Boundary Concepts in System Dynamics

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Abstract

This paper explores the use of boundary concepts in the system dynamics modeling process. It draws on the author's experience in teaching system dynamics as well as recent work on boundary objects in system dynamics and studies of best practices in SD modeling. The paper examines the iterative process of model development through the lens of boundary development. Boundaries regarding time, stocks, rates and other variables are considered. Boundary concepts are organized into a taxonomy with types and subtypes. The implications associated with each subtype are specified. An approach to boundary concept utilization, in the iterative model development process, is recommended. Recommendations for extending these efforts are an essential component of this paper.

Keywords: modeling process, boundary objects,

BACKGROUND AND MOTIVATION

Boundary Objects

The motivation for writing this paper has two sources. First, two articles in a recent System Dynamics review. (Black 2013) explores the use of modeling representations as boundary objects and (Martinez-Moyano and Richardson 2013) present the results of a study of best practices in system dynamics modeling. The second motivation is the author's experience in teaching system dynamics modeling as an iterative process.

(Black 2013) draws from sociology, ethnographic studies and cognitive science to explore the use of boundary objects in group model building. "A boundary object, most simply, is a representation – perhaps a diagram, sketch, sparse text, or prototype - that helps individuals collaborate effectively across some boundary, often a difference in knowledge, training, or objective." (Black 2013, p.76). The focus is on the use of conceptual system dynamics representations like the reference mode (dynamic behavior of key variable), stock and flow and causal loop diagrams, and simulating models as a basis for collaboration in model building where participants vary in background. The assertion is that executing the system dynamics process in a group setting facilitates the core framing tasks of understanding the problem, proposing a solution and prompting people to act on a proposed solution (Black 2013, p. 74). The paper identifies another boundary particular to the participatory modeling context - the boundary of methodological expertise between the facilitators and modeler with system dynamics experience and the non-modeler participants. The paper provides both theoretical and practical implications. A number of guidelines for using visual representations as boundary objects are recommended. They include "Keep representations of the problem visible … to remind participants why they want to talk to each other" and "Increase the transparency and transformability of models by inviting participants to develop scenarios that can be simulated." (Black 2013, p. 80 -81). The theoretical contribution centers on a set of exploratory questions that establish a framework for further investigation into modeling practices to construct shared meaning.

System dynamics modeling

A number of research efforts over the years have focused on the system dynamics process including (Trimble, Fey 1991). However, Martinez-Moyano and Richardson, 2013, represents the most recent effort to examine the best practices in system dynamics. It draws on a range of previous studies and is based on knowledge elicitation from 20 experts in system dynamics. “The group of experts that participated in this investigation was composed of presidents of the System Dynamics Society and winners of awards from the Society” (Martinez-Moyano and Richardson, 2013, p. 107). The study uses elicitation questions addressing: problem identification and definition; system conceptualization; model formulation; testing and evaluation; model use, implementation and dissemination; and design of learning strategy/infrastructure. Best practices with high importance and high agreement are identified as well as best practices with high importance and low agreement. Boundary concepts are not a significant part of either group. However, Sterman (2000) boundary selection is listed as part of problem articulation when considering textbook approaches to system dynamics modeling.

Best practices were divided into three levels of importance: Highest, High and Average. The study identified 198 statements of best practice. 14 statements were rated as highest importance with high agreement, 13 of highest importance with low agreement, 17 of high importance and 28 of average importance. None of the 27 statements of the highest importance (high agreement and low agreement) explicitly address boundaries. However, they may implicitly be addressed in: identify the reference modes to be studied; formulate a dynamic hypothesis; consider extreme condition tests while writing model equations and assure dimensional consistency in all equations. Two best practices rated high explicitly involve boundary issues: Agree on the time horizon and appropriate time unit; and make sure the boundary of the dynamic hypothesis is large enough to enable the endogenous point of view. The paper concludes that more work needs to be done in exploring and developing best practices in the system dynamics process.

Teaching system dynamics

Boundary identification has been an explicit part of most system dynamics instruction in two instances. The time horizon has been identified as an important aspect in the modeling process. “How far in the future should we consider? How far back in the past lie the roots of the problem?” (Sterman 2000, p.86). This is a precise time boundary placed on the system in constructing the model.

The second instance of addressing boundary is with the distinction between endogenous, exogenous and excluded variables. Sterman (2000) makes use of the model boundary chart to emphasize the differences. Ford (2009) makes use of the Bulls eye diagram to group the variables into these three categories. The center ring of the Bulls eye diagram contains the endogenous variables, the middle ring contains the exogenous variables and the outer ring the excluded variables. While excluded variables are clearly outside the system (a part of the environment), exogenous variables lie on the boundary. They are in the system but are not controlled by the dynamics of the model. The endogenous variables change based on the dynamics of the system and are the basis for studying how to control or improve system performance. This distinction in variable type is the physical system boundary highlighted in most system dynamics modeling processes.

In system dynamics models, a second type of physical system boundary is represented by the cloud icon. In the case of inflows from a cloud, a variable flows into the system from the environment. In the case of an outflow with a cloud, a variable flows out of the system into the environment. The model is not concerned with where these flows come from before they enter the system or where they go when they leave the system. As the stock and flow diagram is treated as a boundary object, these boundary points should be focal points of discussion among the stakeholders in the system dynamics modeling process.

The iterative process of developing the system dynamics model is facilitated by examining the boundary concepts as a source of model refinement (Trimble 2013). Excluded variables may be added to the model. Extensions to the model may convert exogenous variables to endogenous variables. Adjustments may be made to the time horizon to account for delays in the system that effect the dynamic hypotheses. If concerns arise over the source of a flow emanating from a cloud, this boundary can be expanded by including another stock. Also an additional stock may be added, if stakeholders decide that the stock exited from an outflow into a cloud should be considered part of the system. This iterative process guided by boundary concept examination should be used in teaching systems dynamics.

METHODOLOGY

The methodology used defines a theoretical justification and an organizational approach. The organizational approach steps through several iterations of developing a simple system dynamics model, at each stage examining the boundary concepts. At the start of the first iteration a scenario of the problem situation is presented. Each stage of the modeling process refines and expands this scenario. The boundary concepts are the basis for exploring alternatives to expanding the model and the associated scenarios.

The theoretical approach is an effort to establish relationships with the different boundary constructs along with the concept of boundary objects. The development of a generalized taxonomy of boundary concepts with an associated iterative approach to model building is the goal of this effort. This theoretical approach is based on general systems theory.

> "General Systems Theory is a name which has come into use to describe a level of theoretical model-building which lies somewhere between the highly generalized constructions of pure mathematics and the specific theories of the specialized disciplines. … It studies all thinkable relationships abstracted from any concrete situation or body of empirical knowledge." (Boulding 1956, p.197)

DISCUSSION AND RESULTS

The first simple system under study is a small hypothetical boarding school of 500 students. Each flu season the school has to deal with a high number of flu cases due to the continuous contact among students and staff. In this region the flu season is typically four months. The time horizon is set for 120 days. This is the first instance of a boundary construct. The model time step (dt) is set to 0.125 and the flu data is collected and posted at the beginning of each week (every 7 days). Both, of these quantities also represent time boundaries. Figure 1 is the simplest representation of this situation. New sick students add to the number of sick students and students recover reducing the number of sick students. These rates are exogenous and represent a boundary with the environment. This simple model has two stock boundaries represented by the cloud at the beginning of the inflow and the cloud at the end of the outflow. The cloud displayed at the beginning of all singly attached inflows and the end of all singly attached outflows represents a stock boundary. In figure 1 the model is not concerned with where the sick students come from or where they go when they recover. They come from the cloud or leave through the cloud, which represents the boundary with the model environment. This simple stock and flow diagram is a boundary object shared by model developer and other stakeholders. They can engage in discussion over further development of the model by concentrating on the boundaries of the model. Should the time horizon be extended or should the data collection time frame be changed?

Should the inflow boundary be addressed and should the outflow boundary be addressed? Should what determines the 'new_sick_students' and 'student_recovered' rates be addressed?

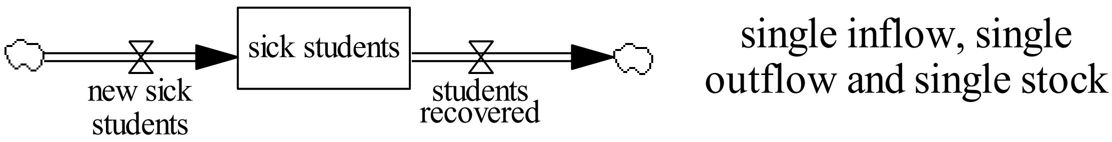

Fig. 1 Initial Model of 'sick students'

The initial scenario is extended to address the concern over the source of sick students as well as the destination of students that recover. This is a simple matter. The model update leads to figure 2. Both clouds are eliminated by creating a circular flow pattern where well students can become sick and sick students recover and become well students. This model has no stock boundary. The stock reflects the closed system nature of this school. The 500 students repair on campus throughout the school session and flu season. Also the model in figure 2 has added links to the two rates creating feedback loops. In both cases the links indicate the stock positively impacts the flow. The two flows now appear endogenous.

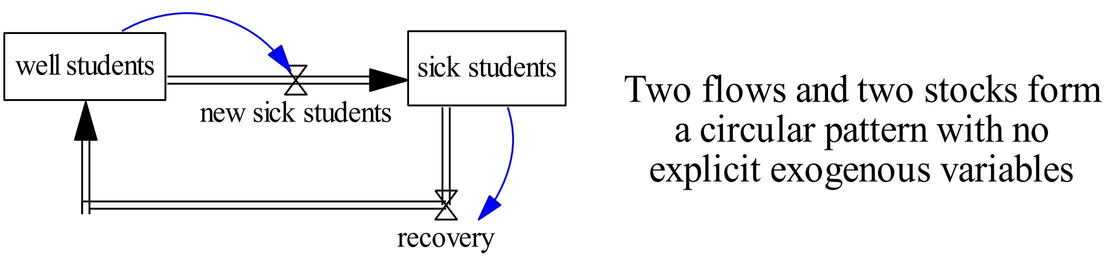

Fig. 2 Model from second iteration

Realizing that other factors influence both rates in the figure 2 model other variables are added to reflect the process of contagion and the process of recovery. Also, it is pointed out that the flu can be fatal so an outflow accounting for flu fatalities is added to the model. We now have two additional endogenous variables and three exogenous variables. The three new exogenous variables as well as the outflow cloud from the deaths flow can be boundary objects used to explore model expansion and revision. These scenario changes are displayed in Figure 3

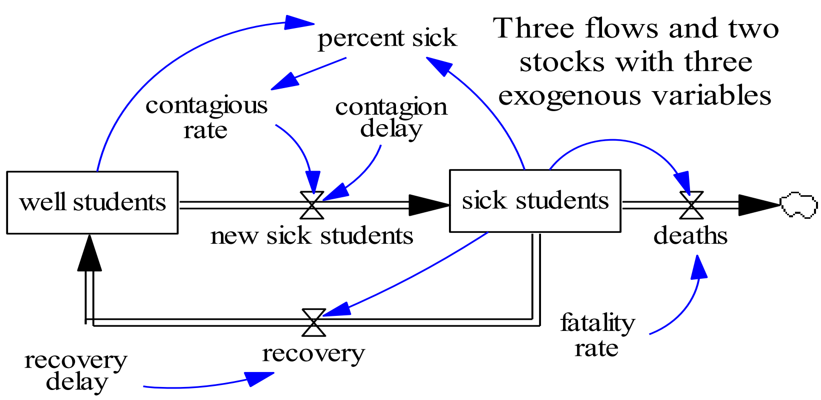

Fig. 3 Model from third iteration

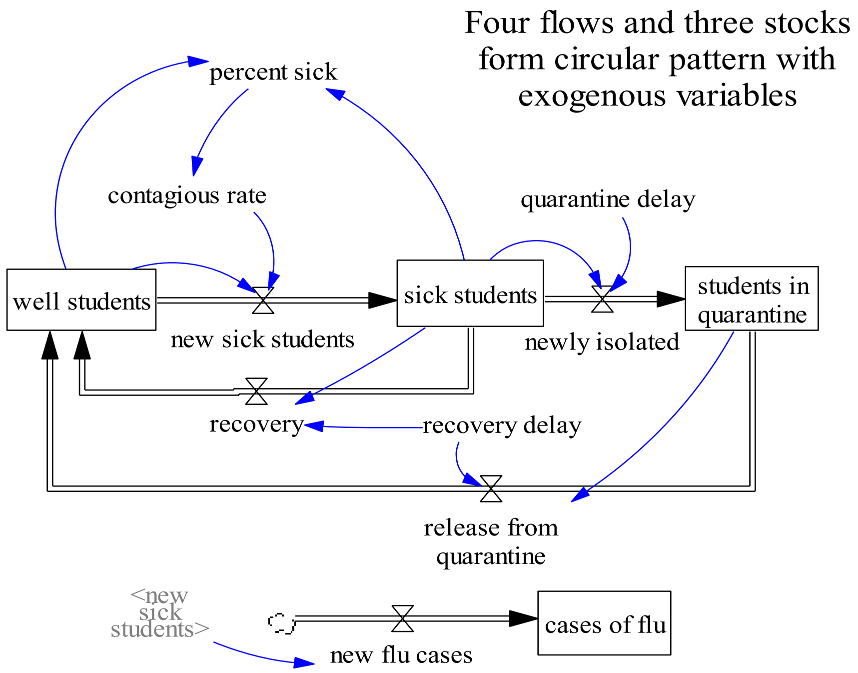

Fig. 4 Model from fourth iteration

In the fourth iteration (Figure 4) we have eliminated the outflow for flu deaths because it proved negligible justifying the aggregation in the model. The policy of quarantine for students with the flu is put in place removing a large number of students from exposure to well students reducing the contagious rate and reducing the number contracting the flu. This model with three stocks has internal boundaries between well, sick and quarantined students. The decision to keep track of the cumulative number of flu cases required the construction of a simple sub-model that consists of a single flow and stock. The 'cases of flu' stock is effectively documentation of the total number of flu cases to date. It is not a student unit like the other three stocks. A new flu case is documented for each new sick student. The cloud boundary on this inflow indicates we are not concerned from where the new flu case documentation comes from. The flu case subsystem is connected to the main system with a link to the 'new sick students' flow. This connection represents an internal boundary (or border) that can be the basis of further investigation. The two exogenous variables 'quarantine delay' and 'recovery delay' represent a physical boundary with the environment and can be the basic of further expansion of the model.

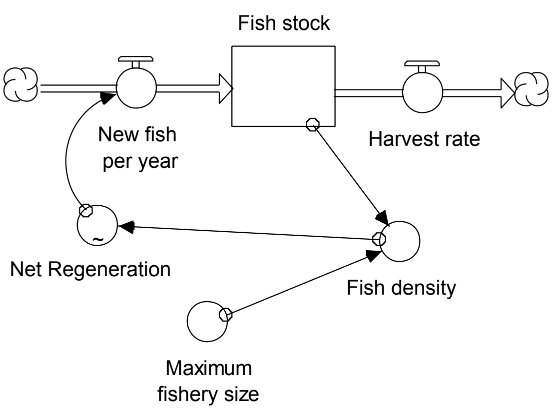

Fig. 5 Initial Stella model of fishery

The fishery models in figure 5 and 6 are based on models from (Morecroft 2011). This is a model of a fishing community with a fixed capacity for fish stock (limits to growth). The initial model in Figure 5 has inflow and outflow boundaries on the fish stock as well as an exogenous variable 'Maximum fishery size'. In this case the undefined 'Harvest rate' also represents a boundary. In this initial model 'Harvest rate' is first set to a constant then a slider input device (Stella feature) is used to allow for different harvest rates. In both cases the setting of harvest rate is exogenous. This is an exogenous variable boundary. This model allows for a longer range time horizon that the previous model of sick students and can also take into account the historical pattern of fish harvesting.

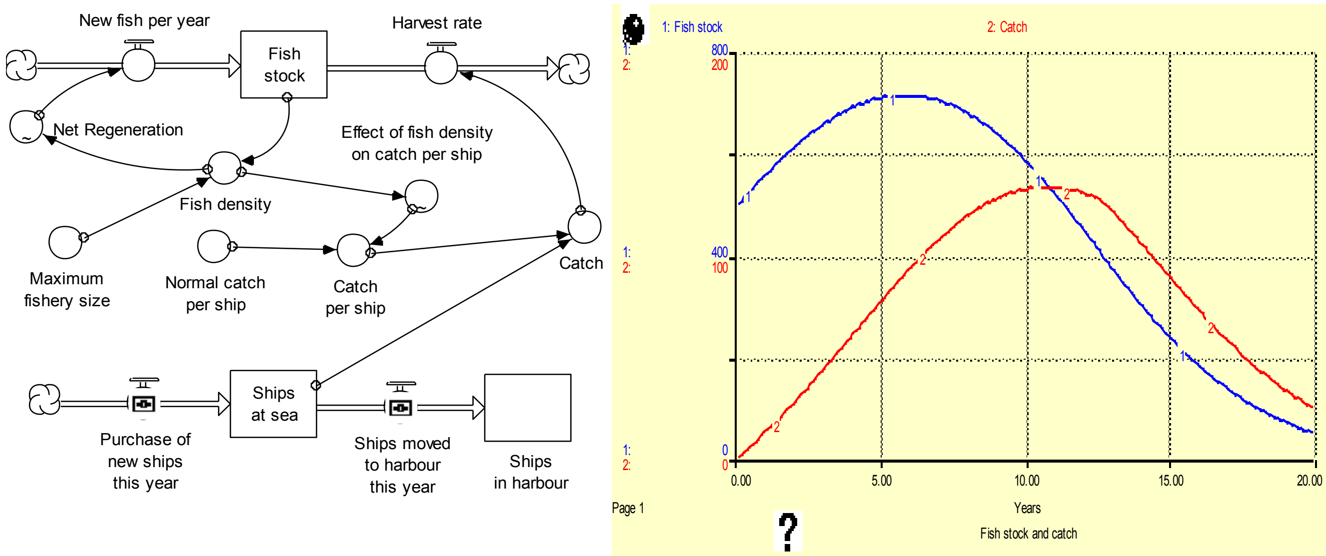

Fig. 6 Final Stella model with Graph

Figure 6 makes several modifications to the initial model. The harvest rate is based on the fish catch. The fish catch is based on the catch per ship and the number of ships at sea fishing. This requires the addition of several endogenous and exogenous variables as well as a sub-system to account for the fishing ships. In this case we are not concerned with where the harvested fish go. The effort concentrates on the dynamic between fish harvested and fish stock over time. The ships sub-system is connected to the main system by a link to catch. This is a border or subsystem boundary. The graph in figure 6 provides insight into two of the three dynamic transition boundaries. Shortly after five years the fish stock hits an extrema point and the stock begins to decline. At this same point the first derivative of the catch variable reaches an extrema (the slope of the curve is at its maximum). These represent boundaries of concern regarding the dynamic behavior of the system. The ships sub-system has an inflow indicating new ships put to sea and an outflow indicating ships retired to harbor. The model is not concerned with the source of the new ships as indicated by the cloud associated with the inflow. However, the model does track the ships returned to harbor with a stock at the end of the outflow. The model uses slider input devices for both of these flow variables to allow for model experimentation. These flows are considered an exogenous variables since their values are not determined by variables in the system. However, policy decisions can dictate the number of ships allowed to fish. This makes the use of slider input devices ideal for exploring policy options over the years. In Stella this model also allows the specification of a 'pause interval'. This is a time dimension boundary that pauses the model after a given interval. It allows further model experimentation.

These two examples are for demonstration purposes. More realistic models would take into account a number of additional variables, particularly factors that would influence or modify human behavior over time.

Taxonomy of boundary concepts

The different boundary concepts discussed in the two examples of system dynamic model development are captured in Table 1 below. Five types of boundary concepts and fourteen subtypes are defined. In each case a short explanation of the implication of the boundary concept is provided. This is viewed as a preliminary effort and merits much more investigation. It is an initial attempt to add order to the notion of boundaries and borders in a system dynamics model.

Table 1: Taxonomy of system dynamics boundary concepts

TYPE	SUBTYPE	IMPLICATIONS
Primary physical boundary	Exogenous variables	These variables are not controlled by the feedback dynamics of the model. They are often based on historical or statistical information. Is it possibly to make meaningful model modifications that would make them endogenous?
	Inflow clouds	The Source of the inflow is outside the model
	Outflow clouds	The outflow leaves the model
Time boundary	Time horizon	Capturing the past can allow a historical reference mode that can match historical data.
	dt	Will impact speed of processing model and accuracy of model
	Pause interval	Pause to examine model values and make adjustments
	Data save interval	Reduces data stored and presented, but can impact displayed accuracy of graphs.
Internal physical boundary	Transition in stock variable	Wide range of stock transitions, flow from one stock to another can be an aging process or more transformative.
	Borders between subsystems	Subsystems have distinctly different stocks and are connected by informational links
Dynamic transition boundary	Extrema point	Local minimum/maximum or global minimum/maximum. Represents a point where there is a shift in the dominant feedback loop.
	Extrema of 1^{st} derivative	The flow goes from increasing to decreasing or decreasing to increasing. This is a qualitative change.
	Point of inflection	Unstable equilibrium point
Variable bounds	Input bounds	Establishing the reasonable or acceptable range for a variable will assist in sensitivity analysis
	Bounds on results	Given sensitivity analysis what is an acceptable range for results?

CONCLUSIONS AND FUTURE EFFORTS

The taxonomy on boundary concepts will be used by the author as a teaching tool to help explore the iterative process of system dynamic model development. It will be used to foster more discussion on the components of the system dynamics model and a better understanding of their interactions. More work is needed on refining the taxonomy. This study used simple demonstration models to provide a proof of concept. The refinement of this process requires its application to robust real life systems.

Also, the development of an iterative process for model development requires more discussion on what to emphasize in each stage of the model development and implementation life cycle. These discussions must be held in the context of further investigation of best practices in the broader system dynamics process. Any concern with improving the instructional process must be grounded in providing better training for system dynamics practitioners.

There is a continued need to place system dynamics in the broader context of decision support (Trimble 2011) and policy studies (Trimble 2012). There is the opportunity to study both system dynamics boundary concepts and visual boundary objects (Black 2013) within this expanded arena. This will open the system dynamics field to a broader audience and improve the skills of system dynamics practitioners. Further work is needed in linking these concepts to the process of knowledge elicitation in working with various stakeholders in developing system dynamics models. Finally there is space for more work on the theoretical relationships between boundary concepts and the philosophical and ideological underpinning of system dynamics.

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