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SYSTEM DYNAMICS: A SOFT AND HARD APPROACH TO MODELLING

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ABSTRACT

System Dynamics (SD) can be employed for qualitative and quantitative modelling. There are important tools and methods within SD that can be easily accommodated within qualitative modeling, also known as Soft Operational Research or problem structuring method. While traditional stocks and flows are the basic components of quantitative SD modeling, quantitative SD modeling shares many commonalities, e.g. empirically driven, thorough testing, and critical focused to outputs, with traditional simulation methods and quantitative Operations Research tools. This tutorial informs novice modelers on the aspects to consider when they want to use SD as a qualitative and quantitative modeling method. In any approach employed, the use of SD modeling needs to be grounded in relevant literature from the perspective employed, qualitative or quantitative.

1 INTRODUCTION

System Dynamics (SD), founded by Jay Forrester at MIT in 1957 (Lane 2006, 2010), is considered both a quantitative and qualitative method for exploration and analysis of complex systems (Kunc 2017). SD modeling involves discovering and representing the feedback processes, which along with stock and flow structures, time delays and nonlinearities, determine the dynamics of a system. Most complex behaviors observed in systems usually arise from the interactions (feedback) among the components of the system (Sterman 2000).

Quoting Lane (2000, page 4), “As a modelling approach, system dynamics has three characteristics. First is the concept of information feedback loops. These involve the collection of information about the state of the system, followed by some influencing action which changes the state of the system. These closed loops of causal links involve delays and non-linearities as well as processes of accumulation and draining. The second characteristic is computer simulation. Although humans can conceptualize such loops, they lack the cognitive capability to deduce the consequent dynamic behavior without assistance... Computer simulation is therefore used rigorously to deduce the behavioral consequences over time of the hypothesized causal network. The shifting interplay of loops means that different parts of a system become dominant at different times. Such behavior is counterintuitive, and may be explored using simulation models. The third and last characteristic of system dynamics is the need to engage with mental models. The most important information about social situations is only held as `mental models', not written down. These mental models are complex and subtle, involving hard, quantitative information and more subjective, or judgmental aspects of a given situation... Hence, eliciting, debating and facilitating change in the mental models of decision makers can result in improved ways of managing a system. Modeling work must therefore be done in close proximity to problem owners, who are then able to see that their mental models are reflected in a computer model.”

Using SD qualitatively involves focusing on discovering the feedback loops to describe a dynamically complex system. In this case, the use of tools such as causal loop diagrams (CLD) (see table 1 for an explanation), and in some occasions stocks and flow networks, without quantitative modeling is enough to provide insights for decision makers (Lane and Husemann 2008; Kunc and Morecroft 2009). Using SD quantitatively implies the development of a 5-step process (Sterman 2000) starting with a dynamic hypothesis about a structure responsible for the performance over time observed in the system followed by model formulation, testing and experimentation. Another important characteristic of SD is the suitability to model development using either isolated or participative model building processes.

Table 1: SD Modeling Steps and Tools Used for Qualitative and Quantitative Perspectives.

Basic steps for qualitative SD modeling	**Five-stages for quantitative SD modeling**
Since the main objective of qualitative SD involves discovering the feedback loops, usually with clients through facilitated workshops, the main tool employed in qualitative SD modeling is CLD. The steps for developing CLDs are: • First, understanding the direction of causality between two variables is usual a source of important discussion among participants in facilitated model building. This is indicated by an arrow between both variables in a CLD. • Second, polarities indicate the relationships between two variables: a positive sign indicates that an increase or decrease in a variable causes an increase or decrease in the related variable. This information can be associated with the first derivative of the related variable is positive or the slope of the line is positive in a regression equation. If the sign is negative, a change in a variable will cause a change in the opposite direction in the related variable. Therefore, the first derivate of the related variable is negative and the slope of the line in a regression equation is negative. SD models are based on causality not correlation between variable. • Third, feedback processes are formed by connecting multiple variables in a chain of cause-and-effect. The chain starts and ends in the same variable, or the outputs of a system are transmitted back as inputs. There are two types of feedback processes: "R" denotes a reinforcing feedback process so positive polarities are predominant, and "B" indicates a balancing feedback process where there are odd negative polarities.	The modeling process for a quantitative model has five steps (Sterman, 2000). • The first step involves defining the boundary of the model through identifying the key variables, time horizon (past, present and future), and the reference modes (behavior) of the key variables. • Secondly, modelers start describing the structure, using stock and flow diagrams or policy structures, to explain the reference modes. • The third step is the formulation of the model. Formulating the model implies specifying the stocks and flow and causal linkages between stocks, flows and auxiliaries variables in the modeling software. Then, equations are developed for each stock, flow and auxiliary variable and parameters, non-linear functions and initial conditions are estimated or calculated from existing data. Finally, diagnostic simulations are performed to verify the consistency of the results. • The fourth step comprises extensive model testing in terms of dimensions, fit with historical behavior of key variables, robustness under extreme conditions and sensitivity. • The final step is the design of policies and experimentation with the model through changes in parameters, feedback processes, what if and decision rules.

To summarize, SD has two basic modes of interventions. First, an essentially descriptive mode, qualitative modeling, in a similar fashion as problem structuring methods (Checkland 1985). Problem structuring methods are considered soft perspectives in Operational Research because they aimed to describe the system without recourse to quantitative data (Checkland 1985), Second, a predictive/prescriptive mode, like regression, forecasting, discrete event simulation and optimization methods, which can be considered a hard Operations Research perspective because it uses a quantitative approach to obtain solutions. SD modeling can also be considered a behavioral modeling method since it involves strong participation of the client on the definition of the model, measurement of the changes in behavior during the project and representation of bounded rational decision makers in their models (Kunc, 2016)

The two modes of interventions in SD are discussed next before presenting two examples that describe the two approaches for novice modelers. The discussion is based on a particular and limited perspective on this debate and additional research has been performed by other scholars such as Lane and Oliva (1998), Wolstenholme (1999), and Lane (2000) .

2 LITERATURE REVIEW

2.1 A comparison between hard and soft perspectives in SD

The next section discusses some authors' perspectives on soft and hard SD.

Table 1: A Comparison between Soft (qualitative) and Hard (quantitative) perspectives in SD.

Author	Soft Perspectives	Hard Perspectives
Forrester (1994)	Understanding of an undesirable system behavior drives the modelling process. The discussion of the understanding leads to an ideal future for the system by solving conflicting viewpoints. This perspective is contingent to the specific project and the owners of the problem. The most difficult step is the implementation of the recommendations since it involves education and debate across the people working in the system.	A simulation model, based on stock and flow, eliminates the inconsistencies existing from a general understanding of the system. A model is a theory of behavior and how some part of the real system works. Formulation implies theory building. Simulation models are employed for the testing of policy alternatives. However, automatic parameter searching (e.g. optimization) is limited because the best alternative arises from changing the structure of the system not optimizing it.
Homer and Oliva (2001)	A soft perspective, or systems thinking, is based on qualitative analysis without quantitative modelling. Qualitative analysis involves the use of CLDs to describe a system in more detail and lead to stand-alone policy analysis. The intention is to improve the thinking about a structure behind a problem. There is no development of dynamic hypothesis to explain the reference mode.	Modelling is utilized to perform an empirical test of a hypothesis about the structure responsible for the performance over time observed in selected variables. Thus, modelling is aimed to comply with empirical traditions in social science CLDs are employed before the development of the model to define the causal mechanisms and they complement a quantitative model

The soft perspective argues the value added is generated through the modelling process since models are made to organize, clarify and unify knowledge (Forrester 1987), which is also a usual assertion in the problem structuring methods field (Checkland 1985). When SD is employed as a problem structuring method, the objective is to represent the system structure and communicate it to relevant stakeholders. One of differences between SD and problem structuring methods is the SD tools for the description of the system can lead to a quantitative model (Forrester 1994).

Under the hard perspective, SD employs numerical data to calculate parameter values, characterize system behavior (reference modes), and to compare with model output (Forrester 1987). This behavior does not differs from the use of numerical data by other modelers. Moreover, the quantitative model is to test a hypothesis about the dynamics observed in the reference modes of the critical variables under study. A key difference between SD and other quantitative methods is the efforts to identify all causal mechanisms responsible for the behavior of a model made by the modeler. Therefore, SD is mostly a deterministic modelling approach (Kunc 2017).

Table 2: A Comparison between Qualitative (soft) and Quantitative (hard) perspectives in the modeling process.

Modeling process	Qualitative SD	Quantitative SD
Objective of modelling	Understand the feedback structure of the system.	Test a hypothesis about the structure driving the reference mode of the variable under study.
Inputs	Text data obtained through facilitated face-to-face meetings, interviews or the interpretation of causal mechanisms in reports and from theories.	The structure of the model is developed using similar inputs employed in qualitative SD. Additional data for the model can take three sources: judgment from experts or clients, numerical datasets for parameters and facilitation processes for nonlinear functions.
Process	The modeling process implies the construction of causal loop diagrams to represent individual and/or group-level interpretations of causal links. Facilitation processes are critical to uncover the causal links.	After defining the boundary of the model, a stock and flow diagram is developed. Then, equations are formulated and parameters populated using the inputs mentioned previously. Testing of structure and outputs are performed to confirm the hypothesis that the structure is able to replicate the behavior observed.
Outputs	There are three main outputs: learning about the structure of the system, changes in participants' perspectives, and agreement on future policies.	There are three outputs. First, time series showing performance over time of relevant variables. Second, policies are tested quantitatively to improve the reference mode. Thirds, learning about dynamic behavior of the system.

3 EXAMPLES OF SYSTEM DYNAMICS PRACTICE FROM EACH PERSPECTIVE

3.1 An example of SD using a soft (qualitative) perspective

Hwang and Kunc (2015) developed a qualitative model describing the dynamics of wine bars. The objective of the model was to obtain deeper understanding of the business model followed by wine bars. The inputs for the model came from two sources. First, an extensive review of the literature describing the operations of wine bars in general. The objective of the literature was to determine the main elements of the business model as well as the issues affecting the performance of wine bars. Second, the authors interviewed six managers from different wine bars. The managers had daily contact with customers, plan the wine lists and order new wines. The wine bars covered different styles but they were mostly small.

The interviews generated a set of different textual explanations of the business processes. The task of the researchers was to analyzed them together to find similarities in concepts and causal linkages. Then, the common concepts and their linkages were mapped in a CLD. See figure 1. Quoting Hwang and Kunc (2015, pages 245-246), "The process driving the dynamics of businesses is embedded in a positive feedback loop (see feedback loop B in figure 1), where a rise in service quality due to knowledgeable staff positively improves customer satisfaction. Higher customer satisfaction increases staff motivation, as staff feels rewarded by the comments from customers, improving service quality even further due to higher levels of confidence. There is an important linkage of the feelings experienced by customers with service perceived. The positive effects of customers' satisfaction, expressed as positive word of mouth, increase the number of customers and contribute to increasing the wine list length and diversity to keep the demands from new customers, experienced our interviewees. The wine list diversity increases customer satisfaction as they have more choices reinforcing the growth of the wine list (positive feedback loop D in figure 1) and augmenting word of mouth bringing more customers….A negative feedback loop (C) reflects the limitations in service firms due to the limits in the front-line employees. Thus, staff training is viewed as an important investment."

The CLD was shown to the managers to validate its structure.

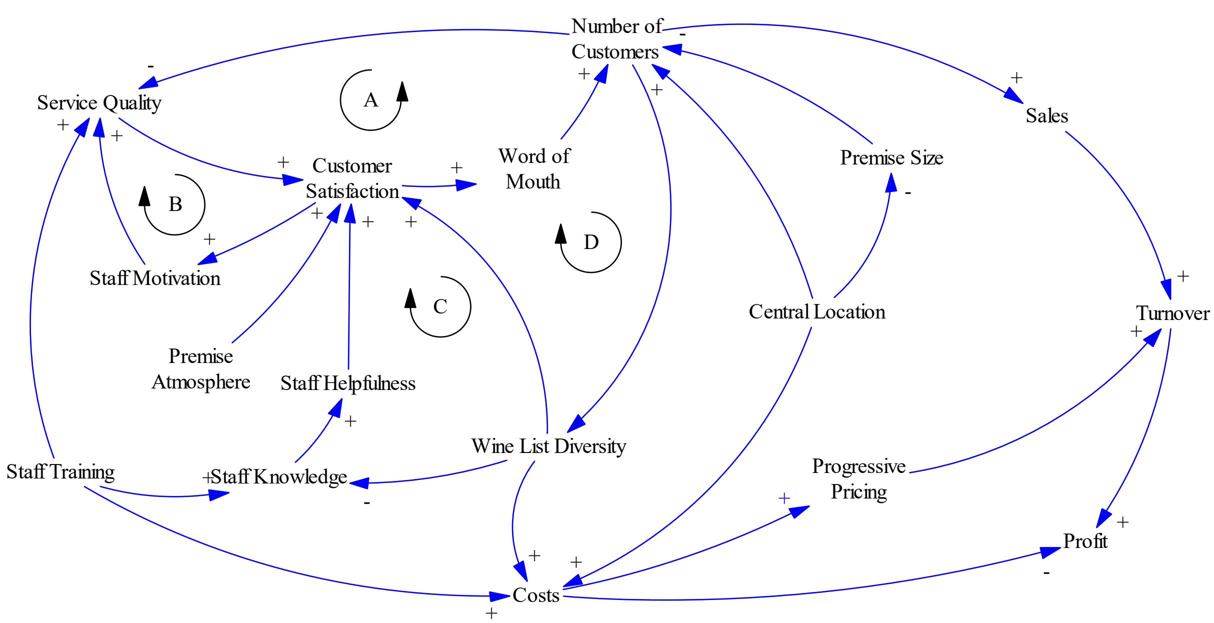

Figure 1: Wine bar business dynamics (Hwang and Kunc 2015, figure 1, page 245).

One remarkable insight from the CLD and the verbal description of the feedback processes was the existence of a number of soft, hard-to-measure, variables, e.g. staff motivation, levels of confidence, customer satisfaction with line list. While there would be opportunity to collect data if there was enough time (a year?) and resources, it was valuable to understand the dynamics of the business in a short period of time.

A final stage of the process involved the discussion of variables and the range of values. This was not a usual step in qualitative SD but it was beneficial to provide not only a systems perspective of the business but also infer the data that can be expected to obtain in case of a quantitative analysis of a wine business. Table 3 shows an excerpt of the information.

Table 3: Description of variables and values for the business dynamics model of wine bars (table 3, page 247, Hwang and Kunc 2015).

Variable	Description	Values
Progressive pricing	Progressive pricing is where the margins applied to the range of wines change inversely. More expensive, fine wines are priced with significantly lower margins than the cheaper, everyday wines. Other factor is the costs to run the business.	(Price margin, % sales) High price (£77): 1.20, 5% Medium price (£27): 1.35, 55% Low price (£13): 1.45, 40%.
Staff knowledge	Knowledge about wine and the wine list: general knowledge from the origin, vintage and tastes to what food make a good marriage with the wine	Partial quadratic curve based on the size of the wine list is a good approximation to the amount of knowledge and training required.

Then, some implications for the management of the business were offered from the interpretation of the CLD. For example, the management of wine list was critical on wine sales. The size of wine list impacted on the level of service and profits. While success, due to good service, might increase wine list, rapid growth of the list increased costs hurting profits. Therefore, wine specialization, as a way of market positioning, could curtail this feedback process.

To summarize, qualitative SD was employed to describe a system and its components from textual data obtained from interviews and theories (Kunc and Morecroft 2007). The main objective was to provide a broad understanding of how the business work and the potential data that can be observed for each of the concepts belonging to the qualitative model. No additional task was performed.

3.2 An example of SD using a hard (quantitative) perspective

This example is based on a project for a financial services firm that was aimed at providing support on human resources strategies (Kunc 2008). Human resources' tensions in the professional firm originated due to short-term (market demand and firm profitability—a static equilibrium issue) and long-term issues (organizational structure and professional development—a dynamic equilibrium issue) affecting the professional staff in the firm. These tensions could only be analyzed using simulation given the dynamic complexity, such as hiring, promotion and leaving flows, existing in the organization (Kunc 2008). In SD, there is a common stock and flow structure to represent organizational structures called "aging chain". The stock and flow structure in figure 2 shows the structure of the firm where the different staff categories in the company were reflected as stocks and the human resources' processes as flows. Each staff category was a box in figure 2 to reflect the accumulation resulting from the diverse dynamic processes, e.g. hiring and leaving flows. In SD, a stock is an integral equation that captures the difference between inflows and outflows. In this case, the number of novice staff was equal to the number of novice staff hired less novice staff leaving the company less the staff being trained to become intermediate staff.

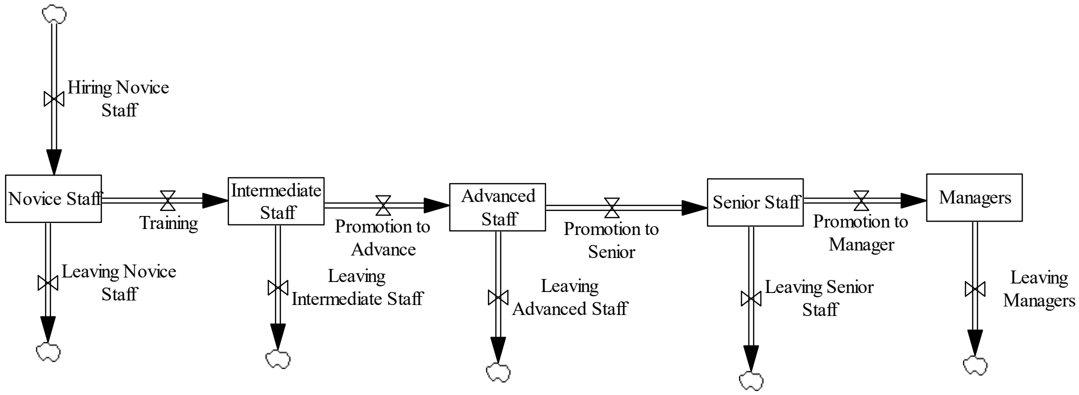

Figure 2: Basic staff dynamics represented using SD.

One of the initial insights from this case was the difficulty to obtain any valuable information unless there was a fully quantified model. The dynamic complexity originated from the processes of accumulation and draining not the feedback loops. Once the stock and flow was generated, additional data, see table 4 below, was necessary to calculate the organizational structure over time and the outputs of the firm. For example, each member of the manager category used their time in three activities: project acquisition, supervising staff, hiring and training with different proportions. When the project required to calculate the amount of time used in each activity, it was simply a multiplication between the number of members in each category and the number of hours devoted to each activity. Then, the demand for their time was obtained, as shown in table 4 bottom part, multiplying the amount of activities by their required time. In other words, a static equilibrium was obtained easily using an excel spreadsheet. However, the complexity was to extrapolate the present situation into the future considering all the human resources processes.

Table 4: Description of variables and values for the dynamics of professional firms model (tables 3 and 4, page 125, Kunc 2008).

			Time available per task						
	Number of staff	Days available per month	**Training**	**Hiring**	**Project Acquisition**	**Supervising**	**Simple Projects**	**Complex Projects**	**Total**
Managers	2	37.00	6	4	19	9	-	-	**37.00**
Senior staff	0	-	-	-	-	-		-	**-**
Advanced Staff	2	35.00	4	4	-	-		28	**35.00**
Intermediate Staff	9	157.50	-	-	-	-	63	95	**157.50**
Novice Analysts	2		-	-	-	-	-		**-**
TOTAL	**15**	**230**	**9**	**7**	**19**	**9**	**63**	**123**	**230**

	Simple Projects	Complex Projects
Time in analyst/days per project	7	14
Number of projects feasible per month	9.0	8.8
Number of projects feasible per year (based in 10-months)	90	88
Total number of projects in 2004	70	70
Total number of expected projects in 2005	91	91
Total number of expected projects in 2006	118	118

To compute the dynamics of the staff categories and obtain a long-term equilibrium, it was necessary to simulate the size of organization and its capacity to manage future demands using the SD model(Kunc, 2008). Figure 3 shows the structure of the organization after 60 months in the base case scenario for the example shown above. One of the key outputs of quantitative SD was the representation of the dynamics using time series, or performance over time, where each line reflects the dynamics of a corresponding staff category. Figure 3 shows an unbalanced organization with mostly novice staff due to their hiring and promotion policies. Figure 4 shows the dynamics of a balanced organization obtained by improving the promotion and retention policies in intermediate staff. Figures 3 and 4 show a traditional output from a SD software.

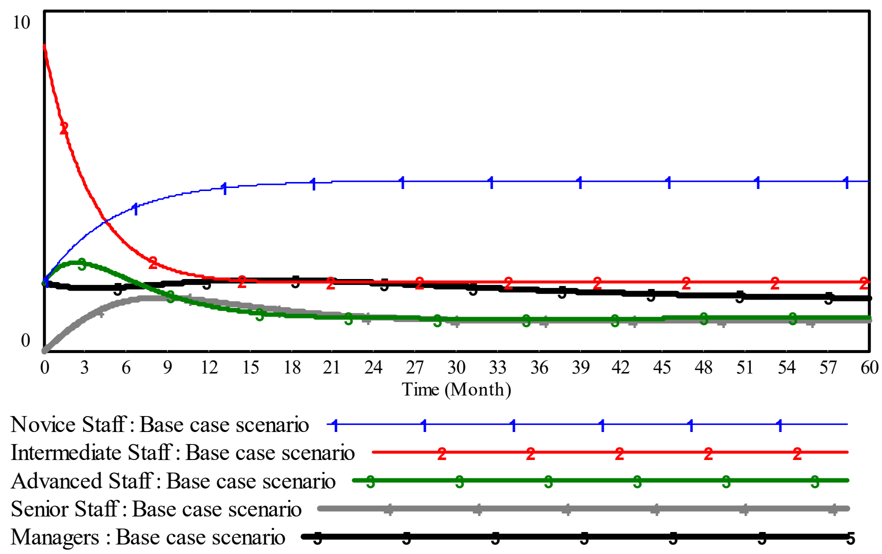

Figure 3: Staff categories dynamics – Base case.

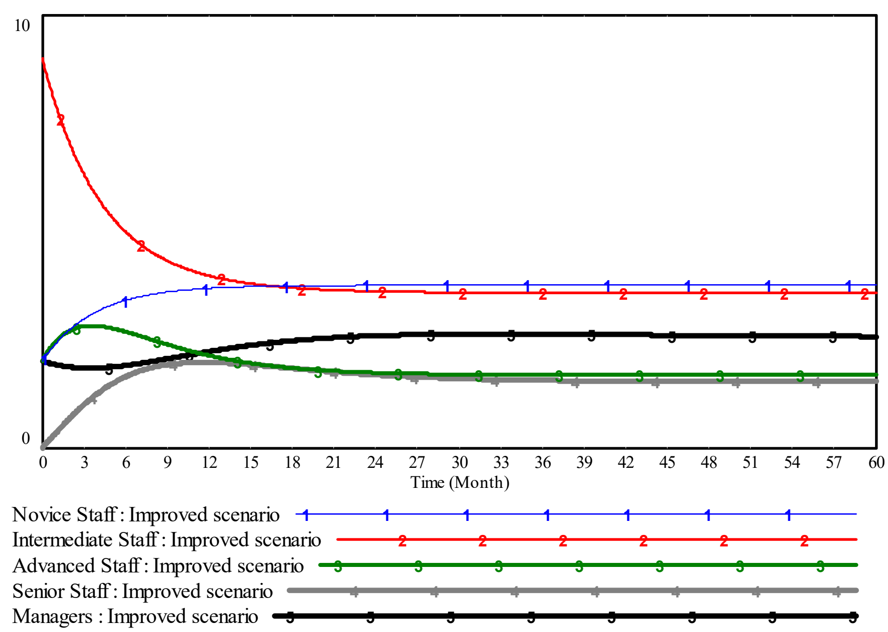

Figure 4: Staff categories dynamics – Improved retention and promotion policies.

The existing example illustrated the importance and suitability of quantitative SD modeling in cases where feedback loops are not predominantly important but the dynamics originated by accumulation and draining processes can generated counterintuitive results.

4 CONCLUSIONS

SD has a rich history on both uses: soft (qualitative or descriptive) and hard (quantitative or predictive/prescriptive) . Soft SD modelling can be easily used as a meta-modelling tool where the use of CLD helps the modeler to understand the system. Then, the modeler uses any quantitative method, e.g. statistical analysis, linear programming, discrete event simulation, SD or hybrid, to improve the performance of the system. Soft SD can also help modeler to engage with their clients to discuss the assumptions about the problem and what it is the best approach to model the problem when it is used in facilitated modeling workshops.

Quantitative SD has progressed substantially with the integration of additional methods to search for parameters and extensive sensitivity analysis so the models can replicate the performance observed in the data. Recently, SD researchers have started using optimization programs to identify policies that optimize the performance of the system ,e.g. Rahmandad et al (2015). Nowadays policy design can have multiple approaches not only the traditional analysis realized by an expert modeler. Moreover, the integration with other modelling methods in hybrid models opens the door to more quantitative approaches to create robust SD models.

My experience with students is the use of SD in either mode indicate that the use will depend on not only the problem and the objectives of the modelling process but also on the ability to formulate more or less complex quantitative models (Kunc, 2012).

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