Towards the use of model structure analysis for designing flexible learning itineraries

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Abstract

Some large system dynamics models drive simulator interfaces used for teaching; this is the case of the MacroLab model. Such a model may be useful for making students with basic instruction in system dynamics explore the economy as a dynamic system, allowing for diverse inquiry itineraries. The question is if different exploration itineraries yield sufficiently similar learning outcomes. This has been tried with ten student groups. The results are encouraging, but also indicate that the inquiry scenario design should be based on systematic analysis of the model's structure: some variables may not be reachable from everywhere. An ad-hoc structure exploration found such isolated areas. The use of a reachability matrix is suggested and an initial example is shown. Also, students need systematic guidance in constructing a loop set that will frame their exploration. Concluding, it is argued that this kind of instructional design may bring other large system dynamics models closer to instructional use.

Keywords: education, model structure, feedback loop set, reachability, macroeconomics.

Introduction

Large system dynamics models have been used in teaching macroeconomics as engine behind gaming interfaces for some years now; one example is thee MacroLab environment (Wheat, 2007b). The interface shields students from the system dynamics part, concentrating on "causal loop diagram" (CLD) based argumentation and using the simulator to generate behaviors. This has been shown to allow focusing cognitive resources to the dynamic processes going on in the economy.

However, it may have other advantages as well. One such advantage may stem from the fact that in system dynamics-models the many feedback loops tie together the parts (Kampmann and Oliva, 2008). A typical macroeconomics model deals with different markets that are usually discussed separately, and the models' variables are distributed across these markets (compare with Table 2 below). In contrast, with system dynamics model, due to its feedback loops one would expect that for investigating the economy's working, the variable where one starts out does not have a large influence on the set of variables inquired during the process. For example, one student could start in the labor market and another in the money market – still their inquiry would lead them across the entire model and all the markets. This would be an interesting complement for textbook-based teaching, where markets (and their immediate variables) are treated chapter by chapter in a linear manner. Additionally, a whole set of learning itineraries might exist where the textbook privileges one [2].

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[2] Even though textbooks may encourage the reader to define an individual reading itinerary, the mere fact of the linear organization of chapters in a book privileges one pathway over the others.

This possibility fueled the idea of a course where it was hoped that despite the individually different itineraries, all students would learn the same relevant items. The present paper reports of the journey that started by recognizing this opportunity and subsequent problems and discoveries that lead the author to believe that model structure analysis tools (Kampmann and Oliva, 2006; 2008; Moijtahedzadeh, 2008) may become used by instructional designers to create flexible itineraries for learner centered teaching (Richmond, 1993; Forrester, 1998), thus making large models useful for teaching processes that go beyond "causal loop diagrams" (CLDs).

An initial attempt was carried out with one course during 2008. Ten groups of third year undergraduate students with a first introduction into system dynamics worked through ten different scenarios each starting out with a shock to a different variable. These shocks consisted of exogenous perturbations in the variable's behavior. The students' resulting mental models of the situation – represented as variables and causal links [3] - were compared amongst each other and also to a representation of the underlying simulation model, using the "distance-ratio" method (Markovski and Goldberg, 1995).

The groups' mental models were found to be similar, which could at first sight be interpreted as success. However, only small parts of the reference model were used by the students and when the small size of their mental models is taken into account, the differences appear to be too large to pass the test.

In order to shed light onto the reasons for these differences, the links between the different feedback loops taken into account by the students were used to construct a reachability matrix amongst loops. Indeed, while there were groups of maximally connected loops, other loops were isolated. Inspection of the groups' mental models and shock variables revealed that "missing" variables were due to shock variables that belong to isolated loops. Ex-post analysis revealed that the apparent isolation was due to mistakes in the students' mental models; however, during the work process, they only had these mental models to work with.

After using this ad-hoc approach to analyze the situation, it appeared to the author that the design of learning experiences would benefit from the use of the tools developed for structural analysis; this would allow to:

1. design a range of shock scenarios that assure the reachability of a given set of variables (in order to guarantee equality across scenarios and to take students from simpler structures to more complex ones).
2. work with a set of feedback loops that is adequate for students. The determination of the loop set used is not a trivial manner. In large models, the set of feedback loops is huge and complex and currently there is no precise indication concerning which loops students will work with.

The paper is organized in the following way. First the MacoLab model is briefly introduced. Next, the goals, methodology and procedure for the initial attempt are presented. Then the results are explained together with how they called for further analysis. The ad-hoc analysis is then discussed, leading to the insight that instructional designers cannot trust in the general idea that in system dynamics models everything is connected with everything else.

[3] For an introduction to the subject of mental models, refer to Schaffernicht and Grösser, 2009

Eventually, a preliminary procedure for designing learning activities is proposed, together with some reflection concerning the use of published analysis methods and the two issues mentioned above – followed by an outlook on the future of large models in education that appears to be possible to the author.

MacroLab

The MacroLab model represents the worldwide economy as consisting of two blocks of countries, which is sufficient for the case of teaching introductory macroeconomics. Economically speaking, it is a fusion model that does not try to represent any particular school of thought and its time horizon is about five years, excluding growth processes from the analysis. The model consists of two groups of 10 sectors each, one for the USA and an equivalent one for the "rest of the world".

Submodel	**Sector**
Production	Labor
	Capital
	Productivity
	Price
Income distribution	
Consumption	
Government	
Banking	Money
	Monetary policy
Exchange rate	

Table 1: MacroLab model sectors

A detailed description of the model is to be found in Wheat (2007a). The whole model counts more than 400 variables and its corresponding stock-and-flow diagram covers more than 20 computer screens. While this amount of detail is required to carry out the simulation task with sufficient fidelity (to textbook models and to historical data), it is an overwhelmingly complex situation for the students exposed to our experience.

In order to work with a manageable amount of complexity and to assure comparability amongst the reference model and students' mental models, a simplified causal loop diagram was derived using a procedure that also was used by students (as described in the following section) and used as reference. The model simplification yielded a set of 81 variables (details reported in Quiroz y Aravena, 2008; Schaffernicht et al., 2008):

Code	*Refers to*
ADer	expected real demand
C	**consumption (nominal)**
ceP	cost effect on price
cpRat	cost productivity ratio
cpRel	cost productivity relation
cProp	**propensity to consume**
ct	compliance time
deP	demand effect on price
diB	disposable income business
divN	dividends (nominal)
dp	dividends pct
dpst	deposits
dTr	net change of FF target rate
eN	effective labor
eti	extra-time index
ExpNN	**Exports (US) net nominal**
ExpNNRW	net nominal Ex (RW)
exR	**exchange rate**
exRsrv	excess reserves
G	**government spending**
Gb	government borrowing
GBdt	government budget
GDbt	government debt
GDef	government deficit
GPch	government purchases
i	**Interest rate**
idi	income / disposable income
ieC	interest elasticity of consumption
ieS	interest elasticity of savings
Imp	**Imports real (US)**
ImpVW	WT of Imp volume (USA)
Inv	**investment**
irec	interest rate effect on consumption
iRise	rise in i
K	**capital**
Kc	capital cost
KDes	desired capital
KDpr	capital depreciation
L	**demand for reserves (liquidity demand)**
lp	loan payments
lter	long term expected results

Code	*Refers to*
M	**resverves (money offer)**
mbr	mean bond rate
mfp	multifactor productivity
mpc	mean propensity to consume
N	**employment**
nce	net capital entry (US)
Nd	**desired labor**
ndr	net deposit rate
nlr	net lending rate
opSrp	operating surplus
P	**price level**
pFac	production factors
pImp	payments for Im (US)
PoB	purchase of bonds
PRW	Price level (RW)
rExp	nominal revenue from Ex (US)
ros	revenue % of salaries
rr	reserves rate
rRW	revenues (RW)
S	**savings (W)**
spc	salaries % of capital
sr	(nominal) sales revenue
sttp	social transfer pmts % of budget
Tax	**taxes**
TaxB	taxes business
TaxHh	taxes households
tp	transfer payments nominal
tpB	business tax pct
tpHh	personal tax pct
tr	FF target rate
tri	FF target rate indicator
ucImp	unit cost of imports
uer	**unemployment rate**
UPC	unit production cost
w	**nominal salary**
wap	working age pupulation
wd	withdrawels
wFrc	workforce
Yd	**aggregate demand**
Ys	**production**

Table 2: variables used

In this table, variable names are abbreviated in order to facilitate diagrammatic representation. The variables in bold typeface correspond to the typical textbook variables.

The pilot experience

Objectives

The aim of the effort was to test if different groups of students, analyzing different shocks, i.e. entering their inquiry at different variables (and sectors) would still learn the same conceptual contents. The research question was:

> *Do student groups who use the MacroLab model from different entry points learn the same variables and causal links amongst groups and in relation to macroeconomics textbooks?*

This yields two hypotheses:

H1: *students' metal models stemming from inquiring different shock scenarios in the context of the MacroLab are similar to the underlying model (which is compatible with the standard textbook model).*

H2: *students' metal models stemming from inquiring different shock scenarios in the context of the MacroLab are similar amongst each other*

Methodology

For the purposes of exercises carried out in the context of MacroLab, the underlying simulation model is the "reality" against which students develop their mental models, which consist of variables and causal links. Since CLDs also contain (and are based upon) variables and causal links, we interpret students' CLDs as expression of their mental models: without the "loop" component, they transform into "causal diagrams" – the representation used by standard methods (Markóvski and Goldberg, 1995). This is widely practiced in the system dynamics community- (Capelo and Ferreira, 2008).

In order to make students' mental models comparable against the "real" MacroLab model, the following procedure is applied to the full stock-and-flow model in order to obtain a comparable causal diagram:

1. select and mark a MacroLab variable that represents a standard macroeconomic variable and put it on the causal diagram;
2. follow a link to a connected MacroLab variable which has not been marked yet:
    - if it is a standard macroeconomic variable or it receives a link from another variable, return to step 1;
    - else repeat step 2.

Application of this procedure leads to a causal diagram with only standard macroeconomic variables and such variables that are needed to maintain any feedback loops; other variables are "collapsed" and the number of variables reduced to 81. Any individual who follows these instructions will obtain the same causal diagram.

This representation of the system dynamics model has the same structure as mental models as captured from students. Accordingly, the differences between students' causal diagrams and this "true" causal diagram indicates how far or close their mental models come to the "truth". Also, students' causal models are compared amongst each other to discover if they are rather similar or different.

In order to produce a systematic and generally understandable comparison, the "Distance Ratio" (DR) method was selected. The method was initially developed by Langfield-Smith et al. (1992) and improved by Markovski and Golberg (1995) which allows measuring the distance between different mental models. The details of this method are explained in Appendix 1.

Procedure and population

Students work through a sequence of phases as follows:

1. Each group is assigned a "domestic" sector of the MacroLab model and a scenario with a shock that affects one of its variables.
2. The group applies the procedure described in the previous section to their respective sector in order work out a CLD.

3. All groups assemble a general CLD from their sector diagrams that will serve as navigation plan; this generates discussion amongst groups and is the opportunity to discover mistakes and produce a shared causal diagram. (Observance of the procedure assures that the causal diagram is comparable to the “true” one without the personal bias each individual would otherwise bring to the process of representing the simulation model.)
4. For the variables included in the CLD, the MacroLab variables' behavior resulting from the shock is inquired; variables which do react noticeably are treated as main variables and their behavior is drawn on the causal diagram; other variables (see supplementary material in http://dinamicasistemas.utalca.cl/5_Educacion/MacroLab/MacroLab.html);
5. A report is written with a step-by-step explanation of how the shock produces its effects on production and employment.

During the whole process, students have full access to the stock-and-flow diagram and the equations of the MacroLab model.

Afterwards, each group's final CLD is interpreted as a causal diagram (without the loops) and distance ratios were calculated between groups' models and between each group's model and the reference model (Quiroz y Aravena, 2008; Schaffernicht et al., 2008)

The exploration was carried out with a group of 25 students from the third year of undergraduate studies in “management and information systems” at the University of Talca. The context is a year-long course which starts out with an introduction into system dynamics that deals with the fundamentals of causal models, stock-and-flow thinking and the basic structures and behaviors during 32 hours of instruction.

The following table indicates the shock scenarios:

Submodel	**Sector**	**Shock**
Production	Labor	Population rises 30 million
	Capital	Earthquaque destroys capital
	Productivity	Innovations rise productivity
	Price	Import costs rise
Income distribution		Household taxes lower 50%
Consumption		Propensity to consume augments
Government		Federal budget rises during years 2 to 7
Banking	Money	Additional reserves
	Monetary policy	Aggegate demand rise causes inflation
Exchange rate		Lower currency offer

Table 3: shock scenarios

Each of the student groups thus had a different scenario, but their tasks had the same goal.

Results from the first experience

Good news and bad news

The students constructed the following causal loop diagram (included in supplementary material):

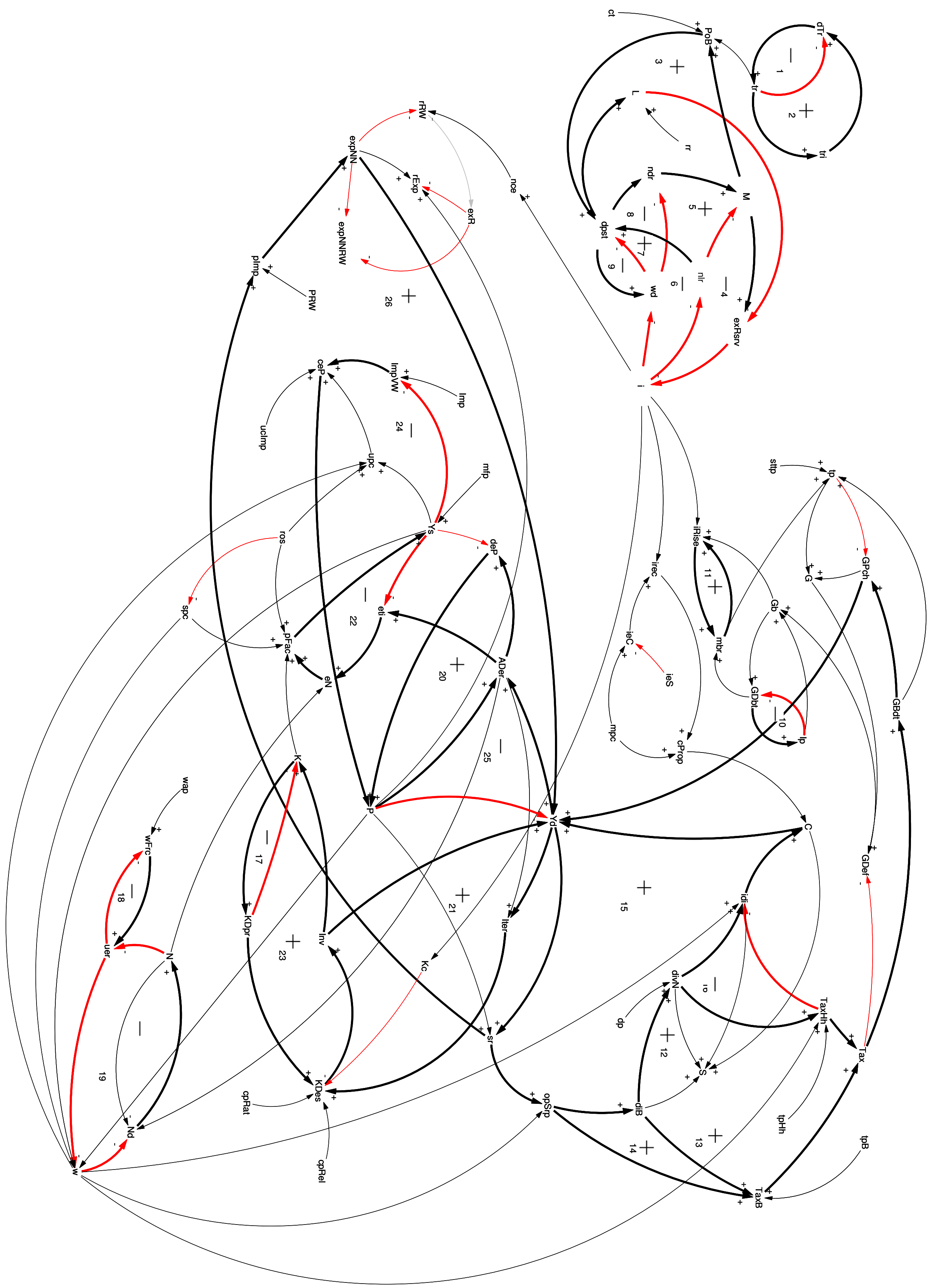

Figure 1: CLD of the MacroLab model (original as “Students_CLD.mdl” in additional material)

In the diagram, causal links that belong to feedback loops are printed bold. This helps to visually recognize the loops detected by the students. It also makes visible the fact that many variables and links are not on any loop for the students.

Overall, students identified 26 feedback loops, which appear with number and polarity in the figure. A detailed presentation would be beyond the scope of this paper; the interested reader will find a detailed description at the web-site http://dinamicasistemas.utalca.cl/5_Educacion/MacroLab/MacroLab.html

The DR analysis produced the following results:

Submodel	Sector	DR (%)	Variables	%Variables
Production	Labor	3,74	21	26%
	Capital	3,62	15	19%
	Productivity	3,75	9	11%
	Price	3,82	17	21%
Income distribution		3,05	17	21%
Consumption		3,75	19	23%
Government		3,59	21	26%
Banking	Money	-		
	Monetary policy	4,12	17	21%
Exchange rate		-		

Table 4: distance ratios

The *Money* and *Exchange rate* groups did not finish their assignment on time and were excluded from the analysis. For the remaining 8 sectors (groups), the DRs range from 3.05% to 4.12%. At first sight this looks like what had been hoped for: students' models are hardly different from the reference model.

However, a look at the columns "Variables" and "%Variables" reveals that students' models cover only a small portion (between 9 and 21 out of 83) of the variables contained in the reference model. This means that the groups excluded the majority of variables from their thinking about the shocks they had to understand. This makes it necessary to ask two new questions:

1. did their models contain different parts of the reference model?
2. did their models include all the textbook variables?

As can be seen in the following figure, the DRs between student models were higher than in relation to the underlying model:

	Labor	Capital	Productivity	Price	Income distribution	Government	Monetary policy
Labor		9,30	13,76	10,38			14,53
Capital			18,44	10,79			18,26
Productivity				15,12			18,60
Price							16,18
Income distribution	12,11	12,86	15,70	9,93		10,40	15,07
Consumption	8,95	11,23	13,04	6,19	10,42	10,50	13,36
Government	10,19	10,48	13,41	10,12			14,16

Table 5: inter-group distance ratios

If one takes into account the fact that student' models covered about 20 variables each, these models were quite similar: this is a reassuring aspect, since the sheer fact of having different numbers of variables already makes out part of these differences. However, with respect to the second question, a different picture emerges:

Shock sector	Variables	Principales	Covered
Consumption	19	12	67%
Monetary policy	17	12	67%
Price	17	9	50%
Labor	21	8	44%
Capital	15	8	44%
Government	21	8	44%
Income distribution	17	6	33%
Productivity	9	4	22%

Table 6: groups' coverage of main variables

None of the student groups included all of the textbook variables into their CLDs. The *Consumption*, *Monetary policy* and *Price* scenarios made their respective groups include between half and two thirds of these main variables; all the other groups have been working with less than half of these variables. This impression is complemented by looking at the coverage of each of these variables (across groups):

Variable	Code	Covered
Employment	N	100,00%
Production	Y^S	100,00%
Unemployment rate	uer	100,00%
Aggregate demand	Y^D	87,50%
Nominal wage	w	87,50%
Price level	P	62,50%
Interest rate	i	50,00%
Consumption	C	37,50%
Investments	I	37,50%
Savings	W	37,50%
Propensity to consume	c	25,00%
Capital	K	25,00%
Reserves demand	L	25,00%
Reserves offer	M	25,00%
Government deficit	Gdef	12,50%
Government spending	G	12,50%
Exchange rate	exR	12,50%
Exports	Ex	0,00%

Table 7: coverage of main economic variables

As one might expect from the shared goal of all the inquiries, *employment*, *production* and the *unemployment rate* were always in the student models. But none of the other main economic variables has been considered be all of the groups.

The following figure presents the variables with text sizes corresponding to the frequency of their use across the student groups:

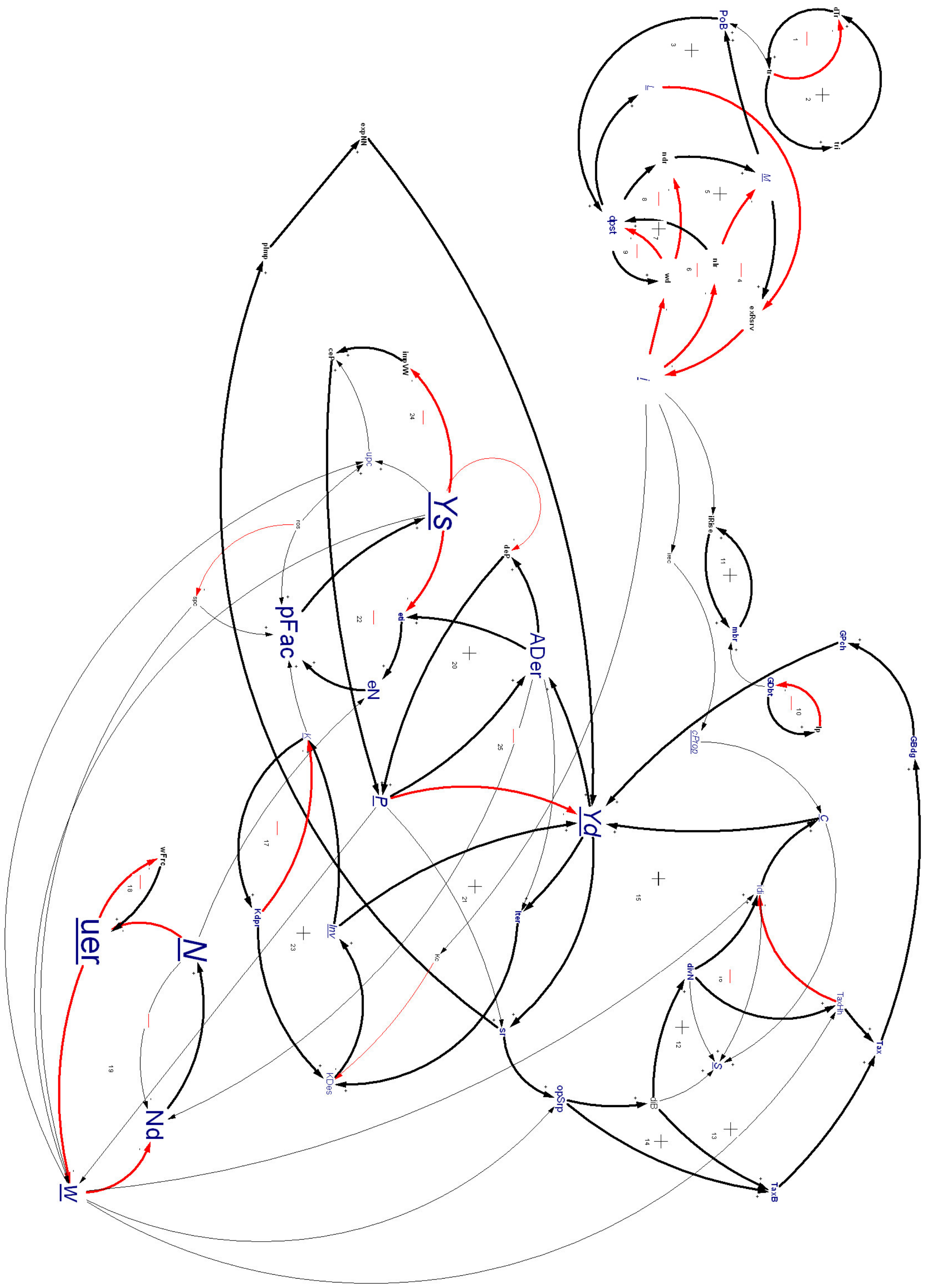

Figure 2: frequencies of use for the MacroLab variables in the students' CLD (included as "students_loops_and_frequencies.mdl" in supplementary material)

This is not what was hoped for: in this project, students learned roughly about the same variables, but not enough. Neither of the two hypotheses can be accepted in this case.

It then becomes important to understand *why* this happened. While some differences may safely be attributed to mistakes made by the students, it is unlikely that this would be a good explanation: in this case, the percentage of covered variables should be similar, which is clearly not the case.

One possible explanation may be that some variables cannot be reached from just any other variable in side the reference model. In this case, the different starting points of the respective scenarios may disclose different parts of the reference model. In order to find out if this was a valid explanation, some additional inquiry was necessary.

Connections between feedback loops

In a first step, the membership of each variable to the respective feedback loops detected by the students was marked in a table with the following structure:

Variables	**Loops**																									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**
2 iRise											1															
3 C															1	1										
5 dTr	1	1																								
6 K																	1						1			
7 KDes																					1		1			
8 PoB			1																							
9 GPch												1	1	1												
13 Yd												1	1	1	1	1					1				1	1
14 ADer																				1				1	1	
15 dpst			1			1	1	1	1																	
16 KDpr																	1						1			
17 GDbt										1																
18 divN												1			1	1										

Table 8: variables and loops

This arrangement allows not only to see which variables belong to a given loop, but –and this is what it is used for here – it shows how the loops are connected amongst each other: if a variable is member of, say, two loops (like *C* in the table, which is on loops 15 and 16), then these loops are connected by means of this variable. In such cases, if one of these loops is touched upon by a shock, the other one will be impacted, too. In this sense, such loops are like a group of loops, and such a group is always reached as whole structure.

Based upon this table (complete version in appendix 2), it is possible to draw a map of all the 26 loops and their interconnections, like shown in the following figure:

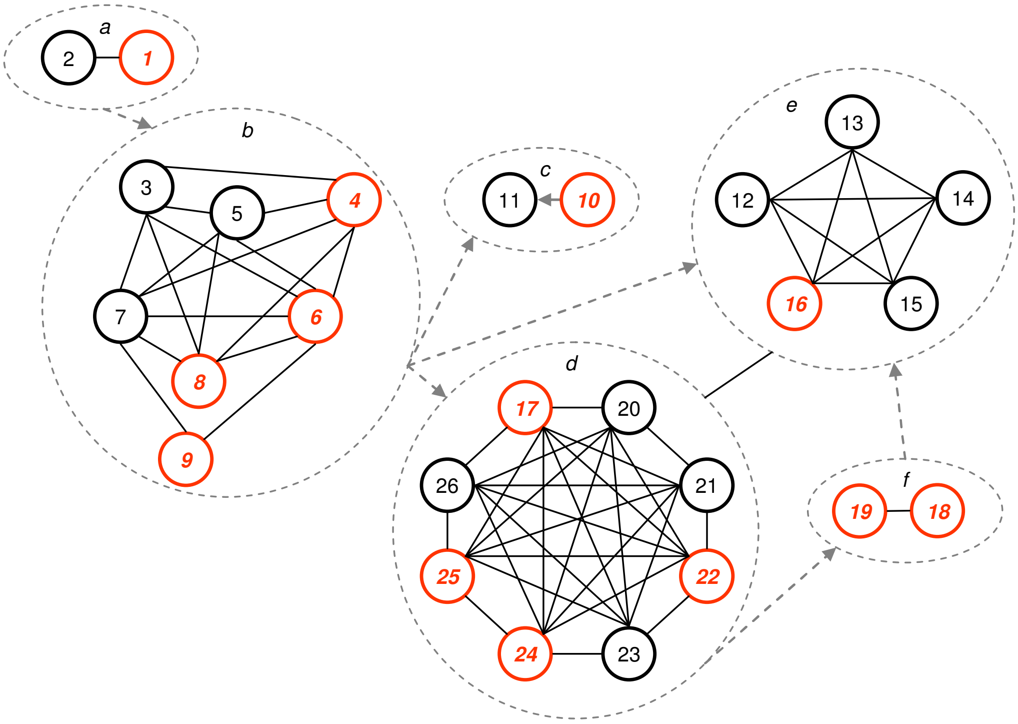

Figure 3: groups of feedback loops

In this diagram, each feedback loop is represented by a circle containing the respective numbers (black = positive, gray = negative). Usually the connection is drawn as an undirected line. For instance, between loops 1 and 2, there is a connection: both have at least one shared variable, and since it is part of each of the loops, the connection is bidirectional.

It turns out that there are six such groups of loops (from *a* to *f*), inside which each loop is connected with all the others. Please note that groups *d* and *e* have only been separated for the sake of readability (by drawing them together, the number of connections would grow strongly) – this is an inconvenient aspect, due to the rather ad-hoc nature of the diagram. System dynamics does not yet have a specific diagram language to represent loops by themselves (other than the CLDs that force the reader to look at the single variables). In the future, better representations like the loop inclusion graph (Oliva, 2004:329) shall be used.

Between some of the groups, there is an arrow. This indicates that there is at least one causal link from one of the first loop group's variables to one of the second loop group. (This has been done inside group *c*, too, in order to avoid having two one-loop groups.)

If a shock scenario hits a variable in loop 20, say, then all the variables on the other loops of groups *d* and *e* will be affected – and no other. If, in turn, the shock impacts a variable of group *a*, all the variables of all the other groups will be concerned, too. This allows to populate a loop reachability matrix, shown in the table below:

Loops	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
1		1	1	1	1	1	1	1																		
2	1		1	1	1	1	1	1																		
3				1	1	1	1	1		1		1	1	1	1	1	1		1	1	1	1	1	1	1	1
4			1		1	1	1	1		1		1	1	1	1	1	1		1	1	1	1	1	1	1	1
5			1	1		1	1	1		1		1	1	1	1	1	1		1	1	1	1	1	1	1	1
6			1	1	1		1	1	1	1		1	1	1	1	1	1		1	1	1	1	1	1	1	1
7			1	1	1	1		1	1	1		1	1	1	1	1	1		1	1	1	1	1	1	1	1
8			1	1	1	1	1			1		1	1	1	1	1	1		1	1	1	1	1	1	1	1
9						1	1																			
10											1															
11																										
12																	1			1	1	1	1	1	1	1
13																	1			1	1	1	1	1	1	1
14																	1			1	1	1	1	1	1	1
15																	1			1	1	1	1	1	1	1
16																	1			1	1	1	1	1	1	1
17												1	1	1	1	1		1	1							
18												1	1	1	1	1			1							
19												1	1	1	1	1		1								
20												1	1	1	1	1		1	1							
21												1	1	1	1	1		1	1							
22												1	1	1	1	1		1	1							
23												1	1	1	1	1		1	1							
24												1	1	1	1	1		1	1							
25												1	1	1	1	1		1	1							
26												1	1	1	1	1		1	1							

Table 9: reachability of loops

In this matrix, entries are read from row to column, like "loop 4 allows to reach loop 3" for instance. Based on this information and the membership of each variable to one sector and to certain loops, one can construct the following table:

Sector	Directly reachable loops	Reachable loops
Labor	18	19,12, 13, 14, 15, 16, 17, 20, 21, 22, 23, 24, 25, 26
Capital	17, 23	12, 13, 14, 15, 16, 17, 20, 21, 22, 24, 25, 27
Productivity	22, 24, 25	12, 13, 14, 15, 16, 17, 20, 21, 22, 24, 25, 28
Price	20, 24, 25	12, 13, 14, 15, 16, 17, 20, 21, 22, 24, 25, 29
Income distribution	12, 16	13, 14, 15, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26
Consumption	15, 16	12, 13, 14, 17, 20, 21, 22, 23, 24, 25, 27
Government	12, 13, 14	15, 16, 17, 20, 21, 22, 23, 24, 25, 28
Money	3, 4, 5, 6	7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26
Monetary policy	3, 12, 13, 14, 15, 16, 21, 25, 26	4, 5, 6, 7, 8, 9, 10, 11, 17, 18, 19, 20, 22, 23, 24
Exchange rate	12, 13, 14, 15, 16, 21, 25, 26	17, 18, 19, 20, 21, 22, 23, 24, 25, 26

Table 10: loops reaches from each sector

In this table, the loops that can be reached from variables of the different sectors are listed. In terms of loop groups, one can now appreciate some differences:

Sector	Initial	Reached	% of Loops
Consumption	b	c, d, e, f	92%
Money	b	c, d, e, f	92%
Monetary policy	b, d, e	c, f	92%
Labor	f	e, d	58%
Income distribution	e	d, f	58%
Government	e	d, f	58%
Exchange rate	d, e	f	58%
Capital	d	e	50%
Productivity	d	e	50%
Price	d	e	50%

Table 11: loop coverage of sector variables

This table has been constructed using the membership of each loop to their respective group. Some sectors' variables are located on loops such as to make most parts of the model reachable. At the same time, other sectors do not allow to reach more than half of the feedback loops (and their variables).

The ordered list of variables used per sector (by the students groups: see Table 6, p. 9) does not correspond exactly to the order of sectors in this last table, but this can be attributed to mistakes made by the students. However, at this point of the argumentation, we are independent from this particular group of students and the quality of their respective work: if the perceived model structure does not allow to reach certain loop groups starting in certain sectors, then the different shock scenarios are deemed to fail the ambition to allow equal or comparable learning about variables. For instance, as long as all the scenarios start in the *consumption*, *money* or *monetary policy* sector, there will be equality of opportunity; but as soon as the *labor* sector is the starting point of a forth scenario, some students will have less opportunity to learn about the whole set of textbook variables.

Clearly, this is not a desirable state of affairs. Accordingly, some consequences shall be explained in the following section.

Consequences from the first exploration – new challenges

This whole reflection and argumentation is made from the viewpoint of the lecturer as the designer of learning activities: the students will realize the MacroLab activity and learn from it. The goal of this design activity is that students learn about the important variables and their causal connections inside the dynamic system "macroeconomy". That they could do so along various itineraries would add flexibility in the sense of learner-directed learning (Forrester, 1998). However, it has to be assured that they have the same opportunities. Additionally, learning activities should provide a progression from simpler to more complex tasks.

It has become evident that the simple heuristic "one sector – one scenario" is not advisable: the hope that the complex of feedback loops will tie everything together is not a good enough guide. In the remainder of this section, a first sketch of a procedure for designing learning activities with large models is introduced.

The goal of the outlined design method is to provide a series of shock scenarios going from simple to complex by involving growing percentage of the model's parts.

The baseline of such instructional design is knowledge about which parts of the model are reached by any particular shock scenario. This can be achieved by two types of analysis, which shall be briefly discussed now.

In the exploration above, feedback loops have been used, because they are the fundamental component of social systems in system dynamics (Forrester, 1968). However, in models of the size of MacroLab, the concrete feedback loops are a tricky affair. The complete set of loops is breathtakingly huge:

Variable	Code	Loops
Employment	N	251
Production	Y^S	653
Unemployment rate	uer	99
Aggregate demand	Y^D	725
Nominal wage	w	510
Price level	P	625
Interest rate	i	9
Consumption	C	122
Investments	I	355
Savings	W	0
Propensity to consume	c	0
Capital	K	354
Reserves demand	L	4
Reserves offer	M	9
Government deficit	Gdef	286
Government spending	G	4
Exchange rate	exR	0
Exports	Ex	19

Table 12: feedback loops per textbook variable (loop count done with VenSim)

As the table indicates, most of the textbook variables lie on a big number of feedback loops. It certainly calls our attention that some variables have between few and no loops; this may indicate that these variables are not of great importance for the purposes of MacroLab's developer. But this is a different question and may be analyzed by a new paper.

Clearly, the variables that have been central for the students' efforts are part of more feedback loops than the naked eye can see – many more than the 26 distinguished by students. Any analyst would work based on a subset of all these loops – so will the instructional designer. But there are many such possible loop sets – so which to chose? And like stated by Kampmann and Oliva (2008), any particular independent loop set is relative to some previous decision like the variable one starts from. In this sense, the loop set may be intuitive (like in our case, where it has been constructed by focusing on the smallest loops) or based on one of the methods for "independent loop sets" (Kampmann, 1996; Oliva, 2004), it will always be one of many possible sets, and the instructional designer heavily intervenes in this by making a selection for the students.

Is there a best loop set, or a criterion to select one? This is an open question, and answers would be welcome (but will have to be provided by future research). Besides this, it may be little desirable in educational terms to construct the loop set for the students: wouldn't it be indicated to give them a procedure and make them construct their loop set?

How to design shock scenarios that would be robust in the face of different loop sets used by different student (groups)? The reachability matrix (Oliva, 2004) comes to mind. It clearly shows the set of variables to be reached from any starting point. Any well-constructed loop set will conserve the reachability expressed in this matrix. So reachability questions may be addressed based on this matrix rather than feedback loop sets (going counter to what has been naïvely done during the initial exploration).

Then the suggested method is:

1. define a collection of sets of target variables that shall be involved in shock scenarios;
2. construct the reachability matrix;

3. select the sets of entry variables from which the target variables can be reached;
4. define one or several shock scenarios that impact the corresponding entry variables.

This procedure will help designing sets of scenarios in such a way that the complexity of the inquiry activities carried out by students remains under control of the designer. Also, the matching with goals referring to specific sets or subsets of variables will become easier. Of cause, it would be desirable to have computer tools that help in performing the steps. While some tools have been developed and freely made available (refer to Oliva, 2004 and Kampmann and Oliva, 2008), specific tools for the purpose of instructional design have to be developed yet.

It would be very desirable to provide students with a method for constructing a loop set that is an "independent loop set" (ILS) or "minimal independent loop set" (MILS). The currently available methods (Kampmann, 1996; Oliva, 2004) can be followed, but they may be too complex for students who have recently been introduced to system dynamics. The question if there is a way to guide "intuitive" loop set construction in a way such as to assure the result is an ILS or even MILS, remains open for now and is a challenge for a future paper.

Still this is a very important issue: during the first application of the suggested procedure, it turned out that the students who participated in the first experience had overlooked some links and thus worked inside a mistaken picture of the "system" (as mentioned above). In a way, this may be reassuring – after all, many variables were more reachable than perceived by students. But beyond this, it shows the second weakness of the intuitive approach behind the first experience: guidance in loop set construction is needed.

In order to make clear the degree of difficulty of visually distinguishing these loops, the following figure displays the "correct" CLD:

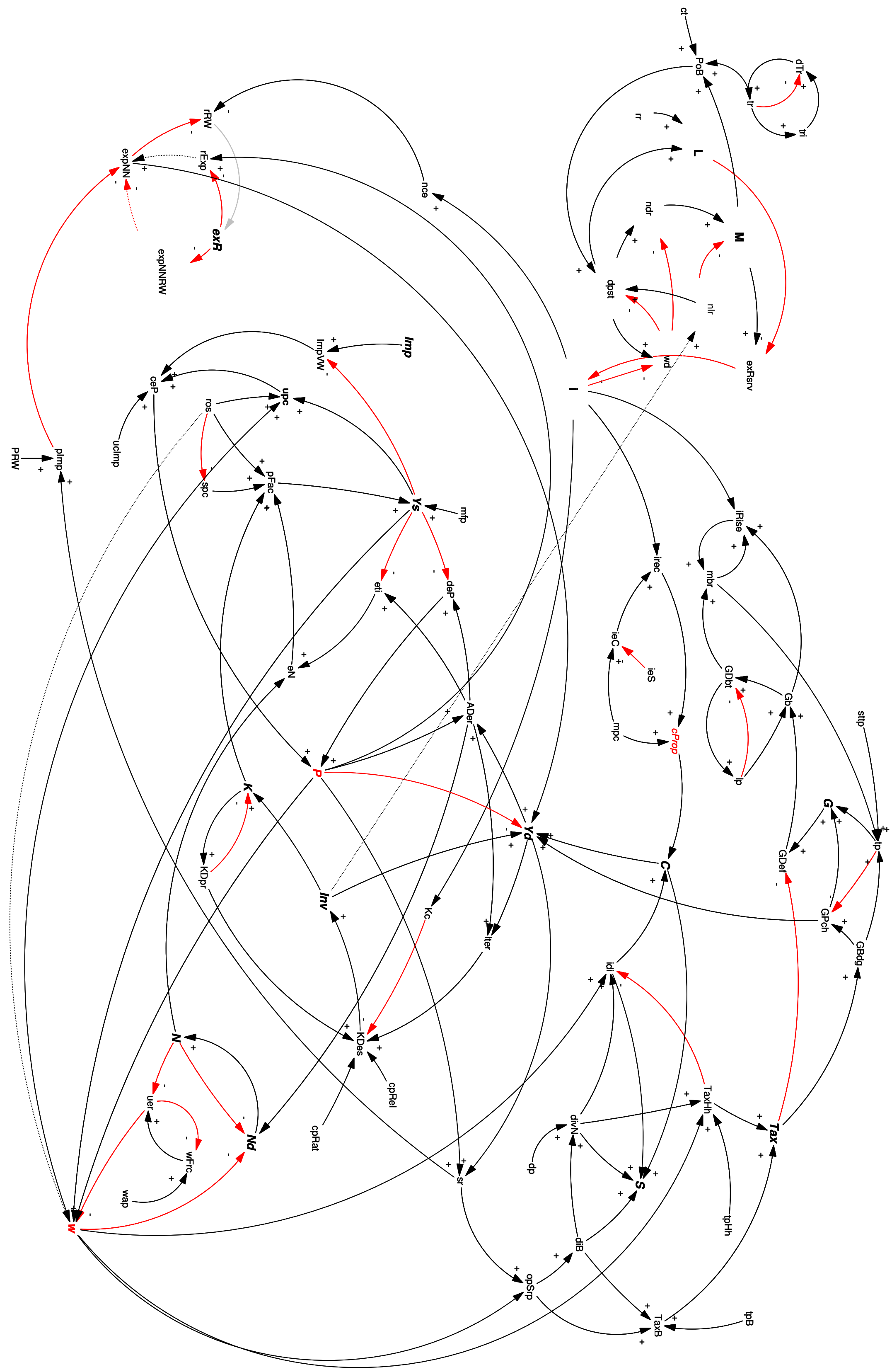

Figure 4: the correct CLD (included as “CausalDiagram.mdl” in supplementary material)

As compared to the students' CLD, there are only few differences at the level of the causal links: **Inv**->nlr, ros->**w**, rRw->**exR**, rExp->**expNN** and expRWNN->**expNN**. The reader will agree that they are hard to detect. However, several of them belong to the set of textbook variables, and not perceiving the links had severe consequences for the reachability and students' results in the exercise.

Looking ahead – towards the use of model structure analysis for instructional design

The steps explained here were made following Oliva (2004). The causal diagram shown in the previous figure can be transformed in an adjacency matrix; for MacroLab's set of 81 variables, this is an 81X81 matrix **A** with one row and one column for each variable. For reasons of readability, it is only included in the additional material. When the variable in row *r* precedes the variable in column *c* in the causal diagram, a "1" is marked in the cell $a_{r,c}$.

After adding the identity matrix **I** to **A**, the reachability matrix **R** can be constructed by successively elevating **A** to the next boolean power until no more differences exist between two successive versions of **A**.

In our example, $\mathbf{A}^2 \neq \mathbf{A}^3 \neq \mathbf{A}^4 \neq \mathbf{A}^5 = \mathbf{A}^6$. The steps executed for this task are described in appendix 3 (p. 25). The resulting matrix **R** can be used to identify the variables from which they can be reached or not be reached. Two examples may be:

1. from which variables can I reach all the textbook variables in the case of a closed economy (no exports and imports)? This question will be answered by setting the textbook variables' filters (except for exports and imports) to "1". Only the variables from which one can, directly or indirectly, reach the textbook variables are selected: it turns out that all the variables in the CLD allow to reach the entire set of these target variables. However, this includes the possibility of reaching result variables (or dead-end variables) that do not have successors (so the trip stops there). (Again, it seems noteworthy that savings appears as a result variable.)
2. from which variables can I reach only variables *i*, *L* and *M* (and no other of the textbook variables)? Answering this question takes setting the filter of *i*, *L* and *M* to "1" and the filters of the remaining textbook variables to "0". However, it turns out that with the exception of imports, all other textbook variables can be reached from any other variable. So it appears that simple exploration scenarios could only be designed by using MacroLab's capability to switch of certain sectors, like "Government", for instance. Analyzing this aspect would require to have a CLD for each "active sectors set" of the MacroLab model.

Of cause this is a primitive way to proceed: clearly, it would be easy to develop a piece of software that constructs and uses the reachability matrix in a more comfortable manner. This shall be done in the following months and will be reported in time.

Structural partitions - level and cycle partitions as described by Oliva (2004:319) will be explored, too. The intuition behind this step is that a clearer image of the dependencies inside the model (level partition) and of the relationships amongst feedback loops (cycle partition) will allow students to improve their systems thinking (Richmond, 1993) beyond the description level of variables – a way to “see the forest and the trees” (Richmond, 1994:140).

Preliminary conclusions

This paper referred to the MacroLab model. It reported work started naïvely trusting in the all-spanning feedback loops and not taking into account the feedback loop complexity inherent to large system dynamics models. Even though some success has been achieved by making students work from in different scenarios – they had a large share of their mental models in common – it became clear that some previous analysis has to be done in order to design adequate studying scenarios. At the time being, the reachability matrix is being used to tailor the scenarios for the class of 2009.

There are several tasks ahead. First, the issue concerning the construction of a convenient feedback loop set has to be settled. Then the work procedure shall receive more comfortable tools to work.

But there is more: this particular case touches upon something larger. There seem to be two kinds of system dynamics books nowadays. The first kind are “textbooks” (Forrester, 1961; Forrester, 1969; Morecroft and Sterman, 1994; Sterman, 2000; Morecroft, 2007; Schaffernicht, 2008); these have been written to help students learn system dynamics, and they contain models with one, two, three or four feedback loops. This is because most of the important issues are well captured by these rather little models, and it would not be desirable to needlessly add complexity.

The other kind are books like “Urban dynamics” (Forrester, 1969), “World dynamics” (Forrester, 1972), “Limits to growth” (Meadows et al., 2004). These are texts written above a model that has been built and used to understand a given problem and maybe find ways out of it. These models are much more complex than their textbook cousins.

Why not use the “world3” model from “Limits to growth” to generate a set of exploration scenarios, using the same procedure and tools? Wouldn’t this bring together learning about a system/problem and learning about system dynamics (on the task)? Wouldn’t it make some important features of the system dynamics method accessible to users, and allow individuals with relatively little expertise in systems dynamics to engage with complex models in a meaningful way? When Forrester called our attention to the fact that modeling is not the same as using a model like a simulation game (1985), he was concerned by the fact that “consuming” a game does not trigger enough reflection. Looked upon from this angle, students who work through their way from a previously unknown perturbation to understanding its effect and even to designing a solution or mitigation policy, must reflect a lot: sure, they receive some guidance, and the model is already there – but they have to construct their understanding (or mental model) themselves.

In this sense, the use of structural analysis methods and tools (Kampmann, 1996; Oliva, 2004; Kampmann and Oliva, 2006; 2008; Moijtahedzadeh, 2008) for instructional design promises to bring larger – and more applied or problem-related- system dynamics models to a larger audience. As stated by Moijtahedzadeh (2008:451), if these methods and currently still “targeted towards a small interest group. However, the ultimate goal is to reach a wider audience [...]”. It seems possible that specific sets of scenarios can be developed by the system dynamics community and recommended for teaching in wider fields, bringing the benefits of system dynamics to a wider public without requiring full training in modeling.

The author hopes that MacroLab will be but the first step in this direction.

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Appendix 1: the "distance ratio" method

The DR is a number that expresses how different one model is from another one, based upon the comparison between the two sets of variables and causal links. It varies from 0 (identical models) to 1 (no shared variable or link). In order to compare two mental models, each of them is represented as association matrix, *A* and *B* respectively, where each of the model's variables is a row and a column. Rows will be numbered from 1 to *p* using an index *i* and columns from 1 to *p* using index *j*. Each variable is assigned a row and column with a specific number and $i=j$. If variables *x* and *y* are located at row *r* and column *c* respectively, possible links between them will appear in cells a_{rc} and b_{rc}. Links from a variable *x* to a variable *y* are denoted as "1" for positive polarity and "-1" for negative polarity; "0" means "no link". So if $a_{rc} = 1$ and $b_{rc}=-1$, it means that in the model *A*, there is a positive link from *x* to y, while in model *B* the link from *x* to *y* is negative.

We will us *p* to denote the total number of possible nodes; P_c is the set of common nodes in *A* and *B*, and p_c is the number of common nodes. P_{uA} is the number of nodes unique to *A* and P_{uB} the number of nodes unique in *B*. N_A and N_B are the sets of nodes in the two models.

The complete formula of the distance ratio is then

$$DR(A,B) = \frac{\sum_{i=1}^{p}\sum_{j=1}^{p} diff(i,j)}{(\varepsilon\beta+\delta)p_c^2 + \gamma'(2p_c(p_{uA}+p_{uB}) + p_{uA}^2 + p_{uB}^2) - \alpha((\varepsilon\beta+\delta)p_c + \gamma'(p_{uA}+p_{uB}))}$$

diff(i,j) =

- 0 — if $i = j$ and $\alpha = 1$;
- $\Gamma(a_{ij}, b_{ij})$ — if either i or j $\notin P_c$ and $i,j \in N_A$ or $i, j \in N_B$;
- $|a_{ij} - b_{ij}| + \delta$ — if $a_{ij} * b_{ij} < 0$;
- $|a_{ij} - b_{ij}|$ — otherwise.

$\Gamma(a_{ij}, b_{ij})$ =

- 0 if $\gamma = 0$;
- 0 if $\gamma = 1$ and $a_{ij} = b_{ij} = 0$
- 1 otherwise

γ' =

- 0 if $\gamma = 0$;
- 1 otherwise

The parameter β represents the highest possible link strength, which is 1 in our case; thus β is replaced by 1. It follows that δ − which would give different importance to polarity change according to the strength of links involved – will be set to 0 (so that nothing will be added to the difference). Since we are not interested in analyzing models where a variable influences itself directly (a "self-loop"), $\alpha = 1$. The parameter ε is the number of possible polarities, which must be 2 in our case. The last parameter, γ, is a little more complicated. In two models, a potential link may be absent because the subject believes there is no causal link between the two variables, or one (or both) of the variables is not part of the model. If this is taken to mean something different, then $\gamma = 2$, which is our case. When substituting the chosen values into the parameters, the equation transforms into

$$DR(A,B) = \frac{\sum_{i=1}^{p}\sum_{j=1}^{p} diff(i,j)}{2p_c^2 + 1(2p_c(p_{uA} + p_{uB}) + p_{uA}^2 + p_{uB}^2) - (2p_c + 2(p_{uA} + p_{uB}))}$$

Since the method takes into account variables and causal links with positive or negative polarity, it can in principle be used to compare system dynamics oriented mental models.

Appendix 2: the table of loop membership

Variables		Loops																									
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
1 sttp	social transfer pmts % of budget																										
2 iRise	rise in i											1															
3 C	consumption (nominal)															1	1										
4 cProp	propensity to consume																										
5 dTr	net change of FF target rate	1	1																								
6 K	capital																	1						1			
7 KDes	desired capital																					1		1			
8 PoB	purchase of bonds			1																							
9 GPch	government purchases												1	1	1												
10 Kc	capital cost																										
11 UPC	unit production cost																										
12 GDef	government deficit																										
13 Yd	aggregate demand												1	1	1	1	1					1				1	1
14 ADer	expected real demand																				1				1	1	
15 dpst	deposits			1			1	1	1	1																	
16 KDpr	capital depreciation																	1						1			
17 GDbt	government debt										1																
18 divN	dividends (nominal)												1			1	1										
19 deP	demand effect on price																				1						
20 irec	interest rate effect on consumption																										
21 ceP	cost effect on price																								1	1	
22 ieS	interest elasticity of savings																										
23 ieC	interest elasticity of consumption																										
24 nce	net capital entry (US)																										
25 opSrp	operating surplus												1	1	1	1	1										
26 exRsrv	excess reserves				1	1	1	1	1																		
27 ExpNNRW	net nominal Ex (RW)																										
28 ExpNN	Exports (we) net nominal																										1
29 pFac	production factors																						1		1	1	
30 wFrc	workforce																		1								
31 G	government spending																										
32 Inv	investment																					1		1			
33 Imp	Im real (US)																										
34 Tax	taxes												1	1	1												
35 TaxB	taxes business													1	1												
36 TaxHh	taxes households												1				1										
37 tri	FF target rate indicator		1																								
38 PRW	Price level (RW)																										
39 eti	extra-time index																						1		1	1	
40 rRW	revenues (RW)																										
41 rExp	nominal revenue from Ex (US)																										
42 L	demand for reserves (liquidity demand)							1	1																		
43 M	resverves (money offer)			1	1	1	1																				
44 N	employment																			1							
45 tr	FF target rate	1	1																								
46 P	price level																				1				1	1	
47 lp	loan payments										1																
48 pImp	payments for Im (US)																										1
49 spc	salaries % of capital																										
50 ros	revenue % of salaries																										
51 wap	working age pupulation																										
52 dp	dividends pct																										
53 tpHh	personal tax pct																										
54 tpB	business tax pct																										
55 Gb	government borrowing																										
56 GBdt	government budget												1	1	1												
57 mfp	multifactor productivity																										
58 Yd	production																						1		1	1	
59 mpc	mean propensity to consume																										
60 cpRat	cost productivity ratio																										
61 cpRel	cost productivity relation																										
62 diB	disposable income business												1	1		1	1										
63 lter	long term expected results																					1					
64 wd	withdrawels					1		1		1																	
65 idi	income / disposable income															1	1										
66 uer	unemployment rate																		1	1							
67 i	Interest rate				1	1	1	1	1																		
68 nlr	net lending rate				1		1		1																		
69 rr	reserves rate																										
70 ndr	net deposit rate			1		1	1																				
71 mbr	mean bond rate											1															
72 ct	compliance time																										
73 exR	exchange rate																										
74 Nd	desired labor																			1							
75 eN	effective labor																						1		1	1	
76 tp	transfer payments nominal																										
77 ucImp	unit cost of imports																										
78 sr	(nominal) sales revenue												1	1	1	1	1										1
79 S	savings (W)																										
80 w	nominal salary																			1							
81 ImpVW	WT of Imp volume (USA)																								1	1	

Appendix 3: constructing MacroLab's reachability matrix

The author is not in possession of the Matlab used by Oliva(2004), nor did he have previous exposition to the use of graph theory and its software tools. Accordingly, the steps have been carried out by simpler means, which can be replicated by any person, using MS Excel and GNU Octave, a software tool available at http://www.gnu.org/software/octave/download.html.

The first step is to create the adjacency matrix A in an Excel spreadsheet (see additional material of the paper). Then a text-only file is generated for import into Octave. The format is as follows:

```
# Created by Octave 3.0.3, <date> <unknown@unknown>
# name: {name of the variable that stocks the matrix; in the example, I use "M"}
# type: matrix
# rows: 81
# columns: 81
 57 57 57 57 0 0 57 0 57 57 57 0 57 0 57 57 57 57 57
57 57 57 57 0 57 57 57 57 0 0 0 57 57 57 57 57 57 57
57 57 0 57 57 57 0 0 57 57 57 57 57 57 57 57 57 57 57
0 57 0 0 57 58 0 57 0 57 57 57 57 0 0 0 0 0 57 57 57
0 57 57
```

Note that the cells of the matrix appear without row or column header. The values are separated by a BLANK character. An easy way to convert the Excel cells into this format is:

1. copy the cells
2. special-paste "without format" into a MS Word document to make cells appear with values separated by a TAB character.
3. search-replace all TABs by a BLANK
4. hand insert a BLANK before the first value
5. save as text only with a ".mat" extension into the Octave folder on your computer. For instance "myMatrix.mat"

Then you create a new variable in octave:

```
load myMatrix.mat M
MM = M * M
save myMatrix.mat MM
```

Now you have to import the contents of the ".mat" file back into a new sheet in Excel. Then generate a sheet with the same format and – for each cell – convert the values to binary values (because this must be a binary multiplication) by EXCEL's built-in min(1;{value}) function. The last step is to compare the current matrix with the previous one. Copy the structure to the right side of the matrix and a formula like "IF({current value}={previous value};0;1)": this leaves a 1 for each cell that has a different value from its previous version. Now sum up all the cells: once the result is "0", the previous version of the matrix corresponds to the reachability matrix. If the result is greater than 0, start over the whole cycle. The files "matrices_all.xls" and "matrices_A_R.xls" in the additional material of the paper contain the data.

The last sheet of "matrices_A_R.xls" has auto-filters set for the variables. If one defines the filter of variable *v* to "1", this hides all rows representing variables from which one cannot reach *v*. It follows that by adequate definition of the filters, one can precisely find the set of variables that would be convenient for a desired scenario.