Energy Technology Systems Analysis Programme

Documentation for the MARKAL Family of Models

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Authors:

Richard Loulou
Gary Goldstein
Ken Noble

Part II: MARKAL-MACRO

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3. Concepts and Theory

3.1 Introduction

MARKAL-MACRO (Manne and Wene, 1992) is the result of merging two existing model approaches into a single, self-contained new model. On the one hand, there is the MARKAL model (see PART I), with its detailed, explicit technological representation. On the other hand, there is MACRO (Manne and Richels, 1992), a succinct, single sector, optimal growth dynamic inter-temporal general equilibrium model, based on the maximization of a national utility function. Merging these two models results in a new model that captures the characteristics of an intertemporal general equilibrium model, while retaining the rich technological detail of MARKAL. The equilibrium is based on the assumption of perfect foresight and competitive markets, in the sense of neo-classical economic theory. The economic agents in MARKAL-MACRO are: the generic suppliers and consumers of energy (as in MARKAL), plus the other suppliers of goods and services (regrouped into a single representative producing sector), the consumers (regrouped into a single generic consumer), and a simplified, generic capital market. Government is not represented as such in MARKAL-MACRO. Export markets may be represented if a multi-regional MARKAL-MACRO model is constructed.

A precursor of this approach is ETA-MACRO (Manne and Richels 1992), where the ETA module was however a less detailed energy supply module than MARKAL is. ETA-MACRO was subsequently used as a component of the MERGE model (Manne et al. 1995), a global multi-regional G.E. model with emphasis on modeling global emissions and concentrations of Greenhouse Gases.

The linkage between MARKAL and MACRO is done at the level of demands for energy services. In MARKAL these demands are specified exogenously in the reference case, and are then endogenously altered by the model for alternate scenarios, as long as own-price elasticities for the energy service demands are specified by the user. In MARKAL-MACRO, a different approach is used: the demands are variables of the model that are aggregated to become the Energy input into the MACRO production function, alongside Labor and Capital. Figure 3-1 shows the links between the MARKAL and MACRO modules of the new model. The solid lines indicate physical flows, whereas the dashed lines indicate monetary flows. The MARKAL module thus provides one physical input to the MACRO module (aggregate energy), and the MACRO module provides one monetary input to the MARKAL module (energy cost).

We now provide a full formulation of the model. Much of the material in this chapter is taken from Manne and Wene (1992), which provides additional detail to the interested reader.
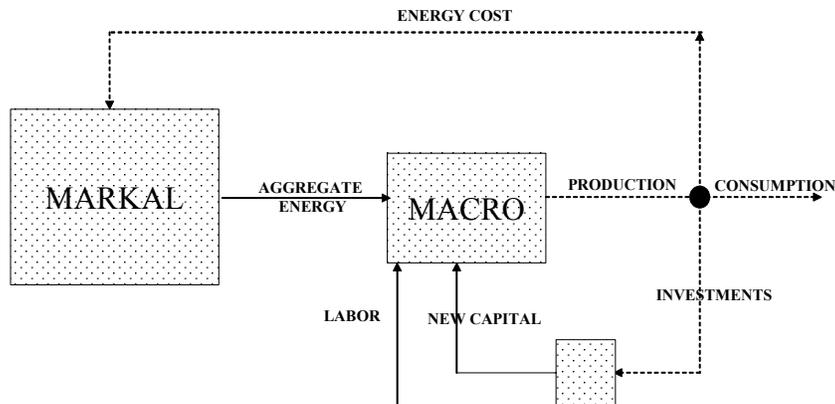
Figure 3-1. The MARKAL-MACRO flows

3.2 Formulation of MARKAL-MACRO

MARKAL-MACRO consists of Macroeconomic equations and variables (Macro module), MARKAL equations and variables (MARKAL module), and Linking equations.

3.2.1 The Macroeconomic equations (MACRO Module)

The MACRO part of the model is a one-sector neoclassical growth model (see Allen 1968) based on the maximization of a utility function subject to a national budget constraint. National output is produced by a single sector, represented by a nested production function with constant elasticities of substitution between three inputs (Labor, Capital, Energy).

- The utility function is the discounted present value (at year 1) of the logarithms of the aggregate consumptions at each period, with an end-of-horizon term to account for utility accrued after the end of the planning horizon. It is expressed as (1.2-1) below.
- The national budget equation expresses that national production may be used for consumption, investments, and energy costs. This is expressed as (1.2-2).
- The national production results from three substitutable inputs: Capital, Labor, and Energy, via a nested function shown in equation (1.2-3).
- The investments are used to replace depreciated capital and to provide new capital, as shown in equation (1.2.4). Depreciation occurs at constant rate α per period, making a fraction *(1-α)* of period *(t-1)*'s capital available for

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period t. Additional (new) capital may be added during period t. This new capital results from new investments made each year during the period.

The computation of the stand-alone MACRO equilibrium would be done by solving the following convex, non-linear optimization problem:

$$\textbf{Max } \sum_{t=1}^{T-1} \textbf{\textit{udf}}_t \cdot \ln(\textbf{\textit{C}}_t) + \frac{\textbf{\textit{udf}}_T}{(1 - \textbf{\textit{udr}}_t)^{\textit{NYRS}}} \cdot \ln(\textbf{\textit{C}}_T) \qquad\qquad 1.2-1$$

$$\textbf{\textit{Y}}_t = \textbf{\textit{C}}_t + \textbf{\textit{INV}}_t + \textbf{\textit{EC}}_t \qquad\qquad 1.2-2$$

$$\textbf{\textit{Y}}_t = \left(\textbf{\textit{akl}} \cdot \textbf{\textit{K}}_t^{\rho\alpha} \cdot \textbf{\textit{L}}_t^{\rho(1-\alpha)} + \sum_{dm} \textbf{\textit{b}}_{dm} \cdot \textbf{\textit{D}}_{dm,t}^{\rho} \right)^{1/\rho} \qquad\qquad 1.2-3$$

$$\textbf{\textit{K}}_t = (1 - \alpha) \cdot \textbf{\textit{K}}_t + \frac{\textbf{\textit{NYRS}}}{2}\left(\textbf{\textit{tarv}} \cdot \textbf{\textit{INV}}_t + \textbf{\textit{INV}}_{t+1} \right) \qquad\qquad 1.2-4$$

$$\textbf{\textit{K}}_T \le \frac{\textbf{\textit{I}}_T}{\textbf{\textit{grow}} + \textbf{\textit{depr}}} \qquad\qquad 1.2-5$$

where:

$\textbf{\textit{C}}_t$ is the annual consumption in period $\textbf{\textit{t}}$
$\textbf{\textit{Y}}_t$ is the annual production in period $\textbf{\textit{t}}$
$\textbf{\textit{INV}}_t$ is the annual investments in period $\textbf{\textit{t}}$
$\textbf{\textit{EC}}_t$ is the annual energy cost in period $\textbf{\textit{t}}$
$\textbf{\textit{K}}_t$ is the total capital in period $\textbf{\textit{t}}$
$\textbf{\textit{NYRS}}$ is the number of years per period (usually 5 or 10)

The utility function (1.2—1) is the discounted sum of the logarithms of consumption at each period. The discount factor $\textbf{\textit{udf}}_t$ is equal to: $\Pi_{\tau=0}^{t-1}(1 - \textbf{\textit{udr}}_\tau)^{\textit{NYRS}}$, with $\textbf{\textit{udr}}_t$ equal to year $\textbf{\textit{t}}$'s discount rate.

The last period's term has a larger weight, calculated to represent the discount factor over the infinite horizon from period $\textbf{\textit{T}}$ on. This implies that the last period's utility applies to the rest of the infinite horizon, and is in harmony with the assumption implicit in 1.2—5, as will be discussed below.

The production function is a nested, constant elasticity of substitution (CES) function. The first term within the bracket is a value added aggregate, in which capital and labor may be substituted directly for each other. The second term indicates that the energy services defined in MARKAL may also substitute for one another. Finally, the two aggregates (labor-capital on one hand, and energy on the other) may substitute for each other, although with a different elasticity than the lower level substitution of labor and capital. The exponent α is interpreted as the value share of capital in the value added aggregate, whereas the exponent ρ is directly related to the elasticity of substitution between the two aggregates (usually denoted $\textbf{\textit{esub}}$). More precisely, we have:

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$\rho = 1 - (1/\textbf{\textit{esub}})$. This form of production function is adapted from neoclassical growth models (Allen 1968).

Note that MACRO does not include any endogenous dynamics for Labor, which is exogenously specified as an index (expressed in efficiency units) with growth rate $\textbf{\textit{growv}}_t$:

$$L_0 = 1, \quad and \quad L_{t+1} = (1 + \textbf{\textit{growv}}_t)^{NYRS} \bullet L_t$$

Capital formation is endogenous and has its own dynamics, expressed as 1.2—4. The last period's constraint 1.2—5 ensures that the rate of investment is sufficient to provide for replacement and net growth (at constant rate) during the remainder of the infinite horizon. This is coherent with the last term of the utility function 1.2—1, as already mentioned.

3.2.2 The MARKAL and Linking Equations

The MARKAL-side equations include all equations in the stand-alone MARKAL model *with own price elasticities of useful demands set to zero*. As noted above (equation 1.2—3), the useful demands $\textbf{\textit{D}}_{dm,t}$ of MARKAL provide the physical link from the MARKAL to the MACRO modules.

The other link between the two modules equates MACRO variable $\textbf{\textit{EC}}_t$, with the MARKAL expression of the annual energy cost. However, in MARKAL-MACRO, an extra cost term is added to the usual MARKAL costs, whose function is to dampen excessively rapid market penetration of technologies: for each technology $\textbf{\textit{k}}$, the model imposes a soft upper bound 1.2—6 on its capacity increase between two successive periods. In this equation, $\textbf{\textit{expf}}$ represents the normal expansion factor over one period, and the new variable $\textbf{\textit{XCAP}}_{k,t}$ represents the excess capacity expansion over and above the normal capacity limit. Thus, the usual MARKAL annual energy cost at period $\textbf{\textit{t}}$ ($\textbf{\textit{ANNCOST}}_t$, see PART I, Section 1.4) is augmented with the quadratic damping term shown in the cost linking equation (1.2—7).

$$CAP_{k,t+1} \leq expf \bullet CAP_{k,t} + XCAP_{k,t+1} \qquad\qquad 1.2 - 6$$

$$ANNCOST_t + 0.5 \cdot qfac \sum \frac{ecst_k}{expf \cdot capfy_k} XCAP_{k,t}^2 = EC_t \qquad\qquad 1.2 - 7$$

where $\textbf{\textit{qfac}}, \textbf{\textit{ecst}}_k,$ *and* $\textbf{\textit{capfy}}_k$ are suitably chosen parameters reflecting the estimated penalty incurred when the expansion of technology $\textbf{\textit{k}}$ exceeds the normal expansion factor (Manne and Wene 1992 provides additional comments on the choice of these parameters).

3.3 Calibration and other modeling issues

This section provides some indications on the estimation of some parameters, mostly related to the MACRO module. The MARKAL calibration is done independently using energy statistics.

First of all, most MACRO variables are equal to standard macroeconomic statistics in the initial year, namely: Consumption (C_1), Production (Y_1), Investments (INV_1), Capital (K_1). Labor index at time 0 is set to 1. The initial year's energy cost should be taken equal to the MARKAL annual energy cost at initial period, augmented by the annualized capital cost of residual capacities (which are not counted in MARKAL).

We now discuss the benchmarking of the parameters appearing in the equations.

3.3.1 Production Function Parameters

The value of ρ is directly obtained from $\rho = 1 - (1/esub)$. The latter parameter cannot be found directly, first of all because it relates to the elasticity of energy demand services, and their quantities and prices are not available from statistics, unlike final energy uses. Secondly, it is an aggregate governing the reaction of *all* demands to changes in their prices and thereby necessarily a compromise. It is recommended to vary *esub* and analyze the results before deciding on a 'best guess'. Realistic ranges are thought to be between 0.2 and 0.5. The higher end estimates are more appropriate for models in which end-use demand sectors are modelled in MARKAL with little detail and/or have limited opportunities for energy conservation or substitution. In that case the technological response to higher prices inside MARKAL is relatively small, and the econometric response should contribute more to the overall demand reaction. Vice versa, if a large number of technological response options are present in MARKAL, *esub* should be at the lower end so as not to overestimate the combined demand response.

Parameters *akl* and b_{dm} may be determined using base year statistics, via the following two-step procedure:

- First, the reference price of energy service *dm* is equated to the partial derivative of Y_t w.r.t. to D_{dm}, yielding:

$$\partial Y / \partial D_{dm|t=0} = pref_{dm,0} = (Y_0 / D_{dm,0})^{1-\rho} \cdot b_{dm}$$

thus allowing the computation of b_{dm}, for all *dm.*

Next, the expression of the production function in base year is used to directly compute *akl.*

Important remark: The MARKAL shadow prices of the demands are normally used as reference prices. However, it is strongly advised to first closely examine them, since they often are heavily distorted in period 1, due to the heavy constraining usually employed to calibrate MARKAL to the energy statistics in the initial period. Users should inspect these shadow prices and make sure they are reasonably smooth over time without unrealistic spikes or drops. The worst case is when shadow prices drop to zero (typically this occurs when the sum of lower bounds, plus residual capacities, of all technologies satisfying a certain demand, exceed the level of demand in that period. The problems can, however, also be caused further 'upstream' in the RES, e.g. forcing minimum amounts of energy carriers to be used by end-users. Additional special user constraints are another possible source of problems observed in the initial shadow prices. In summary: no trustworthy or meaningful result from any MARKAL-MACRO run can be expected if the demand shadow prices in the MARKAL model are not smoothed before establishing the link with MACRO.

3.3.2 Demands

The useful energy demands $D_{dm,1}$ are calibrated to energy statistics in year 1. Note that the original report describing MARKAL-MACRO advises to apply an autonomous energy efficiency improvement factor (***aeeif***) to the MARKAL demands $D_{dm,t}$ before injecting them into the production function. This procedure is advisable only if the base case MARKAL demands do *not* already include autonomous improvements.

3.3.3 Energy Costs

The choice of the parameters entering the quadratic damping term in the energy cost (1.2—6) requires some precautions. Suppose for instance that the parameter ***qfac=1***, and that ***capfy_k*** represents the maximum level of capacity that can be installed during the first year in which technology ***k*** becomes available. The penalty coefficient may then be chosen so that the marginal cost of providing capacity is doubled if the rate of capacity expansion is twice its normal level during that first year.

Note that equation (1.2—7) is written for each relevant technology, and its quadratic nature may represent a non-negligible computational burden for the optimizer. Replacing the quadratic damping costs with linear costs would alleviate this difficulty, but would have other drawbacks, such as the well-known razor-edge effect.

3.3.4 Utility discount rates

The annual discount rate ***udr_t*** at period ***t*** is calculated as follows:

$$udr_t = kpvs/kgdp - depr - grow_t$$

where:
kpvs is the capital's value share;
kgdp is the initial capital-to-GDP value; and
depr_t is the depreciation rate at period ***t***

$grow_t$ is the potential growth rate at period t

$kpvs$ and $kgdp$ can be extracted from macro-economic statistics like national accounts. As they may fluctuate, multiple-year averages are more appropriate than single year values. Some care must be taken, and consultation of macro-economists familiar with such statistics and their definitions is strongly recommended. For OECD economies, typical $kpvs$ estimates range from 0.2 to 0.3. For less developed, but rapidly growing economies substantially, higher values are quoted. Again for OECD economies, $kgdp$ estimates may range from roughly 2 to 3. In the absence of specific information, a rule-of-thumb ratio of 10:1 (say 2.5 and 0.25) can be adopted for $kgdp$ over $kpvs$, but must be lowered in case of anticipated rapid growth. The depreciation rate $depr_t$ may be taken equal or close to the MARKAL discount rate.

3.4 Other Modeling Issues

3.4.1 Increasing period length via COLLAPSE

Since MARKAL-MACRO is a non-linear optimization problem, it may be desirable to try and reduce its overall size, for instance by increasing period length. The COLLAPSE option converts an instance with 5-year period length into one with 10-year period length.

COLLAPSE makes a number of changes to the parameters of a MARKAL database, including START, LIFE, BOUNDS, etc. It is strongly recommended to check the log file created by this utility before proceeding to MARKAL-MACRO it will also be helpful to find the cause of infeasibilities arising after COLLAPSE is switched on.

3.4.2 Differential Costing

In most MARKAL models, the investment cost of end-use technologies is fully modeled. In some sectors, the cost modeled in MARKAL may include the cost of equipment that does not qualify as an energy expenditure. For instance, the investment cost of an automobile may represent the full cost of buying the car. Therefore, the aggregate cost function of MARKAL may overestimate the pure energy cost that is required by MACRO. In some other sector such as residential space heating, the full cost of a space heating device should be fully accounted for in the MACRO energy cost. To remedy this problem, a MARKAL-MACRO utility will subtract the undesirable portion of the investment cost of some or all end-use technologies as follows: consider the set of $INVCOST_k$ values for all technologies k fulfilling a given demand. The utility will subtract from each $INVCOST_k$ the smallest such cost. The $INVCOST_k$'s thus obtained now represent the *differential* costs of each technology, and not the full costs The user has full control over which demands should be treated in this way, and which not. Again, actions taken by the utility are listed in a log file that may be consulted by the user.

References for Part II, Chapter 3

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- Manne, A.S., and R.G. Richels, *Buying Greenhouse Insurance: the Economic Costs of Carbon Dioxide Emission Limits*, MIT Press, Cambridge, Mass., 1992.
- Manne, A.S., and C-O Wene, "MARKAL-MACRO: A Linked model for Energy-Economy Analysis", *Bookhaven national Laboratory*, BNL-47161, 1992.

4. Reference Guide for MARKAL-MACRO

As discussed in Part II, Chapter 3 MARKAL-MACRO merges the bottom-up MARKAL model with the top-down MACRO model to realize a general equilibrium model that retains rich technological detail. This integrated model is non-linear in structure.

MARKAL-MACRO must go through a calibration procedure to determine some of the key input parameters, most notably the Demand Decoupling Factor (DDF) that reflects the relationship between trends in the overall economy as represented by GDP, and the movement of the individual demand sectors. Similarly to MARKAL-MICRO, the calibration utility, DDFNEW, must be run by the user in a Command Window. Beginning with a MARKAL run, and a few basic macroeconomic parameters including the elasticity of substitution and projected GDP, the DDFNEW utility establishes the DDF and other initial parameters (e.g. reference prices, PREF). For details on running the calibration procedure see Appendix A

In the next section the switch and parameters that activate and control MARKAL-MACRO are presented, followed by the variables and equations.

4.1 Sets, Switches and Parameters

Like all other aspects of MARKAL the user describes MARKAL-MACRO by means of the Switches and Parameters described in this section. Table 4-1 and Table 4-2 below describe the User Input data, and the Matrix Coefficients and Internal Model Sets and Parameters, respectively, that are associated with MARKAL-MACRO.

Table 4-1. Definition of MARKAL-MACRO user input data

Input Data (Indexes)	Alias/Internal Name	Related Parameters	Units/Range & Defaults	Instance (Required/Omit/ Special Conditions)	Description
ADDER[98] *(d,t)*			• Scalar. • [0-any]; no default.	• May be provided for each demand sector in place of MM-DDF.	The demand decoupling adder, obtained as part of the ADDER calibration procedure and optionally used in place of the AEEI factor applied to each demand in the coupling equation (R_DD).
COLLAPSE			• Switch. • [0,1]; default = 0.	• Provided to activate the period collapse mechanism.	The collapse algorithm can be used to reduce the size of a model by doubling the period length, and making related adjustments to technology lifetime (LIFE) and start period (START) information, as well as the RESIDs. This is done when looking to reduce solve times, sometimes necessary for large NLP models.
DIFF_DM *(d)*			• Switch. • [0,1]; default =0.	• Provided when the DIFFCOST entry is to be used as part of the DIFFDMDS algorithm.	Under normal circumstances the DIFFDMDS algorithm normalizes the investment costs (INVCOST) associated with each demand to the least expensive device. This switch for a demand instructs the DIFFDMDS algorithm to use a user provided minimum (DIFFCOST) instead.
DIFFDMDS			• Switch. • [MARKAL-MACRO]; default not done.	• Provided when the DIFFDMDS algorithm is to be applied.	As MARKAL-MACRO encompasses both the energy and economy it may be necessary to adjust the investment cost (INVCOST) of demand devices as entered normally for MARKAL, as some of those costs are embedded in the MARKAL investment variable (R_INV). When activated the DIFFDMDS algorithm normalizes the investment costs (INVCOST) associated with each demand to the least expensive device servicing the demand. This default approach may be overridden by the DIFF DM flag and associated user provided

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[98] ADDER was developed where a model has difficulty being calibrated using the DDFCalib procedure. It results in an absolute level, rather than a factor, applied to each demand sector. Its use is rather straightforward and is presented in Appendix B. However, the DDFCalib procedure is the recommended way to calibrate MARKAL-MACRO.

Input Data (Indexes)	Alias/Internal Name	Related Parameters	Units/Range & Defaults	Instance (Required/Omit/ Special Conditions)	Description
					minimum investment cost (DIFFCOST).
DIFFCOST *(d)*			• Money units / commodity units, e.g. Million US$2000 / PJ. • [0-any]; no default.	• Provided when a user provided minimum investment cost is to be used instead of the lowest INVCOST servicing a demand.	The value to be subtracted from all the devices servicing a demand when the DIFF_DM override is requested indicating that a user provided value is to be used in place of the lowest investment cost (INVCOST) in the group.
MARKAL-MACRO			• Switch. • [MARKAL-MACRO]; default not run.	• Provided when running MARKAL-MACRO (see next column).	Unlike the more recent additions to Standard MARKAL, MARKAL-MACRO is activated through the data handling system (ANSWER or VEDA-FE) by passing the 'MARKAL-MACRO' switch to the main GAMS routines by the matrix generation (GEN), solve (SLV) and report writer (RPT) steps on multi-region runs[99].
MM-DDATPREF *(d)*	DDAT(d,'pref')	*B(d)*	• Money units / commodity units, e.g. Million US$2000 / PJ. • [0-any]; no default.	• Provided for each demand sector.	Reference marginal price of meeting the demands. The value is obtained from the calibration MARKAL run, and taken from the second modeling period.
MM-DDF *(d,t)*	DDF (d,t)	*AEEIFACT(d,t)*	• Percent. • [0-100]; no default.	• Provided for each demand sector.	The demand decoupling factor, expressed as a percentage, obtained as part of the DDFCalib calibration process and used to establish the AEEI factor applied to each demand in the coupling equation (R_DD).
MM-DEPR	*DEPR*	*DFACTCURR(t)* *IV0*	• Percent. • [0-100]; no	• Provided for each demand sector.	Net return on capital, expressed as a percentage. • Besides being used when calculating the related

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[99] Single-region MARKAL runs are performed in one job step and only require a <case>.GEN file.

Input Data (Indexes)	Alias/Internal Name	Related Parameters	Units/Range & Defaults	Instance (Required/Omit/ Special Conditions)	Description
			default.		intermediate parameters, the parameter is also involved in the terminal condition equation (R_TMC).
MM-DMTOL	DMTOL		• Fraction. • [0-1]; no default.	• Provided to determine the lower bound for MACRO demands.	Fraction by which MACRO demands may be lowered. • Used to set the lower bound on each demand (R_D) to DMTOL times the demand level for the first period.
MM-EC0		*Y0*	• Macro money units, e.g. Billion US$2000. • [0-any]; no default.	• Provided when running MARKAL-MACRO.	Energy costs in the first period.
MM-ESUB	ESUB	*RHO*	• Fraction. • [0-1]; no default.	• Provided when running MARKAL-MACRO.	Elasticity of substitution between capital and labor.
MM-GDP0	GDP0	K0 *Y0*	• Macro money units, e.g. Billion US$2000. • [0-any]; no default.	• Provided when running MARKAL-MACRO.	GDP in the first year of the model.
MM-GROWV (t)	*GROWV (t)*	*DFACTCURR(t)* *IV0*	• Percentage. • [0-100]; no default.	• Provided when running MARKAL-MACRO.	Potential GDP annual percentage growth rates. • Besides used when calculating the related intermediate parameters the parameter is involved in the terminal condition equation (R_TMC).
MM-IVETOL	*IVETOL*		• Fraction. • [0-1]; no default.	• Provided when running MARKAL-MACRO.	Investment and energy tolerance. • Used to set a lower bound on the capital variable (R_K). • Also involved in bounding the sum of investment and energy in equation MR_IVECBND.

Input Data (Indexes)	Alias/Internal Name	Related Parameters	Units/Range & Defaults	Instance (Required/Omit/ Special Conditions)	Description
MM-KGDP	KGDP	*DFACTCURR(t)* *K0*	• Fraction. • [0-#]; no default.	• Provided when running MARKAL-MACRO.	Initial capital to GDP ratio.
MM-KPVS	*KPVS*	*DFACTCURR(t)* *AKL*	• Fraction. • [0-1]; no default.	• Provided when running MARKAL-MACRO.	Optimal share of capital to labor. • Applied to the capital variable (R_K) in the objective function (MR_UTIL).
MM-SCALE	*MMSCALE*		• Fraction. • [.001 or 1]; default. = 1.	• Provided if the MACRO monetary units are more than 1000x those in MARKAL.	MACRO/MARKAL monetary unit scalar. • Applied to every equation in the model to scale the costs, when necessary.
MM-EXPBND (p,t)	EXPBND (p,t)	*CAPTB(t,p)*	• Units of capacity. • [0-any]; no default.	• Provided if it is desired to apply the quadratic market penetration penalty function is to be used.	The maximum accumulated capacity above which the penalty is to be applied for new investments in a technology.
MM-EXPF	*EXPF*		• Percent. • [0-100]; no default.	• Provided if a demand is to be subject to price.	Annual percent expansion factor.
MM-QFAC	*QFAC*		• Switch. • [0-1]; default = 0.	• Provided to activate the quadratic market penetration penalty function.	The market penetration penalty function can be used to slow the investment in technologies, for example when a major infrastructure investment is required beyond a certain modest level of deployment.

Table 4-2. MARKAL-MACRO-specific matrix coefficients and internal model parameters[100]

Matrix Controls & Coefficients (indexes)	Type	Description & Calculations
AEEIFACT (d,t)	I	Autonomous energy efficiency and demand coupling factor which is applied to each demand in the objective function, established as - $$AEEIFACT_{d,t+1} = AEEIFACT_{d,t}\left(1-\left(DDF_{d,t+1}/100\right)\right)**NYRSPER$$
AKL	I	Production function constant, defined as - $$AKL = \left[Y0**RHO - \sum_d\left(B_d*\left(D0_d**RHO\right)\right)\right]/\left(K0**\left(KPVS*RHO\right)\right)$$
B (d)	I	Coefficient on demands in the MACRO objective function established as - $$B_d = .001*DDAT_{d,'pref'}*\left(DM\_DEM_{d,t0}/Y0\right)**\left(1-RHO\right)$$
CAPTB (t,p)	I	Cumulative quadratic capacity level beyond which the penalty is applied, defined as sum of EXPBND values.
DFACTCURR (t)	I	Component used in the calculation of DFACT(t) which is an objective function coefficient - $$DFACTCURR_t = \left[1-\left(KPVS/KGDP - DEPR/100 - GROWV_t/100\right)\right]$$
DFACT (t)		Objective function coefficient that is the utility discount factor for period t, determined recursively from – $$DFACT_{t0} = 1$$ and $$DFACT_{t+1} = DFACT_t*\left(DFACTCURR_t\right)**NYRSPER$$ with a special utility discount factor for period t_{last}, determined as follows - $$DFACT_{tlast} = DFACT_{tlast}/(1-DFACTCURR_{tlast}**NYRSPER)$$
IV0	I	Investment in the first period, determined as - $$IV0 = K0*\left(DEPR+GROWV_{t0}\right)/100$$

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[100] All the internal MACRO parameters are determined in the GAMS module MMACRO.MM.

Matrix Controls & Coefficients (indexes)	Type	Description & Calculations
K0	I	Capital in the first period, determined as - $K0 = [KGDP*GDP0]$
L (t)	I	Labor, determined recursively from – $L_{t0} = 1$ and $L_{t+1} = L_t * (1 + GROWV_t/100)**NYRSPER$
RHO	I	Exponent derived from ESUB as - $RHO = 1 - 1/ESUB$
TSRV	I	Exponent derived from ESUB as - $TSRV = (1 - DEPR/100)**NYRSPER$
Y0	I	Production (gross output) in the first period, determined as - $K0 = [GDP0 + EC0]$

4.2 MARKAL-MACRO Variables

MARKAL-MACRO needs additional variables to reflect the components of the rest of the economy, and to link them to the MARKAL information. The variables are presented in Table 4-3 below.

Table 4-3. MARKAL-MACRO variables

VAR Ref	Variable (Indexes)	Variable Description
MM.1	R_D (r,d,t)	Endogenously determined demand level.
MM.2	R_EC (r,t)	Total energy costs, from MARKAL.
MM.3	R_IV (r,t)	Total investment throughout the economy.
MM.4	R_K (r,t)	Entire capital stock of the economy.
MM.5	R_RESID (r,t,p)	Residual capacity, charged the annualized investment payments when determining the total cost of the energy system.
MM.6	R_SP (r,d,t)	Artificial variable for scaling shadow price of energy.
MM.7	R_XCAPP, R_XCAPP1, R_XCAPP2 (r,t,p)	Market penetration bounds - linear variables for the additional capacity steps.

4.3 MARKAL-MACRO Equations

As is the case with the variables, MARKAL-MACRO needs additional equations to handle the linking of demands (R_D) and energy costs (R_EC) to the rest of the economy, and to model the rest of the economy. The objective function is also entirely new. The various equations involved are first presented in Table 4-4, and then the mathematics is detailed in the following sections.

Remark: The MARKAL-MACRO model described in this documentation is a single region model. Using MARKAL-MACRO for multiple regions linked by trade variables requires an additional mechanism to insure the overall economic coherence of the equilibrium. One method is to embed the M-M model in an iterative algorithm using Negishi weights. In this documentation, no attempt is made to describe the embedding algorithm.

Table 4-4. MACRO Model constraints[101]

EQRef	Constraints (Indexes)	Constraint Description
MM.1	MR_COSTNRG(r,t)	Total cost of the energy system in each period is equated to the energy cost variable of MACRO, linking MARKAL with MACRO.
MM.2	MR_DD(r,d,t)	The demand coupling equation for each demand and period that links MARKAL with MACRO.
MM.3	MR_IVECBND(r,t)	Bound on the sum of investment and energy costs.
MM.4	MR_MCAP(r,t)	Capital dynamics equation.
MM.5	MR_MPEN(r,p,t)	Defines the market penetration penalty variables for those technologies to be subjected to the market penetration penalty function.
MM.6	MR_TMC(r,t)	Terminal condition on investments.
MM.7	MR_UTIL	The MACRO objective function corresponding to the utility of a representative consumer, to be maximized.
MM.8	MR_XCAPBD(r,t,p)	Linear approximation of the quadratic constraint limiting the penetration of those technologies to be subjected to the quadratic market penetration penalty function.

4.3.1 MR_COSTNRG(r,t)

Description: Total energy system cost, as determined by the cost expression in the MARKAL part of the model.

Purpose and Occurrence: To define the energy system related costs that must be paid by the rest of the economy.
This equation is generated for each region and time period.

Remarks: This equation is essentially identical to the standard MARKAL MR_ANNCOST equation, with the addition of the linearized version of the quadratic market penalty costs,. The cost is augmented by an exogenous component representing taxes/subsidies, in order to calibrate to national energy cost statistics.

GAMS Routine: MMEQUA.MM (single-region), MMEQUAMM.REG (multi-region).

MATHEMATICAL DESCRIPTION

$$EQ\# \; MM.1: MR\_COSTNRG_{r,t}$$

> All the components of MR_ANNCOST, see Chapter 2, section 2.5.2 for details, scaled by a factor of 1/1000.

$$.001 * [\quad ... \; +$$

---

[101] All the MACRO equations are defined in MMEQUA.MM or MMEQUAMM.REG for single/multi-region models respectively.

$$\sum_{p\$(CAPTB_{r,p})} \left[\begin{array}{c} .5*QFAC_r*COST\_INV_{r,t,t,p}* \\ \left(CAPTB_{r,p} / EXPF_r* \right) \\ \left(\begin{array}{c} R\_XCAPP_{r,t,p}+ \\ 6*R\_XCAPP1_{r,t,p}+ \\ 12*R\_XCAPP2_{r,t,p} \end{array} \right) \end{array} \right]$$

$$\{=\}$$

$$.001*[\boldsymbol{R\_EC}_{r,t} +$$

$$\sum_{taxsub} \boldsymbol{TSUB\_TOT}_{r,taxsub,t} +$$

$$\sum_{v} \boldsymbol{ENV\_TAX}_{r,v,t}]$$

4.3.2 MR_DD(r,d,t)

Description: Demand coupling equation that associates the flexible demand variable (R_D) with the level of output from each of the demand devices.

Purpose and To determine the level of the endogenous energy demand services.
Occurrence: This equation is generated for each region, demand sector and period.

GAMS Routine: MMEQUA.MM (single-region), MMEQUAMM.REG (multi-region).

MATHEMATICAL DESCRIPTION

$$EQ\# \, MM.2 : MR\_DD_{r,d,t}$$

Output of each demand device that services this demand.

$$\sum_{p\$DMD\_DM_{r,p,d}} \left(DEM\_CAP_{r,t,p,d} * R\_CAP_{r,t,p} \right)$$

$$\{=\}$$

RHS variable corresponding to the level of the demand, which is linked into the objective function to determine the consumer surplus.

$$R\_D_{r,d,t}$$

4.3.3 MR_IVECBND(r,t)

Description: Limit on the sum of overall investment and energy costs.

Purpose and To establish the relationship between total investment and energy costs versus
Occurrence: initial production and labor growth.

This equation is generated in each region for all the projection periods.

GAMS Routine: MMEQUA.MM (single-region), MMEQUAMM.REG (multi-region).

MATHEMATICAL DESCRIPTION

$$EQ\#\,MM.3:MR\_IVECBND_{r,t}\,\forall\big(t\neq 1st\;period\big)$$

Total investment + energy costs.

$$R\_IV_{r,t}+R\_EC_{r,t}$$

$\{\leq\}$

Total initial production augmented by labor taking into consideration the investment/energy tolerance.

$$Y0_r * L_{r,t}**IVETOL_r$$

4.3.4 MR_MCAP(r,t)

Description: A balance equation expressing the dynamics of capital accumulation in each period.

Purpose and Occurrence: To ensure that total Capital in the current period reflects the Capital in the previous period, minus depreciation, plus new investment.
This equation is generated in each region for each period after the first.

GAMS Routine: MMEQUA.MM (single-region), MMEQUAMM.REG (multi-region).

MATHEMATICAL DESCRIPTION

$$EQ\#\,MM.4:MR\_MCAP_{r,t}$$

Non-depreciated capital in period t, plus new investments.

$$R\_K_{r,t}*TSRV_r+(NYRSPER/2)*\big(R\_IV_{r,t+1}+R\_IV_{r,t}*TSRV_r\big)$$

$\{=\}$

Capital in period t+1.

$$R\_K_{r,t+1}$$

4.3.5 MR_MPEN(r,p,t)

Description: Decomposes the increase in capacity of a technology into two variables, the first being the "normal" amount of capacity increase, the second being the amount of capacity increase subject to extra penalty costs. See also equation XCAPBD.

Purpose and To determine cost when the market penetration penalty kicks in.
Occurrence: This equation is generated in each region for each technology subject to the market penetration penalty, in each period.

GAMS Routine: MMEQUA.MM (single-region), MMEQUAMM.REG (multi-region).

MATHEMATICAL DESCRIPTION

$$\text{EQ\#MM.5:} \ MR\_MPEN_{r,p,t+1}\$ \left(\begin{array}{l} CAPTB_{r,p} \wedge \\ (QFAC_r \neq 0) \wedge \\ (COST\_INV_{r,t+1,t+1,p}) \end{array} \right)$$

Total installed capacity in period t+1.

$$R\_CAP_{r,t+1,p}$$

$$\{\leq\}$$

The two components of capacity: normal expansion plus expansion subject to penalty.

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$$EXPF_r * R\_CAP_{r,t,p} + R\_XCAP_{r,t+1,p}$$

4.3.6 MR_TMC(r,t)

Description: This quantity expresses that investment in the last period must be sufficient to insure an imposed growth rate of capital at the end of the planning horizon.

Purpose and Occurrence: This constraint is a terminal condition to avoid the liquidation of assets at the end of the horizon. It is compatible with the last term in the objective function. This equation is generated once in each region, for the last time period only.

GAMS Routine: MMEQUA.MM (single-region), MMEQUAMM.REG (multi-region).

MATHEMATICAL DESCRIPTION

$$EQ\#MM.6 : MR\_TMC_{r,t} \, \forall (t = tlast)$$

Total capital in the last period taking into consideration expected economic growth.

$$R\_K_{r,t} * \left(GROWV_{r,t} + DEPR_r \right) / 100$$

$$\{\leq\}$$

Investment in the last period.

$$R\_IV_{r,t}$$

4.3.7 MR_UTIL

Description: The MACRO objective function representing the utility of the representative consumer. It is equal to the sum of discounted consumptions in each period,

Purpose and Occurrence: To serve as the non-linear, convex objective function of the MACRO optimization problem. This equation is generated once.

MATHEMATICAL DESCRIPTION

EQ# MM.7 : MR_UTIL

Discounted utility of consumption.

$$\sum_{r,t}\left[DFACT_{r,t}*\log\left\{\begin{pmatrix} AKL_r * \begin{pmatrix} R\_K_{r,t}**(KVPS_r*RHO_r)* \\ L_{r,t}**((1-KVPS_r)*RHO_r) \end{pmatrix} + \\ \sum_d \left(B_{r,d}*R\_D_{r,d,t}**RHO_r\right) \end{pmatrix}**1/RHO \\ -R\_IV_{r,t}-R\_EC_{r,t} \right\}\right]$$

$\{=\}$

RHS variable to be maximized corresponding to the utility of consumption.

$$\left(R\_UTILITY / 1000\right)\$(MMSCALE_r = .001) +$$
$$\left(R\_UTILITY / 1000 * \log(1000)\right)\$(MMSCALE_r = 1)$$

4.3.8 MR_XCAPBD(r,t,p)

Description: Further decomposition of the increase in capacity of a technology subject to penalty into 3 variables, each bearing an increasing penalty cost coefficient in equation COSTNRG. These three increasing penalty costs approximate the quadratic penalty cost function

Purpose and   To establish the excess capacity limit.
Occurrence:

This equation is generated in each region for each technology subject to the market penetration penalty, in each period.

GAMS Routine: MMEQUA.MM (single-region), MMEQUAMM.REG (multi-region).

MATHEMATICAL DESCRIPTION

$$EQ\#MM.8:MR\_XCAPBD_{r,t+1,p}\$\left(\begin{array}{l}CAPTB_{r,p}\wedge\\(QFAC_{r}\neq0)\wedge\\\left(\left(COST\_INV_{r,t+1,t+1,p}\right)\right)\end{array}\right)$$

Expansion in capacity once penalty kicks in.

$$R\_XCAP_{r,t+1,p}$$

$$\{=\}$$

Components of the quadratic approximation for the market penalty.

$$R\_XCAPP_{r,t+1,p}+R\_XCAPP1_{r,t+1,p}+R\_XCAPP2_{r,t+1,p}$$

4.4 Appendix A: the Demand Decoupling Factor (DDF) Utility[102]

This Demand Decoupling Factor (DDF) utility can be used to setup the MARKAL-MACRO reference scenario which matches both the user specified GDP growth rates and the demand levels of each demand category. This utility has been named DDFNEW.

The DDFNEW utility will generate the demand decoupling factors and reference prices of each demand category, the potential GDP growth rates and the initial energy system cost needed by MARKAL-MACRO database. That is the DDFNEW utility will generate tables DDF and DDAT, parameter GROWV, and EC0 of table CONSTANT, which will match the projected GDP growth rates and demands of each demand category.

The procedure for setting up and running the utility is briefly described here.

Procedure

1. Modifications needed for MARKAL database:
    a) Set up the demands of each demand category to be the projected demands (DEMAND (T) in table DM(DM)).
    b) In table CONSTANT, add the following data:
        i. DIFFDMDS: = 1 for using differential costing in MM run;
        ii. DEPR: The depreciation rate on capital (in percent);
        iii. ESUB: The elasticity of substitution;
        iv. KGDP: The capital-GDP ratio in the 1st period;
        v. GDP0: GDP in the 1st period (in billion US$), and
        vi. EXPF, QFAC: Parameters associated with the quadratic penalty function on excessively rapid growth, if used in MM.

2. Generate and run the MARKAL BASE scenario, called <MRK case> in the write-up (but you can use any name you'd like)

3. Check table T11 in <MRK case>.ANT to make sure that the shadow price of each demand category in 1st time period is nonzero. If shadow price of a demand category is zero, modify the database so that total lower bound (BOUNDLO) or fixed bound (BOUNDFX) of capacities of demand technologies related to that demand category is a little bit smaller than that required by the demand in the 1st time period. The demand satisfied by a given capacity is equal to the capacity times the utilization factor (CF) and the capacity unit factor (CAPUNIT). Rerun MARKAL case until all shadow prices of demand categories are non-zero at the 1st time period. If any of the shadow prices is zero, the DDFNEW utility will give **ERROR** message.

---

[102] Originally written by Yu-Hua Chu and Gary Goldstein. Modified by Socrates Kypreos for matching M-M demands with externally determined demand levels.

4. Edit the GR.DD file (found in the GAMS_SrcXXX folder, but it may be moved to your GAMS_WrkXXX folder if desired, so that it is not overwritten by future code updates) providing ESUB and GR, where GR is the projected GDP growth rates, and ESUB is the same as used in step 1.

5. Copy the MARKAL command run file (<MRK case>.GEN) to one that will control the MARKAL-MACRO run (<MM case>.GEN, where <MM case> is used in this write-up but any name will do). Change
   a) <MRK case> to <MM case>;
   b) "GMARKAL" to "MARKAL-MACRO";
   c) If last command is $BATINCLUDE MMINCLUD.INC MARKAL-MACRO START SOLVE, change it to $BATINCLUDE MMINCLUD.INC MARKAL-MACRO RESTART SOLVE, and
   d) Add $INCLUDE DDF.DD on the line right before the last command.

6. Copy the DDFCalilb.CMD file from your GAMS_SrcXXX folder to your GAMS_WrkXXX folder.

7. From you GAMS_WrkXXX folder run the calibration utility by typing

   DDFCalib <MRK case> <MM case> ..\GAMS_SrcXXX\ Run#

   where GAMS_SrcXXX is your source code folder and Run# sequences the output files if you run DDFCALIB more than 1 time. Note that Run# MUST = 1 on the 1st call so that MARKAL is run first (for values other than 1 the routine restarts from the last MARKAL-MACRO run).

   This will rerun your MARKAL job when Run# = 1, to "seed" the DDFCalib procedure, and then perform 5x MARKAL-MACRO and DDFNEW runs. For each MARKAL-MACRO/DDFNEW combined run the _LASTRUN file is moved to the _RESTART file and the new DDF<Run#>_1-5 file is produced and used for each subsequent run.

8. At the end of the DDFCalib run:
   a) Compare the MM calculated GDP growth rates with GR (the projected GDP growth rates listed in the file GR.DD), for all but the final period. MM calculated GDP growth rates are listed as "M-M GDP" at the bottom of the DDFNEW.DD file, and
   b) Compare the resultant energy system cost with EC0 in DDF.DD file. MM calculated energy system cost is listed as "M-M EC0" at the bottom of the DDFNEW.DD file.

   If M-M GDP growth rates are close to GR, and M-M EC0 is close to EC0, then go to step 10.

9. Repeat steps 7 and 8 call DDFCalib with Run# not = 1, until satisfied.

10. Compare demands from the <MRK case> and <MM case> for each demand category. These can be found in table DEMAND of the <case>.ANT files. If there are some categories whose demands differ too much, it might be that the value of DMTOL in table CONSTANT is too big. In this case, lower the value of DMTOL, and repeat steps 7, 8 and 10.

    The reason for lowering DMTOL is simply to prevent MM calculated demand (D) from hitting the lower bound set in MMACRO.MM, i.e.:

    D.LO(DM,TT) = DMTOL * D0(DM).

    If for some demand categories (in any time period), D needs to be smaller than D.LO to match the projected demands, then MM calculated demands will be higher than the projected demands. This is the only possible cause for MM calculated demands to differ much from the projected demands.

11. Move the information from the DDF.DD file into your database.

Comments

1. The matching of MM calculated GDP growth rates with projected GDP growth rates is separable from the matching of demands.

   Since the usual projection for the economic indicators are for GDP growth rates, not the potential GDP growth rates (GROWV), DDFNEW incorporates the matching of projected GDP growth rates with the matching of projected demands in the utility. However, it is possible to match only the projected demand, but not the projected GDP growth rates. In this way, the # of iteration to get the demand matching will be less than the standard version of DDFNEW.

   Matching only the demands can be done by not updating GROWV, but to keeping it constant in the DDFNEW.DD file. This can be done, for example, by simply setting

     GROWVN(TP) = GROWV(TP);

   instead of

     GROWVN(TP)$(TLAST(TP)) = GR(TP);
     GROWVN(TP)$(NOT TLAST(TP)) = GROWV(TP) + GR(TP) - GG('GDP',TP);

   in the RWDDF.MM file, in your GAMS_SrcXXX folder. [Note, you should move RWDDF.MM to you GAMS_WrkXXX folder before editing it.]

In this case, the MM calculated GDP growth rates will not be the same as the projected GDP growth rates. The iterative procedure is the same except that in part (a) of step 8, instead of matching "M-M GDP" with GR, the user should continue the iterative procedure until "M-M GDP" converges, i.e., its value does not change much for each iteration.

2. When to stop the iteration procedure:

A reasonable criterion to stop the iteration procedure is when the GDP growth rates are correct to the 2nd decimal place. Considering the case of 2.00 percent annual growth rate. If the MM calculated GDP growth rate is 1.995 or 2.005, there is an error of 0.005/2.00 = 0.0025%. With a 10-year period, the accumulated error will be 1.0025**10 - 1, around 2.5%. So, by matching GDP growth rates to the 2nd decimal place will generally produce an error less than 2.5% in the demands. It is up to the user to choose the stopping criteria depending on how good a match he/she wants.

4.5 Appendix B: The Adder Procedure

```
* The ADDER sub-system was created at DOE to iteratively solve M-M
adjusting
*   the demands toward the original demand level specified in
DM_DEMAND.

* To use ADDER the user simple needs to create a <case>.GEN file
matching that
*  below, with <case> corresponding to the run name.

$TITLE  MARKAL-MACRO -- VERSION 3.2
OPTION LIMROW=0, LIMCOL=0, SOLPRINT=ON, ITERLIM=50000;
OPTION RESLIM=50000, PROFILE=1, SOLVEOPT=REPLACE;
*OPTION LP=OSL;
$OFFLISTING
$INCLUDE MMINIT.INC
$ONMULTI
* DUPLICATE AND UNCOMMENT ANY OTHER DATA DICTIONARIES NEEDED!
*$INCLUDE OTHER.DD
* accept the actual scenario data
$INCLUDE <case>.DD
$INCLUDE ADDER.DD
* SET THE PERIODS CONTROLLING THE CURRENT RUN, OR DO IN MUSS
*SET TP(YEAR) /1990,1995,2000,2005/;
DIFFDMDS=1;
* INCLUDE THE APPROPRIATE SET OF MODEL FILES
$BATINCLUDE MMINCLUD.INC MARKAL-MACRO RESTART SOLVE

* To run with ADDER simply type RUNADDER <case>. A previous MARKAL or
MARKAL-
*  MACRO run must have been run prior to this to create the _LASTRUN
files.
*  MARKAL-MACRO will then be solved as many times as there are CALL
MARKAL-M
*  blocks in the code (default 4). The first solve uses an empty ADDER
table
*   (ADDER.DD copied from NULADDER.DD). If an existing ADDER.DD exists
then
*  comment out the copy. Each successive run uses the ADDER table
created by
*  ADDER.GMS and written to *  ADDER.DD. The <case>.LST/ANT file are
overwritten
*  by each iteration, thus only the final result is available when the
*  successive runs complete.
*
* The user needs to check the PREFDIFF in the ANT file to ensure that
they are
*  near enough to 0 for proper calibration. If not provide the 2nd
period
*  marginal costs (reported in table MC) for DDAT PREF and re-run
*  RUNADDER <case>.
```