SENSITIVITY ANALYSIS IN SYSTEM DYNAMICS

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ABSTRACT

This paper describes some of the central, non-procedural aspects of sensitivity analysis in system dynamics.

First section focuses on the objectives of sensitivity analysis in this particular field of modeling.

The second section concentrates on the types of model change involved, with emphasis on changes in model structure and parameters.

The third section discusses the interpretation of model response to changes. The central questions are how the sensitivity is judged and by whom.

The final section discusses the parts in the modeling process entailing sensitivity testing.

Overall the paper asserts a more comprehensive role for sensitivity analysis than seems to be commonly accepted among model builders and model users. The subjectivity and individuality of sensitivity analysis is also emphasized.

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INTRODUCTION

Sensitivity analysis constitutes an element of most formal modeling processes. However, as each field of modeling has its distinct and characteristic features, so has the sensitivity analysis that accompanies it. It is the purpose of this paper to describe some of the central issues related to sensitivity analysis in system dynamics.

To portray the complete role of sensitivity analysis in system dynamics I will define sensitivity analysis as "the study of model responses to model changes." It is, compared to other modeling fields, a rather broad definition. This definition should be kept in mind when reading the paper.

Sensitivity analysis is a primary concern in system dynamics model building and review. One reason being the nature of the problems analyzed in this field of modeling; problems which necessitate the incorporation of relationships and parameters for which little empirical data are available. Quantifying the system elements is often quite difficult. Consequently, any model evaluation must include a consideration of the arbitrariness of representation. Another related reason is the complexity of the problems being modeled. The models of the problems are often equally hard to understand. Sensitivity analysis has proved to be a useful tool in generating insight in these models.

A complete description of the subject would roughly distinguish between:

1. Objectives in sensitivity analysis.
2. Types of model change in sensitivity analysis.
3. The interpretation of model response to changes.
4. How to most efficiently conduct the sensitivity analysis.

This paper focuses on issues relating to the first three aspects. The fourth aspect is discussed by J.A. Sharp (1976), W. Thissen (1976), and to some extent by A.K. Graham (1976).

THE OBJECTIVES

A sensitivity analysis should always be related to the purpose of the model under investigation. In this respect it is important to keep in mind not only the explicit goals of the model, but also the goals inherent in the types of modeling which the specific model represents.

The explicit purpose usually stated by a system dynamics model is to explain the causes of an undesirable behaviour mode, and to identify policy variables aimed at eliminating the undesirable behaviour. Implicit in system dynamics as a discipline, however, are also the objectives of finding the simplest recognizable[1] structure capable of explaining the initial dynamic hypothesis and to identify those areas of a problem where further research is necessary and critical. The following description of the objectives in sensitivity analysis is based upon a recognition of both the explicit and implicit goals of system dynamics models.

To test the effect of uncertainties in parameter values

Uncertainties in a system dynamics model's parameter values may affect its response and thereby the conclusions derived from the model. As system dynamics models tend to :

1. include parameters for which no observations exist;
2. analyze such a long time-span that the model parameters vary over a much larger interval than observed in the real world,

uncertainties in model parameters are characteristic features of the models. Typically, their values will be known within a range, but not precisely.

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[1] If a model is simplified to the extent that it is difficult to recognize the basic real-world mechanisms at work within the system, its function as a communication tool may be destroyed. Such a simplification is normally not the goal.

Testing these uncertainties within this range in order to evaluate the impact of variations on model conclusions, constitute an important part of sensitivity analysis in system dynamics.

The sensitivity testing itself may be a three-stage process. As system dynamics models normally will be insensitive[2] to variations in most model parameters provided that the variations are kept within a realistic range, the sensitivity testing should first sort out the parameters that the model is sensitive to.Secondly, the sensitive parameters should be varied within their estimated[3] range of variation in order to see if they change the overall model behaviour. If some of them do change the behaviour, more effort should be put in estimating them. Another alternative may be to reformulate the model to reduce the model's sensitivity. In the latter case, sensitivity analysis should be applied for the third time in order to evaluate the success of the reformulation. A.K. Graham (1976) has described the reformulation problem in more detail.

To generate insight

When talking about a system dynamics model as an insight-generating model, we are actually talking about two types of insight. First, a mathematical one which relates structure to behaviour. Secondly, we are talking about insight in the real word. Sensitivity analysis has proved to be an important and efficient tool to gain both types of insight. In the following, the role and objectives of the sensitivity analysis in gaining these two types of insight, will be described separately and in the order they are mentioned above.

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[2] This aspect will be discussed in more detail in a later section, "The parameter change".

[3] For a description of estimation of parameter values in system dynamics modeling, see A.K. Graham (1976).

Model insight

To attain insight into a model, that is to attain an understanding of the relation between model structure/model parameters on the one hand and model behaviour on the other, is a primary concern in system dynamics. This insight forms a basis for understanding the causal mechanisms underlying the problem being modeled and to identify policies to deal with the problem.

A system dynamics model is usually so complex that very few, if any, would have a clear understanding of it, unless the model were exposed to an extensive sensitivity testing. Some understanding is of course obtained from the testing of uncertainties in parameter values. In this case, however, the variations were restricted to values that the parameters could realistically assume. In a context of model understanding, the model should be tested over an unusually wide range of values. Only such a wide range can reveal the inherent dynamics of the model. Furthermore, the focus of the sensitivity analysis should be on alterations in model structure as well as in the parameter values. Changes in structure often imply to cut one (or more) feedback loop(s) in order to find which parts of the structure that contribute to the different behaviour modes of the model. There is, however, a possible fallacy in this procedure which may be worth while to mention. To cut a loop to see its effect on model behaviour could actually lead to the wrong conclusions. Because the possible difference in behaviour which may result does not necessarily contribute to that specific loop, but rather to the loop's interaction with some other loops.

The objective of model insight in system dynamics implies a number of more detailed objectives:

1. To find which behaviour modes the model can generate.
2. To identify the model changes which drive tha model from one behaviour model to another. This identification helps to sort out the parameters and structural relationships whose precise values are of critical importance for model behaviour, thereby establishing which aspects a more comprehensive study should focus on. Furthermore, the

modeler discovers where to allocate limited research resources. Finally, such identification helps to locate appropriate levers for an efficient and robust policy.

3. To identify the active and dormant parts of the model structure. This procedure establishes a basis for finding the simplest recognizable structure which can generate the initial dynamic hypothesis. To find such a simple model structure is often a goal in system dynamics modeling, because it will indicate the most fundamental processes at work within the system. Moreover, as a forum for discussing the problem under study, a simple model is preferable.

4. To evaluate whether the dynamic behaviour in models with exogenous inputs is generated by external or internal forces. If the behaviour is determined by exogenous forces alone, something is wrong with the model because system dynamics models are by nature substantially self-driven. Either the conceptualization of the problem or the selection of a system dynamics model to analyze the problem is faulty.

The ultimate objective of model understanding is to provide a basis for comparing the formal model with our perception of the real world.

Model confidence and real world insight

The underlying idea of employing formal models is that they may help us understand the real world. The better a model matches the real world system it is meant to portray, the more of the previously mentioned model understanding can be transferred to the real world system. How then, can we achieve sufficient confidence in the formal model to say that the model insight also has given us real world insight?

One way to deal with the confidence problem is to subject the model to a comprehensive sensitivity testing. This testing should be a confrontation between the real world on the one hand and the philosophy underlying the model as well as the conceptualization and the representation of the problem under study on the other.

In system dynamics modeling the testing will typically focus on changes in the following three aspects of a model:

1. System boundaries,

2. interaction variables, and
3. values of parameters.

The test conditions should deliberately be set so that the system operates under extreme situations. In these situations it is often easier to reveal whether the model's behaviour is plausible or not.

The result of the comprehensive sensitivity testing helps to answer the following questions related to model confidence:

1. Are the behaviour modes produced by the model realistic?
2. Does the model's sensitivity (or robustness) accord with human knowledge of the real world system?
3. Is the model (in)sensitive to the same perturbations as the real system?

If the answers are yes, the experimentation has helped to increase model confidence. Otherwise, the sensitivity analysis will indicate some model deficiency, either in the mental model, the formal model or both. The deficiency necessitates a review of the model -- an indication of the iterative nature of modeling.

Even if a comprehensive sensitivity testing of a model yields reasonable results, it is no certain proof of the model's correctness. At best, testing can only increase model confidence.

To direct further work on parameters and structure

It has previously been mentioned that the sensitivity analysis helps to sort out the parameters and structural relationships whose precice values are of critical importance for model behaviour. This section will discuss this aspect of sensitivity analysis in more detail.

A lack of precice data, difficulties in determining which parts of available information that is important to the problem or not, has often been a reason for not making a formal model of the problem. In system dynamics modeling the opposite will be true. To make a rough model at an early stage and subject it to a sensitivity analysis, will be a help in sorting out the data that are of importance and to distinguish between relevant and irrelevant information. In this case, sensitivity analysis will actually direct further work on the problem.

The sensitivity testing will indicate the rather few parameters that have the potential to alter the model's behaviour mode. Whereas effort should be put into estimating, controlling or reformulating these parameters, the current precicion of the other parameters is sufficient to let the model fulfill its purpose.

Moreover, sensitivity testing reveals the feedback loops that govern the model's behaviour and those which do not. Consequently, further work should be directed toward verification and understanding of this part of the structure.

Even if the sensitivity analysis itself tends to be time consuming, there is no doubt that such a use of sensitivity analysis saves a lot of effort.

TYPES OF MODEL CHANGE IN SENSITIVITY ANALYSIS

All changes, with the possible exception of perturbations in the exogenous variables (including noise functions), can be viewed as being either a structural change, a parameter change, or a combination of the two. Altering the system boundary implies a structural change. Changing the initial value of a level is a parameters change. Reformulating a parameter may imply a structural change as well as a parameter change.

In their impact on model behaviour perturbations in model parameters and structure are usually very different. The division line between them, however, is not always clear. One reason being that changing a parameter value may induce a structural change as well. Another reason being that parameters are in a way a reducement of structure. Underlying each parameter is a structure. Altering the value of a parameter reflects a change in the structure producing that parameter.

The parameter change

Parameters in system dynamics models consist of

- table functions and
- constants (including initial values and time delays).

Whether or not this category includes exogenous variables will not be discussed here. (See Forrester, 1961, pp 112 - 114 and 124 - 129.)

System dynamics models are usually rather insensitive to parameter changes, as are real complex systems. The source of parameter insensitivity can be found in model structure. One source is the dynamic properties of the negative feedback loop. Such goal-seeking loops tend to counteract any alterations imposed by perturbations in parameters, very often with success. A second reason is that model behaviour is primarily generated by only certain feedback loops. Changes outside these loops -- perturbations in the non-dominant or dormant loops -- will normally not affect model behaviour.

There are, however, exceptions. A given model structure is capable of exhibiting different behaviour modes. The shifts that can drive the model from one mode to another must be instigated in the model parameters (and/or the exogenous variables).

Considering the large number of parameters in most system dynamics models, an arbitrary search for the most sensitive parameters would be hopelessly time-consuming. The "key parameters," however, can be located in specific parts of the model structure.

Therefore, when saying that system dynamics models are insensitive to parameter changes, what actually is meant is that they are insensitive to most parameter changes. Behaviour is sensitive to a few points in any system. These sensitive spots have certain identifiable locations in the model structure. Such locations, or influence points tend to be situated in or near positive feedback loops, delay times, and intersections of several positive and negative feedback loops.

Parameter testing should focus on the location and perturbation of "key parameters." In addition, parameters which are controversial and thus disputable, should be tested, not necessarily with the intention of altering model behaviour. A disputable parameter's potential for altering behaviour may be small. The intention with the test, however, is more often to demonstrate the insignificance of the precise parameter value with respect to model conclusions. Such a result will tend to increase the model confidence.

The structural change

A structural change in a system dynamics model is an alteration of a causal relationship in the model. Structural changes will normally be visible in the revised model's causal loop diagram, whereas parameter changes can only be seen in the model equations or in the explicit graphing of table functions.

System dynamics models as a rule are more sensitive to structural than parameter perturbations, because the possible behaviour modes are actually embedded in the model structure. Different structures will normally be capable of exhibiting a different set of modes.

The models are usually more sensitive to structural changes that affect positive loops than negative loops. A positive loop normally encourages exponential growth (in some few cases, exponential decline). A negative loop will be goal-seeking, and consequently act to stabilize model behaviour. The addition or removal of a positive loop versus a negative loop, may therefore have quite a substantial impact on model conclusions. However, the impact will be dependent on the rest of the model structure. Adding a negative loop to an already stable system may have little effect, unless the addition embodies a structure with two interacting negative feedback loops. Such an alteration could lead to system oscillations. On the other hand, removal of a negative loop from a stable system may destabilize the system, provided that the loop was active in the structure. As with parameter variations, the impact of a structural change depends on its connection to the dominant part of the model structure. Removing a dormant structure has little effect. Actually, eliminating the inactive part of the structure to find the basic mechanisms underlying a problem is one of the objectives of structural sensitivity testing. The other important objective is to evaluate the impact of controversial or disputable relationships.

Parameter changes with structural implications

In some cases, the division line between parameter and structural perturbations is unclear. As will be illustrated below, changing a table function may induce an alteration in model structure.

Considering the simple model structure illustrated in Figure 1.

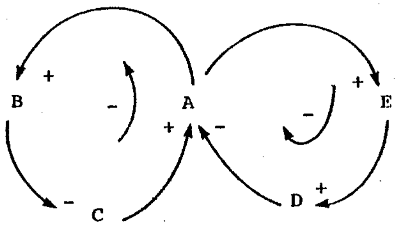

Figure 1. Model structure corresponding to the relationship between A and B in Figure 2.

Assume for a moment that A's influence on B is given by the table function in Figure 2. Now, if the relationship between A and B, for some good reason, were changed to the pattern in Figure 3, the alteration would obviously have the characteristics of a parameter change. However, the alterations would also imply a change in structure.

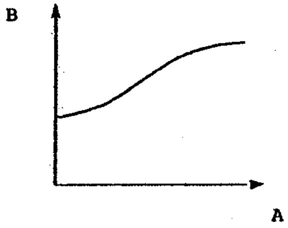

Figure 2. Assumed relationship between A and B.

Whereas a rise in "factor A" now induces a decrease in B, a rise in A tended to increase B in the previous situation. The model structure corresponding to the alteration is drawn in Figure 4. Figure 4. contains a positive and a negative loop interaction at A instead of two negative loops. Actually, the change is much more than a parameter change. It reflects a reconceptualization of both the two variables, A and B, and their interaction.

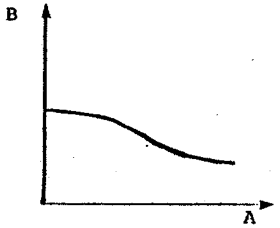

Figure 3. Alternative relationship between A and B.

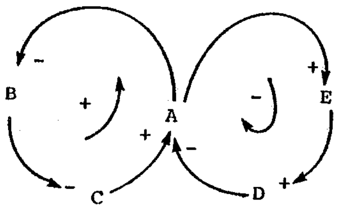

Figure 4. Model structure corresponding to the relationship between A and B in Figure 3.

If, for instance, the relationship between A and B were assumed to be that in Figure 5 a. the structure would look as indicated in Figure 5 b.

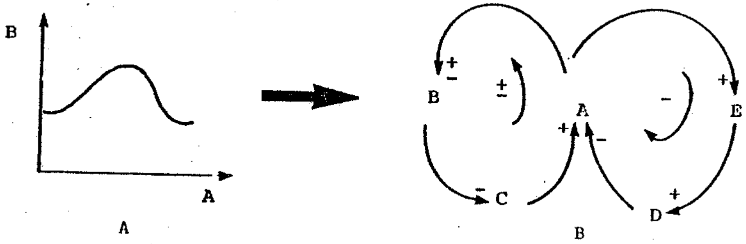

Figure 5. Another change in the relationship between A and B and its structural consequence.

Once more, the parameter change has structural implications. The loop to the left in the figure will be positive or negative, dependent on A's variation within its parameter space.

Finally, changing the relationship between A and B to the pattern in Figure 6 a eliminates one of teh two loops completely. Whatever the value of A might be, B is a constant. Dynamically then, the loop containing A, B, and C has no significance. The resulting structure is indicated in Figure 6 b.

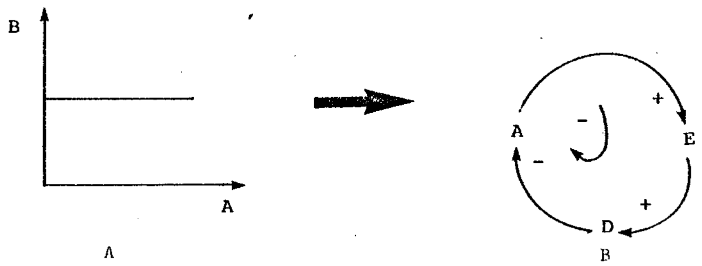

Figure 6. A flat table function and its structural consequence.

THE INTERPRETATION OF MODEL RESPONSE TO CHANGES

The interpretation of model response to changes in parameter and structure depends on the definition of sensitivity. There is no strict objective definition. It is also impossible to define once and for all sensitivity in general terms as it depends on the purpose of the sensitivity analysis. This implies that even one model can have different measures of sensitivity for different purposes of the modeler, his clients, and his critics. To define sensitivity, therefore, constitutes in itself an important part of the individual sensitivity analysis.

The subjective and individual character of a sensitivity analysis is not to say that the interpretation of its results is difficult. It is, however, important that:

1. the interpretation is based upon a definition of sensitivity which is consistent with the purpose of the sensitivity analysis as well as the purpose of the model;
2. the changes that induce the new model response are consistent with the same two purposes;
3. the model's client is involved in the judgement of sensitivity.

How these three aspects direct interpretation of model response to changes

in system dynamics are outlined in the three following subsections.

Sensitivity of qualitative Versus quantitative models

An overall purpose of most system dynamics models is to describe the qualitative behaviour of the systems under study. If a model qualitatively describes a phenomenon, the evaluation of sensitivity must focus on qualitative, not quantitative differences in model behaviour. On the other hand, in a point predictive model quantitative discrepancies are critical.

Consider a system dynamics model with the purpose of explaining the causes of an observed mode of behaviour (that is the qualitative aspects of a system). Let us further assume that the mode in question is an overshoot mode. Now, if a change in a model parameter alters the magnitude of that overshoot mode, the alteration will not be considered significant. The behaviour mode, from a qualitative point of view, is still the same. However, if a change that caused the model to shift from an overshoot mode to stable equilibrium would be regarded as significant, the model would be considered sensitive to the given parameter change.

From a point predictive point of view, the model is sensitive to both changes. In this context such an interpretation is wrong because it is inconsistent with the stated purpose of the model. A model should never be required to answer questions that it is not made for.

Reasonable versus unreasonable changes

In the context of sensitivity analysis any change, as long as it is consistent with the purpose that underlies the model and the sensitivity analysis, is reasonable. This implies that the meaning of a reasonable change is altered as the purpose of the model and the sensitivity analysis are altered. These purposes will always change, as models always will be used by other people, as they are open to everybody. Inconsistency between purpose and change in model structure or parameters may lead to a misinterpretation of the results derived from the sensitivity testing.

In evaluating the effect of uncertainties in model parameters, changes should be restricted to values within the intervals of estimated uncertainty. Alterations which go beyond these intervals will not reflect the model's sensitivity to uncertainties in parameters. If, however, such alterations are made in connection with the above evaluation, the interpretation of the model's response may be quite wrong.

In testing how well the model duplicates the real-world system it is meant to portray, reasonable alterations include any changes which can be conceptually verified, at least at a level of confidence to that of the model elements they replace or modify. Variations in parameters should be restricted to values that they could realistically assume. Structural changes should always have a real-world counterpart. The modeler or reviewer must always consider all the ramifications of a structural or parameter change. A real-world phenomenon may appear to be caused by a change in one variable, while it actually corresponds to variations in several model variables (and vice versa). The change in one variable alone may have no real-world counterpart.

System dynamics models often treat the long-term behaviour of a system through a historical period and on into the future. An alteration which destroys the historical behaviour does not necessarily indicate that the model is wrong. On the contrary, the change itself may be inconsistent with the rest of the model.

A model is typically tuned to recreate history. Deviation from the historical trend is inconsistent with the modeler's mental picture of the system. If, for example, a parameter appears to be inaccurate and its alteration

produces a non-historical result, then the accuracy of the alteration will be dependent on whether some other change in the model restores the historical behaviour. The two or more changes together may recreate history, while producing an alternate prediction. Non-historic behaviour is a simple indication that a parameter test value may be inconsistent with the rest of the model and must be justified by the proper adjustment of related parts of the model. If, however, such an adjustment proves impossible and if the test value is reasonable, then the model itself must be faulty.

In the context of model understanding, however, the concept of "a reasonable change" should be interpreted somewhat differently. Test alterations are no longer restricted to realistic values. Model understanding implies discovering the possible behaviour modes of the system, whether they are likely to happen in the real world or not, and, furthermore, finding the values at which the shift from one model to another occurs. Therefore, nearly any change would be considered reasonable.

The role of the client

When modeling a problem there is always the danger that the real problem is modified to suit the methodology used to analyze it. If this modification goes too far, the model will address quite another problem. And in the client's mind, a wrong one.

Disagreement between the modeler and the client in interpreting the results of a sensitivity analysis may indicate a wrong problem definition. The ultimate judgement of sensitivity should, therefore, rest in the hands of the client. The role of the client underlies the subjective nature of sensitivity evaluation.

SENSITIVITY ANALYSIS IN THE PROCESS OF SYSTEM DYNAMICS MODELING

Unlike other modeling fields in which the sensitivity analysis often is performed after the model building, it is in system dynamics modeling spread over the model building process. In general, every experiment carried out on a model contains an element of sensitivity analysis. The sensitivity analysis, in reality part of the model construction itself, will often constitute the basis for review and possible redesign of the model. The following two subsections outline the involvement of sensitivity analysis in the system dynamics modeling process.

Sensitivity analysis contained in the model experimentation

Several of the different stages in the analysis part of the system dynamics modeling process involve sensitivity testing in one form or another. The tuning of a system dynamics model is in reality a limited sensitivity test. This process, which usually concentrates on parameter values, may give the first indications on a model's sensitivity to perturbations in its parameters.

Policy analysis can also be viewed as a limited sensitivity test. A policy is nothing other than a change in model structure and/or a change in parameters -- a change that is feasible in the actual system, and to which model behaviour is sensitive. Moreover, an important part of policy analysis is testing the robustness of recommended policies vis-a-vis uncertainties in model parameters and structure. The strange situation arises, therefore, where policy analysis, which can be considered a component of sensitivity testing, should also be subjected to sensitivity investigations.

The validation of a model, another important aspect of system dynamics

modeling, also involves an element of sensitivity testing, and vice versa.

In summary, every experiment carried out on a model contains an element of sensitivity testing.

Sensitivity analysis as a means to generate new dynamic hypothesis

In principle model testing may generate a new dynamic hypothesis in two different situations. Both situations will be exemplified later in this subsection. The first situation arises when a model's response to some change is very fast, compared to the model time-horizon. The model cannot explain this rapid response, but instead the model implicitly assume that such a response is plausible. If the response is believed to actually be slower in the real system, thereby interfering with the present model conclusions, the hypothesis embodied in the quick response should be investigated further. Any new model will have a different purpose and a considerably shorter time-horizon. However, if the new model confirms the new dynamic hypothesis, it also increases confidence in the original model. The new model then, indicates that the implicit assumption of the original model was correct.

The second situation occurs when testing reveals a response generated by very slow processes within the system. Again, the processes are slow, compared to the model time-horizon. Such a response will usually be visible toward the end of the model time-horizon. In this case, the model suggests the presence of a new behaviour mode. The alternative behaviour mode will often address another question than the original model. Therefore, the occurrence of a significant change in the behaviour mode at the end of a model time-horizon may establish the foundation for a new dynamic hypothesis.

The two contrasting situations can be exemplified by results obtained from two system dynamics models. The first example, shown in Figure 7, illustrates the results of one of the tests carried out on the "Solid Waste Model" (Meadows, D.L., Meadows, D.H., eds. 1973, pp. 165 - 211). The behaviour mode of interest is that of the market price of raw materials. In the test, a 50 per cent increase in the price is imposed on the system in year 25 -- a surrogate for the implementation of a 50 per cent tax on extraction of raw materials. As shown by the figure, the system manages to compensate extremely quickly for the price hike. Approximately 5 years after implementation of the hike, the price returns to the same level as in the basic run. The quick response can be attributed to lower demand and a higher recycling rate, both caused by the price increase.

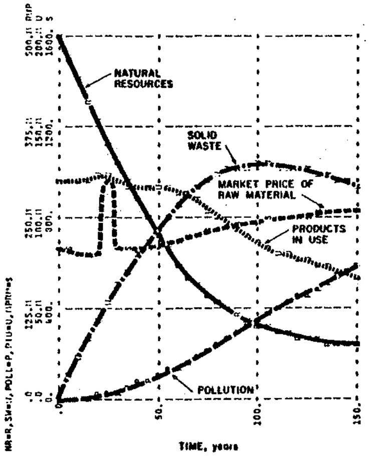

Figure 7. From Meadows, D.L., Meadows, D.H., eds. 1973, p. 195. The response in market price of raw material ($) to a 50 per cent tax on extraction, introduced in year 25. An example of a very fast response, compared to the model time-horizon.

Implicit in the model, then, is the assumption that the recycling rate is able to respond quickly to a change in price. The assumption is reflected in the table function shown in Figure 8, and the lack of a delay in reaching the "indicated value." The model structure is illustrated in Figure 9. The model cannot explain the response of the recycling rate. On the contrary, the implicit assumption is a part of the model's basic premises.

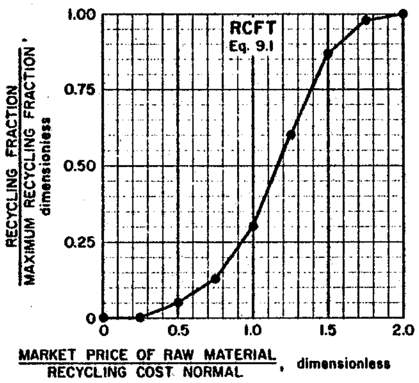

Figure 8. From Meadows, D.L., Meadows, D.H., eds. 1973, p. 185. The recycling fraction's dependence on the market price of raw material.

Some critics might dispute the quick response in the recycling rate. Rather than accepting the assumption, they may call it a hypothesis. An investigation of this dynamic hypothesis would require another model with quite a different problem focus, however, and a time-horizon of about 15 years. If the hypothesis were confirmed in the new model, the confidence in the original model would increase. Consequently, an investigation of the new dynamic hypothesis, derived from the original model, actually contributes to the validation of the model.

The second example is taken from a model (SOCIOMAD) of the interaction between the ecosystem (rangeland) and the social system (represented by the human and animal populations) in the Sahel area (Picardi, A.C., 1975). The model purpose is to describe the ecological problem of desertification and

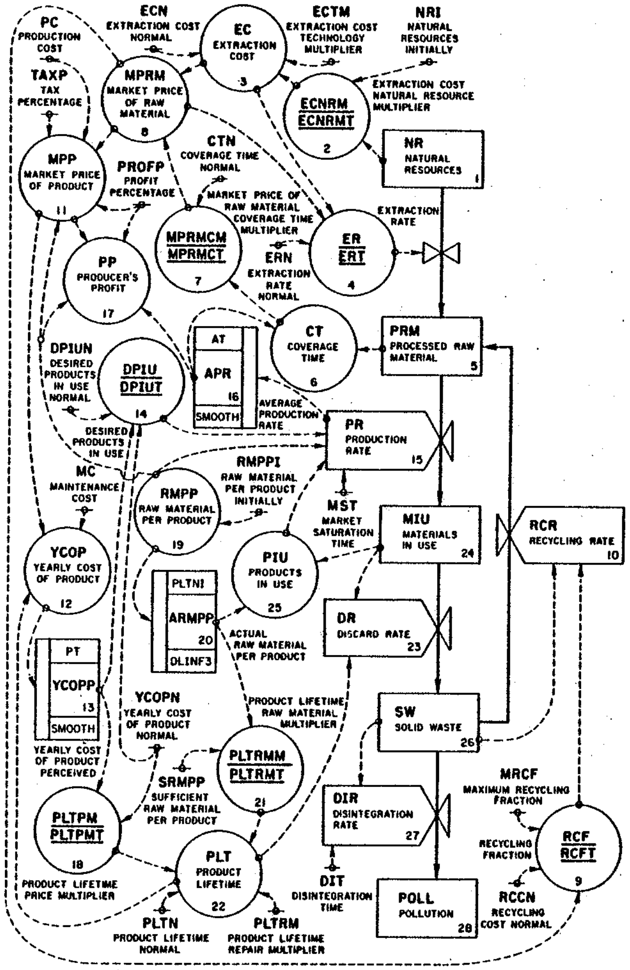

Figure 9. Dynamo flow diagram of "Solid Waste Model". From Meadows D.L., Meadows, D.H., eds. 1973, p. 191.

the human problem of starvation and herd losses in the Sahel, and to suggest policies to avert the reoccurence of the 1971 - 1974 catastrophe.

During a comprehensive sensitivity analysis of this model, one test revealed a significant shift in model behaviour toward the end of the model time-horizon (100 years). In all but this specific test, the most important system variables -- soil conditions, and animal and human populations -- seemed to stabilize at a very low level at the end of the model time-horizon. The basic run of the SOCIOMAD model, Figure 10, illustrates this behaviour. At one point in the testing, the evaluators became convinced that it was impossible to restore the system to its pre-drought (1970) levels. Would it at all be possible to rehabilitate the system after the serious collapse in the early 1970's? This question falls somewhat beyond the scope of the original model. A deliberate change in the future rainfall pattern was done, aiming at giving the ecosystem a chance to recover. Since ecosystem dynamics are asymmetrical, soil regeneration is much slower than degeneration. In the SOCIOMAD model, the recovery time of the soil condition is assumed to be 80 years at maximum. The results of the more favourable rainfall pattern are illustrated in Figure 11. As shown in the figure, the variables are in a growth mode, rather than an equilibrium mode, at the end of this particular simulation. However, the model cannot confirm that a complete recovery is possible. It only provides a rationale for generating the dynamic hypothesis, that a very long long-term recovery may take place. To test this hypothesis, a model with a much longer time-horizon would be necessary. Prolonging the time-horizon of the original model is no alternative. Such an extension would be mixing two models that address quite different questions.

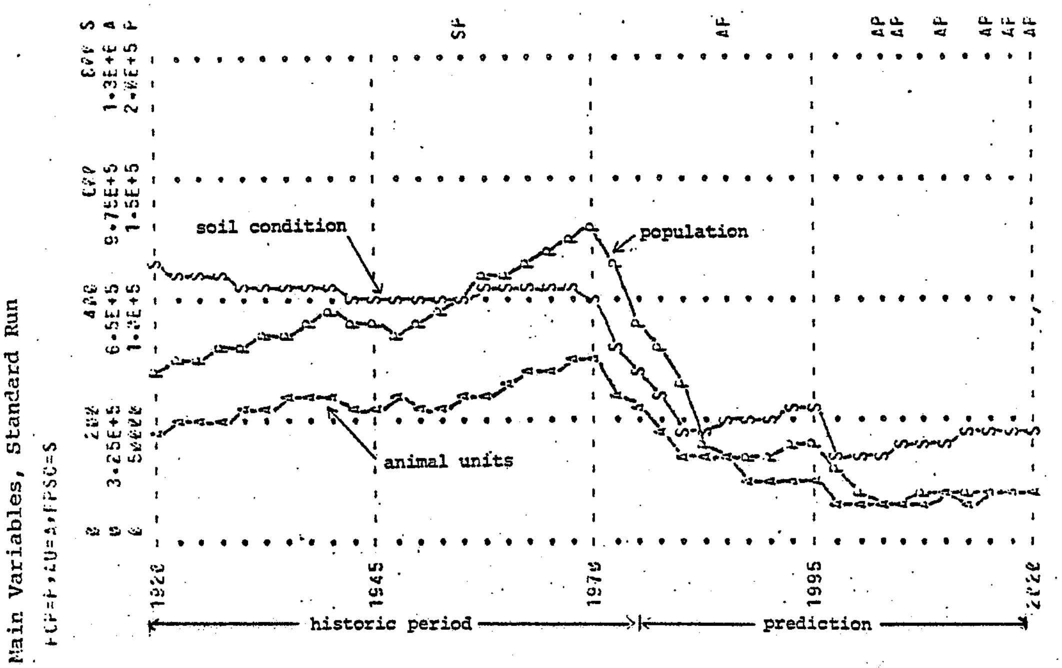

Figure 10. The main variables, P = human population, A = animal units, S = soil conditions, standard run of SOCIOMAD. (Brown and Tank-Nielsen, 1975, p. 42.)

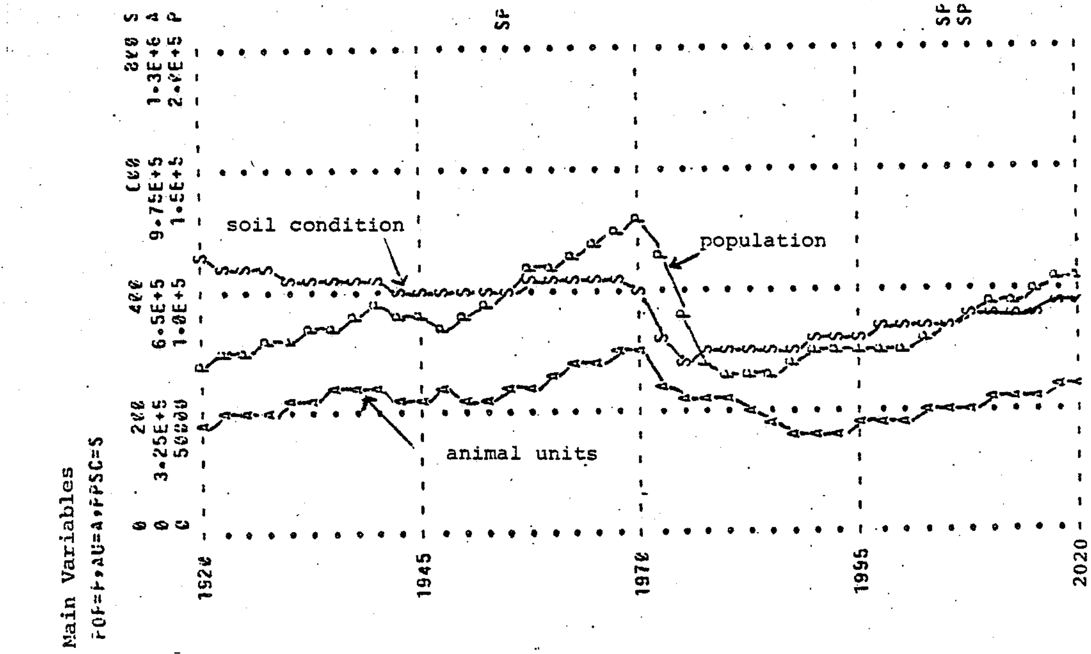

Figure 11. The behaviour of SOCIOMAD's main variables under more favourable rainfall conditions. (Brown and Tank-Nielsen, 1975, p. 65).

FINAL REMARKS

The nature of the problems being modeled in system dynamics, demands a comprehensive sensitivity analysis of the models. In judging how well this demand is met, it is necessary to employ a different perspective on sensitivity analysis. Traditionally, the sensitivity testing has been connected to the finished model. If this perspective is employed, the conclusion will be that the sensitivity analysis that system dynamics models are subjected to, normally is rather moderate, which will be a wrong conclusion. It is, however, a conclusion often arrived at by critics of system dynamics models, probably due to the reason suggested above.

Instead, a perspective which reflects the actual role of sensitivity analysis in system dynamics should be used. This role indicates that unlike many other modeling fields, the sensitivity testing is spread all over the modeling process. The extent of the sensitivity analysis at each step of that process may be moderate, in sum, however, it will as a rule be extensive. It constitutes in fact a necessary element of the model construction itself.

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