# Whose Model is it Anyway?[1]

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**Abstract**

*Increased community participation in developing system dynamics models holds much appeal, but what we mean by 'participation' and 'model' varies greatly. This can create ambiguity and confusion about what is meant by participatory modeling, especially in projects involving multiple community representatives, several modeling stages, and different types of models. More specifically, questions can arise about whether the results were based on "true" participation and the degree to which model-based insights and recommendations were based on the participants' model or the expert modeler's version of social reality. In this paper, we argue that confusion arises from imprecision about the different types of models we use in system dynamics for theory specification, operations we apply in developing models, and relationships between different types of models. To address this imprecision, we propose a formal framework for specifying different types of models that can arise in participatory research, and illustrate the approach through a series of case examples from previous and ongoing system dynamics research on childhood obesity, nonprofit organizational performance, and household economic security. Implications for future research in participatory modeling and the use of system dynamics diagramming are also discussed.*

Keywords: group model building, participatory methods, community participation

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> *"…Similarly the possibility of describing the world by means of Newtonian mechanics tells us nothing about the world: but what does tell us something about it is the precise way in which it is possible to describe it by these means. We are told something about the world by the fact that it can be described more simply with one system of mechanics than with another."*
>
> *Ludwig Wittgenstein (1974, , TLP 6.342, p. 68)*

> *"…Today's knowledge about something is not necessarily the same tomorrow. Knowledge is changed to the extent that reality also moves and changes. Then theory also does the same. It's not something stabilized, immobilized"*
>
> *Paulo Freire (Horton and Freire 1990, p. 101)*

> *"One way to focus on this problem is to discover that we have no conception of objectivity that enables us to distinguish the scientifically 'best descriptions and explanations' from those that fit most closely (intentionally or not) with the assumptions that elites in the West do not want critically examined."*
>
> *Sandra Harding (1991, p. 97)*

## 1. Introduction

Group model building (GMB) has emerged as an important tool for developing models with stakeholders or participants in the system (Andersen and Richardson 1997; Richardson and Andersen 1995; Vennix 1996; Vennix, Andersen, and Richardson 1997). Historically, GMB was developed as a means of including key stakeholders or decision makers in the process of building a model where the participants in the process were essential to the solution. Participants were mainly professionals, often in government or business, where some problem needed to be solved and implemented. GMB methods grew from these early experiences with more ambitious intentions to go beyond the immediate decision makers and involve those ultimately most affected by the decisions and plans being made.

However, pushing GMB methods toward greater levels of participation by involving communities raises a number of issues that at times present major barriers to designing and planning GMB sessions. Of particular note for us has been a recurring issue about what we mean by the terms 'participation' and 'model' when engaging communities.[2] It is important to realize that in many settings, modelers and facilitators in GMB can operate quite effectively without considering these issues. A modeler developing a simulation model for an organization through a consulting agreement, for example, is not confused about what a model is or whose model it is. The model is the simulation model, e.g., an electronic file that can be simulated and will be delivered to the client at one or more points during the project.

[2] In this paper, we will referring to both terms and the concepts they refer to, and draw on how we speak about models and participation as a way to draw out what we mean. To make the distinctions explicit, we use single apostrophes to designate terms (e.g., 'model'), quotes to designate a term being used (e.g., "We developed a model."), and the word by itself to refer to the concept (e.g., model).

In a community context, however, the picture gets murkier in part because modelers come with a variety of tools for describing models, and community members engaged in a GMB process may expect much more insofar as owning and having access to the model. For example, where a causal loop diagram (CLD) may be a satisfactory representation of the problem from the community's perspective, the limitations of the CLD and privileging of a simulation model by the modeler on a computer can lead to confusion or conflict. Confusion arises because it may not be clear to the community whether the proper referent of the term 'model' is the diagram or simulation model, and conflict arises because if the simulation model is the proper referent and only the modeler has access to it, then the role of the community is much more limited at best and appropriated and exploited at worst.

This variation in meaning leaves much room for misinterpretation and misrepresentation of the final results. The term 'participation' can refer to anything from providing information about the system through focus groups, surveys, and key informant interviews to involvement in model formulation, testing, and analysis. By 'model', we can refer to any number of things including mental models, pictures of systems, causal loop diagrams, stock-and-flow diagrams, and computer simulation models. In system dynamics, we also use the term model to actually refer to iterations of a model and say, "the model has evolved" instead of, "this is a new model". Adding to the confusion is the jargon that modelers use including 'concept models', 'scoping models', 'research models', 'management models', 'small models', 'preliminary models', 'seed models' or 'seed structures', 'backbone models' or 'backbone structures', 'integrated model', 'hybrid model', and 'toy models' to name just a few. Given these variations, it can quickly become unclear what is meant by community participation in the development of a system dynamics model.

Do we mean that community members participated in the development of a scoping model or formulation of the research model? Did they contribute to model structure in the form of a causal loop diagram that was subsequently used to develop a simulation model? Or, was their initial participation more about defining the problem with the actual modeling done by expert modelers? To what extent did the modelers' choice of seed structures determine the model that was developed? There is, in fact, no shortage of ways that misunderstandings can arise when we attempt to combine the terms 'participation' and 'model'.

We see this as a problem because people tend to interpret the results from models that claim to have been developed with community participation differently from those developed by modelers. People expect that models that have been built with community participation of some type to have higher validity, more feasible solutions, and solutions with greater buy-in for implementation and sustainability. In some circumstances, we may also expect that community involvement reduces the likelihood that the successfully implemented solutions will adversely affect marginalized communities through their involvement in developing a model. In short, we tend to view the results of models that involved community representatives in the process *differently because of a presumed correspondence between their understanding of a situation, the model being analyzed, and the informing and organizing of actions that lead to a solution.*

Yet, we rarely if ever make this correspondence explicit, leaving much room for false claims about participation and models, and hence "the model" is open to the unexamined and undocumented biased interpretations and judgment of the modelers. This can become especially problematic when we consider the fact that there can be significant differences in power and status between the modelers or researchers and community members. Without a clear understanding of what we mean by 'participation', 'model', and the correspondence between community members' stories and a model, we are unable to formulate criteria for evaluating the quality of models and their results.

It is important to recognize that the problem exists *because we seek to involve participants in the process* in a way that does something more than the most minimal definition of participation as data sources. We seek participation because participation is seen as essential to making decisions, coordinating activities, and ultimately solving the problem at hand. These problems do not arise—at least not in the same way—if one is primarily working as a consultant or researcher and only involving community members in the process as potential data sources because it is clear who is developing the model and theory.

Of particular concern in this paper are situations where the problem or structure of the system is largely unknown—that is, "messy" problems in systems science. Much has been made of the limitations of using system dynamics for tackling messy problems, which is often viewed outside system dynamics as an approach best suited to well-defined problems (e.g., Jackson 2000; Checkland 1981). The assessment of suitability of system dynamics for messy problems depends on how one views the process of developing system dynamics models and the role of simulation in that process. If one takes a more pluralistic view of system dynamics to include both qualitative and quantitative simulation models (e.g., Vennix 1996, 1999), then it is easier to view system dynamics as an appropriate tool for unstructured and messy problems.

What has generally not been discussed in this debate about the appropriateness of system dynamics for messy problems is the reason these problems are messy in the first place. In this paper, we are primarily concerned about situations where the systems change through increased participant self-awareness and agency within the system. That is, these are systems such as organizations, neighborhoods and communities where there can be a great diversity of system structures that vary from highly stable to constantly changing because people do in fact change the structures and have agency. While participants' views may contain a variety of biases and attribution errors, and they may be vulnerable to influence based on status and power differences, it is at least a good place to start by involving participants in the modeling process to uncover the structures underlying these messy problems. More importantly, we believe that participants often provide a complementary view if not a more objective view of the social relations if they have actively been trying to change the system (Harding 1991).

Moreover, because we are interested in both advancing social science research and influencing positive change within such systems, we take a pragmatic stance that involving participants is critical to both understanding the system in an objective sense, and enabling participants to use the fruits of research for their own mobilization to create more effective action. It is from being in the trenches of participatory methods and seeing the potential for change that motivates us to develop this framework and clarify our positions on participation and modeling. So, despite the theoretical emphasis of this paper, we see the theory as immediately practical within the contexts of our ongoing projects. Is this not ultimately what good theory should be, that is, focused on resolving theoretical distinctions that have practical importance?

This paper is organized into five major sections. We begin by grounding our approach in the existing discussions within system dynamics about the distinctions between diagrams and models, and then draw some distinctions between levels of theory specification, models, and diagrams. In the next section, we frame some of the main concerns we have about the nature of participation in modeling. We are then ready to introduce a set of formal definitions. This formality is helpful in delineating the different ways that models are commonly transformed and can be related to each other, which we illustrated through several case examples in the next section. Having introduced the formalism and our concerns, we can then bring the elements together into a discussion that addresses the overarching concern in this paper, "Whose model is it anyway?"

## 2. Diagrams, Models, and Theories

In system dynamics, we build causal models, and specifically causal feedback models with the primary goal of providing an endogenous understanding of a dynamic problem (Richardson, 2010). These models are typically illustrated as causal loop diagrams or stock and flow diagrams, and formally represented and numerically simulated on a computer as a system of differential equations.

The possibility of doing participatory modeling arises from the use of diagramming in system dynamics for model conceptualization and model exposition (Lane 2008). Without causal loop diagrams (CLDs) and stock and flow diagrams (SFDs), models as systems of differential equations are largely inaccessible to lay audiences with little or no calculus background. Diagrams have minimally made it easier to explain the results of system dynamics models, but they have also led to controversial claims where the diagrams are used as a more accessible alternative to the analysis of a formal simulation model for inferring behavior and policy from diagrams.

While system dynamicists have correctly tended to focus on the limitations of diagrams for inferring behavior and policy from diagrams alone (Lane 2008; Richardson 1986), it is important to note that the term 'diagram' is too broad when compared with system diagramming methods in general, which can range from pictorial representations of a system to a wide range of methods for representing systems (e.g., organizational charts, network diagrams, genograms). The very fact that we can have a disagreement about the relative merits of CLDs and SFDs speaks to the fact that CLDs and SFDs do have a syntax that is at least close enough to the simulation model to make the disagreement possible. Diagrams, such as CLDs and SFDs, say more than we give them credit for in system dynamics and more than the term 'diagram' conveys.

The term 'model' can be used in social science to mean anything from a conceptual model or framework to a probability model, causal model, or simulation model. However, most causal models in social science are less specific than the CLDs or SFDs used in system dynamics. Currently, the more sophisticated quantitative models in social science consist of path diagrams or structural equation models with some limited examples of feedback in the form of non-recursive associations (Bollen 1989). However, these have been shown to be inadequate for capturing the nonlinear interactions and emergent shifts in feedback loops that are the focus of system dynamics modeling (Hovmand 2003). In this paper, we are interested drawing out comparisons between the different levels of specification of models and the substantive theories of a situation they represent, so we will use the term 'model' in the broadest sense. This will become clearer in the next section, and we will return to the distinction between diagrams and models at the end of the paper.

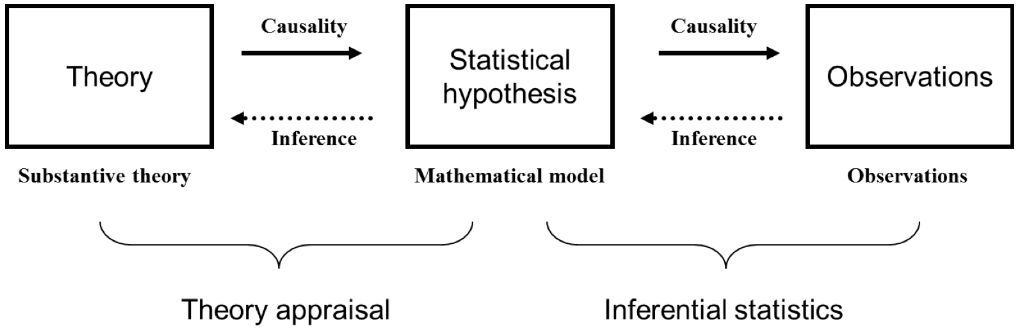
Adding to the confusion is that in both social science and system dynamics, there is a tendency to ignore the fact that the models we build articulate a substantive theory about a situation (Meehl 1990; Pearl 2009). The general tendency is to conflate the substantive theory with the model, and focus on the correspondence between the model and observations, which include computer simulations in addition to data from the real world. In this sense, we can behave much the same as social scientists testing their theories using statistical analyses. This is easy to do especially when one is in the habit of building simulation models because one is frequently creating and testing the theory and modeling through multiple iterations of model formulation and testing. So, for the system dynamicists building formal simulation models, the model and theory are reasonably thought of as being one and the same.

This practice, however, is atypical in social science in general. Consequently, there are often significant logical inconsistencies between substantive theories of dynamic situations and their mathematical representation as a model, which are often hidden in empirical work because the logical relationships in theory appraisal have not been rigorously verified. That is, most social scientists presuppose that the verbal theory corresponds, and is logically consistent with, the statistical hypotheses being tested. Meehl (1990) has been especially critical of this, arguing that what is needed are not more sophisticated statistical techniques, but much stronger mathematical specification of theories in social science. Pearl (2009) is even sharper in his criticism, calling much of conventional thinking in social science about causal explanations "pseudo-science".

It is therefore unsurprising that the rigorous exercise of using computer simulation models in system dynamics to develop logically consistent theories has great potential for advancing theories in social science about dynamic phenomena (e.g., Lane 2001a; Schwaninger and Grösser 2008; Lane 2001b). System dynamics provides a meta-theory on how to translate and test theories of a dynamic situation into a formal simulation model (Lane 2001a), and a set of diagramming tools (CLDs and SFDs) that, despite their limitations, provide a means visually conceptualizing and describing the substantive theories in a manner that is consistent with this meta-theory.

While Meehl (1990) was unaware of system dynamics, he introduced a way to think about theories, models, and observations in social science that can be quite useful. Meehl drew a distinction between the substantive theories that are often stated in verbal form, mathematical models that are typically represented as statistical hypotheses in system dynamics, and empirical observations as shown in Figure 1 below. Meehl emphasized two different kinds of assessments—theory appraisal and inferential statistics—and their role in informing each other. The causality depicted in Figure 1 represents the direction of influence so that the hypotheses are generated from theory and the observations are collected and analyzed based on the statistical hypotheses, while the inferences go in the opposite direction. Meehl's major point with introducing this is that for complex and messy systems as typical in social science, most of the objects of study eventually *are connected* and therefore what is needed is much more emphasis on theory appraisal as opposed to inferential statistics.

**Figure 1** Adapated from Meehl (1990, p. 16)




To support this type of theory appraisal, Meehl drew distinctions between different levels of theory specification moving from weak specification to progressively stronger forms of theory specification as shown in Table 1. The simplest and least specified theories are the types of entities postulated or ontology of the system (level 1 in Table 1) following in increasingly stronger levels of specification by causal links (level 2), polarity of the causal links (level 3), relative strengths of multiple causal links in additive relationships (level 4), relative strength of causal links in nonlinear interactions (level 5), functional forms of causal links (level 6), generalizability of parameters across different situations (level 7), quantitative relationships between the parameters (level 8), and numerical values of parameters or point estimates (level 9).

**Table 1.** Progressively stronger specifications (adapated from Meehl, 1990)

1. Type of entity postulated (substance, structure, event, state, disposition, field)
2. Compositional, developmental, or efficient-causal connections between the entities in (1)
3. Signs of derivatives of functional dynamic laws in (2)
4. Ordering relationships among the derivatives in (2)
5. Signs of mixed partial derivatives (“interactions”) in (2)
6. Function forms (e.g., linear? logarithmic? exponential?) in (2)
7. Trans-situationality of parameters in (6)
8. Quantitative relations among parameters in (6)
9. Numerical values of parameters in (6)

In comparing two model specifications of theories, *M* and *N*, we then first consider at what level these theories are specified.[3] If model *M* is at level 6 and *N* is only at level 2, we would say that model *M* is a stronger theory specification than *N*. This does not mean that *M* is more correct than *N*, for it often is the case that it is easier to “be correct” when risking less in a theory. It is

[3] We will use the terms ‘model specification of theories’ and ‘model’ interchangeably.

important to realize that CLDs as even the least rigorous diagrams in system dynamics represent a stronger specification of theory than is typical in social science at level 3, and that formal simulation models in SD are generally among the strongest theories in Meehl's framework being at level 6 or higher.

## 3. Participation

Participation by community members entails some contribution towards the model building process and the model. As discussed earlier, when there is community participation, there is an expectation regarding increased validity of the model and buy-in for implementation of solutions. To label something participatory thus has its own benefits. But how much participation is necessary to meet such expectations? How much community participation will significantly increase the validity of the model compared to a system dynamicist's model?

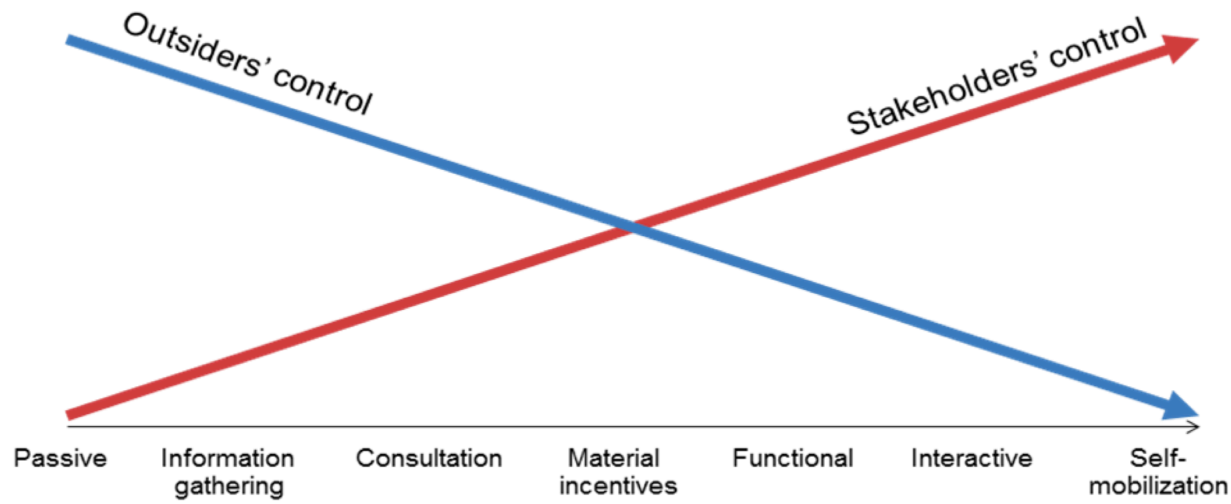
It is helpful to think about participation itself as a process. Kumar (2002) categorizes different levels of participation based on the amount of input and the roles participants play in the process. At one end of the spectrum is "passive participation" where people participate by being mere spectators and receiving information about the model or the model development process. In this case, the model belongs fully to the system dynamicists. In one sense, this is also participation because the model is shared with community members providing opportunities for information exchange about the model, which, depending on the purpose of model development, may be an adequate level of participation. Yet, if stakeholders were only given the problem and information about how the model was built, this does not suffice to increase the validity of the model or make implementation of solutions easier. Collecting data from participants falls on the level just higher than passive participation, which entails people answering questions from modelers and researchers. If the given information then belongs to the modeler or researcher to construct the model (i.e., the participants do not have a role in model formulation, review, or integration), it typically follows that participants do not have ownership of the model, minimizing their control over how the information will be used and published.

At the other end of the spectrum is "self-mobilization," where community members are in full control of the process. Community participants play a major role in defining the problem, developing the process of modeling, and making decisions regarding who to involve in modeling sessions. The results from this process belong to the participants. Because of their active role in the entire process, community representatives are more likely to: share concern about the problem and see the relevance of the problem for the community; identify with the model content and structure, leading to greater critical reflection and feedback about the model during model integration and refinement; and use the model for priority-setting, strategic planning, and implementation.

Participation is a process. It is often easy for people to see how research expertise across different disciplines might plausibly translate into greater comfort with participation in the formulation and refinement of a model, given familiarity with the processes of problem identification, data collection, data analysis, and interpretation of findings. Yet, there is hesitation in considering how community expertise across different sectors (e.g., government, community-based organizations, businesses, residents) relates to the modeling process. Modelers may tend to exaggerate the degree of input by community representatives by defining participation in relatively passive terms, whereas participatory action researchers may insist on active participation, or self-mobilization, where participants are defining problems and acting collectively. Both views tend to be flawed, and ignore the fact that participation is not a static but a dynamic process.

One can imagine a participatory modeling project initiated by modelers, which in the beginning, starts out in the low end of the spectrum with passive participation of community members. The outsiders, or modelers, have control over the decisions related to the modeling process. The community members have control over what information gets shared, how it gets shared, and with whom it gets shared. However, as time goes by, rapport builds up between the two, negotiations arise to develop ways to meet the needs of both groups, comfort increases with shared language and new terminology, and skill-building activities and repetition contribute to greater efficiency in the process. As community members learn more about modeling, they begin to take charge and create initiatives based on the model. As the need for facilitation and technical assistance from the modelers diminish, the community participants increase their ownership over the modeling process and the model, thus traversing the spectrum of participation shown in Figure 2 below.

Figure 2 Changing role of participation. Adapated from Kumar (2002, , p. 25).




The benefit of viewing participation as a process is that it makes it easier to figure out how one starts the group model building process with marginalized communities and makes the long-term intentions more explicit, transparent, and accountable. For example, it is unreasonable to expect that a client organization or community will initially appear with a well-defined system dynamics problem on their own, so there is typically a higher degree of control by the modeling team over how the problem is defined.[4] The problem definition can also be influenced by the funding opportunities that create the impetus and resources for starting the work in the first place. This means that there is a third set of expectations, albeit usually behind the scenes, for

[4] Over time, however, it is quite possible that communities engaged in participatory systems modeling may become quite sophisticated and begin to identify and solve well-defined system dynamics problems on their own.

what can be learned from the model and the modeling process. These expectations have to be factored in to the negotiations between the modelers and the community representatives as well.

However, over time, the participants learn the skills and develop the capacity for identifying and framing problems. If this happens, then it is now possible to imagine that the participants would be able to define their own problems. With more time, it becomes possible to imagine that the organization or community will develop their own internal capabilities for pursuing and advancing system dynamics.

Participation also varies by what we call the "linguistic context" of a group or subgroup, or "language game" to use Wittgenstein's (1958) term. A linguistic context or language game is a set of local rules that determine meaning, criteria for evaluating propositions, communicating speech acts, and so on. In system dynamics, we might call this the mental models of a group or subgroup.[5] For example, when modelers use the term 'bottom-up', we are generally referring to a way of building a computational model characterized by discrete-event simulations and agent-based simulations, where these simulate individual actors. However, in a community context, 'bottom-up' means the equivalent of grass roots, community-driven efforts, or modeling grounded in community experience. The right interpretation of 'bottom-up' depends on its use and the linguistic context of the discussion. The point we want to emphasize is that different participants in a community modeling context operate from different linguistic contexts, and misunderstandings and conflicts can arise by not being aware of how these might influence the ownership of a model.

Table 2 below provides a comparison of the different dimensions related to modeler context, community context, and community modeling context where we practice group model building. These are largely based on our research experience in community modeling, reflecting what we presently believe to be the most salient aspects of what makes a successful collaboration work.

***Purpose:*** Each context has an implicit purpose or goal. For the modeler, it is to understand the problem endogenously whereas for the community it is to solve some problem. The common purpose that allows the modelers and community members to work together is the shared purpose of solving a problem in the community by understanding the problem from an endogenous perspective.

***Perspective:*** Each context also brings a certain perspective. For the modeler, it is primarily a scientific perspective, whereas for the community, it is their experience living and being in the community. In community modeling, the experiences of the community inform the research design, data collection, modeling and analysis, while the science informs the learning and designing of community initiatives.

[5] We prefer the term 'linguistic context' here because we think of this as external and linguistic in nature, whereas the term 'mental model' is too broad and includes cognitions and shared norms in addition to language.

**Table 2.** Dimensions of linguistic contexts in participatory modeling

| ***Dimension*** | ***Linguistic Context*** | | |
|---|---|---|---|
| | **Modeler** | **Community** | **Community Modeling** |
| ***Purpose*** | To understand a problem from an endogenous perspective | To solve a problem in the community | To solve a problem in the community by understanding the problem from an endogenous perspective |
| ***Perspective*** | Scientific | Experiential | Experiences inform research design, data collection, modeling, and analysis; science informs learning and design, planning, implementation, and evaluation of community initiatives |
| ***Activity*** | Researching | Organizing & radical learning | Simultaneous researching, organizing, & radical learning |
| ***Source of topics*** | Scientific meetings and publications, prior research, model, data, analysis | Individual, family, organizational, and community resources and needs | Topics combined, negotiated and prioritized jointly |
| ***Criteria for evaluating the results*** | Scientific rigor, specifically quality of model and insights | Relevance, specifically positive impact on community | Common model that is both scientifically rigorous *and* relevant to community |
| ***Main constraints on collaboration*** | Time | Trust | Time for building trust, and trust for building research capacity and participation |
| ***Factors affecting sustainability of activity*** | Publications, research funding, training of modelers | Community buy-in, positive impact in community, resources for supporting new programs and services | Modeling activities increase capacity in community to design and fund new programs and services, achieve positive impact in community, and create new opportunities for training, research grants, and publications |

***Activity:*** In the modeling context, the primary activities include researching the problem and building the model. In the community context, the primary activities are organizing the community for change and radical learning in the sense of understanding the system and viable actions through dialogue and reflection. In the community modeling context, activities are often designed in such a way that researching, organizing, and radical learning happen simultaneously. That is, in community modeling, one should expect to see activities to varying degrees do all three *at the same time*.

***Source of topics:*** Each context provides a source of topics. Modelers come at issues with questions that are mainly generated from the scientific literature, overarching policy debates, prior research, modeling, and data analysis. Community members bring topics to the table from their own experiences in the community, particularly the resources and needs of the community. In a community modeling context, the different topics are combined and then jointly prioritized and negotiated.

***Criteria for evaluating the results.*** The modelers are generally preoccupied by questions about rigorous modeling, whereas the community is mainly focused on producing results that are relevant and lead to positive change in their community. This distinction reflects Schön's (1983) articulation of the dilemma between rigorous research and relevant relent practice that is characteristic to professions working with "messy" problems like urban planning, nursing, and social work. In the community modeling context, results are evaluated not by how well they achieve one over the other, but how they deal with the pragmatics of balancing both.

***Main constraints on collaboration.*** Collaborations can be difficult in part because different contexts impose different types of demands or constraints. In the modeling context, the most frequently encountered constraint is time (and its antecedent, financial resources). For the community, while time is important, the more pressing constraint is often trust. In the community modeling context, the scare resource of modeling time is used to build trust, and the trust then enables capacity building and participation.

***Factors affecting sustainability of activity***. Each context has criteria that influence the likelihood that the activity can be sustained over time for the "long haul". For the modeler context, this often amounts to funding to support the research and academic products such as books, peer reviewed journal publications and conference presentations. For the community, activities can be sustained with increasing community buy-in that is often achieved through tangible benefits in the community, and resources to support the development and funding of new programs and services to achieve that impact. In the community modeling context, these different sets of factors need to be considered jointly by finding synergies between the modeling context and community context. For example, modeling should lead directly to the design and funding of new programs and services that address relevant problems in communities; and, the implementation of these programs and services can create new opportunities for research, training, and publications.

Having discussed different forms of participation and identifying the linguistic contacts associated with participatory community modeling, we are now ready to return to the main focus of this paper. Specifically, we are most interested in highlighting is nature of participation with respect to different types of transformations of a system dynamics model. Some transformations generally do not warrant concern that they would affect participants' contributions or ownership of a model. For example, revising a model by re-organizing the position of variables is not changing the substantive content of the model. In addition, combining several models into one model by taking the union of the models maintains the integrity of the connections between the original models and resulting union.

However, other types of transformations are more problematic, and identifying these and ways to address them, is the central focus of this paper and the framework we propose. For example, adding structure to a model in an effort to realize a formal simulation model, fixing unit inconsistencies, or adding first order balancing loops may to varying degrees raise questions about the nature of participation in model formulation.

## 4. Formally Defining Relationships and Operations in Modeling

Modeling involves a series of operations or transformations on a model. To make things explicit, we will denote the current status a theory specification or model $M$ as being the *i-th* iteration at level $j$ of theory specification by $M_{i,j}$. This will allow us to talk about relationships between the different iterations of a theory specification or model as well as the different kinds of operations that appear in a participatory modeling process. We provide below an initial list of definitions and operations. The overarching goal of doing this is to be able to distinguish which types of transformations or "moves" in modeling are ones that require some type of participation from those that we would generally not worry about as they do not change the essential character of a model.

***Definition 4.1, model expansion:*** model expansion involves adding model structure to an existing model while keeping the model at the same level of theory specification. We denote model expansion of the model $M_{1,3}$ up to the *k-th* iteration as $M_{1,3}$, $M_{2,3}$, $M_{3,3}$, … , $M_{k,3}$.

***Definition 4.2, entailment:*** The notion of entailment is adapted from logic. The basic idea is that some models have substructures that correspond to substructures of another model. The trivial case is where the two models have essentially the same diagraph but with different names for the variables. The more common and interesting situation to explain is when two models have similar structures where the number of variables, the names of the variables, and only some of the structures appear similar. What we want to capture through the notion of entailment is that where there is commonality between the two models, these take the same basic relationship. Or put differently, if we extract the common model elements allowing only the names to differ, then we can create a one-to-one correspondence between these two structures such that any element being false in one structure would imply the other structure was also false. Formally, we can describe this as, model $M_{i,j}$ entails $N_{l,m}$ if and only if $N_{l,m}$ being false makes $M_{i,j}$ false.[6]

***Definition 4.3, model integration:*** model integration consists of taking two or more models at the same level of theory specification and combining their structures to create a new third model, which has the properties that the resulting model entails the models being integrated. If we are integrating three models, $M_{i,3}$, $N_{j,3}$, and $O_{k,3}$, then the resulting model will be $P_{1,3}$ and $P_{1,3}$ will entail $M_{i,3}$, $N_{j,3}$, and $O_{k,3}$.

[6] Although we can consider the actual one-to-one correspondence between two submodels as a mechanical way of establishing this, it is actually unnecessary. Propositions that are in one model and not the other can be true or false without implication for the other model. So the only comparisons that will lead to a false result are the ones where logical comparison between entities in the model are possible and make sense.

***Definition 4.4, model reduction:*** model simplification consists of eliminating model structures and creating a new model at the same level of theory specification such that the resulting model is entailed in the original model. Specifically, if $M_{i,3}$ is the original model and one reduces $M_{i,3}$ to create $N_{i,3}$, then $M_{i,3}$ entails $N_{i,3}$. We denote the resulting model as a new model because it no longer contains all of the relationships from the earlier model.

***Definition 4.5, model specification:*** model specification involves increasing the level theory specification. Specifically, if $M_{i,j}$ is the original model and one specifies more theory by formulating additional structure, then the resulting model will be $M_{i,j+1}$.

***Definition 4.6, model simplification:*** model simplification involves decreasing the level of theory specification. Specifically, if $M_{i,j}$ is the original model and one removes model formulation, then the resulting model will be $M_{i,j-1}$.

***Definition 4.7, strong equivalence:*** Two models are *strongly equivalent* if they have the same logical implications for equivalent parameters over a given set of conditions. For example, a population model $M_{1,3}$ with one stock that has one inflow controlled by a fractional birth rate and one outflow with a fractional death rate and a model $N_{1,3}$ with one stock a net inflow controlled by a net fractional growth rate, are strongly equivalent because the logical implications (e.g., behaviors that can be generated by the models via simulation) are the same for the same set of equivalent parameters. Models do not need to be at the same level of theory specification for them to be strongly equivalent.

***Definition 4.8, weak equivalence:*** Two models are *weakly equivalent* if they can have the same logical implications while allowing the parameters to vary over a given set of conditions. In this case, the two structures may differ along with the meaning of their parameters, yet they would be considered weakly equivalent if it was possible for every logical implication of one model to be reproduced by the other model.

We do not suggest that this is a complete set of modeling transformations. Providing a complete set of modeling transformations, if such a set could be constructed, is outside the scope of this paper. Instead, we more modestly suggest that these definitions provide a basic language for considering different situations in modeling and discriminate between changes that affect the community ownership of a model from those that do not. To illustrate the framework, we provide a number of examples based on several different research projects.

**Seed Structures.** Participatory modeling exercises can often begin with a seed structure. A seed structure *is* a model in the sense that we have been using throughout this paper. The seed structure can be a CLD or SFD, but typically is the latter and depicts a key stock that defines the problem variable of interest. This seed structure is usually developed by modelers and the core modeling team in a group model building project and needs to be chosen in such a way that it will help a group identify model structures related to the focal problem. Let $M_{1,3}$ be the initial seed structure. The primary question of interest with respect to participation and ownership over the seed structure is whether or not $M_{1,3}$ is adequate for representing the problem variable of interest. That is, does $M_{1,3}$ have face validity among the participants? More precisely, is there sufficient correspondence between $M_{1,3}$ and the way participants define the dynamic problem? If the answer is “yes”, then we can conclude that $M_{1,3}$ is an adequate interpretation of the verbal theory of *the dynamic behavior pattern* (that is, not the structure generating the dynamic behavior pattern, but the dynamic pattern itself). In the case of a childhood obesity model, the question is whether or not the right terms are in the model for articulating phrases such as “children are overweight” or “children are gaining weight”.

**Results from Causal Mapping using Seed Structures.** Participants can contribute model structure through a structure elicitation exercises where participants are initially shown a seed structure, $M_{1,3}$, and then asked to identify relationships that affect the inflows and outflows to the stock or set of stocks, as well as things that are affected by the stocks. In this type of exercise, the model $M_{1,3}$ is projected on a screen via a data projector, presented on a whiteboard, or flip-chart. Participants than suggest variables and linkages. The model expands through multiple iterations until the exercise is complete with the *k-th* iteration: $M_{1,3}$, $M_{2,3,}$ $M_{3,3}$, … , $M_{k,3}$. In this scenario, the initial seed structure, $M_{1,3}$, was provided by the modeler and endorsed by the participation with the subsequent models based on structures provided by participants. This series of *expansions* of a model by participants can reasonably be considered the participants’ model. We expect that the results of this model expansion $M_{k,3}$ will entail the seed structure.

**Multiple Casual Mapping Exercises using the Same Seed Structures.** It is not unusual to seek out and ask multiple stakeholders to participate in multiple causal mapping exercises with one exercise per stakeholder group. Each stakeholder group may begin with the same seed structure, e.g. $M_{1,3}$, The primary motivation for doing this is to replicate the modeling exercise. For example, we may be interested establishing the reliability of the model results. Thus by repeating the exercise with another stakeholder group using the same seed structure, we are able to assess to what extent we arrived at equivalent models. We would denote this as two separate model expansion sequences, $M_{1,3}$, $M_{2,3,}$ $M_{3,3}$, … , $M_{k,3}$ and $M_{1,3}$, $M'_{2,3,}$ $M'_{3,3}$, … , $M'_{l,3}$ for $k$ and $l$ iterations respectively, and then *comparing* the results $M_{k,3}$ and $M'_{l,3}$ to see to what extent they are equivalent. We also expect that $M_{k,3}$ entails $M_{1,3}$ and $M'_{l,3}$ entails $M_{1,3}$.

**Multiple Casual Mapping Exercises using Equivalent Seed Structures.** In some circumstances, the different perspectives of different stakeholders call for the use of the same basic seed structure with language tailored to the specific stakeholder group. For example, in an exercise designed to elicit structure about trends in the unbanked and under-banked, the customer perspective would view the main stocks as ‘unbanked’ and ‘under-banked’ whereas the bank managers would view the stocks with the same referent population as ‘non-customers’ and ‘customers’. The essence of the seed structure in these two groups is the same, but the specific terms differ. Here, our primary motivation is often on triangulating models when we expect that different stakeholders will have different and complementary perspectives on a situation. We write $M_{1,3}$ and $M'_{1,3}$ as the two seed structures, and the resulting model expansions as $M_{1,3}$, $M_{2,3,}$ $M_{3,3}$, … , $M_{k,3}$ and $M'_{1,3}$, $M'_{2,3,}$ $M'_{3,3}$, … , $M'_{l,3}$ for $k$ and $l$ iterations respectively. Our assumption would then be that $M_{1,3}$ and $M'_{1,3}$ are *strongly equivalent*. Should this be disputed or found not to be the case, then we would have committed a methodological error and instead of replicating the exercise with the same process, conducted two different exercises. The result from the two separate model expansions, $M_{k,3}$ and $M'_{l,3}$, could then be *integrated* to create the first iteration of a new model, $N_{1,3}$, which could then be further *reduced* to create $O_{1,3}$. We also expect that $M_{k,3}$ entails $M_{1,3}$ and $M'_{l,3}$ entails $M'_{1,3}$.

**Multiple Casual Mapping Exercises using Different Seed Structures.** Sometimes what we want to do is elicit different structures from stakeholder groups. We do this because we are interested in getting each stakeholder group's view of the dynamic problem they are most familiar with. More specifically, we are interested in understanding how the dynamic problem of interest actually involves several dynamic problems, one from each stakeholder perspective. For example in childhood obesity, the focal problem from a grocery store chain may be declining demand for fresh fruits and vegetables whereas from the residents' perspective it may be the increasing trend in childhood obesity. The system contributing to childhood obesity trends in a community is probably a combination of both facets. However, to elicit structure from each group requires different initial seed structures, $M_{1,3}$ and $N_{1,3}$, resulting in two distinct model expansions, $M_{1,3}$, $M_{2,3}$, $M_{3,3}$, … , $M_{k,3}$ and $N_{1,3}$, $N_{2,3}$, $N_{3,3}$, … , $N_{l,3}$. The results from these two separate expansions, $M_{k,3}$ and $N_{l,3}$, would then be *integrated* to create $O_{1,3}$, and then simplified to create $P_{1,3}$. We also expect that $M_{k,3}$ entails $M_{1,3}$ and $N_{l,3}$ entails $N_{1,3}$.

**Formulating a Simulation Model from a Causal Map.** We create a formal simulation model based on a model from a lower level of theoretical specification by through model *specification* by adding additional structures to the model, specifically the differential equations that will be used by the simulation software. For example, starting with $O_{1,3}$ we create $O_{1,4}$, $O_{1,5}$, … , $O_{1,8}$. We do not consider these new models in the sense of what happens through model integration or reduction, but instead different levels of specification of the same model. With the addition of new structures, we would expect $O_{1,4}$ and $O_{1,8}$ to only be weakly equivalent.

**Formulating and Revising a Simulation Model based on a Causal Map.** Models at a weaker level of theory specification often contain inconsistencies that may only be apparent at a stronger level of theory specification. As a consequence, a common practice is to revise models during model specification. These revisions may include model expansions and model reductions. For example, starting with an initial model $O_{1,3}$, an initial specification step may yield $O_{1,4}$, which leads to the discovery of several inconsistencies and model expansions including $O_{2,4}$, $O_{3,4}$, and $O_{4,4}$, then further specification to produce $O_{4,5}$ and $O_{4,6}$. Through model analysis, we may then realize that the model $O_{4,6}$ can be reduced to create $P_{1,6}$.

**Simplifying a Model based on Simulation Model.** Through model simulations and analysis, we develop rigorous explanations of the structure-behavior relationship for a particular situation. Often we do not present the actual simulation model with equations to audiences, but instead a simplified version of the model. For example, we might take a model $M_{10,8}$ and simplify it to produce $M_{10,3}$. Our expectation would be that $M_{10,8}$ and $M_{10,3}$ are strongly equivalent over the conditions being considered during the explanation.

**Forking a Model Based on a Causal Map.** Sometimes the results from group model building generate interesting pathways for model development that are outside the scope of a participatory process. A typical situation is where the results from the model expansion and reduction from a participatory suggest a generic structure. The results from the initial expansion and reduction yield $Pj_{,3}$, then the formal simulation model that is developed based on this result involves first a step in model reduction to create $Qj_{,3}$, and then model specification to create $Qj_{,9}$.

## 5. Discussion

We are now in a position to discuss the implications of different types of models and different operations on models in terms of participation and ownership of the results. Both entailment and strong equivalence represent relationships between two models that are for all practical purposes the same. Participation in one part of a modeling process, where the resulting models are related to the participants' earlier experience with a model through entailment or strong equivalence, is effectively transitive, and, in principle, each step can be explained to illustrate a one-to-one correspondence between participants' contributions to the model structure and the results.

Problems in tracing the participants' involvement in a model arise when we consider operations such as model reduction and specification. Model reduction and specification involve judgments by someone—a modeler, substantive expert, core modeling team, etc.—about how the model is to be developed. When these judgments are not understood and consented to by community representatives, then it is no longer possible to claim that the resulting models are the participants' models. It is important to state here explicitly that participants may in fact see the modeler as responsible for providing new insights and generating new model structures developed "in the back office" as the inherent added value of their participation in the modeling, but this does not change the fact that it is now the modeler who has created or recreated the model as opposed to the participants.

Of primary interest then is determining what 'consent' means to community participants and this gets at the heart of the distinction we wish to draw here between the substantive modeling expertise and community expertise in the room. In many situations, we are quite happy consenting to an expert handling the details of some activity, whether that is repairing an automobile, performing some medical procedure, or preparing a gourmet meal. In many cases, in fact, we expect these services, and to be brought into a process to deliberate all the detailed decisions would not only raise suspicion, but also create frustration and a sense that one was doing the work of the expert for them. But, the fact that some people may consent to some judgments, or even normally prefer to allow the expert to apply their judgment, should not be taken as form of universal consent.

We anticipate the same types of expectations to emerge from community representatives with respect to modelers using their skills and expertise to facilitate an inclusive process and to provide expert judgment for model development that positively impacts the community. Given time constraints for modelers and community representatives, gaps in linguistic contexts, and a collective sense of urgency for change, particularly in marginalized communities, the ability to maximize participation from modelers and community representatives alike can increase the efficiency and accuracy of the model development process.

Unfortunately, participation is further complicated by community history, funding mandates, local leadership and networks, hidden transcripts, and other relative power advantages. For example, depending on the community's previous experiences with research, there may be resistance to the modeler bringing resources into the community for the modeling project. In many communities, this resistance has evolved from a history of researchers coming in to the community with resources, engaging with the community around projects, and leaving the community after a short time with the resources leaving the communities relatively unchanged over the long term. In addition, modelers may have requirements from funding institutions that do not align directly with community priorities as well as restrictions on the use of funding that prevent resources going in to the community. In some cases, local leaders may or may not be representative of the interests of the community at large.

## 6. Conclusion

We have argued in this paper for a need to more clearly define the types of models we are developing in system dynamics by their level of theory specification rather as opposed to whether they are system dynamics diagrams or formal simulation models. Using the framework presented here, we have then illustrated how a diverse set of modeling activities can be represented more clearly to delineate under what kinds of conditions we should be concerned about losing participants' ownership of a model. We have suggested that potential problems arise in two specific moves in modeling—model specification and model reduction—because they necessarily involve judgments that must be made and impact the correspondence between the results and participants' contribution to earlier stages of the model.

Our resolution to this is to advocate for an explicit negotiation with participants on the nature of these judgments and the rules that guide them. This, we argued, provides an operational understanding of consent as process and enables a specific individual or group to make these modeling judgments accordingly.

The value of the formal framework we have provided supports this negation and shared understanding within the modeling team. In particular, it provides explicit criteria for what types of logical relationships between different models should be expected, and, if violated, indicates a flaw in the modeling process that needs to be corrected. Additionally, notions such as entailment and different forms of model equivalence allow additional criteria to be established and monitored for deviations from the mutually agreed upon process. Equally important, the framework allows for derivative modeling without conflating the participatory modeling with what modelers might see and pursue in a modeling project, and perhaps equally importantly, provides a means whereby participants can take a range of positions from consenting to a process that brings these modeler's models into the overall project to simply seeing these modeler's contributions as potentially interesting but secondary to the primary focus of the participants' model.

Additional work needs to be conducted to expand this initial proposal for a framework since it is largely based on one group's experience. Surely there are additional operations that other modelers apply in constructing models of different types, and a solid framework should incorporate these as well.

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