns in "consumption mode"	These coefficients also relate to a three-step-consumption model (see Market.xls) and should be set to zero if this model is not used.
7	Fine tuning parameters	Can be used to alter crop yield expectations when taking production decisions to capture risk.
8	Type and range of constraints	Relates to the sign of the constraints (see text)
9	Marked integers	Indicates which activities are integers
10	Lower bounds on columns	The minimum value to which an activity can be selected
11	Upper bounds on columns	The maximum value to which an activity can be selected
12	Integers sets / SOS	Special integer treatment to speed up solution in the case that the MILP includes many integers.

Structure of the programming matrix

Activities and constraints are identified using an activity and constraint index that starts with zero (index = 0,1,2, …n). The index of the first activity has the cell name iact_0 while the index of the first constraint has the cell name icon_0. When inserting or deleting activities and constraints, it is important that the indices are updated. The VBA will otherwise give a warning message when converting the workbook to ASCII.

The programming matrix needs to be structured in a pre-determined order of activities and constraints.

Figure 6 shows this structure schematically.

Table 4 shows the correct order of the activities. The first and the last activity are not used and should be filled with zero values; they contain cell names which position should not be changed when inserting columns. All selling and buying activities follow next. It is important that these activities have the same order as in the market file where their prices are listed for each simulation period. Hiring in labor should come before hiring out labor. Activities that have a price coefficient come first, followed by all other activities. These can be ordered using any logic. Lastly come activities called "future selling activities" that refer to the future yield of investments such as fruit orchards and livestock; these have an entry in the objective function but have no entry in the current disposable income inside the MP tableau.

Figure 6 Schematic overview of activities and constraints in Matrix.xls

		Activities								
		Empty	Selling of crops and livestock	Buying inputs	Credits & deposits	Acess to innovations	Livestock	Growing crops	Selling future products	Empty
Constraints	Empty									
	Cash									
	Labor use									
	Land									
	Livestock									
	Perennials									
	Innovations									
	Credit									
	Crop yield balances									
	Empty									

Table 5 shows the correct order of the constraints in the programming matrix. As with the activities, the first and the last constraints are left blank, i.e., filled with zeros, as these have cell names that should not be changed. This is followed by a set of constraints that determine the resource endowments of the agent. This includes liquid means, which is the amount of accumulated savings by the agent, which is available for investment, variable inputs, or market consumption. It furthermore includes the available amount of labor, land, livestock, and areas of plantations, each of which can be subdivided into many categories (e.g., labor into different age groups, land into soil fertility classes).

Table 4 Order of activities in the programming matrix

	Activities	Explanation
A.	First activity	empty, filled with zeros
B.	Selling and buying activities Short-term deposits Hiring in labor Hiring out labor	All these activities have objective function coefficients (prices) and have to appear in exactly the same order as in the first block of entries in the market file.
C.	All other activities	The order does not matter
D.	Future revenues from investments	Activities with objective function coefficients for selling of future products, related to investments
E.	Last activity	empty, filled with zeros

Table 5 Order of constraints in the programming matrix

	Activities	Explanation
A.	First constraint	empty, filled with zeros
B.	Liquid means	This is a transfer row
	Labor	Labor endowments (can be age and sex-specific)
	Land	Land endowments (can sub-divided into soil classes)
	Irrigation	Amounts of available irrigation
	Livestock	Livestock endowments in heads
	Perennial crops	Hectares of existing plantations
C.	Access to innovations	Controlled by the Network.xls, a value is entered if an agent has access to an innovation otherwise
D.	Capital use in period 0	Required cash in period 0 of investment (start-up cost)
	Capital use in average year	Average amount of capital required
	Short-term credit	The amount of short-term credit required for an activity
E.	All other constraints	The order doesn't matter here
E.	Last constraint	empty, filled with zeros

Information about the activities

Figure 7 shows the upper left corner of the first block of the programming matrix. Activities are ordered in rows, while constraints are ordered in columns. For each activity, 10 types of information need to be specified (ordered a-j). The first five of these, are only to assist the model builder as these are not read by the MPMAS:

THE ACTIVITY INDEX: explained above, starting with number 0.

THE NAME OF THE ACTIVITY: should ideally be short and clear.

THE UNIT OF THE ACTIVITY: e.g., hectare, kilogram, $, etc..

THE SOLUTION VECTOR: or decision variable, shows the optimum solution.

THE OBJECTIVE FUNCTION: which is only required when using the stand-alone-solver. When using the MPMAS, than it should contain as prices are derived from the market file. The product of the objective function and solution vector is what is optimized.

The following five variables are required by the MPMAS:

MARKET INTEGERS: set to 1 if the activity can only obtain integer values, 0 otherwise.

FIXING IN CONSUMPTION MODE: only applies to the use of a three-stage optimization procedure of sequential investment, production, and consumption decisions. When set to 1, then the selected activities in production mode cannot be changed in the consumption mode. This captures the timely sequence and irreversibility of investment and production decisions. When using the one or two-stage optimization, than all values should be set to 0.

LOWER BOUNDS ON THE ACTIVITIES: the minimum value of the decision, usually 0.

UPPER BOUNDS ON THE ACTIVITIES: the maximum value of the decision, usually infinite ($10E^{31}$)

The variables are specified left of the programming matrix as shown in Figure 7. This is only to minimize errors. The MPMAS requires these data to be ordered sequentially as listed in Table 3. Manually entering these data in this order would be cumbersome, especially when the programming matrix is large. This procedure is therefore automated using the VBA. To do this, the VBA needs to know the location where the information has to be copied from and where it has to be pasted to. This is provided using cell names as listed in Table 6.

Figure 7 The programming matrix

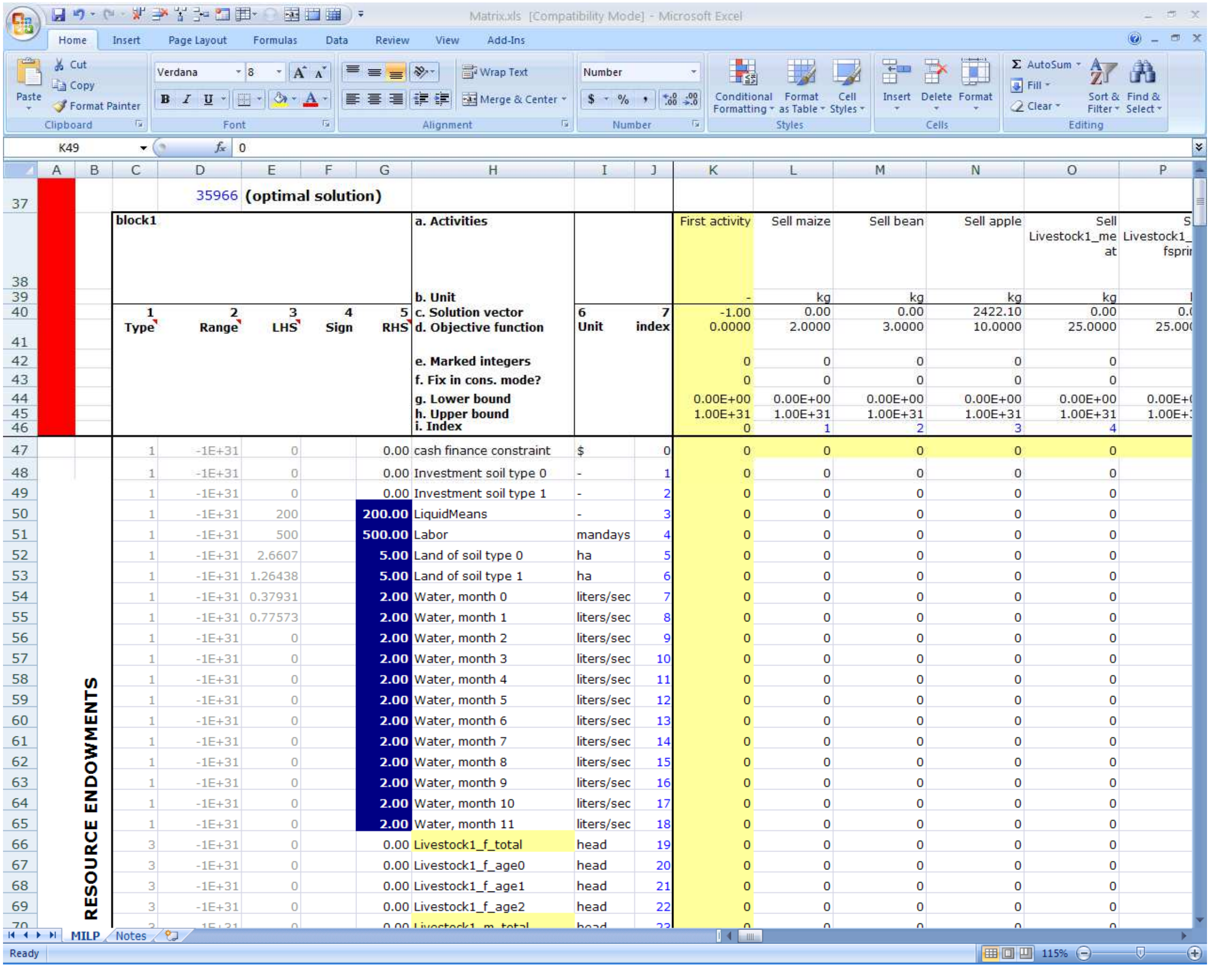


Table 6 Cell names of activity information

	Data category	Matrix-file cell names	
		Copied from	Pasted to
e.	Objective function coefficients	ObjFunctionCopy0	ObjFunctionPaste
f.	Activity type	ActTypeCopy0	ActTypePaste
g.	Marked integers	IntegerCopy0	IntegerPaste
h.	Fixing in consumption mode	FixConsCopy0	FixConsPaste
i.	Lower bound	ActLBoundCopy0	ActLBoundPaste
j.	Upper bound	ActUBoundCopy0	ActUBoundPaste

Information about the constraints

Figure 7 also shows the constraints ordered in columns. For each constraint, there are seven types of information added to the matrix:

TYPE OF CONSTRAINT: directly related to the sign of the constraint equation: a value of 1: “smaller or equal than”; 2 “greater or equal than”; and 3 “is equal to”.

RANGE OF THE CONSTRAINT: also directly related to the sign of the constraint equation: a value of 1: “-1E+31”; a value of 2: “-1E+31”, and a value of 3: “0”.

THE LEFT-HAND-SIDE: only used for evaluating the programming matrix and does not have to be filled in.

THE SIGN: smaller or equal than (“≤”), greater or equal than (“≥”), or is equal to (“ =”). Note the use of one space before the is-equal sign, because Excel would otherwise treat this sign as a formula. The sign is not directly used by MPMAS, which uses the type of constraint as a number.

THE RIGHT-HAND-SIDE: which is only used in the stand-alone-solver version. Right-hand-side values are agent-specific and are constructed from an agent’s resource endowments (land, labor, knowledge, etc.).

THE UNIT OF THE CONSTRAINT: e.g. kilogram, hectare, etc. This is not obligatory and is not read by the MPMAS

THE CONSTRAINT INDEX: which is not directly used by the MPMAS, but is however very important, as other cells are referenced through this index to specific locations in the matrix.

Like in the case of the activities, the MPMAS requires these data in a specific order as listed in Table 7. This ordering is handled by the VBA and only needs a correct specification of cell names as shown in Table 7. If using the split and transposed matrix, than the constraint-related data needs to be read from separate blocks. The cell names need therefore to be given for each block separately. The cell names in block 1 get the suffix 1, in block 2 the suffix 2, etc.

Table 7 Cell names of constraint information

	Data category	matrix-file cell names Copied from	 Pasted to
1	Type of the constraint	ConTypeCopy0	ConTypePaste
2	Range of the constraint	ConRangeCopy0	ConRangePaste
3	Right-hand-side	RHSCopy0	RHSPaste

Developing the programming matrix is the most time consuming part of building the MPMAS. Large matrices are best build step-by-step, adding one feature at a time and then trying it before adding another feature. This involves frequent solving of the MP matrix. To facilitate this process, the MPMAS has a stand-alone solver to check the programming matrix separately from all the other input files. This stand-alone solver can be run from the file the MPMAS menu as explained in the section "Solve matrix" on page 51.

Population.xls: Initiation of the agent population

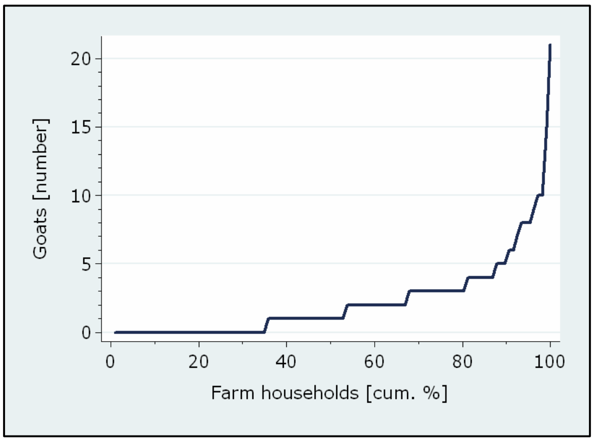
The population file contains two types of information: (1) the demographic composition of the population (age and gender); and (2) the asset composition of the population (livestock, machinery, area of tree plantations, and liquidity). The methodology is based on Monte Carlo techniques, which is shortly described in the following.

Use of Monte Carlo techniques

The methodology to randomly generate agent populations from a sample of farm households is based on Monte Carlo techniques (Berger and Schreinemachers 2006). The objective is to generate a multitude of potential agent populations, with all agents being different both within a single population and between different populations.

One of the challenges in generating an empirically based agent population is to represent each real-world farm household with a unique agent. Yet, data are often available only for a sample of the farm household population. The challenge hence became how to extrapolate the sample population to generate the remaining non-sample agents.

Figure 8 Empirical cumulative distribution of goats over all households in the sample



The most obvious route would be to multiply the sample farm households with their probability weights. Average values in this agent population would exactly equal those of the sample survey. Yet, this copy-and-paste procedure is unsatisfactory for the several reasons. First, it reduces the variability in the population. For instance, a sampling fraction of 20 percent would imply about five identical agents, or clones, in the agent populations. This might affect the simulated system dynamics, as these agents are likely to behave analogously. It becomes difficult then to interpret, for instance, a structural break in simulation outcomes; e.g., is the structural break endogenous, caused by agents breaking with their path dependency, or is the break simply a computational artifact resulting from the fact that many agents are the same? This setback becomes more serious for smaller sampling fractions, because a higher share of the agents is then identical. Second, the random sample might not well represent the population. The sample size is small and the sampling error is unknown but can be large. When using the copy-and-paste procedure, only a single agent population can be created, while for sensitivity analyses a multitude of potential agent populations would be desired. For these reasons, the procedure for generating agent populations is automated using random seed numbers to generate a whole collection of possible agent populations.

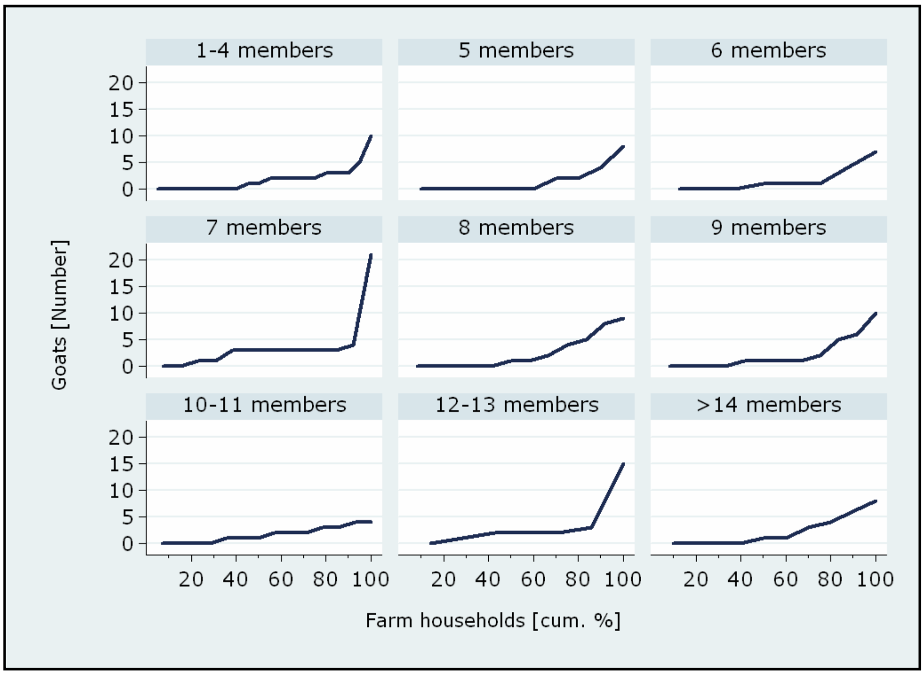
Monte Carlo studies are generally used to test the properties of estimates based on small samples. It is thus well suited for the present purpose as data about a relatively small sample of farm households is available but the interest goes to the properties of an entire population. The first stage in a Monte Carlo study is modeling the data generating process, and the second stage is the creation of artificial sets of data.

The methodology is based on the use of empirical cumulative distribution functions (ECDF). Figure 8 illustrates such a function for the distribution of goats. The figure shows that 35 percent of the farm households in the sample have no goats; the following 8 percent has one goat, etc. This function can be used to randomly generate the endowment of goats, and all other resources, in an agent population. For this, a random integer between 0 and 100 is drawn for each agent and the number of goats is then read from the y-axis. Repeating this procedure many times recreates the depicted empirical distribution function.

Each resource can be allocated using this procedure. Yet, each resource would than be allocated independently, excluding the event of possible correlations between different resources. However, actual resource endowments typically correlate, for example, larger households have more livestock, and more land.

To include these correlations in the agent populations, the sample is divided into a number of clusters based on statistical analysis (e.g., using cluster analysis). In this example, nine clusters are formed based on the variable household size, as this variable correlated most strongly with all other variables. Cumulative distribution functions are then calculated for each cluster of sample observations. This is illustrated in Figure 9 for the random allocation of goats to the agents.

Figure 9 Cumulative distribution of goats over households per cluster



Implementation in the MPMAS

The ECDFs are included in the file <Population.xls>. This file includes a separate data-sheet for each cluster (hence nine files in the above example). In each data-sheet two blocks of information appear. The first block relates to the agents' household age and sex composition, while the second block relates to all other assets.

As most resources only come in discrete units (e.g., number of agent household members, heads of livestock), a piecewise linear segmentation is used to implement the distribution functions. The default is five linear pieces but more can be specified in the need arises.

Table 8 shows an example for the first block of information related to the household composition. The abbreviation "UB" stands for upper bound, while the abbreviation "UV" stands for upper value. The first line in this table is interpreted as follows. An object names "m04" is allocated to the agents in this cluster. This object has an ID of 50, and its sex is 1 (male). The lower age limit of this object is 0 and the upper age is 4. Every agent in this cluster has a probability of 40% (UB1) of having 0 members (UV0) in this category, a probability of 30% (70-40) of having 1 member, a probability of 10% (80-70) of having 2 members, a probability of 10% of having 3 members, and finally, a probability of 10% (100-90) of having 4 members in this category.

Table 8 Demographic composition

Object	ID	Sex	Lower	Upper	UB1	UV1	UB2	UV2	UB3	UV3	UB4	UV4	UB5	UV5
m04	50	1	0	4	40	0	70	1	80	2	90	3	100	4
m59	50	1	5	9	50	1	90	2	100	3	0	0	0	0
m1014	50	1	10	14	20	0	50	1	90	2	100	4	0	0
m1519	50	1	15	19	30	0	50	1	80	2	90	4	100	5
m2024	50	1	20	24	40	0	80	1	100	2	0	0	0	0
m2529	50	1	25	29	70	0	80	1	100	2	0	0	0	0
m3034	50	1	30	34	80	0	100	1	0	0	0	0	0	0
…														

Note: UB and UV stand for "upper bound" and "upper value" respectively, of which the UB is expressed cumulatively as a percentage of total agents.

The second block of information is the similar, except that these objects have no sex and no lower and upper age limit, but can optionally have a land requirement (**Table 9**). The objects include livestock (e.g., cows and goats), a farm structures (e.g., a henhouse), or hectares of coffee plantation:

- a female head of the household
- innovation segment: early adopters to laggards
- form of expectations: rational, ..
- liquidity: liquid means available for investments
- leverage:…

The specification of these five assets is not optional. If no data on these are available, then all values are to be set to zero.

Table 9 Asset composition

Object	ID	Type	LR	UB1	UV1	UB2	UV2	UB3	UV3	UB4	UV4	UB5	UV5
Female head	44	-1	0	100	1	0	0	0	0	0	0	0	0
Innovat.	45	-2	0	10	1	40	2	60	3	80	4	100	5
Expect.	46	-3	0	29	0	100	2	0	0	0	0	0	0
Liquidity	47	-4	0	100	500	0	0	0	0	0	0	0	0
Leverage	48	-5	0	89	0	95	0	100	0	0	0	0	0
Cow	2	8	.91	50	0	70	2	80	4	90	7	100	23
Goat	3	8	.13	40	0	60	1	80	3	90	4	100	8
Cow in shed	4	8	0	100	0	0	0	0	0	0	0	0	0
Coffee 1	14	1	1	30	0	40	0	60	0	80	0	100	4
…													

Note: LR stands for land requirement; UB and UV stand for "upper bound" and "upper value" respectively, of which the UB is expressed cumulatively as a percentage of total agents.

Maps.xls: The physical landscape

MAS models of land-use/cover change (MAS/LUCC) couple a cellular component that represents a landscape with an agent-based component that represents human decision-making (Parker *et al* 2003). The landscape component is defined in the map-file. It contains six spatial layers of information as summarized in Table 10. The interface offers two options for analyzing a matrix file. The first is “Solve again”, which takes the matrix file, removes all string values from the file, saves it under a different name, and solves the file again using an executable called “MilpCheck.exe”. Three different solving routines are available and if the matrix is feasible then the solution vector is saved as a separate file.

The other option “Back to Excel” takes the matrix file and copies and pastes its values (matrix coefficients, bounds, and right-hand-side values) to Matrix.xls saving it under its original name, but with the extension “.xls”. If the matrix has first been analyzed using “Solve again” then the solution vector is automatically imported into the file. This option is suitable for analyzing matrices that were infeasible.

The information is numerically encoded and organized in a raster format. Grid cells with no information get a value “-1”. Each cell represents a certain amount of land, e.g., 1 hectare.

The map-files can be produced in two ways: in a Microsoft Excel workbook, if the number of columns is less than 256 and which is then converted to plain text format using ScenarioManager.xls, or in ArcView GIS using the exporting routine to save it in ASCII format. All maps have to be in a grid cell format. Polygons must be converted to grid cells. Yet, by defining the grid sufficiently small, the grid format can approximate any polygon.

Table 10: Spatial layers in Map.xls

Nr.	Layer
1.	The location of agents’ farmsteads
2.	Each agents’ membership of a population
3.	Each agents’ membership to a population cluster
4.	Each agents’ membership to an innovation segment
5.	The location of agents’ plots
6.	The soil type of each plot

Figure 10 shows an abstract of a very simple map-file in Excel for the location of farmsteads. This simple landscape shows two farmsteads (coded with IDs 0 and 1). All locations without a farmstead should be denoted with "-1". Note that when using the downloadable version of MPMAS, the maximum number of farmsteads that can be included is 50.

Figure 10 Example spatial layer for the location of farmsteads

2	LOCATION OF FARMSTEADS (ID)				
		-1	-1	-1	-1
		-1	0	-1	-1
		-1	-1	1	-1
		-1	-1	-1	-1

Network.xls: The diffusion of innovations

Population.xls randomly assigned each agent to a network segment. The file Network.xls can be used to control the access of agents to innovations. If all agents have access to a particular technology (e.g. a traditional crop variety), then this technology does not have to be included in the Network.xls, yet if the technology is relatively new (i.e., an innovation) and is only partially diffused in the sample population, then the network file can be used to represent this partial diffusion.

The diffusion of innovations is based on a network threshold model (Valente 1994). This type of model is based on the idea that information diffuses gradually through interpersonal networks and that once enough information has reached a particular agent, it will then consider adoption. How much information is 'enough' is agent-specific and determined by the threshold level. In line with Valente (1994), five network thresholds are specified as shown in Table 11.

Agents that belong to the group of *early adopters* (nr.2) will only consider adoption after the group of *innovators* has adopted, that is when the adoption rate has reached 2.5 percent.

Table 11 Network threshold values

	Threshold	Characterization
1	< 2.5%	Innovators
2	2.5 – 16%	Early adopters
3	16 – 50 %	Early majority
4	50 – 84 %	Late majority
5	84 – 100 %	Laggards

The actual adoption decision is both a function of these individual network thresholds and the expectations of agents. Agents will only adopt if (a) they have reached their network threshold; (b) they expect the innovation to bring a positive net contribution to meeting their objectives (it brings an agent utility). This two-stage adoption procedure yields a realistic way of simulating the diffusion of innovations.

Agents' membership to network thresholds was assigned Population.xls. The diffusion model is sensitive to the proportion of agents in each network. The allocation of many agents to the first segment will speed up the diffusion of innovations, while the diffusion will be stagnant if less than 2.5 percent of all agents are allocated to the first segment. Ideally, the distribution of agents follows the threshold values -- that is 2.5% is defined as *innovators*, 13.5% as *early adopter*, 34% as *early majority*, etc. This can, however, not be guaranteed as the assignment to network groups is partially random. To overcome this, a calibrating factor called '*overlap*' is included. The overlap factor is multiplied by all network thresholds and can attain values between 0 and 1. If set to 1, then the network thresholds are unadjusted, while if set to 0, then all thresholds become 0 and all agents can hence immediately adopt. The model needs to be tested for an appropriate value of the overlap factor (most usually it will have to be set to values between 0.5 and 0.8).

Table 12 Innovations

Nr.	Parameter	Explanation
1	Object ID	This should match with the object ID in all other files (e.g. <perennials.xls>, <population.xls>, and <demography.xls>.
2	Type	The type of object. There are two basic types: Objects with a negative type refer to agent characteristics, while objects with a positive type refer to asset characteristics (incl. innovations).
3	Divisibility	Set to 1 for all divisible innovations. E.g., a cow is indivisible (set to 0) while a hectare of coffee is divisible (set to 1)
4	Acquisition costs	The purchasing price of an innovation in the first year. For livestock, make sure this is consistent with <livestock.xls>.
		Note that this cost refers only to “proper investments”, i.e. productive activities with a gestation between first input use and full output of more than 1 year. If shorter than 1 year, then the price must be included in file <Market.xls>.
5	Lifetime	The maximum age of an object. For example, a coffee plantation lasts 12 years, and cows are culled before they turn 10 years old.
6	Suitability	The soil types an innovation can be used on, if not restricted to any soil type then set the suitability to 0.
7	Minimum investment	Optionally a minimum amount can be specified. E.g, when investing into a new coffee plantation, the investment should be more than 0.2 ha.
8	Column	The activity index in the programming matrix. In case of investment objects, the MATRIX includes two separate activities: one for production and one for investment. This index must refer to the production activity.
9	Row	The constraint index in the programming matrix.
10	Permanent crop yield	The row coordinate in the programming matrix where the yields appear (-1 if not a permanent crop)
11	Coefficient	The pieces per unit of the investment good (e.g., days/laborer)
		The solution in the investment mode is taken and enters the production mode after multiplication with this factor. The factor is therefore used to convert the units in the solution vector of the investment mode to units of the RHS in the production mode.
12	Level of innovation	Specifies for what segment the innovation is accessible, if accessible for all set to 0.
13	Availability	The year at which the innovation is introduced into the population
14	Accessibility	The year at which the innovation can be acquired for the particular innovation segment.
15	Share own capital	The share of the acquisition cost that needs to be paid from own liquid means.
16	Interest rate on borrowed capital	For what is not paid from own means an additional interest cost is incurred.

Network.xls lists all innovations and specifies various types of information for each of these as is briefly explained in Table 12. The network-file uses three types of interest rates. (1) The long-term interest rate is the interest over borrowed capital with a gestation of longer than one year. (2) The short-term interest rate is the rate for borrowing capital from, say a bank, for a period of one year. (3) The interest rate on equity is the rate you receive when depositing money at a bank (say, at your current account). This is the opportunity costs of capital. In absence of any banks or informal savings, this rate can be set very low.

BasicData.xls: General parameters

Parameters that do not immediately relate to a single input file but are required by several separate model components are included in BasicData.xls. About 48 parameters are included in this file. For instance, the choice of consumption model is included in BasicData.xls because this impacts both on the matrix-file and on the market-file. The file is organized in eight categories of parameters as shown in **Table 13**. Most parameters in this file are self-explanatory.

Table 13 Parameters in BasicData.xls

	Category	Explanation
1	General parameters	Integers counting the frequency of same events, like the number of catchments, villages, networks, etc.
2	Innovation parameters	Various parameters that allow the user to fine-tune the innovation diffusion process, such as the 'overlap' parameter described in Section 6.
3	Rental markets	For making land markets endogenous in the model
4	Policy parameters	For the simulation of policy options such as subsidies for permanent crops
5	Switches for various sub-models	Defines which consumption is implemented and whether there is a crop growth model, livestock or perennial crop model. If not then no respective file is read by the program.
6	Soil information	Defines the size of a single grid cell in hectares and defines which number of different soil types and classes. Soil classes refer to land suitability.
7	Debugging of the programming matrix	The most important dynamics can be switched off using these options: (a) aging of agent household members and assets; (b) and updating of soil fertility (only if a soil model is defined). In addition matrices can be saved by entering a matrix number.
8	Fine-tuning of the solver	This tells the solver how long it can maximally take to solve a single MP model or how many iterations is can go through.

CropWat.xls: Crop water requirements

Crop yields were modeled following the FAO CropWat model (Clarke et al. 1998, Smith 1992). The workbook CropWat.xls specifies for each crop activity that appears in Matrix.xls the crop water requirement and the crop yield potential. For each selected crop activity in the MP tableau, MPMAS will recalculate a crop yield based on the crop water requirement and the crop water supply—the latter specified in Routing.xls and is explained in the next section.

The crop-water requirement (CWR) for crop c in month m is the product of a crop water coefficient (Kc), the potential evapotranspiration (ET0), and the planted area (Area):

$$CWR_{c,m} = Kc_{c,m} * ET0_m * Area_{c,m} \quad (1)$$

in which ET0 is a function of the local climatic conditions and can be derived from CropWat 7.0. The Kc values can be obtained from specialized literature or as standard values in the CropWat model.

Monthly values for CWR do not change over time and are therefore specified in the workbook CropWat.xls. Each of the crop activities specified in Matrix.xls also needs to be included in CropWat.xls. In CropWat.xls the activity and constraint indices in the MP tableau are specified for each crop activity and are linked to Matrix.xls.

The CWR can either be met through irrigation (IRR) or precipitation—converted into effective precipitation (EP) to capture the share of precipitation that is actually available to the crop, depending on its growth stage. The calculation of effective precipitation is rather complex in CropWat and was simplified using a regression equation. The equation can be parameterized by inserting into CropWat a large range of precipitation values and crop water requirements for a selection of crops and then obtaining the EP values. The EP values can then be regressed on the crop water requirements and precipitation using ordinary least squares:

$$EP_{cm}=a+b1*CWR_{cm}+b2*(CWR_{cm})^2+c1*PREC_m+c2*(PREC_m)^2+d*CWR_{cm}*PREC_m \quad (2)$$

The part of the crop water requirement that is unfulfilled by either precipitation or irrigation is called the deficit irrigation (DIRR):

$$DIRR_{cm} = CWR_{cm} – ER_{cm} – IRR_c \quad (3)$$

If there is deficit irrigation then the crop yield is reduced. The magnitude of the deficit is expressed as the quotient of the deficit irrigation and the crop water requirement ($DIRR_{cm}/CWR_{cm}$), which is called the Kr value. In reality it matters much in what stage of the growing period the water deficit occurs. Yet, as a simplification, the quotients of deficit irrigation and the crop water requirement are simply averaged over all months with non-zero crop water requirements:

$$\boldsymbol{Kr_c} = \left({}^{\mathbf{1}}\!/_{\boldsymbol{m}} * \sum \frac{\boldsymbol{DIRR_{cm}}}{\boldsymbol{CWR_{cm}}} \middle| \boldsymbol{CWR_{cm}} > \mathbf{0} \right) \tag{5}$$

Following Berger (2001) it is assumed that the crop yield is lost completely if the average Kr falls below 0.5, while for Kr values greater than or equal to 0.5 the average Kr value is multiplied by the crop yield potential ($YPOT_c$) to simulate the actual crop yield (Y_c):

$$\boldsymbol{Y_c} = \begin{cases} \boldsymbol{Kr_c} * \boldsymbol{YPOT_c}\ \boldsymbol{if}\ \boldsymbol{Kr_c} \geq \mathbf{0.5} \\ \mathbf{0}\ \boldsymbol{if}\ \boldsymbol{Kr_c} < \mathbf{0.5} \end{cases} \tag{4}$$

Routing.xls: The crop water supply

Routing.xls simulates the irrigation water supply as based on the Edic-cedec model (Berger 2000). The physical landscape is divided into irrigation sectors while the irrigation water supply is defined per sector. There are three sources of irrigation water in MPMAS:

- River flows: This is the water supply from streams in the watershed
- Surface runoff from neighboring irrigation sectors: The runoff from neighboring irrigation sectors.
- Lateral flows: The sub-surface flows from neighboring irrigation sectors.

The first three worksheets in Routing.xls define the quantity of water from each of these sources. The first worksheet <EdicRiverFlows0> defines this quantity in m3/second while the two other worksheets <EdicSurfaceRunoff0> and <EdicLateralFlows0> define it as a proportion of the river flows. These last two sheets contain a matrix in which the surface and sub-surface flows between all sectors can be defined. If irrigation water is only directly derived from streams then all values can be set to zero.

The last worksheet in Routing.xls, <EdicIrrigationMethods0>, defines the efficiency of various irrigation methods and contains parameters of the Edic-cedec model.

Table 14 Efficiency of various irrigation methods defined in Routing.xls

Name	Surface runoffs at night	Evapotranspiration	surface	subsurface	groundwater
Flood	0.111	0.267	0.400	0.133	0.089
Furrow	0.111	0.400	0.311	0.111	0.067
Terracing	0.111	0.544	0.233	0.067	0.044
Drip	0.111	0.800	0.000	0.053	0.036
Improved Furrow	0.111	0.444	0.267	0.111	0.067
Advanced Furrow	0.111	0.444	0.267	0.111	0.067
Sprinkler	0.111	0.711	0.067	0.067	0.044
Tape	0.111	0.800	0.000	0.053	0.036
Center Pivot	0.111	0.800	0.000	0.053	0.036
Micro sprinkler	0.111	0.800	0.000	0.053	0.036

Region.xls: The distribution of water over agents

Region.xls defines the distribution of water rights over agents. Water rights are defined as a proportion of the total irrigation water supply of an irrigation sector that an agent is allowed to use. This proportion is assumed constant over the whole year and during all years in the simulation run.

MPMAS has two options for distributing water over agents:

1. **Random water rights:** Similar to the data structure in Population.xls, the water rights can be distributed over agents randomly. Upper and lower bounds can be defined for each inflow and for each sector.
2. **Actual water rights:** For each agent it is defined what proportion of the total irrigation water supply per sector and per inflow the agent can use.

Perennials.xls: Parameters of perennial crops

Whereas the population file specifies the course of human life, the permanent crop file specifies that of trees. It contains the following information for each year in the life span of a permanent crop:

- yield
- pre-harvest costs (e.g., spraying)
- harvest cost
- total labor requirement
- total machinery requirement
- peak labor requirements

Furthermore, it specifies the acquisition cost and life span, both of which should be the same as specified in the network file.

Because alternative levels of input use are possible for a crop, a separate permanent crop activity is specified for each input level. For instance, in the Uganda case, coffee can be grown on five different soil types, with 3 alternative levels of labor use, and with or without fertilizer; this translates into 30 different coffee activities. Switching between input levels and between soil types is thereby prevented and to switch input levels the agent is required to fulfill the acquisition cost and start anew in year 0.

Livestock.xls: Parameters of livestock

The livestock file is similar to the permanent crop file in that different parameter values can be specified for each year. The livestock file is, however, different from the permanent crop file in that more than one output can be specified and the matrix coefficients of these outputs are directly entered in this file, rather than the network file.

The first two outputs of each livestock type are gain in live weight, which is specified cumulatively, and numbers of female offspring. Female offspring is treated differently as this has a course of life of its own starting with year zero. Male offspring remains in the file as its sole purpose is meat production.

Livestock.xls is furthermore different from the permanent crop file in that it allows labor to be specified per period, while in the permanent crop file only average labor is specified which is distributed over all periods according to fixed coefficients in the programming matrix.

Soils.xls: Soil fertility dynamics and crop yields

Soils.xls contains parameter values for a biophysical model to simulate soil fertility changes and the resulting crop yields as based on the Tropical Soil Fertility Calculator (TSPC). This integrated model was developed for an MPMAS application to Uganda. For more details about this component the reader is referred to Schreinemachers et al. (2007) and Schreinemachers (2006). The TSPC does not have to be included in the model but can be switched off in ScenarioManager.xls. If switched off then the file soils.xls does not have to be included in the input data.

Market.xls: Market prices and consumption

Market.xls contains two types of information. First, it specifies market prices for all products and second, it specifies which type of consumption model is implemented. Each is described in the following.

Market prices

Market prices define the prices for all tradable goods and is equivalent to the objective function of the MP model. Market prices include: (1) selling prices of agricultural products; (2) buying prices of food products; (3) buying prices of seed, chicks and fertilizer; and (4) prices of leasing in a tractor, and hiring in or out labor. The MPMAS software copies these values and pastes them into the MP matrix. The order of these goods must therefore be the same as in the file <matrix.xls>.

All market prices are exogenous in the model and need to be defined for each period in the market-file. The effect of price changes can be simulated by adjusting the prices in this file; this file can therefore be used to test various price-related scenarios.

Market prices include the price of hiring labor in and hiring labor out. Make sure that the price of hiring in is greater than the price of hiring out otherwise the MP model might become unconstrained. A higher price for hiring in is justified by transaction and monitoring costs.

A special type of prices are 'future prices', these are expected selling prices related to investment activities such as livestock or trees. These, for instance, include milk and meat. These products cannot be sold in the same year of investment and hence do not add to the current revenues but only to the future income. Whereas the current prices always enter the matrix in a pre-determined order as the first activities, the user can determine where the future prices enter the matrix by specifying an activity index for each entry. Hence, the order in which they appear in the matrix file does not matter. Activity indices are ideally linked to the matrix-file so that they are automatically updated when adding activities or constraints to the matrix.

Two types of consumption models can currently be specified: one very basic and one very complicated model. More intermediate consumption models will be included in the future. The choice of consumption model should be included in BasicData.xls. If using the extended consumption model then Matrix.xls needs to include the consumption model in the matrix.

The basic consumption model

When using the basic consumption model, then consumption is handled by simple heuristics outside the MP model and after the income level has been determined. Buying activities for food products do therefore not have to be specified in the market file. The basic consumption model simply specifies how much of the income will be consumed. The remainder will be added to the agent's cash endowment and is available for investment in the next period. The basic model requires specification of three parameters:

1. Extra consumption [proportion]: This is the proportion of each additional monetary unit that is consumed and ranges between zero and one. If set to zero then no income is consumed and all is saved; if set to one then all income is consumed and nothing is saved.
2. Minimum consumption per head/year [monetary value]: This value specifies the minimum amount of income that is consumed by each member of an agent's household. It must be set to a positive value.

3. Foregone consumption [monetary value]: In case that income is too low to meet the consumption specified by (1) and (2) then this value determines the proportion by which the consumption level is to be reduced. If set to zero then the minimum consumption level is reduced to zero. If set to one then the consumption is not adjusted downward.

The extended consumption model

If using the extended consumption model then the program uses a three-stage solving procedure of investment, production, and consumption (the last stage is not needed if using the basic consumption model). The assumption is that production and consumption decisions are inseparable because of market imperfections as is typically the case in rural areas of low-income countries (Sadoulet and de Janvry, 1995). Different from the basic consumption model, that simply allocates part of the revenues to consumption and the rest to savings, the extended model implements the consumption decision within the MP model so that production and consumption decisions are simulated simultaneously. Because the parameters of the extended consumption model are household-specific its implementation requires much additional input in both the market- and the matrix-file.

The implemented consumption model itself has a three-step procedure of savings, food/non-food expenditures, and expenditures on specific categories of food products. The model is described in Schreinemachers (2006) and Schreinemachers and Berger (2006b). Including this model requires the estimation of econometric models at each step. The advantage of this model is that it allows a detailed simulation of food security dynamics. If food security is not much of an issue and market imperfections are few then the basic consumption model is preferred.

Savings

In the first step of the system, agents decide how much of their income to expend and how much to save. Let the variable SAV be the savings and INC the disposable income, H the household size measured in an equivalence scale (joules), D the matrix of district dummies, and α_0 a constant term. The amount of savings is specified as a quadratic function of disposable income:

$$SAV = \alpha_0 + \alpha_1 INC + \alpha_2 INC^2 + \alpha_3 H + \sum_{i=1}^{n-1} \alpha_{4,i} D \qquad \text{with } \alpha_2 > 0 \qquad (5)$$

in which the alfas are the parameters to be estimated. Micro-economic theory suggests that the share of savings increases with income, which is the case if α2 is positive.

Food/non-food expenditures

Total expenditure (TEX) is the income available to spend, which is derived from the income identity:

$$INC = SAV + TEX \qquad (6)$$

In the second step, agents decide how much of this total expenditure to allocate to food (FEX) and non-food items (NEX). A modified version of the Working-Leser model quantifies this relationship (Hazell and Roell 1983):

$$v = \beta_0 + \beta_1 \ln TEX + \beta_2 H + \sum_{n=1}^{40} \beta_3 D \qquad (7)$$

in which *v* is the expenditure share on food and the *betas* are parameters to be estimated. It follows that the value of food expenditures (FEX) equals TEX*v/100 while NEX can be derived from the parameter estimates using the properties of symmetry and adding up.

Expenditures of food categories.

In the final step agents decide to spend their food budget on broad categories of food products. The use of categories instead of individual items gives agents more scope for substitution. The third step is quantified using a linear approximation of the Almost Ideal Demand System (LA/AIDS) (Deaton and Muellbauer 1980):

$$w_k = \delta_{0,k} + \sum_k \delta_{1,k,l} \ln p_l + \delta_{2,k} \ln(M/P^*) + \delta_{3,k} H + \sum_{n=1}^{40} \delta_{4,k} D \qquad (8)$$

where the subscripts k and l denote individual food categories of a total of n categories (k,l=1,2,..,n) and the *gammas* denote parameters to be estimated. The variable w_k is the share of category k in the total food budget; M is per capita food expenditures measured in an equivalence scale for household size. P^* is an index of prices, which in the original (non-linear) version has a translog functional form but in its linear version can be replaced by the logarithm of the Stone geometric price index (Deaton and Muellbauer 1980):

$$\ln P^* = \sum_k w_k \ln p_k \qquad (9)$$

Demography.xls: Population dynamics and labor supply

The age of each household member naturally changes over time. Aging impacts on the household labor supply and is therefore an important dynamic in the model. Demography.xls specifies age-specific variables that optionally include, apart from labor supply, mortality, fertility, and nutritional requirements. Table 15 shows an abstract of this file, for the labor category of unskilled male labor for the first 4 years.

Labor supply can be estimated from farm household survey data. If the programming matrix uses an agricultural production function that relates output to labor use, then it is important that the labor supply is estimated from the same data source. Data on time allocation are typically inaccurate and variable between surveys. The importance here is not so much to get an accurate estimate but an estimate that is consistent with the production function used.

Mortality and fertility are specified in terms of the probabilities of dying and giving birth. Mortality and fertility can be obtained from official statistical sources or demographic studies. Make sure that the probability of dying at the maximum age is set to unity otherwise the program might crash.

Table 15 Abstract of the demography file

B. Unskilled male members				
Career ID	**64**			
Number of different ages (lifespan)	**100**			
	Age 0	Age 1	Age 2	Age 3
Sex-age group	1	1	1	1
Labor hours / year	0.0000	0.0000	0.0000	0.0000
Mortality (probability of dying)	0.0764	0.0257	0.0123	0.0074
Fertility (probability of giving birth)	0.0000	0.0000	0.0000	0.0000
Energy needs (billion joules/year)	1.0684	1.5055	1.7312	1.8747
Protein needs (kg/year)	5.1100	8.0300	8.0300	9.4900

Food nutrition, such as calories and protein, can be included to quantify food security. This is only useful in case a detailed food consumption model is included that estimates food consumption into detail. This consumption model, simulating the nutrient supply, would have to be specified in Market.xls; while Demography.xls estimates the nutritional demand and the balance of the two would be an indicator of food security. Food nutrition is location specific and moreover depends on the intensity of physical activity performed. One possible source of country-specific default values is James & Schofield (1990).

Additional features

MPMAS includes additional features that assist the model builder in tracing back changes, analyzing certain MP models, looking at the results, or solving the model in a stand-alone version. Each of these options is detailed in the following.

XChanges.txt

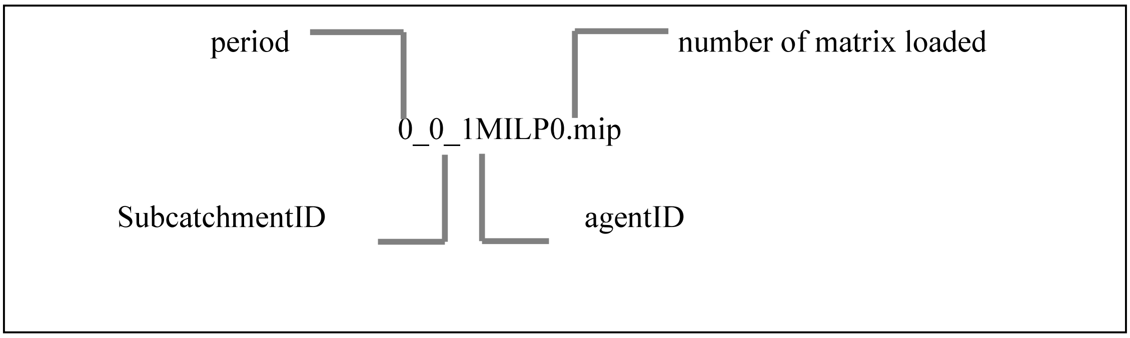
This is a plain text file in which the model builder can keep a diary of changes made to the model. We previously recommend that the modeler proceeds in a step-wise fashion in which small changes are made one by one after which the model is solved, the complete file set is saved, and a copy is used as a basis to make a subsequent change. In this way, the modeler always has one running version of the model and if the MPMAS reports an error than one can always go back to this latest running version and try to make the change again, but perhaps in smaller steps. If all changes are well documented in the file <XChanges.txt> then it will be easier to detect the source of possible errors when these are encountered.

Check matrix files

If an MP model for a particular agent is infeasible then MPMAS saves it with the extension ".mip" in the folder `out/test`. The name syntax of saved programming matrices is shown in **Figure 11**. In ScenarioManger.xls users can also request MPMAS to save additional matrices, either by either:

- Specifying the matrix (as a positive number) in the option "Save a matrix […]"
- Specifying the agent ID (as a negative number) in the option "Save a matrix […]"
- Including the flag "-M" in the MPMAS command line will save all matrices

Figure 11 Name syntax of saved MP matrices



The agentID is an integer value that identifies each agent. Note that the numbering does not start at 0 but at 1. AgentID 0 is reserved for a 'special agent': it contains all land that is not currently allocated to all other agents. This agent does not solve any MP model; it just acts as storage for the village (or subcatchment). Hence, for each village (or subcatchment) the remaining land is stored in a separate agent. Because of this procedure the agentID from the map-file might be different from the agentID used internally by the program, which is only in the case of multiple villages/subcatchments. It is therefore recommended to adjust the agentID in the map-file by not assigning the first ID to an agent (for each village/subcatchment).

If a matrix is infeasible then this can indicate one of the following:

(a) there is a problem with some of the input files that update the matrix;

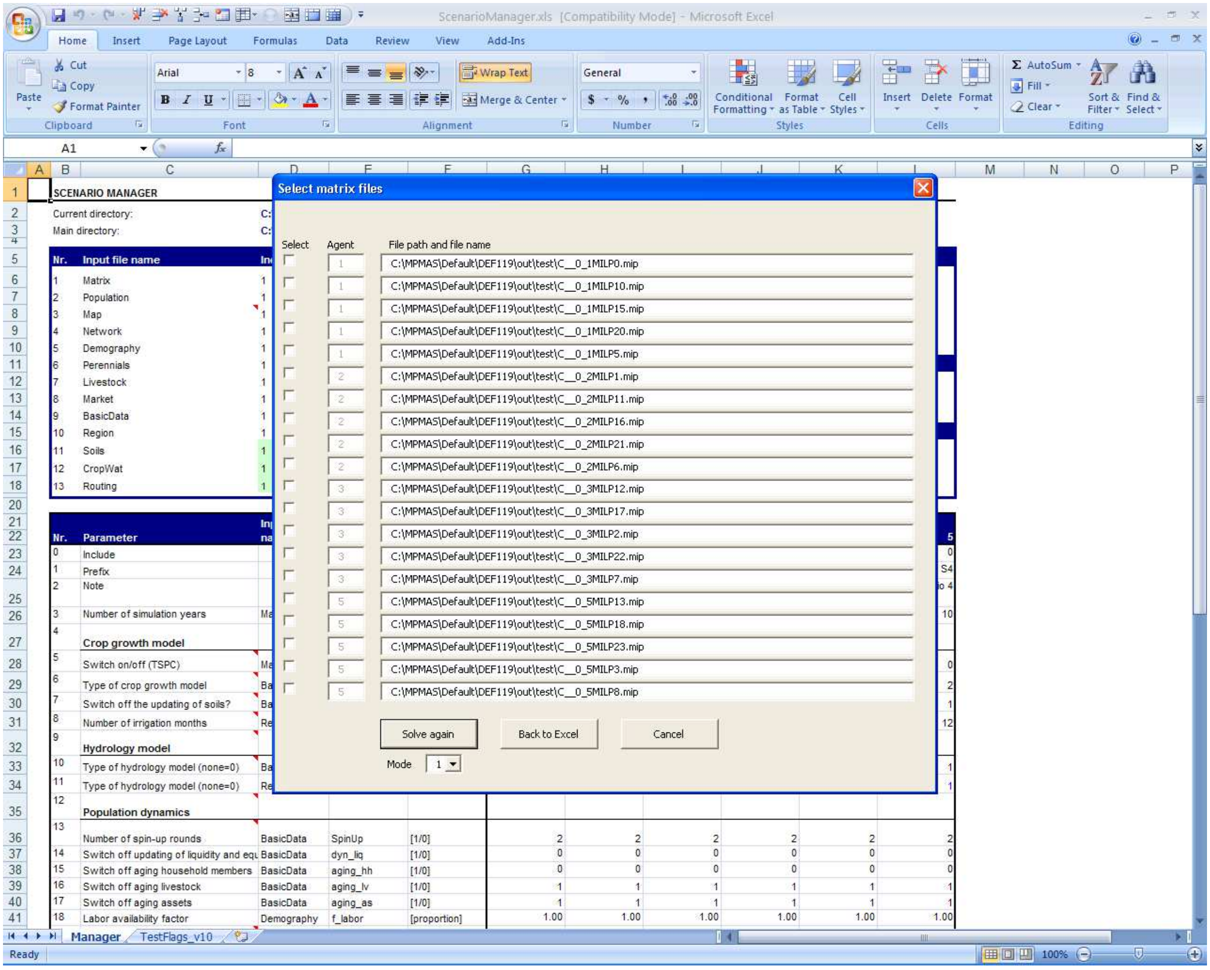
(b) there is a problem in the design of the matrix; or

(c) there is a problem in the source code of the MPMAS.

Most frequently the first or the second option will be the case as the model has been tested extensively. The produced error matrix has a format similar to the matrix input file in ASCII format (**MILP.dat**), except that it has textual remarks for each block of information. It will be difficult to study the matrix in this format, for which reason the macro "Check matrix files" was developed. It is accessed through the MPMAS menu bar in ScenarioManager.xls or by using the shortcut ALT+CTRL+M. It opens a Graphical User Interface that suggests which matrix files are available from the last model run (Figure 12). The interface offers two options for analyzing a matrix file. The first is "Solve again", which takes the matrix file, removes all string values from the file, saves it under a different name, and solves the file again using an executable called "MilpCheck.exe". Three different solving routines are available and if the matrix is feasible then the solution vector is saved as a separate file.

The other option "Back to Excel" takes the matrix file and copies and pastes its values (matrix coefficients, bounds, and right-hand-side values) to Matrix.xls saving it under its original name, but with the extension ".xls". If the matrix has first been analyzed using "Solve again" then the solution vector is automatically imported into the file. This option is suitable for analyzing matrices that were infeasible.

Figure 12 Screenshot of “Check matrix files”



A few tips for finding an error in a programming matrix

To find an error and what causes it can sometimes be a challenge. Here are some tips that could help:

Find out whether the matrix is an investment model or a production model. The investment model has a value ‘1’ in the right-hand-side of the first activity (called the investment switch), which allows investments in perennial crops. If no value ‘1’ appears then the matrix is a production model.

- Check whether all right-hand-side values have positive values
- Check for strange combinations of right-hand-side values:

- Is male or female adult labor zero or very high?
- Is land zero or very high?
- Are livestock numbers very high?
- After finding a 'suspicious' value in the programming matrix then change it and try to solve again.

In addition, the IBM Solver can help to locate an error in the matrix. Often it is able to point to a specific cell value (by row and constraint index) that makes the problem infeasible. For this, the error matrix can be solved using the stand-alone-solver, which is the file **MilpCheck.exe**..

XResults.xls

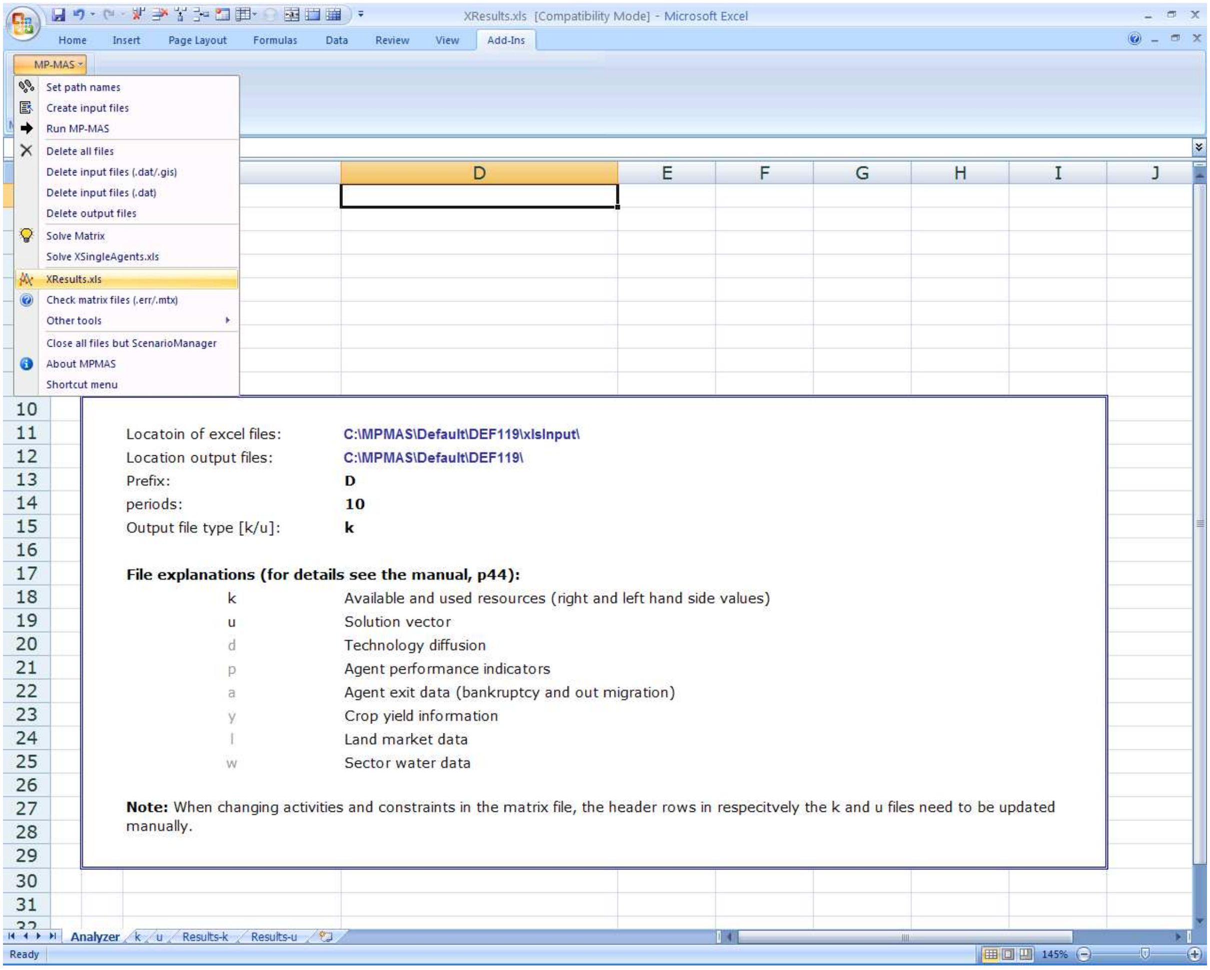
Model results can be analyzed using standard statistical packages such as STATA, SPSS, or MATLAB. The file `XResults.xls` was developed for the default data set to get a quick look into the results of the model. Figure **13** shows the interface of this file. The file contains VBA code that imports two types of output files:

u-files: these contain the price and solution vector; and

k-files: these contain the right-hand-side values and left-hand-side values.

All output files are described in a following section of the manual. In addition to the VBA importing routine, the file does some simple analyses of a few selected variables using database functions in Excel. Users can add other types of analyses.

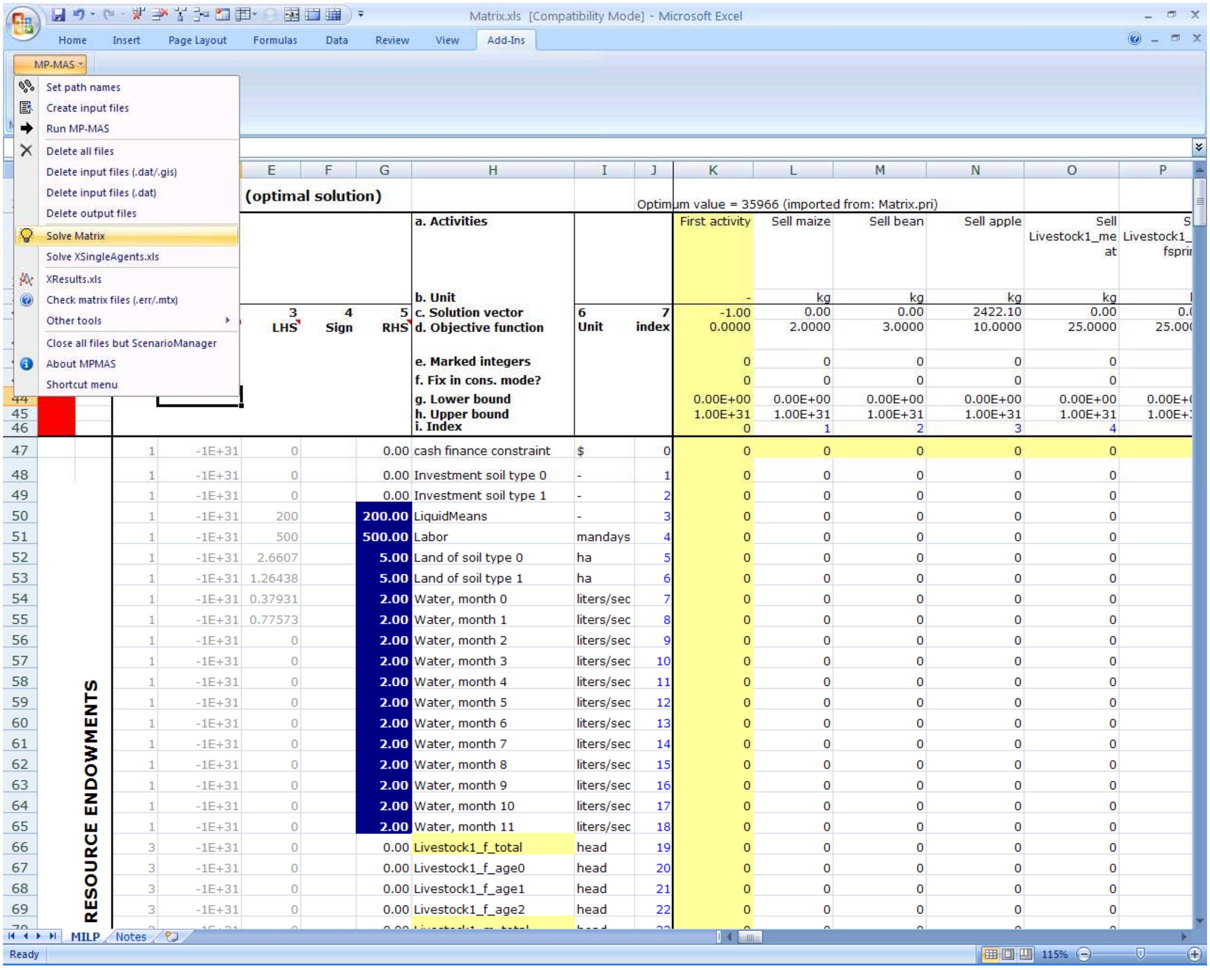
Figure 13 XResults.xls



Solve matrix

The MP tableau in Matrix.xls can be solved independently. For small tableaus, the standard solver available in MS Excel can be used yet for larger tableaus the OSL can be used as a stand-alone solver as shown in Figure 14. This macro will save Matrix.xls and convert it to ASCII, creates a batch file calling the IBM-OSL, re-open Matrix.xls and import the solution vector into the matrix. We note that the macro only works with Matrix.xls.

Figure 14Solving Matrix.xls with the stand-alone solver

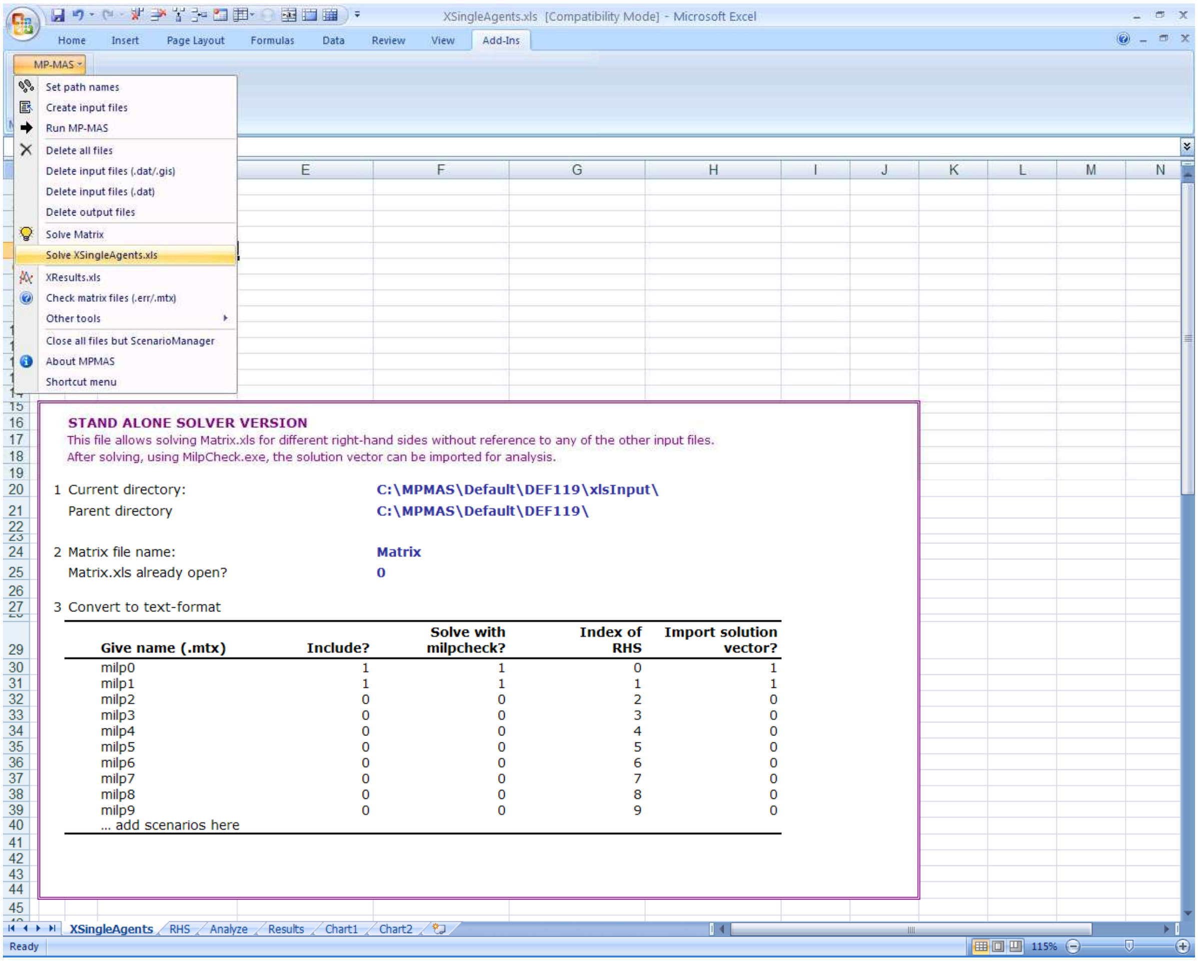


XSingleAgents.xls

The developed programming matrix (Matrix.xls) can be tested for different sets of right-hand-side values using the file XSolver.xls. **Figure 15** shows the main interface of this file. The VBA code is run through the MPMAS menu bar in Microsoft Excel. The VBA code goes through the following procedure: Right-hand-side values from the worksheet <RHS> are copied to the matrix (Matrix.xls) and saved it in mtx-format. Make sure that the right-hand-side value has the same range otherwise an error message will pop up to the screen.

A batch file calling MilpCheck.exe is created for and run. This will create an MS-DOS pop up window for each file that is solved. Each feasible matrix will result in a solution vector saved to the hard disk; these files are recognizable by their extension ".pri" (standing for primal). All solution vectors are imported to the worksheet <Analyze>. The results are shows in simple charts, which can be adjusted or extended by the user.

Figure 15 XSolver.xls



Scenario output files

Scenario results are written to the folder `/out`. A first set of output files returns the outcomes of the random agent generator (**Table 16**). The first contains the input as read by the program and the second contains the output representing the generated agent population. This second file, with extension .LT2, can be analyzed and compared with the survey data. For each period in the simulation, there is a set of output files in plain text (ASCII). There are nine types of files listed and shortly described in Table 17.

.

Table 16 Agent generation output files

Nr.	Extension	Description
1	.LT1	Input to the random agent generation. This contains the asset assignment as in the file <Population.xls> with a separate file for each cluster.
2	.LT2	Output from the random agent generation. Assigned assets to each agent with a separate file for each cluster of agents. Note that the first agent is the 'special' agent which comprises all non-allocated land.

Table 17 Output files

Nr.	suffix	Description
1	$\_a_t$	Agent exit data (e.g., due to bankruptcy or out-migration)
2	$\_d_t$	The diffusion of innovations
3	$\_k_t$	Available and used resources
		With $\_xk_t$ for agents having exited the population
4	$\_p_t$	Agent performance (e.g. income, depreciation, liquidity, etc.)
		With $\_xp_t$ for agents having exited the population
5	$\_u_t$	The solution vector (primal)
		With $\_xu_t$ for agents having exited the population
6	$\_y_t$	Crop yield information (only when having yields endogenous in the model)
7	_w	Sector water data
8	_l	Land data
9	diff	Innovation diffusion over all periods in one file

Each row in the p, u, and k-files contains information on a separate agent. The first 13 columns are the same in each of these three files and listed in Table 18.

Table 18 First entries in the k, u & p-files

Nr.	Short name	Explanation
1	typ_str	Type of information: 1: performance data (p-file); 2: primal solution (u-file); 3: objective values (u-file) 4: available capacity (resources) (k-file) 5: actually used capacity (k-file)
2	aID	Identifies the agent
3	catchID	Identifies the (sub-)catchment or village
4	secID	Identifies the agent sector
5	fstID	Identifies the farmstead as read from the file <map.xls>
6	popID	ID of agent population
7	clustID	Identifies the population cluster (i.e., each sheet in the file <population.xls> is a separate segment
8	nwID	Identifies the network through which innovations diffuse (e.g., separate networks of large-scale commercial and family farms)
9	segID	Identifies the innovation segment (0,1,2,3,4)
10	expectID	Type of (price and yield) expectations
11	colorID	Color of grid cell in the map
12	xcoord	x-coordinate of the farmstead (column number in raster map)
13	ycoord	y-coordinate of the farmstead (row number in raster map)

Table 19 Entries in the a-file: agent population dynamics

Nr.	Short name	Explanation
1	GiveUp	Type of information: 14=planning error 15=reason of exit
2	nwID	Number of separate networks
3	segID	Segment ID
4	f_per_seg	Number of agents remaining in each segment
5	nr_m_plan	Number of planning mistakes
6	nr_giveup_vol	Number of agents that give up voluntarily (e.g., migrate out due to high opportunity costs outside farming)
7	nr_giveup_invol	Number of agents that were forced to give up (e.g., bankruptcy)

The a-file contains information on the agent population dynamics, such as exits due to migration and bankruptcy. Table 20 shows the structure of this file.

Table 20 Entries in the d-file: Innovation diffusion

First column ID	Explanation
06	Number of users of an innovation (absolute value)
07	The total acreage of all users of an innovation (absolute value)
08	Total Gross Margins (absolute value)
09	Value Added (absolute value)
10	users (percentage)
11	acreages of users (percentage)
12	Total Gross Margins (percentage)
13	Value Added (percentage)

Table 21 Exit of agents

Code	Explanation
-1	**Bankruptcy / forced migration:** The liquid means are less than zero.
-2	**Voluntary migration:** The opportunity cost of labor (defined in Network.xls) is greater than the returns from the farm times the migration full factor (also defined in Network.xls)
-3	**No household members left:** Because of mortality and fertility rates (defined in Demography.xls) the agent has lost all household members and thereby seizes to exist.
-4	**No active labor force:** The labor supply is zero (the labor supply for each age and sex category is defined in Demography.xls).
-5	**No adult labor force:** The agent household has only children. Note that the difference between children and adults is defined in Demography.xls.

Table 22 Farm performance data

Nr.	Short name	Explanation
1	nplots	The number of plots owned by the agent
2	totgrossmargin	Total gross margin. The optimum solution of each LP, yet excluding the future prices.
3	cashflow	The net cash flow or net cash surplus = total gross margin – Fixed costs – Transport costs
4	income	Household income = Net cash flow + appreciation of assets – depreciation of assets + income transfers – debt service
5	valueadded	Value added
6	equitycapital	Equity capital
7	Paymtoland	Payments to land
8	Relfactorpayment	Relative factor payments
9	onfarmlabor	On farm labor use
10	onfarmcapital	On farm capital use
11	interestpaid	Interest paid on investments (specified in Network.xls)
12	distancecost	Distance costs (specified in BasicData.xls)
13	addtranscost	Transport costs (specified in BasicData.xls)
14	consumption	Value of household consumption (specified in Market.xls)
15	liquidmeans	Liquid means at the end of the period
16	migration	Migration decision (see above)
17	lastlp	Last LP (investment, production, or consumption)

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