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An Expert View of the System Dynamics Modeling Process: Concurrences and Divergences Searching for Best Practices in System Dynamics Modeling

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Abstract

We intended this research both to discover a set of core practices in the system-dynamics modeling process and to identify the best of them according to the knowledgeable opinion of a recognized group of experts in the field. The paper addresses two questions: (1) What aspects of the system dynamics modeling process are common to all model building regardless of the modeler, the model, the type of practitioner, the tool used or the purpose of the model? (2) Which of these areas can be described as "best practice"?

We used a multi-method approach starting with interviews, then two virtual meetings with the former presidents and award winners from the System Dynamics Society to elicit best practices and, lastly, a discussion of the results and the implications for further research was conducted. The paper identifies 71 'best' practices grouped into six categories: problem identification and definition (15), system conceptualization (9), model formulation (11), model testing and evaluation (8), model use, implementation and dissemination (8), and design of learning strategy/infrastructure (7). More importantly, the study also identified (13) practices in which experts appeared to disagree.

Keywords: *System Dynamics, Conceptual Framework, Best Practices, Modeling Process, Expert Judgment, Expert Disagreement, and Knowledge Management.*

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Introduction: the importance of best practices

The system dynamics literature brings together examples related to the concept of *"best practices"* from a number of threads, starting with the earliest work done in *Industrial Dynamics* (Forrester, 1963) and *World Dynamics* (Forrester, 1973). Over the years, important papers have been collected such as *Modeling for Management* (Richardson, 1997) and *Modeling for Learning Organizations* (Morecroft and Sterman, 1994). Furthermore, specific pieces on what practices are currently used as *best,* such as *Benchmarking the System Dynamics Community* (Scholl, 1995), or where in the literature we can find them like *Desert Island Dynamics: An Annotated Survey of the Essential System Dynamics Literature* (Sastry and Sterman, 1993). Finally, textbooks have attempted to locate many, if not all, the best practices that are there in the field such as *Introduction to System Dynamics Modeling* (Richardson and Pugh, 1981) and *Business Dynamics* (Sterman, 2000). The work cited here is just a small sample of the work developed by experienced system dynamicists in the world (for more examples of good work see, among others, Lyneis, 1980; Homer, 1985; Saeed, 1992; Milling, 1996; Repenning, 2000; Hines and House, 2001; Oliva and Sterman, 2001).

We intended this research both to discover a set of *core* practices in the system-dynamics modeling process and to identify the *best* of them according to the knowledgeable opinion of a recognized group of experts in the field. This was an initial effort that we may extend later to a wider group of practitioners. This paper addresses two questions: (1) What aspects of the system dynamics modeling process are common to all model building regardless of the modeler, the model, the type of practitioner, the tool used or the purpose of the model? (2) Which of these areas can be described as "best practice"?

The set of practices identified in this paper is intended to be independent of the type of system modeled, the tool used to develop it, the purpose of the model, and the type of practitioner or the individual modeler. Practices that meet these criteria are by definition *core* practices. Despite the accomplishments of many talented individual practitioners, the lack of concurrence over core practices makes it difficult to broadly evaluate system dynamics as a modeling practice and can prevent the field from continued development (Scholl, 1992).

The system dynamics model building process involves six key activities as shown in Figure 1 (adapted from: Richardson and Pugh, 1981).

The activities are (1) problem identification and definition, (2) system conceptualization, (3) model formulation, (4) model testing and evaluation, (5) model use, implementation and dissemination, and (6) design of learning strategy/infrastructure. We used these six activities as conceptual framework in this study.

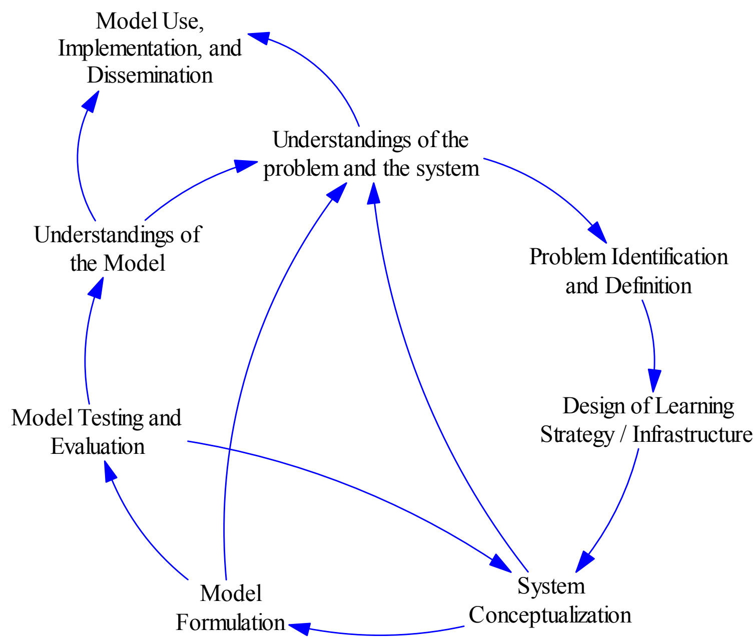

Figure 1. – Overview of the System Dynamics Modeling Approach
[Adapted from (Richardson and Pugh, 1981)]

The overview of the system dynamics modeling approach presented in Figure 1 has two characteristics: (1) it is depicted as a feedback process, and (2) it explicitly presents the key products of the process as integral part of it. Understandings of the model and understandings of the problem and the system are the key products that a system dynamics modeling effort should accomplish (Richardson and Pugh, 1981). Any system-dynamics modeling effort should have as goal to understand better the problem under study and the system in which it is happening. An orientation towards understanding and learning grants meaning to the definition-type activities (problem identification and definition, design of learning strategy) and offers context and meaning for the formalization-type activities (system conceptualization, model formulation) of the process incrementing the possibility of being successful at the insight-generation type of activities (model testing and evaluation, model use, implementation and dissemination).

Method of Study

This research used a multi-method approach that included interviews and a web-based participation method (Rohrbaugh, 2000) as group decision support system that seemed appropriate to the needs[1] of this specific study.

The web-wide participation method incorporated two virtual meetings with experts in the system dynamics field—former presidents and award winners from the system dynamics society.

Elicited in that virtual meeting were the "*best*" practices. Lastly, in a facilitated discussion, we explored the results and their implications for further research.

Process

1) Preliminary Interviews

A group of experts from the System Dynamics Group at Albany was interviewed to generate the framework to be used for the study.

The framework was generated and implemented in the research design and an asynchronous facilitated web-based meeting was selected to elicit the ideas from the participants.

2) WebWide Participation Meeting

Idea Elicitation

The experts wrote their ideas.

The lists were used as a trigger for new ideas.

Idea Clustering

The complete list per area was available for the participants.

The participants put together the ideas that belonged together in clusters.

The minimum common multiple was obtained for the clusters in which all participants agreed.

Idea Prioritization

The complete list of clusters was available for the participants.

The clusters were equi-weighted initially.

The participants changed the weights on the clusters to reflect their priorities.

The weights expressed by the participants became the realtive importance of the clusters.

Products

1) Raw Data (Appendix 3)

A series of statements directly typed by the participants are reported presented by area and priority.

The original clusters are presented as prioritized by the participants.

Four tables are presented, one for each area studied and one for the controversial statements.

2) Summary the Results (Section III of the paper)

The summary presents an slighly edited version of the raw data reducing each cluster to a single summary statement.

Again, four tables are presented, one for each area studied and one for the controversial statements.

Figure 2. – Description of the method of study.

[1] Having many people to contact geographically disperse and with very different time slots available for the study.

As described in Figure 2, the facilitated meeting had three parts: (1) Idea elicitation, (2) idea clustering, and (3) idea prioritization. These parts were consecutive and designed to generate the highest participation possible in the study. We conducted two meetings for the study.

Figure 3 shows the order followed of the activities in the study. The first six-week period covered the initial three areas of the modeling process, then, after a recess period, a second six-week period dealt with the final three areas of the modeling process.

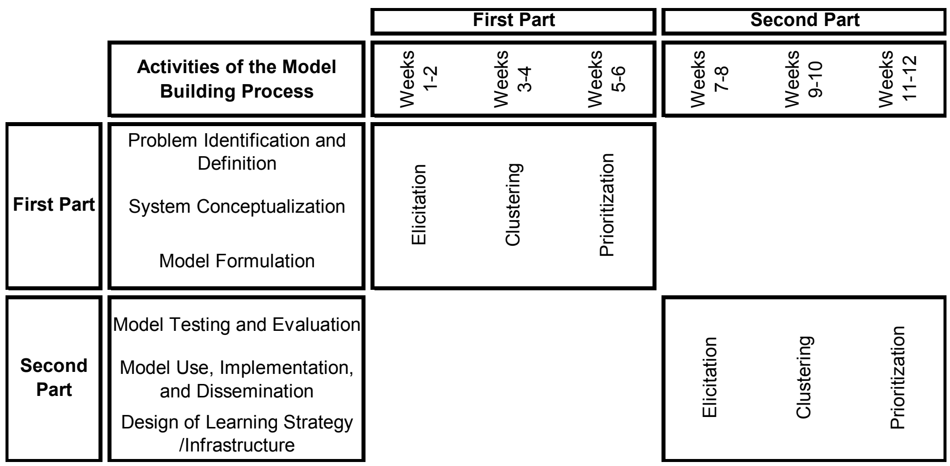

Figure 3. – Order of activities.

Participants of the Study

The group of participants included all the presidents of the System Dynamics Society and the winners of awards from the Society (Jay W. Forrester Award, the Lifetime Achievement Award, and the Lifetime Service Recognition Award). This was a purposeful sample of experts to provide a group of individuals with the highest level of recognition in the field. We will define experts to be those who are regarded as such by others within a certain field of knowledge or activity (Mumpower and Stewart, 1996, p. 193). One important consideration regarding the composition of the sample was their busy schedules and the probable constraints on time available for this project. Out of 23 people invited, only two declined due to time constraints. The participation level exceeded 80%, 19 out of the 23 invited experts participated in the study. The levels of participation fluctuated in the different stages of the process; the elicitation part was the most active, then the prioritization part, and then the clustering part.

The Web Wide Participation Meeting

The total time span for the facilitated meetings was twelve weeks. In the first stage, the participants listed ideas related to the *elicitation question* posted on the web site for the meeting. The participants browsed in the web and looked at a screen presented in Figure 4.

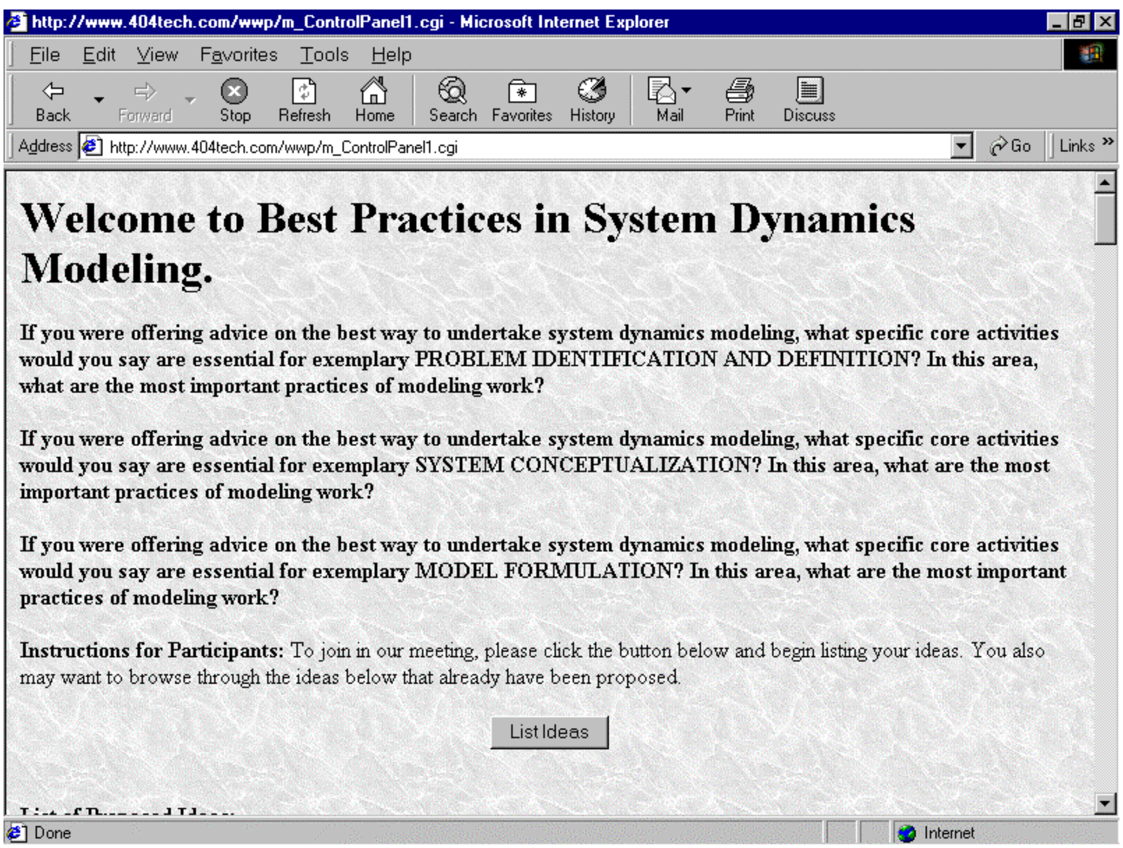

Figure 4. – Web Page for the Facilitated Meeting (Part 1)

We used six elicitation questions:

1. If you were offering advice on the best way to undertake system dynamics modeling, what specific core activities would you say are essential for exemplary PROBLEM IDENTIFICATION AND DEFINITION? In this area, what are the most important practices of modeling work?

2. If you were offering advice on the best way to undertake system dynamics modeling, what specific core activities would you say are essential for exemplary SYSTEM CONCEPTUALIZATION? In this area, what are the most important practices of modeling work?

3. If you were offering advice on the best way to undertake system dynamics modeling, what specific core activities would you say are essential for exemplary MODEL FORMULATION? In this area, what are the most important practices of modeling work?

4. If you were offering advice on the best way to undertake system dynamics modeling, what specific core activities would you say are essential for exemplary MODEL TESTING AND EVALUATION? In this area, what are the most important practices of modeling work?

5. If you were offering advice on the best way to undertake system dynamics modeling, what specific core activities would you say are essential for exemplary MODEL USE, IMPLEMENTATION AND DISEMINATION? In this area, what are the most important practices of modeling work?

6. If you were offering advice on the best way to undertake system dynamics modeling, what specific core activities would you say are essential for exemplary DESIGN OF LEARNING STRATEGY/INFRASTRUCUTRE? In this area, what are the most important practices of modeling work?

After the two-week period of idea generation, participants then clustered the ideas elicited in the first stage into categories that included ideas that they considered similar or that belonged together. Individually generated clusters were compared to extract the ideas that everyone considered that belonged to the same cluster; a 75% agreement threshold was used. The final clusters were used in the next part of the study.

In the third part, participants assigned priority scores to the clustered ideas according to the relative importance of each one as essential for the particular area covered. To complete this task, participants received the next set of instructions.

> **Instructions for Participants:** After clicking on the button "Prioritize Categories" you will see ***X*** categories with one to ten ideas listed in distinct clusters. At first, all ***X*** categories are shown with 100 points as equally important, but you may believe that some categories of best practices may be more or less important in <u>specific area</u>. You may raise or lower the 100 points for each category as you prefer: a category with 1000 points would be interpreted as a more important best practice by ten times a category with 100 points. Any time you click on a "Sort" button, your screen will be refreshed with all the categories reordered by your changes. The full set of ***X*** ideas is displayed below.

Figure 5 shows the number of ideas generated by the group related to each of the activities of the model-building process and the number of categories into which they were consolidated by the group. As one can see, there is a declining tendency in the categories-to-ideas ratio [2] reaching a level of approximately 50% reduction, meaning that, for every two ideas proposed, on average one category emerged. Additionally one can see that, during the first part of the study, the average ratio was 60% (in a tight distribution) and for the second part, the average ratio declined to approximately 40%.

	Activities of the Model Building Process	**Ideas**	**Categories**	**Cat/Ideas Ratio**	
First Part	Problem Identification Definition	81	49	60%	**60%**
	System	65	38	58%	
	Model	69	42	61%	
Second Part	Model Testing and	68	32	47%	**42%**
	Model Use, and	52	20	38%	
	Design of Learning Strategy /Infrastructure	42	17	40%	
	Total	**377**	**198**	**53%**	

Figure 5. – Categories-to-ideas ratio.

[2] Reduction rate = categories / ideas

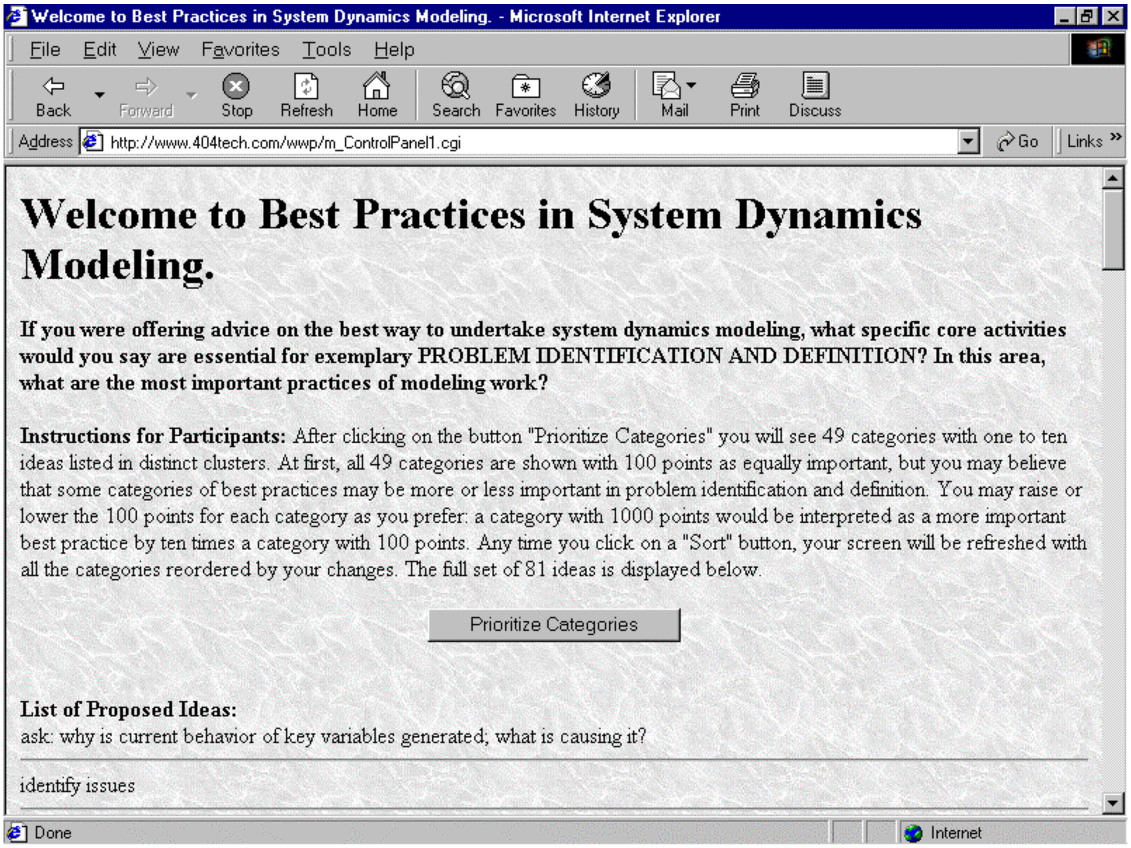

Figure 6. – Web Page for the Facilitated Meeting (Part 3)

Figure 6 shows the screen that participants saw during the prioritization part of the meeting. Each participant used a different scale to evaluate the categories of practices; the sum of the ratings accounted for a total that served as a normalizing factor for the evaluations. Then it was accumulated with the others' responses and weighted to obtain the total relative assessment for each category or practice[3]. There were four thresholds chosen for the final selection process.

The meeting was facilitated by 404 Tech Support (L.L.C.) that administers the Web-Wide Participation pages that were used for this study (Rohrbaugh, 2000).

[3] For details on the computation method, see appendix 1 of the paper.

Summary of the Results

The results of the two three-part meetings are presented [4] in Tables 1 to 6 below. These tables are part of what constitutes *best practice* in systems dynamics modeling as seen by the group of experts from the system dynamics society that participated in the study. Each table focuses on one of the six key areas of activity in system dynamics modeling: problem identification and definition, system conceptualization, model formulation, model testing and evaluation, model use, implementation and dissemination, and design of learning strategy/infrastructure. Each item in these tables summarizes a cluster of ideas generated by study participants and ranked highly by all participants. Tables 1 to 8 present the results of the study [5]. Tables 7 and 8 differ from tables 1 to 6 in that them represent in summary form clusters of practices on which study participants seem to have disagreed. These practices—*controversial practices*—tend to divide the opinion of leaders in the field.

[4] For the raw data, see appendix 2 of the paper.
[5] The exact words in Tables 1 to 8 were selected by the author team and represents a slight editing on one of the participants own words shown in the "raw data" tables in Appendix 2.

Table 1. - Best Practices in Problem Identification and Definition

Highest Rated

Talk and listen reflectively to problem owners (clients).
Clarify the purpose (e.g. strategy/policy, theory building, education, and training).
Identify the reference mode: The central "process" or time development to be studied and use reference mode diagrams to explore people's expectations of future behavior.
Ask why is current behavior of key variables generated, and what is causing it.
Formulate the dynamic hypothesis (i.e., "this behavior is caused by that structure").

Highly Rated

Identify clearly the clients of the model or the person to whom you need to answer.
Identify and engage key stakeholders.
Describe clearly the symptoms that initiated the modeling proposal.
Identify carefully the time horizon and the time unit of the model (years, months, and weeks).
Develop and sketch out desirable vs. undesirable futures of key variables over time.

Moderately Highly Rated

Verify whether problem stated by client is suitable for system dynamics study.
Form a study team consisting of technical people and system participants.
Generate a concise and specific dynamic feedback time-dependent problem statement.
Identify available time and budget for the study.
Identify all available data sources.

Table 2. - Best Practices in System Conceptualization

Highest Rated

Recognize that conceptualization is creative –there are no recipes– approach it from different angles and avoid rigid separation of the identification / conceptualization stages.
Generate a dialogue with the problem's owners that addresses their mental models and the dynamic hypothesis.
Start with major stock variables to describe the system, draw their reference modes and make sure their names are nouns, not verbs or action phrases.

Highly Rated

Set main goal to generate an endogenous dynamic hypothesis.
Be sure dynamic hypothesis boundary is large enough for endogenous orientation.
Identify key variables representing behavior.

Moderately Highly Rated

Be sure that each variable is measurable –at least in principal.
Look at all available data.
Maintain a clear documentation of the process.

Table 3. - Best Practices in Model Formulation

Highest Rated

Work up through a series of simple -to more comprehensive- models adding detail as needed to improve realism and show policy impacts quantifying the structure a bit at a time.
Leverage the power of dimensional consistency; use it from the very beginning.
Be sure equations make sense: all parameters must have real life (explicable) meaning.

Highly Rated

Set main goal to generate the smallest model that captures dynamic hypothesis.
Simulate as early as possible and often, testing even simple models extensively.
Discuss model and simulation outcomes with a study team that includes the client, and revise as necessary.

Moderately Highly Rated

Develop a small (<100 equations) prototype (full scope not detailed) and use it to test dynamic hypothesis and identify shortcomings.
Avoid making equations unnecessarily complicated and avoid chained table functions.
Bear bounded rationality in mind, especially in rate equation formulation (but also in general).
Try always to describe truthfully what happens in real world (limited rationality / information).
Take an apprenticeship (1 – 2 years) with an experienced system dynamics coach and acquire experience with many types of models from the literature.
Start with a (very) small model (fit stock-and-flow diagram on one page).

Table 4. - Best Practices in Model Testing and Evaluation

Highest Rated

Compare behavior patterns against real ones, use statistical measures of pattern fit, not point-by-point fit.

Highly Rated

Ensure that the model responds appropriately to extreme (but possible) shocks and values.
Test each equation for logical plausibility.
Analyze unexpected results from predicted upcoming behavior to find their causes.

Moderately Highly Rated

Ensure that all variables and parameters have real meanings.
Conduct partial model testing for understanding the role of structure and for refinement of structure and parameters.
Use client group's expert judgment to evaluate system structure.
Discover high leverage parameters and structure that change model behavior.

Table 5. - Best Practices in Model Use, Implementation, and Dissemination

Highest Rated

Understand that the entire exercise most revolve around the problems of concern for the audience (problem owner, client).

Highly Rated

Communicate the findings of the process in a clear language telling “system stories” that identify problems, causes, and solutions.

Moderately Highly Rated

Derive “chunks” of policy insight that the clients can grasp intuitively.
Assist the client with the planning and development of implementation of policy recommendations based on model.
Involve the client group in the model building process from step one.
Focus on implementation from the start involving the audience in policy design and evaluation. Involving top management in the discussions of implementation plans is desirable.
Report findings using the jargon of the audience and provide good documentation of model assumptions.
Create interactive “test-drive” sessions with multiple audiences within client organization to involve them to the maximum, particularly in policy experimentation.

Table 6. - Best Practices in Design of Learning Strategy/Infrastructure

Highest Rated

Use simplified causal-loop diagrams (CLDs) and tell system stories repeatedly and in many ways – do not let the model tell its own story.

Highly Rated

Ensure that learning exercises are always debriefed carefully and adequately so that players understand what really happened and key learning are reinforced.
Use counterintuitive results to explain reality (via the model).

Moderately Highly Rated

Build and use small models focusing on interesting patterns of behavior of selected issues.
Make sure that learners are decision makers and vice versa.
Work on securing the commitment and support of top management.
Think through in advance, who needs to learn from the model-based study and how they will learn it.

Table 7. – Controversial Best Practices (First Part)

<u>Problem Identification and Definition</u>

Identify the class of systems to which the particular case belongs.
Model the class to which the case belongs, not the case at hand.

<u>System Conceptualization</u>

Iteratively sketch causal loop diagrams, identify state variables / levels, identify system boundary.
Draw the structure of your dynamic hypothesis as a causal-loop diagram if stock-and-flow structure presents difficulties. Concentrate first on identifying main connections and major loops (loop explanations for reference modes).
Identify / draw stock-flow structures (resources, customers, products / services) and identify influences on flows.

<u>Model Formulation</u>

Select a "*core*" piece of structure and grow from it (select / add / analyze) never straying too far from a running model.
Think of extreme condition tests in writing equations; simulate different extreme conditions and check if equations work in those conditions; otherwise modify the model.

Table 8. – Controversial Best Practices (Second Part)

Model Testing and Evaluation

Ensure that dimensional consistency of model equations exists.
Test and validate as an iterative process.
Ask, Do I understand the behavior?

Model Use, Implementation, and Dissemination

Ask, Do I understand if the study is related to an important, dynamic problem?

Design of Learning Strategy/Infrastructure

Build and use interactive gaming versions (flight simulators) of the model(s).
Emphasize the learning process and outcome, more than the model itself.

Figure 7 shows a summary of the results of the study per activity of the model building process. An interesting result is that out of 198 practices ranked, 126 or about two thirds of all suggestions are considered indistinct issues.

Type of agreement	Problem Identification and Definition	System Conceptualization	Model Formulation	Model Testing and Evaluation	Model Use, Implementation, and Dissemination	Design of Learning Strategy /Infrastructure	Total of practices	Relative Percentage
	Areas of the Model Building Process							
Highest Rated	5	3	3	1	1	1	14	**7%**
Highly Rated	5	3	3	3	1	2	17	**9%**
Moderately Highly Rated	5	3	6	4	6	4	28	**14%**
Indistinct Issues	32	26	28	21	11	8	126	**64%**
Controversial	2	3	2	3	1	2	13	**7%**
Total	49	38	42	32	20	17	198	

Figure 7. – Summary of Results of the Study per activity

The number of indistinct issues follows the behavior of the total number of practices reported, as shown in Figure 8.

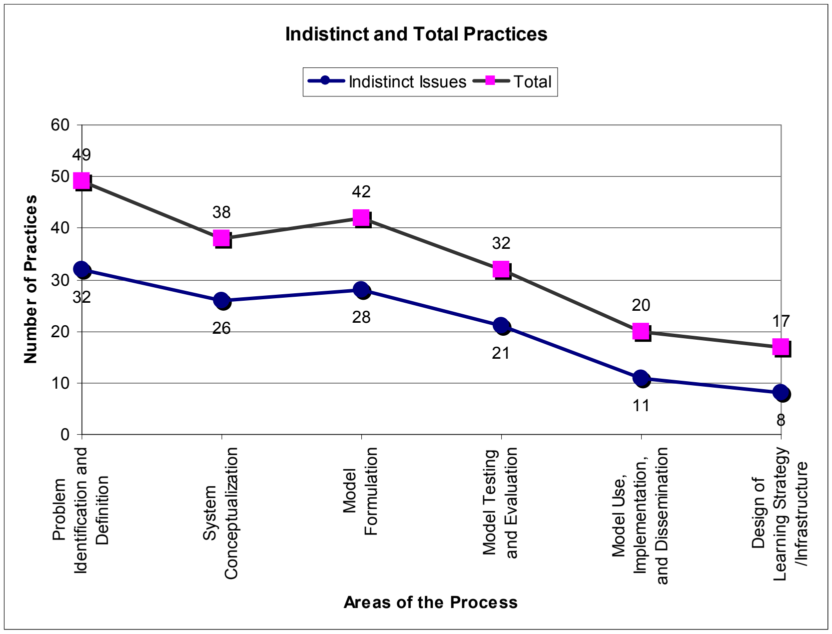

Figure 8. – Behavior of Indistinct and total number of practices in the study

This behavior shows the consistency of the fact that, this group of experts consider that, approximately two out of three practices as elicited originally are not necessarily 'the best' way to do system dynamics modeling, even though the design invited all participants through the eliciting question to contribute examples of exemplary work in system dynamics. This does not necessarily mean that these practices constitute 'bad' practice either, this just says that these practices did not generate consensus in the expert group.

Discussion and Conclusions

The main implications of this study are presented in three categories. (1) Tangible results and their implications, (2) the general process followed in this study, and finally (3) the controversial category. The discussion and conclusions follow.

Tangible Results

The results of the study (Tables 1 to 6) represent what a group of experts think are key elements in *problem identification and definition*, *system conceptualization*, *model formulation, model testing and evaluation, model use, implementation and dissemination, and design of learning strategy / infrastructure*. Several, if not all, of the results are present in the system dynamics literature (see, among others, Forrester, 1963; Richardson and Pugh, 1981; Andersen and Richardson, 1997; Sterman, 2000). The distinctive element of these results is the advantage of having them presented in a concise form. Additionally, the group of experts who participated in the study, share the perception of these practices as being "*best practices*" in the field that bring credibility and guidance to a larger group of practitioners.

One interesting characteristic of the 'best practices' found in all six areas of the model-building process is that in each one of the areas there is at least one practice related to group model-building activities or processes. This recurrent theme of group model-building type of practices suggests that group model building is an important way to create system dynamics models and that additional research in this area is important to continue expanding the capabilities if the system dynamics modeling processes. In the system-dynamics literature there are excellent examples of the efforts made in this area (see Andersen and Richardson, 1997; Andersen, Richardson and Vennix, 1997; Vennix, 1999).

The practices related to group model building are (presented in order of the areas that they belong):

(1) The formation of a study team consisting of technical people and system participants.
(2) Dialogue generation with the problem's owners that address their mental models and the dynamic hypothesis.
(3) The discussion of a model and simulation outcomes with a study team that includes the client revising as necessary.
(4) The use of client group's expert judgment to evaluate system structure.
(5) Involvement of the client group in the model building process from step one.
(6) Work on securing the commitment and support of top management.

General Process

The processes followed in the study allowed the participation of geographically dispersed experts. This, in itself, is an interesting by-product of the study that enlightens us about the capacity of collaboration within the field has today. A great deal of what happened during this research dealt with the alignment of group processes. The process used created the opportunity for the experts to provide their input in a collective creation of the 'reality' of the practice today.

The task the experts had to develop can be seen as an expert-judgment task in which expert agreement and expert disagreement can arise as a function of various factors.

In addition, elicitation, clustering, and prioritization of 'best practices' can be seen as an ideological negotiation of the group that is aimed to create an intersubjective agreement on what system dynamics modeling is all about. In 'best practice' studies, expert judgment is crucial.

In each step of the process of determining best practices—from identifying it to copying it and implementing it in your organization—an expert judgment takes place. Allegedly, only experts should be able to discriminate among practices and eventually determine standards of practice. Consequently, agreement among experts seems desirable to improve the confidence in 'best practices' studies. Additionally (at least in theory), experts in a certain domain have similar knowledge about the topic and, therefore, should be able to reach agreement regarding the utility of certain recommendations.

When there is disagreement among experts, understanding the sources of disagreement, might allow us to identify ways to minimize their effect on the credibility of the recommendations generated by the group of experts (Mumpower and Stewart, 1996, p. 251). Also, the quality of individual experts is subjective and open to interpretation. Who qualifies as an expert and who defines the criteria are fundamental questions that are crucial to the credibility of the judgments rendered by those experts (Martinez and Luna, 2001).

Controversial Category

The controversial category is a very interesting finding of the study because it can represent a great opportunity to expand our understanding of the different theories, methods, and procedures used in the field. Additionally, it can highlight what experts in the field do not agree on and, therefore, can become fertile soil to generate distinct threads of thinking within the field. These disagreements are not necessarily detrimental for the field; they can be natural and even beneficial in the growth of the field.

When different worldviews collide, a new environment emerges; this new status can generate a major break-through way of thinking that would expand the borders of the field that experiences these differences. Alternatively, they could lead to divisions, miscommunication, and aggravation.

The controversial category presents some possible *'conceptual divisions'* in the field. However, it also presents some odd elements that, possibly, can be related to the research design used in the present study and not necessarily to *'genuine'* disagreements among the experts in the field. Figure 9 presents a hypothesis of the origin of the experts' disagreements found in the study. In this hypothesis two possible explanations are presented: (1) the observed disagreement is related to the *research design* of the study (Bernard, 2000), and (2) the observed disagreement is related to *conceptual differences*—differences in theory, in methods, and/or in procedures (Hammond, McClelland and Mumpower, 1980)—that experts have in their modeling efforts.

In reference to the conceptual differences, we say that differences in theory, methods, and procedures can be the causes of the disagreements observed. We will now describe what we mean in each of these cases:

The *theory* element deals with how expert approaches vary in terms of their origins (academic background, area of specialization, etc), intended function of the approach (descriptive, prescriptive, etc), and the intended use of the results (cognitive orientation, action orientation).

The *method* element refers to the basic methodological claims from an epistemological stance dealing with how we know what we know. Under *method,* we find issues that pertain to strategic choices for testing or implementing *theory*. The *method* element deals with choices made by experts with respect to aggregation and decomposition of the modeling effort.

The *procedure* element focuses on description and comparison of the operational definitions that each expert provides for the concepts identified in the study. The distinction between the two elements—methods and procedures—can be similar to the distinction between strategy and tactics, whereas *method* is concerned with 'grand plans' for action, *procedures* are related to specific techniques or elements used to carry out those plans (Hammond, McClelland and Mumpower, 1980, p. 171).

The purpose of this analysis of differences is that of integration—the development of a cumulative scientific discipline (Hammond, McClelland and Mumpower, 1980, p. 13)—and understanding the general method we employ to carry out system dynamics modeling efforts.

We agree with Hammond, McClelland and Mumpower (1980) in that integration requires, denotation of similarities and differences, denotation of gaps and redundancies in the coverage of issues, denotation of antinomies that point to the need for empirical testing and/or logical or conceptual reconciliation, and logical and conceptual reconciliation whenever possible. Our effort in this study tries to address these requirements for integration. The purpose of this integration effort is not to eliminate differences[6] but to provide a framework in which a rich dialogue for improvement in the field can exist.

[6] Provided that the differences are not trivial or related to the choice of words or the language used.

		Research Design	Conceptual Differences		
			Theory	Method	Procedure
Problem Identification and Definition	1) Identify the class of systems to which the particular case belongs.			X	
	2) Model the class to which the case belongs, not the case at hand.		X		
System Conceptualization	1) Iteratively sketch causal loop diagrams, identify state variables / levels, identify system boundary.	X		X	
	2) Draw the structure of your dynamic hypothesis as a causal-loop diagram if stock-and-flow structure presents difficulties.		X	X	
	3) Identify / draw stock-flow structures (resources, customers, products / services) and identify influences on flows.	X		X	
Model Formulation	1) Select a "*core*" piece of structure and grow from it (select / add / analyze) never straying too far from a running model.				X
	2) Think of extreme condition tests in writing equations; simulate different extreme conditions and check if equations work in those conditions.			X	
Model Testing and Evaluation	1) Ensure that dimensional consistency of model equations exists.		X		X
	2) Test and validate as an iterative process.			X	
	3) Ask, Do I understand the behavior?	X		X	
Model Use, I&D	1) Ask, Do I understand if the study is related to an important, dynamic problem?	X			X
Design of Learning S/I	1) Build and use interactive gaming versions (flight simulators) of the model(s).		X	X	
	2) Emphasize the learning process and outcome, more than the model itself.		X		

Figure 9. - Controversial Category

In *problem identification and definition*, there is disagreement over whether to model the class of the system or the case at hand. We think that this difference of opinion can be explained either by the differences in theoretical basis or methodological approaches of practitioners who participated in the study possibly related to their different backgrounds—educational and cultural.

In *system conceptualization*, even though there is agreement on starting with major stock variables, there is disagreement on iteratively using a casual-loop diagram approach or a stock-and-flow approach to conceptualize. Most of these experts agreed on where to start the conceptualization (stocks), but not on how to proceed from there. This may possibly reflect a methodological difference in approaches.

In *model formulation*, there are two major areas of disagreement on how to formulate models. The first relates to the issue of starting small and continuously simulate and, preferably, always have a running model. This disagreement tells us that there is groups of experts who formulate piece by piece, always trying to have a running model at hand; and another group who prefers to formulate in big chunks and is not concerned about continuously having running prototypes. This difference can be understood as a procedural difference in the modeling effort. The second disagreement relates to the use of extreme condition tests on the model. This appears to be a methodological difference. The difference in methods indicates that some experts think the use of the extreme condition tests is crucial while others do not.

In *model testing and evaluation*, the three controversial practices seem ‘not’ so controversial. The most important controversy is related to the iterative approach to test and validation. This controversy can be understood as a way to gain confidence in the model; some practitioners seem to prefer incremental actions; while others are more definite. The fact that a controversy arose regarding the assurance of dimensional consistency seems to be a procedural difference. This same practice is considered 'best practice' in the previous area (model formulation). The fact that pursuing dimensional consistency appears to be a controversy in this area can be because the experts think that this practice really belongs to the previous one. This adds a new dimension to the conception of best practices; it is important 'what' to do but 'when' to do it too. The last controversy regarding the question that if one understands behavior can be related to the research design used that did not allow clarification of the practices posted, or perhaps, the controversy arises because some experts think that this question belongs to previous areas of the modeling process—differences in method.

In *model use, implementation, and dissemination*, the controversy seems to be related to the timing of the proposed question, possibly a procedural difference. Conceivably, to ask this question at this point of the model building process could be too late. A different interpretation of this controversial item is that the intention of the question was different when posted by the expert and if a clarification stage had been available, this controversial element would not have been obtained.

In *design of learning strategy/infrastructure*, an interesting difference of opinion divides the experts' view of what is important when trying to learn from the models we build, manifesting a theoretical difference. First, the use of flight simulators as gaming versions for learning is not shared by everyone and, this opens a very interesting dialogue about how to communicate to larger audiences the insights generated in our modeling studies. Second, to emphasize the learning process and outcome (more than the model itself) can be a two edged sword, especially when most of 'what is tangible' is the model. The generation of understanding and deep knowledge about the structure and behavior of the system sometimes might be 'hard' to sell as opposite as a very 'real' model with equations.

Discussion

A 'best practices' oriented study has several inconveniences. Differences in individual preferences can lead to conflict in the process. Experts might be 'judging' the practices using the same cues to analyze them while having different structures of individual preferences that direct them to different preferred outcomes (Mumpower, 1991)—best practices—and possibly to what Hammond (1973) refers to as cognitive conflict. The search for 'best practices' can be considered by some individuals as a search for 'the ultimate truth' generating the possibility for conflict, our purpose here is to clarify a path that can lead us to many different 'truths' that the community, through its experts, recognizes as valuable and important. To individuals aligned with a fundamentalist point of view, the search for 'best practices' may be of great value only if the results—the truth—coincide with their views (Fernandez-Armesto, 1997). To relativists, the great value of the effort, resides in the process, not the final product generated. Some individuals who subscribe to a deconstructivist point of view argue that the exploration of different theories—including 'best practices'—using language instead of direct observation of the phenomenon—practice—has several limitations (Fernandez-Armesto, 1997) that raise questions regarding the real value of the results. For the orthodox research school, thinking about theories of the world with high degrees of falsificability in which "one cannot prove anything, one only can find evidence to disprove it", gives the concept of best practices little conceptual credit. All these considerations leads us to support the idea that, independent of the different constituencies in a given field of knowledge, the possibility of researching what is the best way one can do something at a given point in time can be very productive. Furthermore, because the system dynamics field has been expanding in the types of systems modeled and number of practitioners all over the world, the general practice, and views of the practice, of model development have been changing over time; therefore the need for integration of this knowledge has become critical (Martinez and Luna, 2001).

The results presented in this paper are in the most part consistent with the literature and indicate to us areas of opportunity for growth in the field. The disagreements encountered can be a vehicle to expand the frontiers of the field. The matter of identifying a comprehensive list of practices and ranking them is not explicitly addressed in the literature, perhaps because what makes a determined practice in a field (e.g., system dynamics) a "*best practice*" is the relation between a personal judgment of the practitioner and the social judgment of the community of that field. The interaction of the individuals and the community generates the social construction of "*best practices*" and theories in use in that field.

Two important findings of the study are that (1) we are not in complete agreement with respect to how to do exemplary work in system dynamics modeling (indistinct issues) which create areas for improvement, and that (2) there are specific disagreements regarding the way to do it (controversial category) which can expand the frontiers of the field. A larger and better field can be obtained if these areas are exploited.

One plausible explanation for these results can be related to the research design of the study. How we conducted the elicitation, the amount of time available to do it, the impossibility of clarification of the meanings of the contributions through a discussion of the issues, among other factors. Other plausible explanation is the existence of differences in theory, methods, and procedures among the experts that participated in the study that, if not properly understood and addressed, can lead to cognitive conflict and problematic situations.

Next Steps

We plan to involve more "*highly skilled*" or "*expert*"[7] practitioners in the study so we can get a more comprehensive view of the status of practices considered "best practices" and the actual use of them. Firstly, we want to explore the "controversial" practices, its nature, its implications, and possible avenues for expanding the frontiers of the field and improving the field. Additionally, we want to explore the emerging result that roughly two thirds of proposed best practices are not embraced as best by experts in the field.

The results of this study have generated additional questions related to "*best practices*". The questions are: (1) Does this results hold up under different ways of eliciting or clustering and with larger groups? (2) Is this in the nature of practice in a complex field? (3) What is the underlying structure that conditions the creation, identification, formalization, diffusion, use, standardization, and termination of practices

[7] The definition of "expert" or "highly skilled" practitioner should be of interest to the community in the future to be able to clarify the levels of the practice and the relative quality of practitioners and models. This could be of great help to advance the system dynamics practice to a –as widely understood– profession (like engineering, etc).

considered 'best practices'? (4) How can we help inform individuals and organizations on what cues to see to understand when the 'best' practices are no longer valid and should be replaced? (5) Who, when, and how gets to determine what practices are to be considered *'best practice'*?

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Appendix 1 Method of Calculation

Computation Method of the Third Stage of the Facilitated Meeting.

Each participant used a different scale to evaluate the categories of practices; we built a matrix with those unstandardized scores of the participants. The matrix *a* (1) has elements $a_{i,j}$ which represent the unstandardized score for element (i) from participant (j).

(1)
$$a = \begin{bmatrix} a_{1,1} & a_{1,2} & a_{1,j} \\ a_{2,1} & a_{2,2} & a_{2,j} \\ a_{i,1} & a_{i,2} & a_{i,j} \end{bmatrix}$$

Then a standardized score was calculated using the total sum of the scores of the participant to normalize the scores to 100 and to capture the relative weight given to the specific element. The standardized scores (2) $\chi_{i,j}$ represent the relative weigh put on element (i) by participant (j).

(2)
$$\chi_{i,j} = \left[\frac{a_{i,j}}{\sum_{i=1}^{n} (a_{i,j})} \right]$$

Matrix (3) *b* was built using these standardized scores to calculate the top elements for the group.

(3)
$$b = \begin{bmatrix} \chi_{1,1} & \chi_{1,2} & \chi_{1,j} \\ \chi_{2,1} & \chi_{2,2} & \chi_{2,j} \\ \chi_{i,1} & \chi_{i,2} & \chi_{i,j} \end{bmatrix}$$

A total score (4) A_i was calculated per element (category) using the elements from matrix *b*.

(4) $$A_i = \sum_{j=1}^{N} \chi_{i,j}$$

And a vector (5) with these total scores was built to be used as total weighted measure of the elements.

(5) $$TotalScores = \begin{bmatrix} A_1 \\ A_2 \\ A_N \end{bmatrix}$$

Three metrics where used to determine the four thresholds that were selected for the process. The results where collected as: (1) Threshold I “Highest Rated”, (2) Threshold II “Highly Rated”, (3) Threshold III “Moderately Highly Rated”, and (4) Threshold IV “Indistinct Rated”.

The average of the total standardized score was used as the primary key to identify the ‘best practices’, the decision heuristic used fallows:

Threshold I: $A_i \geq \mu + 2\sigma$
Threshold II: $\mu + 2\sigma \geq A_i \geq \mu + \sigma$
Threshold III: $\mu + \sigma \geq A_i \geq \mu$
Threshold IV: $\mu \geq A_i$
Where μ = the mean of the averages.

The second metric used was the count of how many times the idea was considered the ‘best’ (or number one ‘top 1’) by the experts, and the third metric was the count of how many times the idea was in the ‘top 10’ ranking of the expert judge.

As a metric for general agreement, a dispersion measurement *d* was calculated using the standard deviation and the variance of the scores (6) and a count of how many times the idea was considered ‘the worst’ by the expert judge was taken into consideration.

If $d_i \geq \psi + 2\sigma_v$ and had at least one count as 'top 10' and as 'the worst' it was considered 'controversial'. Where ψ = the mean of the variances of the averages and σ_v = the standard deviation of the variances of the averages.

(6) $$d_i = \left[\frac{\frac{\sum_{j=1}^{n}(X_{ij} - \overline{X}_{ij})^2}{n}}{\sum_{j=1}^{n} X_{ij} / n} \right] * 100 = \frac{s_i^2}{\mu_i} * 100$$

Appendix 2 Raw Data of the Study

Appendix Table 1. - Best Practices in Problem Identification and Definition

Highest Rated

Listen carefully to Client Stories Let most senior client say "What brought us together" Talk and Listen reflectively to problem owners (clients) Make sure you understand the client's problem Ask client sufficient questions –avoid giving premature answers Check whether (dis) agreement on problem exists (When you are working with more than 1 person)
Clarify purpose (e.g. strategy/policy, theory building, education, training)
Dynamic thinking –drawing graphs over time Have client draw about 5 to 7 reference modes Use reference mode diagrams to explore many people's expectations of future behavior Identify the reference mode: The central "process" or time development to be studied Develop history of key measures Sketch a graph of the time behavior of the supposed problem Observe the behavior of key variables of interest over time Select subgroup of time histories with simpler patterns to represent behavior of interest Draw reference modes of behavior Plot time histories of what ever is available
Ask why is current behavior of key variables generated, and what is causing it.
Formulate the dynamic hypothesis (i.e., "this behavior is caused by that structure")

Highly Rated

Clearly identify clients of the model Pick or invent the person to whom you need to answer Create a common ground of understanding between me (the modeler) and the issue owner (the client)
Identify key stakeholders Immerse yourself in the organization and engage stakeholders
Describe clearly the symptoms that initiated the modeling proposal
Identify carefully the time horizon Select carefully the time unit
Develop desirable vs. undesirable futures of key measures Sketch out the desired behavior of key variables over time

Moderately Highly Rated

Check whether problem stated by client is suitable for System Dynamics Study
Form a study team consisting of technical people and system participants

Set main goal to generate an interesting dynamic feedback problem Define the dynamic feedback problem Generate a concise and specific problem statement Find a puzzling time-dependent problem
Identify available budget for study Identify available time for study
Identify available data sources Look at all available data

Appendix Table 2. - Best Practices in System Conceptualization

Highest Rated

Avoid rigid separation of identification / conceptualization / formalization stages Approach conceptualization from different angles like a new creation Recognize that conceptualization is creative –there are no recipes
Discuss the dynamic hypothesis with a study team Engage in conversations around conceptual building blocks Elicit client's mental models
Identify levels / states first to describe system with and without symptoms of interest Identify the few (critical) main system variables (normally levels; 1-3) Select stock variables in reference mode Make sure stock variable names are nouns, not verbs or action phrases Select one key stock variable in a single conservative system if more than one variable is present Write names of selected stock variables with space between them to draw perceived causal links Start with major stock variables, try to impose your feedback loops Identify "essential" asset stock accumulations

Highly Rated

Set main goal to generate an endogenous dynamic hypothesis
Be sure dynamic hypothesis boundary is large enough for endogenous orientation
Identify key variables representing problematic behavior

Moderately Highly Rated

Be sure that each variable is measurable –at least in principal

Look at all available data
Maintain clear documentation Keep a trace or record of conceptualization

Appendix Table 3. - Best Practices in Model Formulation

Highest Rated

Start small / simple and build out / add complexity later Work up through a series of simple to more comprehensive models Quantify the structure a bit at a time Add detail to prototype as needed to improve realism and show policy impacts
Check dimensional consistency from the beginning Check the units of the equations Leverage the power of dimensional consistency
Support every concept with data or common experience Be sure equations make sense: All parameters must have real life meaning Be clear about what, in reality, the algebra represents

Highly Rated

Keep the model simple / not too detailed Set main goal to generate smallest model that captures dynamic hypothesis Assess carefully whether additional structure is required Require very good reasons to diverge from the simplest molecules Push back hard on demands for more and more detail
Simulate early / as soon as possible Simulate often Test even simple models extensively
Involve client in discussions about simulation outcomes Discuss model with a study team and revise as necessary

Moderately Highly Rated

Develop small (<100 equations) prototype (full scope not detailed) Use Prototype to test dynamic hypothesis and identify shortcomings

Avoid making equations unnecessarily complicated Avoid chained table functions (especially when concepts are overlapping)
Bear bounded rationality in mind (specially) in rate equation formulation (and in general)
Try always to describe truthfully what happens in real world (limited rationality / information)
Acquire experience with many types of models from the literature Take an apprenticeship (1 – 2 years) with an experienced system dynamics coach
Keep the starting model small to fit stock-and-flow diagram on one page Start with a (very) small model

Appendix Table 4. - Best Practices in Model Testing and Evaluation

Highest Rated

Comparison with historical or reference mode behaviors Comparison with reference mode Ensure that the model is capable of reproducing the reference mode Ensure that the model is capable of reproducing history (when, if necessary, subjected to historical time series for exogenous variables) Ask, Does the model generate the reference mode? Validate against historical data Do compare model output to time series data Comparing behavior PATTERN components against real ones. (Behavior test) Use statistical measures of PATTERNS. (NOT measures of point-by-point fit)

Highly Rated

Extreme condition testing for determining model adequacy Ensure that the model responds appropriately to extreme (but possible) shocks and values Drive model to extreme values to see how it behaves Perform Extreme condition testing of each equation (structure test) Extreme condition testing of simulated behaviors. (Indirect structure test) Testing the model under extreme conditions Testing extreme policies Testing an extreme set of parameters

Analyze unexpected results to find their causes
Testing each equation for logical plausibility (structure test)

Moderately Highly Rated

Ensure that all variables and parameters have real meanings
Active client involvement in evaluation process Full discussion of evaluation-based insights even prior to policy testing Client involvement in evaluation Discuss with problem owners (clients) Use Client Group's Expert Judgment to evaluate system structure Show client group the model's output to assess its plausibility
Partial model testing for understanding role of structures Partial model testing for refinement of structure and parameters Verifying the system structure Compare behaviors of alternative structures
Discover high leverage parameters and structure that change model behavior.

Table 5. - Best Practices in Model Use, Implementation, and Dissemination

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Highest Rated

Understand the situation of the problem owner (client) Try to understand the client's problem The entire exercise must revolve around the problems of concern for the audience

Highly Rated

Write an internally consistent presentation, without explicit reference to a model, that identifies the problem, its causes, and a solution Make the runs, and explain in clear language what are the main causes behind the standard run and the various policy conclusions drawn from the model Draw simple and clear causal diagrams highlighting the basic mechanisms in the model Argue on the basis of model understanding not technical details Use CLD extensively Tell "System Stories" or narratives that are based on model output

Moderately Highly Rated

Derive “chunks” of policy insight that the clients can grasp intuitively.
Assist client with development of implementation plans based on model Assist a client with implementation of policy recommendation
Involve the client group directly in model building from step one Involve the audience in as many stages as possible. Involve the client in the model building process
Build Implementation Plans into client work group activities Design and test with client good alternative policies that are implementable Brainstorm policy implementation approaches BEFORE the model is built with client group Involve top management in model use, implementation, and dissemination discussions Focus on implementation from the start. It is vital that the audience be involved in policy evaluation and design stage
Report findings using the jargon of the audience and provide good documentation of model assumptions.
Interactive "test drive" sessions with client as part of policy testing Model use training sessions with client Presentation of model to multiple audiences within client organization Involve client to the max, particularly in policy experimentation

Table 6. - Best Practices in Design of Learning Strategy/Infrastructure

Highest Rated

Make the runs, and explain in clear language what are the main causes behind the standard run and the various policy conclusions drawn from the model Draw simple and clear causal diagrams highlighting the basic mechanisms in the model Use CLD extensively Tell System Stories repeatedly and in many ways--do not let the model tell its own story Use simplified CLDs that connect to key parts of system structures System stories explain how structure gives rise to behavior in intuitive terms Involve the clients in telling model-based system stories

Highly Rated

Always debrief learning exercises carefully--reinforce key learning at all times Prepare real-looking debriefings and discussion materials. Be certain that gaming sessions are adequately debriefed so that players understand what really happened Do not deliver flight simulators with inadequate guidance
Use counterintuitive results to explain reality (via the model).

Moderately Highly Rated

Build small, simplified models focusing on selected issues. Use small models with interesting pattern of behavior
Make sure that learners are decision makers and vice versa.
Get serious top-level support Stay in touch and keep the project alive Work on securing the commitment of top management
Think through in advance who needs to learn from the model-based study and how they will learn it.

Appendix Table 7. - Controversial Best Practices

Problem Identification and Definition

Identify the class of Systems to which the particular case belongs
Model the class to which the case belongs, not the case at hand

System Conceptualization

Iteratively sketch causal loop diagrams, identify state variables / levels, identify system boundary

Create comprehensive set of dynamic hypotheses (loop-explanations for reference modes) Identify loops and develop initial dynamic hypothesis Identify major causal loops determining development over time of the main variables Draw the structure of your dynamic hypothesis as a causal diagram Form dynamic hypothesis before modeling to depict major feedback loops across sectors Draw causal loop diagrams if stock-flow structure presents difficulties Identify feedback loops Look for a few potentially important feedback loops Concentrate first on main connections and major loops
Identify / draw stock-flow structures (resources, customers, products / services) Identify influences on flows

<u>Model Formulation</u>

Select a "core" loopset, add loopset operationally, analyze model; iterate select / add / analyze Never stray too far from a simulatable model
Think of extreme condition tests in writing equations, check if equation works in that condition Simulate different extreme conditions and modify model

<u>Model Testing and Evaluation</u>

Test and validate as an iterative process
Establish dimensional consistency in equations Dimensional consistency of model equations Check dimensions Dimensional consistency check (structure test)
Ask, Do I understand the behavior?

<u>Model Use, Implementation and Dissemination</u>

Ask, Do I study an important problem? Ask, Do I study a dynamic problem? Do NOT model and study WRONG (open, static, short-term) problems

Design of learning strategy/infrastructure

Use flight simulators Have the result user test out his/her own experiments with model runs Use flight simulators as motivational tools--remember that humans do not learn well from dynamic outcome feedback Build user-friendly model experimentation environments Build interactive gaming versions of the model(s). Use flight simulator to stimulate group model
Emphasize the learning process and outcome, more than the model itself.

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