Modeling and calibration of large scale system dynamics models: the case of the ASTRA model

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Abstract:

Though the size of System Dynamics models should be compact focusing on the main feedback loops determining system behavior one kind of model can become quite large: multi-national, multi-sectoral spatially differentiated models. The paper briefly presents such a model called ASTRA (=Assessment of Transport Strategies), which is developed in several versions over the past eight years.

The purpose of the paper is to describe an approach how such a system dynamics model despite its size can be calibrated to make it applicable for Europeanwide policy analysis of transport policies. The approach is designed as a sequential process involving an automated tool combining a C++-coded steering programme with the Vensim® optimizer to enable calibration of large numbers of similar equations that only differ by their parameterization.

Key words:

National model, calibration, transport policy, ASTRA, multi-regional-multi-sectoral

Introduction

ASTRA is developed for the *Assessment of Transport Strategies*, which corresponds to the long version of the acronym ASTRA. Its original development goal in 1997 was to provide a tool for the strategic and long-term assessment (30 years time horizon) of the European transport policy. System dynamics was chosen as the appropriate tool since transport is interacting strongly with other societal aspects like private mobility, trade of goods and services and broadly speaking economic and welfare development, such that feedback loops between transport and these aspects would be manifold. This hypothesis was supported by the outcome of a diploma thesis written at the Institute for Economic Policy Research at the University of Karlsruhe (SCHADE 1997).

Since completion of the first ASTRA model in 1999, ASTRA has passed through a number of extensions or even complete revisions each increasing its size and complexity such that to our knowledge it has become the largest existing and applied system dynamics model worldwide, which, of course, in the system dynamics world can be discussed ambiguous, because reducing reality to a limited number of core feedback loops determining system behaviour and by that limiting model size of system dynamics models constitutes a key goal of every system dynamics scholar. However, we still see ASTRA as a system dynamics model and this paper should briefly present the approach we developed to cope with the growing model size and to continue to apply system dynamics tools and philosophies.

The concept of the first version of ASTRA was presented at the Wellington System Dynamics Conference in 1999 (SCHADE et al. 1999). At that time ASTRA covered the EU15 by a division into four regions representing groups of countries and six functional zones. It consisted of four modules: macro-economy, regional economy, transport and environment. The final version of this model, presented in a report to the European Commission, who was funding the modelling project, was implemented in Vensim® and comprised about 120.000 objects when looking at the Vensim® model info dialogue (IWW et al. 2000a, 2000b). In a first follow-up project the ASTRA model was extended by an EU-to-Rest-of-World trade module, then the fifth ASTRA module, to support the analysis of technology and employment strategies of the European Union that was contributing to the formulation of the EU Lisbon strategy on competitiveness and growth (SCHADE et al. 2001, CHRISTIDIS et al.2002).

A major restructuring and extension occurred with the TIPMAC project and my PhD thesis splitting the EU15 actually into 14 countries (Belgium and Luxemburg forming one region), adding a second level of spatial disaggregation with four zones per country, increasing the number of economic sectors from 12 to 25, developing an Intra-EU trade model as part of the trade module and adding three further modules: population (which was part of regional economic module before), vehicle fleet (which was part of environment module before) and welfare measurement module (SCHADE et al. 2002a). A number of further completions concerning the formulation of selected equations, the inclusion of further feedbacks and the process of calibrating the ASTRA model is documented in SCHADE (2005), which provides the most detailed description of ASTRA to date. The number of objects shown by the Vensim® model info dialogue increased to 5.5 millions, of which 350.000 represent levels, more than 4 million auxiliaries and about 150.000 data variables. Most of the latter are used to calibrate the model over the period 1990 until 2002. Running the model from 1990 until 2020 and using yearly savings interval generates an output data file of 270 MB. The major drivers for this output size are the matrix operations within the transport model (six dimensions with 4x3x15x4x15x4=43,200 equations per variable), the input-output model (15x25x25=9,375 equations per variable) and the trade model (15x15x25=5,625 equations per variable). This model is then successfully applied to analyse European transport infrastructure and transport charging policies.

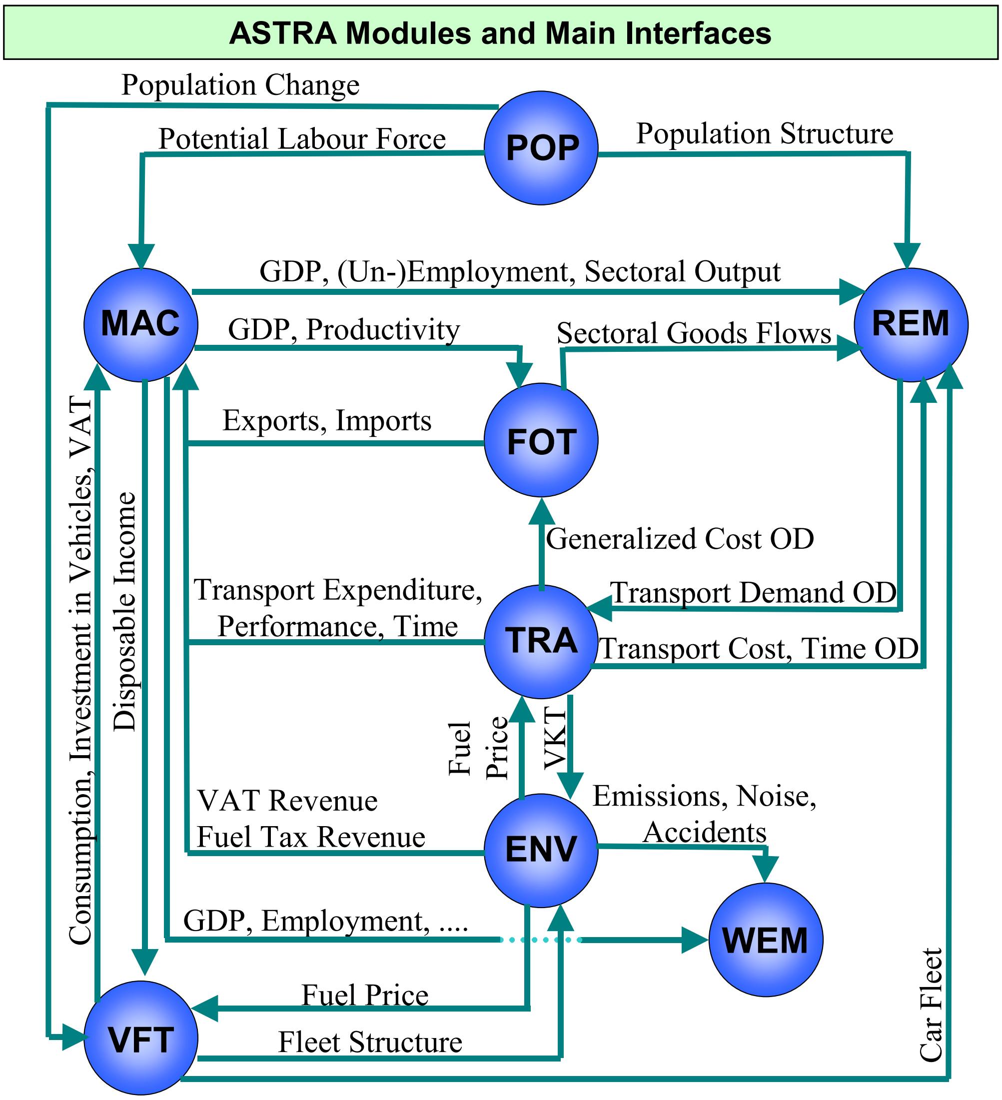
The most recent extension is made in the LOTSE project on behalf of the European Commission DG JRC in which the ASTRA model is extended to cover the EU29 countries i.e. the EU25 member states plus Bulgaria, Norway, Romania and Switzerland. Of course, this increased the size of transport matrices and the full model by a factor of five since new transport origins and destinations have to be considered additionally (KRAIL et al. 2004). Recently the ASTRA model is applied for impact assessment of renewable energy policy in Europe (PWC et al. 2005). In ongoing projects it will be used to analyse the transition towards new transport fuels for the EU (http://www.isi.fhg.de/TRIAS/).

In parallel to the ASTRA model development for the European level a number of system dynamics models following quite similar integrated modelling approaches are developed for the analysis of transport policies. ASTRA-Italy covering only Italian transport was derived from the first ASTRA model in 2000 and presented on the Palermo SD Conference (FIORELLO et al. 2002). In parallel to the first ASTRA model KUCHENBECKER developed a German model based on ithink. He converted the model into C-code and integrated it together with a detailed transport network model for Baden-Württemberg and a number of aggregate regions for Germany and the European Union (KUCHENBECKER 2000). Based on this experience the ESCOT model (Economic assessment of sustainability policies of transport) is developed for Germany to identify pathways towards a sustainable transport system in Germany as part of the OECD-EST project (SCHADE et al. 2002b).

After the presentation of the past and current development of the ASTRA model and its paralleling approaches the following text concentrates on briefly presenting the model structure and the approach to handle the calibration of such a large model.

ASTRA model structure

A detailed description of the ASTRA model is provided by SCHADE in *Strategic Sustainability Analysis: concept and application for the assessment of the European Transport Policy* (2005). The current version of ASTRA at the end of 2005 comprises 29 European countries. The ASTRA model consists of eight integrated thematic modules: population (POP), macro-economy (MAC), regional economy (REM), international trade (FOT), transport (TRA), vehicle fleet (VFT), environment (ENV) and welfare measurement (WEM). The major feedback loops between the modules are shown in Figure 1, while for passenger transport as one selected field the feedback loops are presented at the end of this section in Figure 2.



Abbreviations:

POP = Population Module	**TRA = Transport Module**
MAC = Macroeconomics Module	**ENV = Environment Module**
REM = Regional Economics Module	**VFT = Vehicle Fleet Module**
FOT = Foreign Trade Module	**WEM = Welfare Measurement Module**

Figure 1: Overview on feedbacks and modules in ASTRA

The following paragraphs briefly describe the concepts of the eight ASTRA modules. The Population Module (POP) provides the population development for the 29 European countries with one-year age cohorts. The model depends on fertility rates, death rates and immigration into the EU29 countries. Based on the age structure, given by the one-year-age cohorts, important information is provided for other modules like the number of persons in the working age or the number of persons in age classes that permit to acquire a driving licence. POP is calibrated to EUROSTAT population predictions.

The Macroeconomics Module (MAC) provides the national economic framework, which imbeds the other modules. The MAC could not be categorised explicitly into one economic category of models for instance a neo-classical model. Instead it incorporates neo-classical elements like production functions. Keynesian elements are considered like the dependency of investments on national income and consumption, respectively, extended by some further influences on investments like exports or government debt. Or elements of endogenous growth theory are incorporated like the implementation of endogenous technical progress as one important driver for the long-term economic development.

Six major elements constitute the functionality of the macroeconomics module. The first is the sectoral interchange model that reflects the economic interactions between 25 economic sectors of the national economies (NACE-CLIO categorisation). Demand-supply interactions are considered by the second and third element. The second element, the demand side model depicts the four major components of final demand: consumption, investments, exports-imports and the government consumption. The supply side model reflects influences of three production factors: capital stock, labour and natural resources as well as the influence of technological progress that is modelled as total factor productivity. Endogenised total factor productivity depends on investments, freight transport times and labour productivity changes. Fourth element of MAC is constituted by the employment model that is based on value-added as output from input-output table calculations and labour productivity. Employment is differentiated into full-time equivalent employment and total employment to be able to reflect the growing importance of part-time employment. In combination with the population module unemployment could be estimated. Fifth element of MAC describes government behaviour. As far as possible government revenues and expenditures are differentiated into categories that can be modelled endogenously by ASTRA and one category covering other revenues respectively other expenditures. Categories that are endogenised comprise VAT and fuel tax revenues, direct taxes, import taxes, social contributions and revenues of transport charges on the revenue side as well as unemployment payments, transfers to retired and children, transport investments, interest payments for government debt and government consumption on the expenditure side.

Sixth and final of the elements constituting the MAC are the micro-macro bridges. These link micro- and meso-level models, for instance the transport module or the vehicle fleet module to components of the macroeconomics module. That means, that expenditures for bus transport or rail transport become part of final demand of the economic sector for inland transport within the sectoral interchange model. The macroeconomics module provides several important outputs to other modules. The most important one is, for sure, Gross Domestic Product (GDP). This is for instance required to calculate trade flows between the European countries. Employment and unemployment are two influencing factors for passenger transport generation. Sectoral production value drives national freight transport generation. Disposable income exerts a major influence on car purchase affecting finally the vehicle fleet module and even passenger transport emissions.

The Regional Economics Module (REM) mainly calculates the generation and distribution of freight transport volume and passenger trips. The number of passenger trips is driven by employment situation, car-ownership development and number of people in different age classes. Trip generation is performed individually for each of the 76 zones of the ASTRA model. Distribution splits trips of each zone into three distance categories of trips within the zone and two distance categories crossing the zonal borders and generating OD-trip matrices with 76x76 elements for three trip purposes. Freight transport is driven by two mechanisms: Firstly, national transport depends on sectoral production value of the 15 goods producing sectors where the monetary output of the input-output table calculations are transferred into volume of tons by means of value-to-volume ratios. For freight distribution and the further calculations in the transport module the 15 goods sectors are aggregated into three goods categories. Secondly, international freight transport i.e. freight transport flows that are crossing national borders are generated from monetary Intra-European trade flows of the 15 goods producing sectors. Again transfer into volume of tons is performed by applying value-to-volume ratios that are different from the ones applied for national transport. In that sense the export model provides generation and distribution of international transport flows within one step on the base of monetary flows.

The Foreign Trade Module (FOT) is divided into two parts: trade between the EU29 countries (INTRA-EU model) and trade between the EU29 countries and the rest-of-the world (RoW) that is divided into 9 regions (EU-RoW model). Both models are differentiated into 25 economic sectors and relationships between country pairs. The INTRA-EU trade model depends on three endogenous and one exogenous factor. World GDP growth exerts an exogenous influence on trade. Endogenous influences are provided by GDP growth of the importing country of each country pair relation, by relative change of sectoral labour productivity between the countries and by averaged generalised cost of passenger and freight transport between the countries. The latter is used as a kind of accessibility indicator between the countries. The EU-RoW trade model is mainly driven by relative productivity between the European countries and the rest-of-the-world countries. Productivity changes together with GDP growth of the importing RoW-country and world GDP growth drive the export-import relationships between the countries. Since, transport cost and time are not modelled for transport relations outside EU29 transport is not considered in the EU-RoW model. The resulting sectoral export-import flows of the two trade models are fed back into the macroeconomic module as part of final demand and national final use respectively. Secondly, the INTRA-EU model provides the input for international freight generation and distribution within the REM module.

Major input of the Transport Module (TRA) constitutes the demand for passenger and freight transport that is provided by the REM in form of OD-matrices. Using transport cost and transport time matrices the transport module is performing the modal-split for five passenger modes and three freight modes. Cost and time matrices depend on influencing factors like infrastructure investments, structure of vehicle fleets, transport charges, fuel price or fuel tax changes. For road transport network capacity and network loads are considered for four different road types such that congestion effects may affect the road transport time matrices in a simplified way. For other modes rough capacity models and capacity constraint functions are developed such that interactions between load and travel times can also be taken into account. Depending on the modal choices, transport expenditures are calculated and provided to the macro-economic module. Changes in freight transport times are also transferred to the macro-economic module such that they may influence total factor productivity. Considering load factors and occupancy rates respectively, vehicle-km are calculated. These represent an important input for the ENV module where emissions or accidents are calculated and for the VFT module, which estimates the new purchase of road vehicles besides cars.

Major output of the TRA provided to the Environment Module (ENV) are the vehicle-kilometres-travelled (VKT) per mode and per distance band and traffic situation respectively. Based on these traffic flows and the information from the vehicle fleet model on the different vehicle fleet compositions and hence on the emission factors, the environmental module is calculating the emissions from transport. Besides emissions, fuel consumption and, based on this, fuel tax revenues from transport are estimated by the ENV. Traffic flows and accident rates for each mode form the input to calculate the number of accidents in the European countries. Expenditures for fuel, revenues from fuel taxes and value-added-tax (VAT) on fuel consumption are transferred to the macroeconomics module and provide input to the economic sectors producing fuel products and to the government model.

The Vehicle Fleet Module (VFT) is describing the vehicle fleet composition for all road modes. Vehicle fleets are differentiated into different age classes based on one-year-age cohorts and into different emission standard categories. Additionally, car vehicle fleet is differentiated into gasoline and diesel powered cars with different cubic capacity categories. Car vehicle fleet is developing according to income changes, development of population and of fuel prices. Vehicle fleet composition of bus, light-duty vehicles and heavy-duty vehicles mainly depends on driven kilometres and the development of average annual mileages per vehicle of these modes. The purchase of vehicles is translated into value terms and forms an input of the economic sectors in the MAC that cover the vehicle production.

Finally, in the Welfare Measurement Module (WEM) major macroeconomic, environmental and social indicators can be compared and analysed. Also different assessment schemes that combine indicators into aggregated welfare indicators for instance an investment multiplier are provided in the WEM. In some cases e.g. to undertake a CBA the functionality is separated into further tools to avoid excessive growth of the core ASTRA model by including the assessment scheme directly within the model.

The integrated modular approach of ASTRA has the advantage that feedback loops, which commence on the micro- or meso-level in one of the modules (e.g. transport expenditures for one mode and one OD-pair in one distance band in the TRA) and then end up with an effect on the national level (e.g. changes in sectoral consumption and gross-value-added), can influence the originating module such that the feedback loop is closed e.g. in this case by the integration of the MAC module. Closing the feedback loop then implies to establish either macro-micro-bridges (e.g. from GDP and sectoral output to goods flows) or vice versa micro-macro-bridges (e.g. from transport investments into vehicle fleets to overall investments).

An example for such a feedback loop including several of the eight modules would be the passenger transport feedback loop. Starting the analysis at **passenger modal-split** marked by the grey box in Figure 2 the first effect following an increase of demand for one mode generates increased expenditures for using this mode, which is expressed by the plus sign assigned to the arrow. Only expenditures for private trips become part of private consumption, which provides two effects: first, a shift between sectors of consumption such that some sectors gain demand and others loose demand, and second either a decrease or increase of total consumption level since there is a tax differential between transport and non-transport consumption expenditures such that shifting between the two consumption purposes changes total taxes paid and the money available for consumption. Hence, the outcome of this link for the different sectors remains unclear why it is indicated by "+/-". Assuming a positive or commutated effect with increased consumption a further increase of final demand and GDP follows generating also higher incomes. Linking income growth with population development allows for the calculation of income per adult, which if increasing will drive car purchase. The latter leads to growing car fleets and increased car-ownership then shifting some persons into person groups with higher car availability. The composition of person groups in the population determines passenger transport such that a larger number of persons with high car availability would increase average trip rates leading to growth of passenger volumes. Finally, the growing volume is distributed onto the different destinations that on average also increase their demand and in the last step the OD-pair based demand has to be split onto the modes such that the loop is closed. The overall impact of this loop could not clearly be identified since the link between passenger expenditures and sectoral consumption is ambiguous as explained above (circle 1) such that it could act either as a positive (reinforcing) or a negative (dampening) loop.

A second loop that runs in parallel to the first one in the beginning links growing demand for a mode with increasing investment, which leads to growth of final demand (circle 2). The remainder of the loop is the same as the first loop. However, this loop acts clearly reinforcing as all causal relationships show a positive sign. It should be pointed out that in both loops a second influence of the economic model plays a role in passenger transport generation, which is employment shown like further influences from the same or other modules in cursive letters *Employment/MAC*. Growing employment also alters the composition of the person groups such that e.g. more business trips are made (circle 3).

The number of ten cursive influences affecting only the passenger feedback loop by influences from other loops indicates that the network of feedback loops in ASTRA is quite interwoven, which makes it impossible to present it comprehensively in such a short paper.

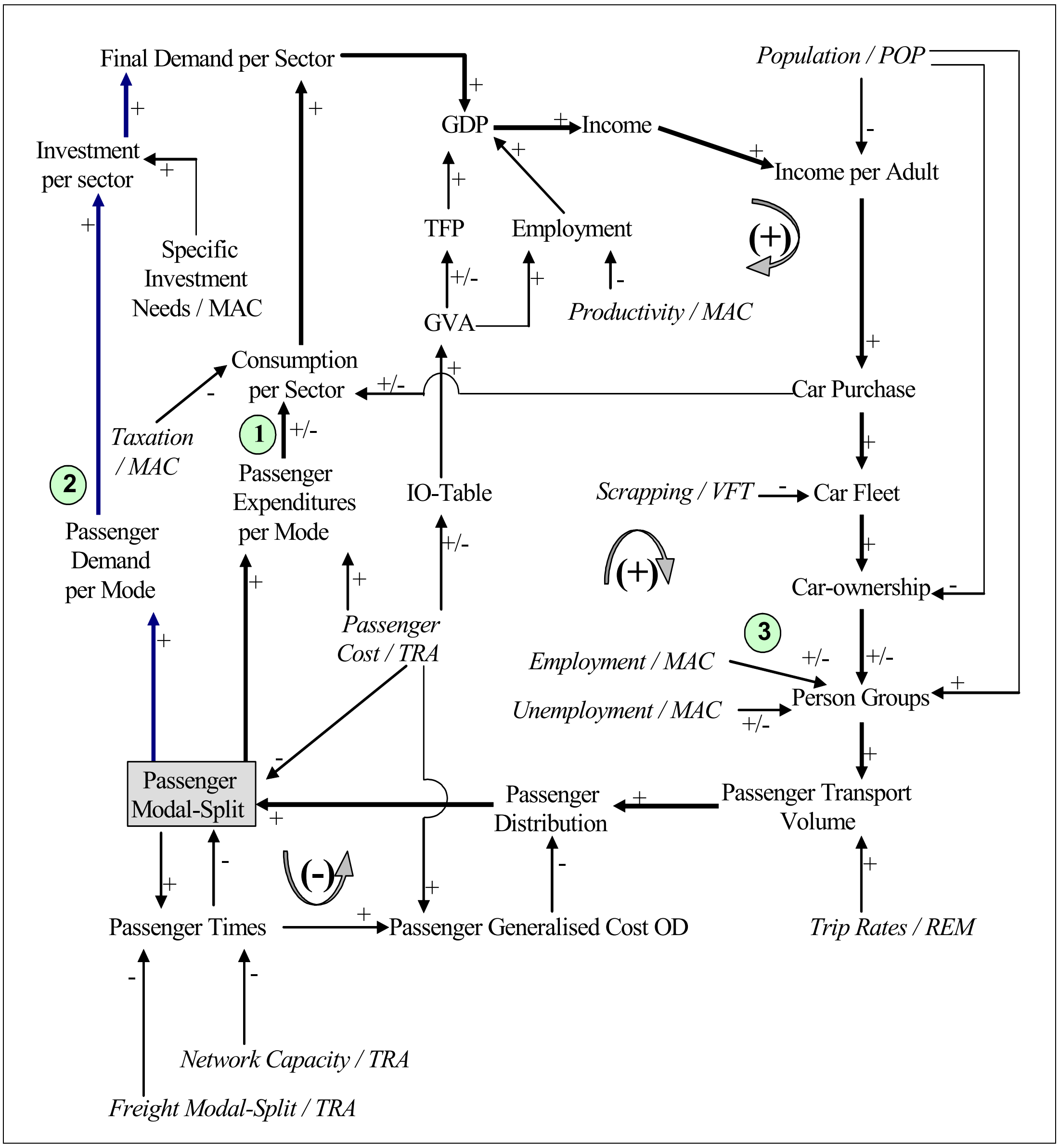


Figure 2: Passenger transport feedback loop

Abbreviations in the figure: GDP = gross domestic product, GVA = gross value added, TFP = total factor productivity, IO-table = input-output table, OD = origin-destination

ASTRA calibration approach

Though we agree to STERMAN observing that initial conditions and historical data on human and social systems usually contain large errors (STERMAN, p.911, 2000) we aspired to calibrate the ASTRA model to historic data from 1990 until 2002 for two reasons:

- a model that reproduces the past development of variables that are well-known to decision-makers is much better accepted than if the model would not be able to do that, and
- since the model is composed out of several modules it would never been possible to integrate all the modules and generate plausible results if they were not be calibrated prior to data, which is consistent with data, input used in or output obtained from other modules.

Though the Vensim® software offers powerful capabilities to calibrate system dynamics models using the Vensim® optimizer the size of ASTRA and the corresponding number of parameters to be calibrated hinders the calibration of the full model en bloc. E.g. for the Intra-European trade model five parameters for each of the 5,626 equations would have to be calibrated, but the experience has shown that using the Vensim® optimizer about 5 to 10 parameters could be calibrated reasonably with one optimization. Hence, a sequential process has been developed by which the single models of ASTRA are calibrated gradually and by different approaches. The process and the main approach are explained in the following sections.

Process of calibrating ASTRA

Calibration of ASTRA is a stepwise process. In the early steps most variables are fixed to exogenously given data during the calibration period 1990 to 2002. This means that the feedbacks from the rest of the model on these variables are cut off and the model behaves as if the inputs to these variables generate the data. In a sense at this stage one could distinguish dependent and independent variables like GDP and other fixed variables. However, this distinction can not be maintained anymore when the feedback loops are closed and "*everything depends on everything else*".

In the following steps major variables like GDP are still kept fixed but now variables of lower importance like export flows or vehicle fleets are calibrated to data. In the final steps the major variables like investment or GDP are calibrated to data. Finally, the model is checked with all feedback loops closed and if necessary further adjustments of parameters are made. The later steps are applied in an iterative process.

For calibration a specific sequence of models is followed that depends on the degree of interaction and the availability and quality of data that is required for calibration of the specific model. Models with a lower degree of interaction e.g. only one or two endogenous inputs in the full model are calibrated earlier in the sequence compared with models receiving many endogenous inputs. Models with good data availability and quality can also be calibrated earlier compared with models with poor data availability or lack of data. In some cases, the "input data" used for calibration actually has to be provided by already calibrated parts of the ASTRA model itself as exogenous data is not available. The basic sequence of calibration and the specific calibrated models are shown in Figure 3.

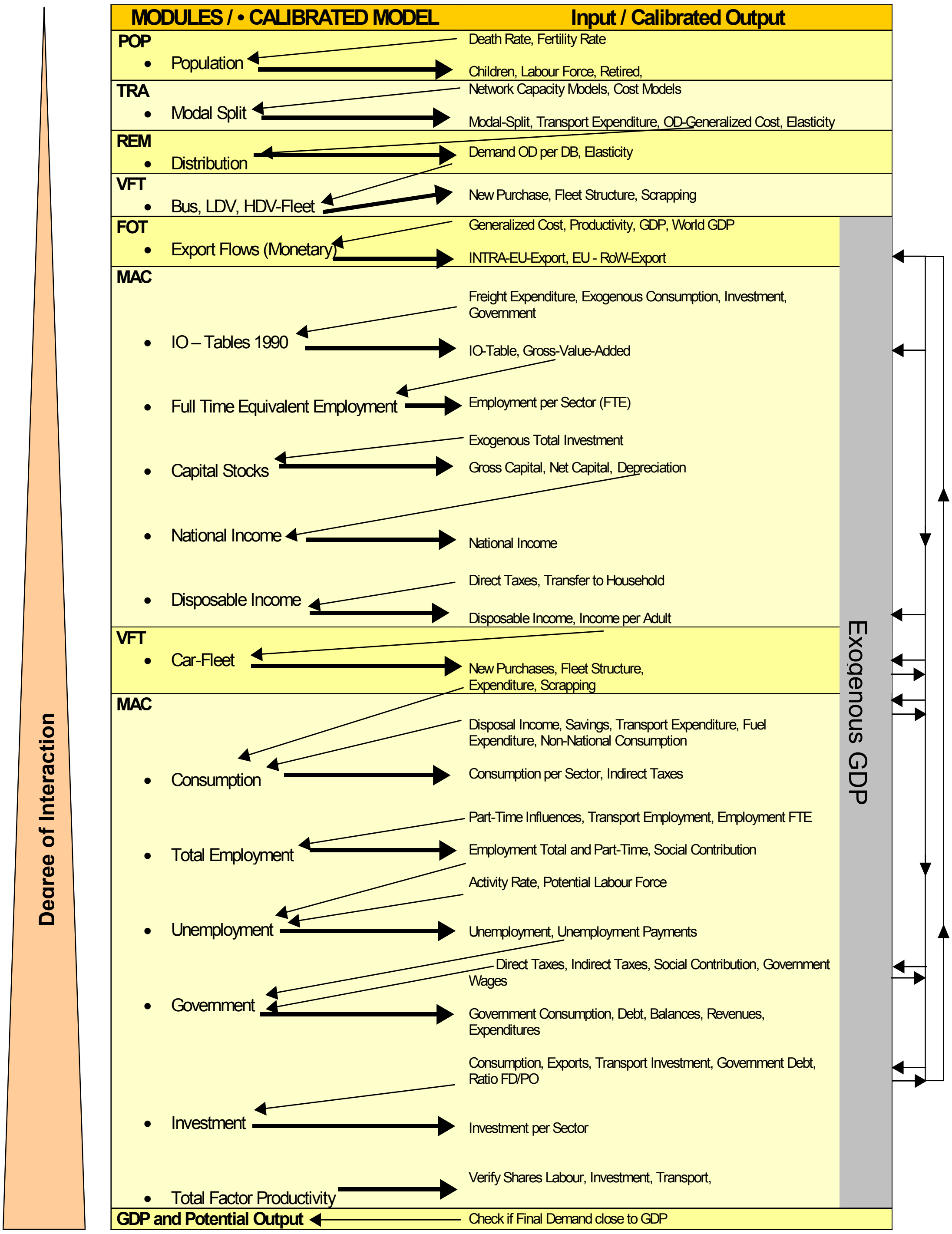


Figure 3: Logical sequence of calibration of single ASTRA models

Two problems had to be overcome when calibrating ASTRA:

- The model size disabled to use the Vensim® optimizer for the full model, and
- For some models matrices of parameters had to be calibrated amounting to sometimes several thousands of parameters for a single model.

Therefore the model was split into so-called stand-alone models, which then were calibrated separately following the sequence as presented in Figure 3. Stand-alone calibrations are developed for the population model, all road vehicle fleet models, car-ownership, input-output model, export model, capital stock, national income, total employment, investment and potential output in conjunction with GDP. For these stand-alone models an automated calibration tool is developed incorporating the optimiser tool of the Vensim® software. It enables to calibrate matrices with large numbers of countries, sectors or zones.

Furthermore a separate calibration procedure for the logit-equations in the regional economic and transport modules are developed based on computations with a Microsoft Access® database.

Calibrating stand-alone models with an automated tool

The process of calibrating a stand-alone model is explained by using the Intra-EU trade model as an example. The calibration requires six phases (see also Figure 4):

(1) Isolation of the current version of the stand-alone model from the full model.

(2) Collection and preparation of the data for calibration. In some cases such data is not available such that the "input data" has to come from already calibrated parts of ASTRA.

(3) Calibration run with automated calibration tool (see Figure 5), usually overnight.

(4) Input of calibrated parameters into stand-alone model.

(5) Verification of results of calibrated stand-alone model and possibly further iterative rounds of calibrating with the automated tool as more experience is gained about the plausible ranges for the calibrated parameters.

(6) Transfer of calibrated parameters into full model and final verification of calibration and reaction patterns of the full ASTRA model. Possibly further iterative rounds of calibrating the stand-alone with the automated calibration tool (i.e. back to phase 3).

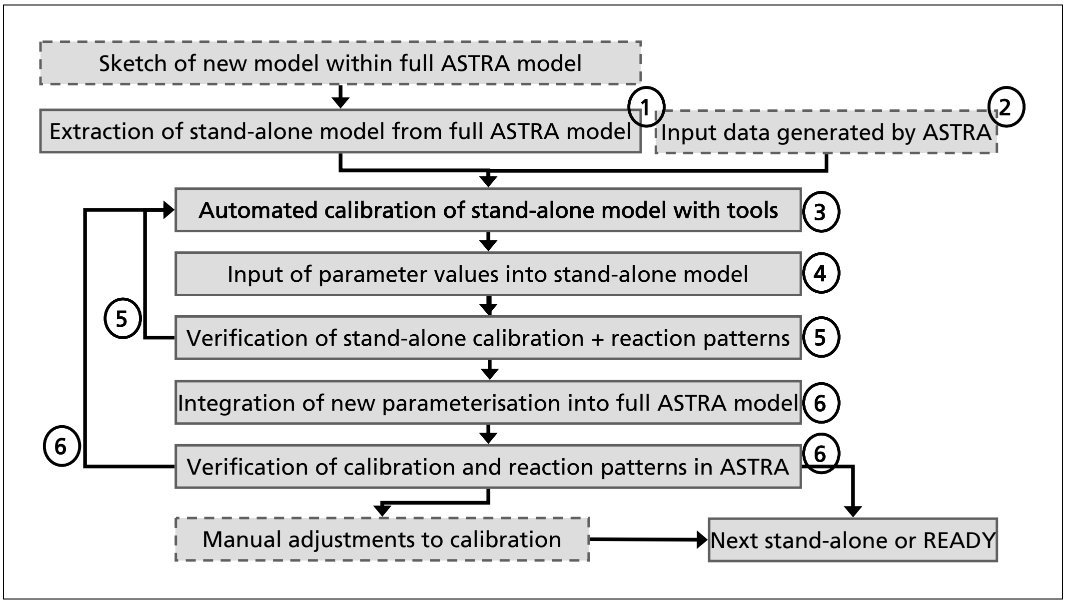


Figure 4: Process sequence of calibration of ASTRA stand-alone models

The Intra-EU trade model is composed out of six equations of which the core equation aggregates the influence of five influencing factors each described by a separate equation and fed into the export equation where it is weighted by a calibrated coefficient as shown in equation 1. All five input functions as well as the calibrated coefficients dispose of the indices exporting country, importing country and sector amounting to 15x15x25=5,625 equations. Each equation then includes five parameters that have to be calibrated.

$$\mathbf{Ex(t)_{EC,EC2,s} = Ex(t-dt) * (1 + (cPRO*f(PRO(t)) + cGDP*f(GDP(t)) + cWGDP*f(WGDP(t)) + cFT*f(fGC(t)) + cPT*f(pGC(t)))} \qquad \text{(equation 1)}$$

where:	Ex =	sectoral exports between two EU29 countries [Mio*EURO]
	cPRO =	calibrated coefficient for sectoral productivity influence [dmnl]
	cGDP =	calibrated coefficient for GDP influence of importing country [dmnl]
	cWGDP =	calibrated coefficient for world GDP growth influence [dmnl]
	cFT =	calibrated coefficient for influence of freight transport [dmnl]
	cPT =	calibrated coefficient for influence of passenger transport [dmnl]
	f(PRO) =	function of relative sectoral productivity impact [dmnl]
	f(GDP) =	change of GDP of importing country [dmnl]
	f(WGDP) =	change of world GDP growth [dmnl]
	f(fGC) =	function of freight generalised cost between the two countries [dmnl]
	f(pGC) =	function of passenger generalised cost between the two countries [dmnl]
	s =	index for 25 economic sectors
	EC2 =	index for importing EU29 country (Belgium&Luxemburg as one region)
	EC =	index for exporting EU29 country (Belgium&Luxemburg as one region)

Such a number of equations can only be calibrated using automated tools. Hence, in the first phase the Intra-EU trade model as described above is extracted from the ASTRA model and put into a separate Vensim® model to preserve exactly the same formulation of equations. We call this separate model a stand-alone model extracted from the full ASTRA model.

In the second phase the data for calibration has to be prepared. The target data for export flows can be taken from the OECD online trade database, which is providing data on the level of 63 SITC categories (Standard International Trade Classification Revision 2), which have to be regrouped to the 25 economic sectors of ASTRA considering further data sources for some of the service sectors. The data for GDP, world GDP and productivity of the sectors can also be taken from OECD and EUROSTAT online statistics. However, the generalized cost data for passenger and freight transport are not available from statistics. They have to be provided from the ASTRA model itself, which presupposes that the freight and passenger transport models have to be calibrated already, which is reflected in the sequence of calibrated models in Figure 3.

In the third phase the automated tool for calibration is started. For a model like the Intra-EU trade model the calibration should run overnight, because it takes a few hours to calculate the calibration for each country. The automated calibration tool is consisting of three interacting elements:

- a C++-coded steering programme,
- the Vensim® optimizer tool running with the model that is to be calibrated, and
- text-files and Excel®-files that provide the parameter specification for the Vensim® optimizer and the calibration data i.e. the objective function.

The structure of the automated calibration tool is shown in Figure 5. The C-coded steering programme is developed especially for the calibration of ASTRA, but is now also used to calibrate other models. It defines in a first step the files for the Vensim® optimizer of one export equation, which define the objective function of the calibration (.vpd-file) and the parameter variation concept (.voc-file). This is done individually for each of the bilateral-sectoral trade equations. In a second step the Vensim® optimizer is started and performs the parameter variations and pay-off calculations for one single equation until a calibration accuracy is achieved that is defined by the parameter variation concept file. In that case, Vensim® writes four output files that can be read by the C-coded steering programme in the third step. The steering programme collects the calibration results from these files and stores them into a results file (step 4). This results file constitutes the final outcome of the calibration providing the calibrated values for the coefficients of the export equations. These four steps are repeated until all export equations are calibrated and the results file contains calibrated parameter values for all equations of the trade model.

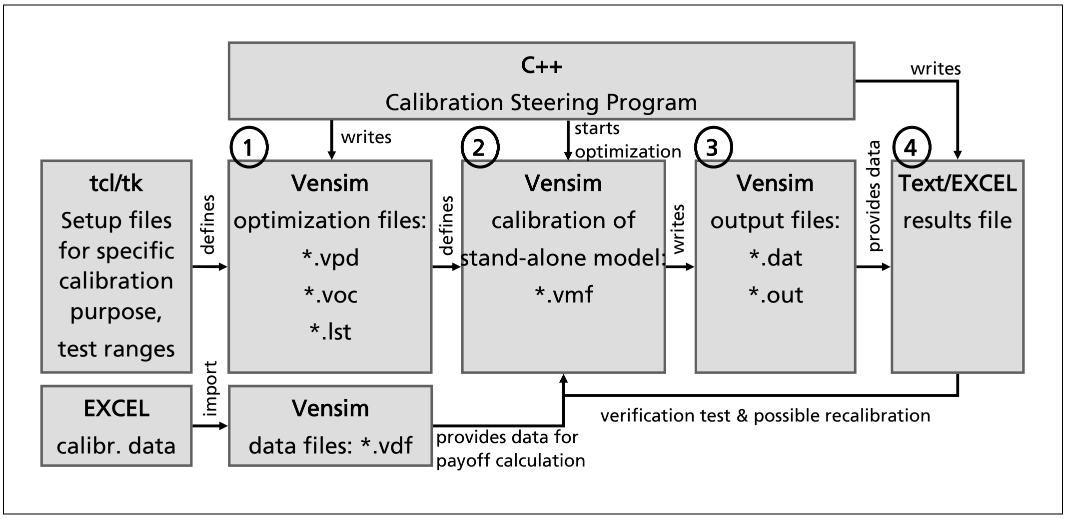


Figure 5: Multi-equation calibration with the C++-coded calibration tool and Vensim®

In the fourth phase the calibrated parameters are implemented into the stand-alone export model such that in the fifth phase the model is simulated and compared for all calibrated equations. E.g. now also the calibration of country totals of exports aggregated from the bilateral sectoral export flows can be verified.

In the sixth and final phase, the calibrated variables are copied back into the full ASTRA model. Simulating the model enables to verify if also within the context of all feedbacks established the calibration remains reasonable. In some cases, re-calibration using the stand-alone model with updated input data e.g. for the freight or passenger transport cost could be necessary.

One strength of using the Vensim® optimizer should be emphasized, which is that it allows for the calibration of any mathematical formulation since it does not aspire an analytical solution for calibration, but varies the calibration parameters iteratively following the rules provided by the parameter variation file (*.voc file). This means, also functions for which no statistical analysis would be available can be calibrated.

Conclusions and outlook

Though System Dynamics is usually applied to problems that can be described by a limited number of feedback loops, the development of the ASTRA model and its successful application for policy analysis reveals that also large scale multi-national and multi-sectoral models can be developed based on the System Dynamics concept.

Due to this multi-national and multi-sectoral setting these models include a very high number of feedback loops because of the inclusion of trade models, where bilateral trade of one sector may affect GDP of one country affecting all its further trade relationships, of transport models, where long distance transport flows crossing one country may affect any other flows in the country, and of input-output models, where each sectoral influence e.g. in the transport related sectors may affect any other sector. However, the number of parameters of these equations is too high to calibrate such a model en bloc.

Hence, ways have to be found to split the full model into smaller parts that can be calibrated separately and afterwards can be merged together maintaining their calibration. This paper shows how for the ASTRA model such kind of stand-alone models have been developed and with which process steps a reasonable calibration could be achieved. This involved the development of a C-coded tool running the Vensim® optimizer with the stand-alone models and generating calibrated parameters for a high number of equations in overnight runs. With such an approach models like trade models built out of about 20.000 equations each incorporating five calibrated parameters can be calibrated and can become part of a system dynamics model.

Past experience revealed that especially the transport module (TRA) contributed to the growth of the model size. Though it consists of a limited number of variables the matrix operations behind these variables describing the origin-destination (OD) transport flows increase the model size significantly. Hence, in the future attempts will be made to extract this module from the ASTRA model to limit growth of the model size and enable to consider further feedbacks within the other models of the socio-economic system.

The past and current application of ASTRA for providing European scenario forecasts and policy advice, shows that System Dynamics models can be used and are accepted for these purposes provided that (A) a reasonable calibration to main variables can be proved and (B) their reaction patterns to realistic policies and shocks are plausible and can be explained by showing the causal chains responsible for the results in the model. Even though such a model is clamped strongly by its calibration ASTRA showed for some policies the worse-before-better reactions or the other way round better-before-worse reactions that are typical for System Dynamics models.

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