Model simplification and validation with indirect structure validity tests

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Abstract

Model simplification distils essential model structures that cause selected problems and increases the quality and understanding of models. It can also be a step towards building theory-like structures and general representations of case-specific problems in various application domains. In this paper, simplification of a large system dynamics model and validation of the simplified version are illustrated. The original model represents agricultural and environmental problems of irrigation development in southeast Turkey and consists of 14 model sectors and 110 stock variables. Its simplified version with a narrow model boundary and higher level of aggregation is a general representation of its selected dynamics and consists of four model sectors and 17 stock variables only. Analysis of reference behaviours, indirect structural validity tests (structure-oriented behaviour tests) and scenario runs reveal the simplified model as a valid and useful simplification of the original one. Copyright © 2006 John Wiley & Sons, Ltd.

Introduction

Model simplification is a semi-formal approach to distil essential structures of a large-scale model so as to produce its fundamental dynamics and is a powerful method to increase model understanding. Eberlein (1989) presents a formal theory of model simplification as a means of increasing model understanding, which identifies important feedback loops in linearized models with respect to a selected dynamic behaviour. Weak feedbacks that generate this behaviour and the stock variables embedded in these loops are eliminated. The original model is collapsed to a substructure that can create the intended dynamic behaviour. Since this method is restricted to linearized models, its applicability in system dynamics is limited. Also, simplification typically involves aggregation of parameters, formulations and stock-flow processes, which requires informal reasoning beyond formal methods. If the objective of simplification is broadened as a move from case-specific to generally applicable model structures, questions regarding the model boundary, level of aggregation, validity, relevance of the simplified structure to the general theory and empirical studies become significant.

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Beyond increasing the quality and understanding of the existing models, the commitment of the system dynamics field to the idea of creating integrative theories of seemingly separate, case-specific management problems motivates simplification practice. Through simplification, a case-specific, large and parameterized model of a dynamic problem can be reduced to a generic representation of the same problem, suitable for transferring knowledge in the same domain and useful for disseminating the essential structures responsible for the problematic behaviour and mismanagement. For instance, Jay Forrester’s customer–producer–employment model in industrial dynamics (Forrester, 1961), and the model of market growth (Forrester, 1968) are cited by Lane and Smart (1996) as general models which are distilled from real-world case studies and data. Forrester (2003) further emphasizes that many applications in education and in policy design might be better handled with a collection of far simpler models. Examining most of the published work, however, it is not evident that simplification is common in system dynamics practice.

Barlas (1998) suggests that there must be an additional final step in system dynamics modelling, namely model simplification, which completes the modelling cycle with a much simpler, fundamental version of the working model. In order to avoid the common “the model is unrealistically simple” type of criticism, modellers are tempted to build large and too detailed models, which often makes the situation even worse since the final product is large and too complicated but still unrealistic. A systematic use of mental models and dynamic insights through an extensive process of model simplification can help the way out of this dilemma (Barlas, 1998). In this suggested final simplification stage, the analyst makes use of a dynamic understanding of the problem that she/he did not have in earlier phases of the study.

In this paper we illustrate the simplification process of a large model built for the long-term environmental analysis of an irrigation project in southeast Turkey (Saysel, 1999) and the validation of the simplified version. Our purpose is to increase the quality and understanding of the model by eliminating its unimportant substructures and ineffective links/feedbacks in creating its behaviour of interest. Another objective is to move from this case-specific representation of the problems of irrigation development to a general representation applicable to similar problems in semi-arid mid-latitude agricultural systems. Both the original modelling and the simplification are done by the authors themselves, so the original problem framework and the dynamic insights learned from the original model analysis are utilized during the simplification process. Therefore, this simplification exercise can be seen as an extension phase of a study cycle as suggested by Barlas (1998). Based on selected dynamics of the original model, we created a simplified model with a narrower boundary and an aggregated view of parameters and stock flow processes (Saysel, 2004). The procedure is based on extensive experimentation with the simplified and the original models. Model components and parameters are eliminated, formulations and stock-flow structures are aggregated and, throughout
the process, each simplified version is iteratively tested against the original model. The tests at each iteration compare the behaviour patterns generated by the current simplified and the original models first in their reference modes, then through indirect structure tests (structure-oriented behaviour tests) and finally in their policy runs.

In the following sections, the original and simplified model structures are introduced. After that, the simple model structure is described. The reference behaviours, validation tests and policy runs of the original and simplified model are compared. An example of an invalid simplification attempt is illustrated. Afterwards, the simplification process is explained with the aid of a flow diagram. In the final section, the use of simplification as a step in the system dynamics method and the advantages and disadvantages of large and simplified models are discussed.

**Overviews of the original versus simplified model structures**

The original model GAPSIM is built for the comprehensive environmental analysis of a large-scale surface irrigation scheme and a regional development project in Turkey (Saysel, 1999). GAPSIM consists of 14 model sectors, namely farmlands (rain-fed farmlands, irrigated farmlands and vineyards–gardens), the development of land and water resources (land–water development), other land resources (rangelands and forests), environmental indicators (irrigation–salinization, soil nutrients, pests, erosion) and population, urbanization, market and government. The model contains 110 stock and 220 flow variables in total. Figure 1 is an overview of the original model with material and information flows (represented by arrows) between its components. Boxes stand for the model sectors, while the bold arrows represent the direction of land flows.

The simplified model GAPSIMPLE (Saysel, 2004) is a reduced version of the original one based on an aggregated reference behaviour selected from the original one and on a specific policy analysis focus. GAPSIMPLE consists of four model sectors with 17 stock and 31 flow variables in total; i.e., it is smaller than one fifth of the original model in the number of stock variables. The model sectors aggregated and retained in GAPSIMPLE are farmlands, land–water development, irrigation–salinization and pests (Figure 2). During the simplification two larger versions of GAPSIMPLE were created. The first one comprised soil nutrients, population and a minimal version of urbanization sectors and consisted of seven model sectors with 25 stock and 54 flow variables. If the selection of reference behaviours and relevant model analysis were to be extended to include leaching fertilizers, population variables, rural food availability and urban employment rates, this larger version of GAPSIMPLE would be justified. However, since the model components population and urbanization do not fundamentally affect the dynamics of other main variables in GAPSIMPLE, we safely left them out of the analysis. A second simplified
version consisted of five model sectors with 21 stock and 45 flow variables and comprised soil nutrients but eliminated population and the minimal version of urbanization. Here again, following observations that the soil nutrients model does not create any systemic effects on the selected reference mode, this component was eliminated.
The simplified model (GAPSIMPLE)

One objective of simplification is to increase the understanding of models. To illustrate how the simplified model helps in understanding the integrity of the water development, land use and environmental processes, we provide a feedback view of GAPSIMPLE in Figure 3. In principle, a similar feedback structure can be extracted from the original model. However, considering the detailed and parameterized structure of GAPSIM, it is much more difficult to distil and communicate this information. During simplification, any elimination of parameters, variables linked to these parameters, decision rules and stock-flow processes effectively eliminated numerous feedback loops which do not contribute to the selected model behaviour. The causal loop diagram in Figure 3 is the product of this elimination process and illustrates those feedbacks important in creating model behaviour as demonstrated in Saysel (2004).

Fig. 3. GAPSIMPLE causal loop diagram: irrigation release, irrigation application, land transformations, salinization and pests. D_i, decision structure i
Figure 3 represents the irrigation authorities’ water release decision (Decision 1: irrigation authorities’ decision in response to irrigation water demand); farmers’ irrigation application decision (Decision 2: farmer’s response to water availability in deciding on how much to irrigate); and farmers’ land transformation decision (Decision 3: farmers’ response to average water availability in deciding on how much land to transform for irrigation) embedded in feedback. Land transformation from rain-fed to irrigated farmlands, shift between two alternative irrigated land use types, salinization and pest accumulation and irrigation schemes construction are depicted by flow variables. A detailed description of this diagram is available in Saysel (2004).

Reference behaviours

Selected reference behaviours guide the simplification process. To demonstrate GAPSIMPLE as a valid simplified version of GAPSIM with respect to the selected behaviour of interest, first, these reference behaviours are compared (Figure 4). The objective of a system dynamics model is behaviour pattern prediction rather than point forecasting. Here, this comparison is based on a visual assessment of behaviour patterns such as s-shaped growth, boom-then-bust etc., without using numerical tools or criteria. For such transient patterns, given the state of the art, there are no quantitative methods that can prove superior to visual comparisons. On the other hand, based on very recent pattern recognition tests and software (Barlas and Bog, 2005) we expect to utilize some formal comparisons of behaviour patterns in the simplification process in future research.

Reference runs are based on exogenous assumptions of hydropower and irrigation structure construction rates, and the development scenario presented here is identical to the one analysed with GAPSIM in Saysel et al. (2002). According to this scenario, the energy production target (after irrigation release) is 22,000 GWh/year and the irrigation target is 1,780,000 ha.

We claim that the reference behaviours generated by the two models are similar. As the construction of physical structures starts, energy production (GWh/year) and irrigated farmlands (million hectares) increase but both of them fall short of target since the water consumption on farmlands is above the irrigation project estimations (first row of graphs, Figure 4). As irrigated lands increase, the ratio of irrigation release to total basin yield (fraction) also increases. After the initial increase and decrease, the average crop yield loss due to water scarcity (fraction of potential yield) stays stable and never reaches alarming levels.

The major reason for the underperformance of energy and irrigation target is the bias towards water consumptive monocultures in the emerging arable land use pattern. As water becomes available, farmers switch from a rain-fed to an irrigated farm system (Figure 4, second row of plots). While rain-fed farmlands (million hectares) decrease, the two irrigated fields, monoculture farmlands...
Fig. 4. GAPSIM (left column) and GAPSIMPLE (right column) reference runs. All variables in the left and right columns are the same and the time axis is years.
(million hectares) and *mixed farmlands* (million hectares) increase; however, the ratio of water consumptive cotton monocultures to irrigated fields is rather high.

As fields are irrigated, evapo-transpiration and the ground water elevation result in salt accumulation (third row of graphs, Figure 4). As *root zone salinity* (mg/l) increases, this favours cotton monocultures since cotton is a salt-tolerant crop. The bias towards monoculture farm activity increases the need for pest control, *average pesticide application* (kg/ha/year) first sharply increases, but then it levels off as monoculture durations decrease: farmers tend to prefer mixed farm systems as pest control on monocultures becomes increasingly costly.

Agricultural production shifts from *winter crops* (food grains in tons per year) to cash crops such as *cotton* and other *summer crops* (all in tons per year; fourth row of graphs, Figure 4).

**Validation with indirect structure tests**

Comparison of the reference behaviours of GAPSIM (110 stock variables) and GAPSIMPLE (17 stock variables) is a preliminary observation on the equivalence of the simplified structure to the original one with respect to the selected dynamics. However, this observation itself is far from being sufficient to claim the reduced model as a valid simplified version of the original one. After all, the observed behaviour match can be spurious; i.e., the simplified model can be creating similar dynamics for the wrong reasons. To build confidence in the simplified model structure as a valid approximation of GAPSIM, we apply several indirect structure tests. Indirect structure tests involve specialized simulation runs and can provide indirect information about possible flaws in model structures (Barlas, 1996). Among these, *extreme-condition*, *behaviour sensitivity*, *boundary adequacy* and *phase relationship* tests are particularly important (Barlas, 1996; Forrester and Senge, 1980). In this section, our approach is similar to that in Barlas (1989), where alternative model structures are compared through indirect structure tests (or structure-oriented behaviour tests) to the so-called “synthetic reality”. Here we illustrate the validity of GAPSIMPLE with respect to GAPSIM, our “synthetic reality” in this case.

Indirect structure tests can be performed for isolated model components as well as for the whole model structure. In this article, we prefer to illustrate two tests on whole model structures rather than the individual components since tests on whole model structures are more sophisticated and would provide stronger information about the analogy of the two structures. For each test, a selected set of behaviours (as opposed to all behaviour patterns) exhibiting significant modifications are demonstrated.

First, we apply an extreme condition test in which the price for cotton crop is set extremely high. Left- and right-hand columns in Figure 5 show these extreme-condition results for GAPSIM and GAPSIMPLE, respectively. Since
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Fig. 5. Extreme high cotton crop price. GAPSIM (left) GAPSIMPLE (right). Time axis is years.

Cotton crop is valuable, profitability of cotton production is much higher than its alternatives and the farm systems shift towards cotton monocultures, while mixed farmlands almost disappear. As the entire farm system shifts towards monoculture, pests prevail, pesticide application rates increase and, since cotton is extremely profitable, monocultures can bear the cost of increasing pesticide use. Note the fundamental similarities of behaviour patterns in the two columns in Figure 5.

Similar tests are applied for extreme low and high winter and summer crop prices with success. A second example is a parameter sensitivity test that illustrates the model behaviour response to changing pest resistance building time (Figure 6). As the parameter time to build pest resistance increases, the increase in pest abundance and therefore the increase in pesticide application are delayed. Delayed increase of pesticide application favours the monocultures since those are the farm systems that highly bear the increasing cost of pesticides. As a result, as pest abundance and pesticide application increase are delayed, the farm systems shift towards monocultures. Note the fundamental similarities of patterns in Figure 6.

The third test is the analysis of behaviour sensitivity to changing freshwater salt concentrations (Figure 7). As farmlands are irrigated by more saline freshwaters (200, 400 and 500 mg/l in this particular test), average root-zone salinity becomes higher. Increased salinity favours the monocultures since cotton is the most salt-tolerant crop. Indeed, this points to a weakness in
GAPSIMPLE, as the response in monoculture farmland is weaker in this case. Finally, as monocultures are favoured by increased root-zone salinity, average pest abundance and therefore average pesticide application rates increase.

The validity of GAPSIMPLE compared to GAPSIM can further be demonstrated by utilizing phase relationship tests. The idea of the phase relationship test is to compare the phase relationships between variable pairs in the model outputs with those observed in or expected from the real system (Forrester and Senge, 1980). In our case, since the original GAPSIM is a controlled “synthetic reality”, we compare the phase relationships observed in the behaviour of the simplified model with that of the GAPSIM, similar to Barlas (1989). For instance, referring back to Figure 4, one can observe that in GAPSIM behaviour the increase in monoculture farmlands and mixed farmlands are in phase and are accompanied by a decrease in rain-fed farmlands. The same observation is true for GAPSIMPLE although it has a much more aggregate representation of farmlands. Similarly, in GAPSIM, the increases in cotton and summer crops production are in phase and are accompanied by a decrease in winter crops production. The same observation holds for GAPSIMPLE, although it has a highly aggregated representation of agricultural products distributed over various farmlands. Furthermore, essential phase relationships are preserved under extreme condition tests. For example, in Figure 6, where monoculture farmlands sharply decline because summer crops have an extremely attractive price, this decline is followed by an increase in mixed farmlands and a decrease in...
rain-fed farmlands. The same observation is true both for GAPSIM and for GAPSIMPLE.

The whole process of model simplification can also be seen as a succession of boundary adequacy tests. The boundary adequacy test considers structural relationships necessary to satisfy a model’s purpose; it asks whether or not model aggregation is appropriate and if a model includes all relevant structures (Forrester and Senge, 1980). What the model boundary of GAPSIMPLE lacks could be relevant aspects in GAPSIM, such as other land resources (farmlands, forests, vineyards and gardens), other land degradation factors (erosion) and a dynamic price adjustment mechanism (market). A model critique can also argue against the aggregation of farmlands, farm products (cereals, pulses, summer cereals, oil crops, vegetables, fruits and livestock) and farm inputs (seeds and farm energy inputs) in the simplified model. For a study targeting the analysis of other land resources, production of individual

Fig. 7. Behaviour sensitivity to increasing freshwater salinity. GAPSIM (left) and GAPSIMPLE (right). Time axis is years.
crops or consumption of individual farm inputs, these criticisms can be relevant. However, for the selected reference dynamics, the comparison of the reference runs (Figure 4) and indirect structure validity tests (such as in Figures 5 and 6) build confidence in the boundary adequacy of the simplified model with respect to the original GAPSIM.

### Policy/scenario runs

How useful is GAPSIMPLE as a simplified version of GAPSIM in policy design and actual implementation? Formal structure validation tests partly answer this question. In order to further discuss the usefulness, we compare the results of policy/scenario analysis from the two models. The runs illustrate-and-compare GAPSIM and GAPSIMPLE behaviours, and they are used throughout the simplification process, generalized below.

According to the selected policy, in order to prevent the farm system shifting strongly to monocultures (consuming large amounts of water, interfering with hydropower production and consuming large quantities of agro chemicals, deteriorating the environment), the water release policy is tightened; farmer decisions on switching from rain-fed to irrigated farming is assumed to be less sensitive to water availability on the individual irrigation outlets; and more favourable conditions for mixed farming systems are advocated. This policy/scenario is described in detail in Saysel (1999) and in Saysel et al. (2002).

Figure 8 compares the overall behaviour of GAPSIM and GAPSIMPLE under this policy/scenario. As water release is tightened, water available for hydropower generation increases. Energy production stabilizes at levels closer to the target level. Farmers not discouraged with decreasing water availability switch quickly to irrigation, irrigated lands increase, but water availability on individual farmlands decreases. This results in increasing yield loss but this does not reach alarming levels. Since conditions favouring mixed farming systems is assumed, monoculture farmlands do not dominate the whole farm system. This successfully reduces the pesticide application rates favouring the environmental conditions. But salinization control is not successful under this scenario. Agricultural production follows parallel dynamics with land use. Again, note the behaviour pattern match between the left and right columns in Figure 8. Also note that the behaviour patterns of summer crops (fourth row of graphs) do not match in the last phase of simulation. This indicates a weakness in the aggregation process of several farm products in GAPSIMPLE.

### How the simplification process stops

If an elimination of a model structure results in a loss of any of the reference behaviours, validation or policy/scenario runs, the simplification attempt is
reversed. If many simplification trials result in such failures, this strongly indicates that either a stage or the whole simplification process is over (see next section). Here we illustrate a failure of GAPSIMPLE, where we further attempt to simplify the structure by eliminating *pest resistance building time* (i.e., pests would not develop resistance). As Figure 9 illustrates,
mixed farmlands stay at negligibly low levels and average pesticide application also levels off. These patterns do not match the GAPSIM reference behaviours.

**The simplification process generalized**

In the above sections we provided overviews of GAPSIM and GAPSIMPLE: the simplified version. Then we compared their reference behaviours and demonstrated indirect structure tests and the policy/scenario experiments. Based on the behaviour pattern matches observed in each case, we concluded that GAPSIMPLE is a valid simplification of the original GAPSIM. In this section, the above simplification process is described in general with the aid of a flow diagram (Figure 10). Simplification starts with identifying a reference behaviour describing a dynamic problem to be represented and analysed with the simplified model (Stage 1a). This selection is not arbitrary but depends on the dynamic insights learned through original model building and analysis. The reference behaviours are illustrated in Figure 4.

For the simplified model to be useful by any measure, it has to have a clear policy focus. Here again, policy insights generated on the original model analysis help in building a set of policy experiments to be tested on both model structures (Stage 1b). The policy experiments are illustrated in Figure 8.
Fig. 10. Simplification procedure flow diagram
Third, since the elimination of all the model elements is an iterative procedure, where the validity of the current simplification is tested against the original, another task is to design appropriate indirect structure tests to be used in each simplification step (Stage 1c). These are demonstrated in Figures 5–7.

Since many variables have aggregated representations in GAPSIM, the reference behaviour of GAPSIM comparable with its simplified version is obtained by simply summing the original variables. For example, rain-fed farmlands for GAPSIM on the land use graph (second row in Figure 4) adds the two stock variables: winter cereal farmlands and winter cereal–winter pulse rotations. Although it is convenient to illustrate Stage 1 as an isolated first step, in practice it is prolonged over the whole simplification procedure. Achievements in succeeding stages create new options for further distilling the reference behaviours, policy analysis and validation tests. We try to make this idea explicit in the flow diagram by showing that we further aggregate the reference modes, policy runs and indirect structure tests at Stage 5, just after deciding on a new aggregation of stock-flow processes.

At Stage 2, the model sectors in weak feedback relations with the selected reference behaviours are eliminated. The original model sectors forests, rangelands, erosion, soil nutrients, government, market, urbanization and population are successively removed. Elimination of these sectors considerably reduced the original model size; i.e., the total number of stock variables decreased from 110 to 54. However, such eliminations are not trivial since these sectors are integrated to the others by mathematical formulations. Each elimination calls for reformulations of equations and aggregations of several variables in the retained sectors. For example, when the rangelands sector is eliminated, the stock variables representing the livestock assets are removed. But in the original model livestock is the basis of fodder demand and a source of income on farmlands. Based on fodder demand, a portion of farmlands is allocated for fodder production, which takes land away from other production activities. Therefore, the elimination of rangelands calls for a relatively aggregated representation of farmland allocation, farm production, farm input and farm profit variables. Once the livestock is eliminated from the model, fodder is eliminated from production in farmlands. Then, no farmland is allocated and no input is used for fodder production. Cost of fodder production and revenue from livestock products disappeared from farm profit calculations.

Referring to the simplification flow diagram (Figure 10), every elimination of a model component is followed by tests comparing the reference behaviours, indirect structure tests and policy runs. After a fail, the elimination is reversed and another candidate model component is selected and eliminated. After a pass, the selected complex structure is eliminated and another model component is selected. When successive eliminations fail in these tests and all candidate simplifications are tested, Stage 2 is finished.

At Stage 3 parameters and their causes (related calculations and variables) are aggregated. For example, GAPSIM had a highly parameterized representation
of farm products, farm inputs and farm economic calculations. Individual farm products, farm input parameters and their corresponding prices were all statistically estimated for the base year 1990. The farm products were categorized under nine groups: winter cereals, winter pulses, cotton, summer cereals, oil crops, vegetables, fruits, milk and livestock. In GAPSIMPLE, these products are combined under winter crops (aggregating winter cereals and winter pulses), cotton and summer crops (aggregating summer cereals, oil crops and vegetables). Fruits, milk and livestock are ignored. Farm inputs are also aggregated. Similar to Stage 2, Stage 3 is iterated until successive eliminations result in fail and all candidate parameter aggregations are tested.

At Stage 4, decision rules are simplified. For example, in GAPSIM, the land flows are biased towards the larger farm stock, representing the assumption that farmers favour prevailing farm systems in a rural environment. This structure does not exist in GAPSIMPLE. Stage 4 is iterated until successive eliminations result in a fail and all candidate decision or flow equations are tested.

The final stage (Stage 5 in Figure 10) is the aggregation of stock-flow structures. By always referring to the dynamic insights learned from the original study, the simplification exercise guides what should be kept in and what should be left out in the simplified model. This process gradually channels the analysis towards an aggregation level, a general representation feasible with a minimal structure. From this new perspective, the original stock-flow representations may appear to be too detailed. This leads to aggregation of existing stock-flow processes together with the respective reference behaviours, policy experiments and validation runs. The aggregation of GAPSIM farmlands stock-flow structures exemplifies this process. For example, in the original (GAPSIM), the farmlands were categorized under six stock variables in two model sectors, two representing rain-fed farmlands and four representing irrigated farmlands. Rain-fed farmlands were disaggregated as farmlands for winter cereals and for winter cereal–winter pulse rotation. Irrigated farmlands were disaggregated into four types: cotton monoculture, cotton–other summer crop systems, winter cereals–other summer crop systems and more complex cotton–winter cereals–other summer crops sequences. In GAPSIMPLE, all farmlands are represented with three stock variables: rain-fed farmlands, monoculture farmlands (irrigated cotton monocultures) and mixed farmlands (irrigated other mixed farm system). A reduction from a seven- to a three-stock representation of farmlands reduces the complications in formulations and presentations of land flows between different farmland stocks. For instance, while it is possible to represent land flows between three farmlands with six unidirectional flow processes, if the farmlands are represented in four stocks the number of unidirectional flows increases to 12. If the modeller wants to represent all possible land flows between \( n \) land stocks, the number of unidirectional flows connecting these stocks would be equal to \( n \times (n - 1) \).

When successive iterations of Stage 5 result in a fail, the simplification process stops, meaning further simplification would create flaws in the target
simplified structure. An example of a failed simplification attempt was discussed and illustrated in the previous section.

How many successive failed attempts are required to skip a stage in simplification? There are no formal criteria. When dealing with complicated model structures, it is possible that the analyst may ignore possible avenues of further simplification, but in further stages of the simplification procedure she/he may realize that further simplification options exist. Indeed, this implies that there may be further iterations as needed even after the final stage of the process. The analyst may make new attempts to aggregate parameters and related calculations, simplify decision and flow equations and aggregate stock-flow structures.

Another relevant question is whether the stages of simplification through 2 to 5 should be carried out one by one for each model sector, or whether each stage should be exercised on the whole model structure. If the analyst prefers a sector-by-sector approach, it implies that after the simplification stops the process in Figure 10 must restart from Stage 3 for each model sector. In our own approach to GAPSIM, we preferred a sector-by-sector approach.

It should be evident from this discussion that simplification as the final methodological step is a laborious, time-consuming and demanding task. An estimate of effort spent in model building relative to the effort put into model simplification can give an idea about the magnitude of the task. In our experience, building of the original GAPSIM model took 2 years of research time of a single PhD candidate. (This period excludes the very first problem identification stage of the modelling process.) In our estimate, this 2-year research period would be roughly equivalent to 12 man-months of full-time equivalent task. When a similar full-time equivalent measure is applied to the simplification process, our estimate is about 3 man-months, which is about one quarter of the original formal modelling effort. Considering the iterative nature of simplification, it is very difficult to give a firm estimate of the number of simulation runs and tests performed to complete the whole process. However, noting that each iteration requires at least three test runs (base, validation and scenario/policy runs, each done on multiple behaviour patterns) and assuming that each of the four model sectors existing in GAPSIMPLE required 50 iterations for full simplification, a first rough estimate yields 600 test runs in total. Indeed, this figure underestimates the actual task involved, because there was also considerable work prior to running the simulation tests (step 1 in Figure 10). Moreover, this estimate assumes a smooth and linear simplification process rather than iterations between the steps.

The number of simulation tests and the simplification man-month estimates above are offered to give an idea about the effort involved. One should keep in mind that these figures reflect our specific experience only and that in different cases the figures would change significantly. Moreover, our expectation is that our simplification guideline and methodology, hopefully developed with further research, will channel the simplification efforts in more efficient and productive directions. Yet in any case, simplification is a demanding task and
in practising simplification one should carefully weigh the alternative benefits and uses of large-parameterized models versus their simplified versions. This issue is discussed in the final section.

Discussion

Simplification increases the quality, usefulness and understanding of models and has important implications for the system dynamics method in general, regarding the problem identification, boundary selection, model formulation and testing phases of the methodology.

The problem-oriented character of system dynamics modelling has been discussed by several authors (e.g., Forrester, 1961; Randers, 1980; Richardson and Pugh, 1981; Saeed, 1992; Ford, 1999; Sterman, 2000). A good system dynamics analysis starts with the articulation of the dynamic problem, which can be represented by the behaviours of selected variables over specific time horizons. These behaviour patterns constitute the reference mode for the analysis. The model boundary is determined by the hypothesized endogenous variables and input factors affecting the reference dynamic behaviour over a given time horizon. Formal model building and validation are perceived as a process of testing and demonstrating the power and validity of the dynamic hypothesis in explaining the causes of the problematic behaviour. This view of the system dynamics method helps the analysts focus on the problem and not fall into unnecessarily detailed, unstructured, aimless, and even hopeless modelling practices.

From this perspective, there are “good” and “bad” models: models with a clear view of stock-flow dynamics and feedback structures that relate to the problem of interest, i.e. a clear theory about the dynamic problem; and models with no clear perspective of stock-flow dynamics and unnecessarily detailed, messy structures that are far from being an explanatory instrument for the problem of interest. Adhering to the general principles of scientific method and experience are two important factors that contribute to the quality of models. But beyond these general principles, in system dynamics practice can there be a specific method to avoid/discard unnecessary structures not contributing to the selected problem dynamics? In this paper we suggest that model simplification can provide an answer.

In large simulation models it may be impossible to detect and avoid structures not contributing to the creation of intended reference modes and policy analysis objectives. Faced with the vast amount of information provided by the theory and empirical data, it is difficult for the analyst to distil the essential knowledge that should form the fundamentals of a good, parsimonious system dynamics model. For nonlinear systems, it may be important to have a model in which several major modes of behaviour exist simultaneously to see how the different modes may interact (Forrester, 2003). Therefore, analysts may
choose to incorporate in their models structures that may not significantly contribute to the selected behaviour on their own, but may produce effects later when coupled with the potential additions to the model structure. It thus seems natural for modellers to start with large models that encompass all sorts of candidate structures that may prove later to be of minor importance with respect to the specific dynamic problem of concern. Discovery of such knowledge requires significant formal analysis of testing of the initial large model. The simplification phase proposed in this article as a late step after model building and validation can increase the quality of models by selecting out the structures most relevant to the problem purpose and thereby contribute to its understanding.

Another use of simplification could be to help obtain general models (theories) from case-specific models. In most case-specific research projects, a disaggregated, detailed and parameterized view of the dynamic processes may be favoured against an aggregated and simplified view, dictated by the needs of the particular study and availability of disaggregate data for validation purposes. Also, clients and stakeholders typically feel more confident when the model structure involves detailed variables and parameters that are familiar from their experience, as well as many typical field studies. On the other hand, supported by and validated against several case-specific models, simplified general structures distilled from these models can serve as generally applicable models transferring knowledge and insights within an application domain or even between domains. These models can contribute to the understanding of the original models while original models form foundations to construct and validate these simplified structures and eventually generalized theories. Case-specific models and their simplified generic versions can feed into each other in practice, in a cyclic process, leading gradually to general theories of important and recurring socio-economic or business problems.

Notes

1. The abbreviation “GAP” is the Turkish initials for “Southeast Anatolian Project”.
2. However, the environmental components consist of repeated modules represented by array structures corresponding to each farmland, rangeland and/or forest land components. In the irrigation–salinization model, there are 4 repeated modules of 5 state variables; in the soil nutrients model, 2 repeated modules of 8 state variables; in the pests model, 2 repeated modules of 8 state variables; and in the erosion model, 2 repeated modules of 2 and 4 state variables each. When these repeating structures are reduced, the model’s stock-flow overview shows 62 stocks and 120 flows in total.
3. The array structures for the environmental components are retained in the simplified version as well, but array dimensions are decreased since farmlands
are aggregated in three categories rather than eight and since rangelands and forests are eliminated. Among these 17 stock variables, the irrigation–salinization and the pests models have 3 repeated modules of 6 state variables each. The model’s stock-flow overview shows 9 stocks and 15 flows.

4. Indeed, starting reference behaviour is one of many options one may choose as the purpose of a simplified model. In fact, starting with different reference behaviours and following different simplification paths, one may arguably create quite different simplified versions of an original model. This can lead to further research on the problem-dependent character of modelling and model validation by pursuing alternative simplification paths on “synthetic reality”, i.e. on model structures assumed to be a perfect representation of a system.

5. Sterman (2000, p. 217) discusses guidelines for aggregating stock-flow processes. Time delays in serial processes and the similarity in decision rules in parallel processes are the two elementary criteria for aggregation. Hence, in this research, although not quite a parallel co-flow process, the similarity of the decision rules guiding the rate of change between farmlands (the stock variables) justifies their aggregation into fewer stock variables.

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References


