COMBINING SYSTEM DYNAMICS MODELING WITH OTHER METHODS: A SYSTEMATIC REVIEW

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ABSTRACT

Although a significant number of system dynamics (SD) studies draw on multi-method approaches, there is not much knowledge on when and how SD is combined with other methods. Yet, combining SD with other methods allows both researchers and practitioners to enhance the contribution of their modeling work. For a comprehensive review of current SD multi-method practices, this paper draws on an assessment of 45 studies that used SD modeling along with at least one other method. We adopt an evidence-based systematic approach in reviewing these studies and find that additional methods can be embedded in two main phases in the SD modeling process: conceptualization and simulation. Our review contributes to the multi-methodology research practice by consolidating one of the main areas where substantial experience in combining methods has been obtained. In addition, this paper provides insights and a reference point for system dynamicists who wish to go beyond stand-alone SD modeling in addressing complex problems. The paper concludes with suggestions for future research in this area.
Keywords: System Dynamics, Multi-methodology, Conceptualization Phase, Simulation Phase, Systematic Review, Evidence-Based Management.

INTRODUCTION

Many studies have shown that system dynamics modeling of complex problems can be enhanced by combining it with other methods (e.g.,, Lane, 1994; Coyle, 1999; Graham & Ariza, 2003; Oliva, 2003; Luna-Reyes and Andersen, 2003; Kopainsky and Luna-Reyes, 2008). In this regard, a significant number of SD studies draw on multi-method approaches in order to be able to more profoundly articulate complex problems and, subsequently, analyze and develop policy. For example, Schwaninger (2004) combined SD with viable systems modeling; Rodriguez-Ulloa and Paucar-Caceres (2005) complemented SD with soft systems methodology; Wu et al. (2010) combined SD with agent-based modeling; Yearworth and White (2013) used grounded theory in the SD modeling process; and Kwakkel (2013) integrated SD in Exploratory Modeling and Analysis (EMA).

As Mingers and Brocklesby (1997) observed, new applications of mixed research methods and triangulation are emerging and flourishing in the social and behavioral sciences (see e.g., Denzin, 1970; Blaikie, 1991); philosophers have been addressing the need and feasibility of methodological and theoretical pluralism (see e.g., Roth, 1987; Rouse, 1971); moreover, in operations research and management science, a discourse on combining different methods and approaches that is commonly referred to as "multi-methodology" has been emerging since the 1980s (e.g., Flood, 1995; Flood and Romm,

1996; Mingers and Brocklesby, 1997; Jackson, 1997a, b; Midgley, 2000; Pollack, 2009; Mingers & White, 2010).

As such, mixing and matching methodologies involve several general challenges and advantages (see Tashakkori & Tedlie; 2010), but it also bring significant advantages. Among these advantages are utility in applications, ability to address the problem more comprehensively, and the opportunity to generate more valid inferences are among the benefits of combining methods (Ivankova & Kawamura, 2010: 582). Yet, despite the generic literature on multi-methodology and combining methods (e.g., Ivankova and Kawamura, 2013; Munro and Mingers, 2002), and the many applications, there is not much explicit (codified) knowledge on when and how SD is combined with other methods, or what were the outcomes of the different combinations.

In this study, we aim to review and synthesize multi-methodology practices in the context of system dynamics (SD). We do so by means of a systematic literature review. The paper begins with an outline of the research methodology. It then proceeds with reviewing the literature, classifying the results, and a synthesis based on the pre-specified questions. Finally, we discuss the implications of our findings for both the SD modeling practice as well as multi-methodology discourses, and conclude with directions for further research.

METHOD: SYSTEMATIC REVIEW

An analytical approach is needed for systematically appraising the contribution of a given body of literature (Ginsberg and Venkatraman, 1985). To this end, we used a systematic review to identify, analyze and consolidate relevant sources of data. Originally developed in medicine, a systematic review involves a comprehensive, explicit, replicable and synthesized review of all relevant literature surrounding the questions of interest (Tranfield et al., 2003). Generally, a systematic review involves three main stages: planning, conducting and reporting the review (Tranfield et al., 2003). During each stage, the reviewer strives "to report as accurately as possible what is known and not known about the questions addressed in the review" (Briner et al., 2012: 115).

In the planning stage, the goal of our review was defined as assessing the most important papers that combine SD with other methodologies, methods and techniques1. We consider a methodology to be a "structured set of guidelines or activities to assist people in undertaking research or interventions" (Mingers and Brocklesby, 1997); a method to be a "structured set of processes and activities that includes tools, method, techniques, and models, that can be used in dealing with the problem or problem situation" (Mingers, 2000); and a technique to be "a specific activity that has a clear and well-defined purpose within the context of a methodology" (Mingers and Brocklesby, 1997). The ISI Web of Knowledge was selected as the key database, since it is one of the most comprehensive databases of peer-reviewed journals. We have used articles across all years available at the time of the research: from 1981 till January 1st, 2014.

We initially searched the database for the topic of "system dynamics". Then, we further restricted the findings to the categories of "management" or "business". According to the

[1] We have excluded "tools" from our review: "an artefact, often computer software, that can be used in performing a particular technique or a whole methodology"(Mingers and Brocklesby, 1997).

research domains (Scope Notes) of ISI Web of Knowledge, "Management"category covers resources on management science, organization studies, strategic planning and decision-making methods, leadership studies, and total quality management. Also,"Business" category covers resources concerned with all aspects of business and the business world. These may include marketing and advertising, forecasting, planning, administration, organizational studies, compensation, strategy, retailing, consumer research, and management. Also covered are resources relating to business history and business ethics. Finally, to focus on the most important and influential papers, we selected papers from the following journals only: System Dynamics Review (304 papers identified), Journal of the Operational Research Society (90 papers identified), European Journal of Operational Research (74 papers identified), Systems Research and Behavioral Science (56 papers identified), Technological Forecasting and Social Change (35 papers identified), and Systemic Practice and Action Research (12 papers identified). These are the top six journals that publish most articles drawing on SD modeling.

All in all, 571 articles were identified for the review. We were looking for papers reflecting the authors' awareness of combining SD, and intentional use of the terms such as "mixing SD with", "combining SD with", "complementing SD with", "enriching SD with", "multi-method", and/or "integrating SD within". We searched for these clues in the title and abstract of these papers. As such, we assume that a key role of multi-methodology in the paper would also be explicitly reflected in the title and/or abstract. Note that we did not consider those articles that built on the accepted body of knowledge on system dynamics modeling (with respect to multi-method methodology). To determine whether a methodology, method or technique was part of the latter body of knowledge, we used Sterman's (2000) widely used textbook as guideline. Furthermore, we only considered those articles that addressed a specific problem or situation. Based on this search strategy, we developed a final set of papers for detailed review. Table 1 provides several illustrations of papers that were *excluded* from the final set of papers, based on these criteria.By applying the mentioned criteria, we decreased the initial sample of 10,440 papers to 45 articles. Table 2 lists descriptives for each journal in relation to the final 45 eligible articles. Furthermore, Figure 1 illustrates the number of eligible papers by year of publication. The obvious point to draw from Figure 1 is that while combining SD with other methods has a long history, there has been a noticeable increase of its use in recent years.

Table 1: Some examples of excluded papers

	Author(s)	**Reason for exclusion**
1	Lane and Oliva, 1998	A synthesis of system dynamics and soft systems methodology without an application to a specific problem.
2	Firddaman, 2002; Miller and Clarke, 2007	Monte Carlo simulation is used in SDM; this combination of methods is explained in detail in Sterman (2000: 885-886, 887).
3	Bianchi and Montemaggiore, 2008; Qi and et al. 2009	Balanced Scorecard (BSC) approach is combined with SD models. However, BSC is in our definition not a research methodology or method, but a framework for performance measurement.
4	Anderson and Edward, 2011	Hill-climbing optimization heuristics are used for sensitivity and policy testing (which is explained in detail in Sterman, 2000: 537-544).
5	Vennix and et al., 1996	This study draws on a series of group model-building (GMB) sessions facilitated by the authors. GMB is considered to be part of the accepted

		body of knowledge in Sterman's (2000) book and has been widely used by SD scholars.

The data do, however, indicate that stand-alone SD still prevails over linking SD with other methods—as can be seen in Table 2. Both *Technological Forecasting and Social Change* and *Systemic Practice and Action Research* appear to publish more SD oriented multi-methodology articles compared to the other journals. We hypothesize that this is due to the policy-oriented nature of these journals, addressing problems of such complexity that they require a multi-methodology approach. However, in terms of the absolute numbers, *System Dynamics Review* is the most important outlet for research applying SD in combination with other methodologies, methods and techniques.

Table 2: Amount of articles included in this study per journal

	Journal	**Final selected number of articles in the journal for detailed review / Initial selected number of articles in the journal for review**	**Percentages of the sample**
1	*System Dynamics Review*	19/304=0.06	19/45=0.42
2	*Journal of the Operational Research Society*	6/90=0.06	6/45=0.13
3	*European Journal of Operational Research*	6/74 = 0.08	6/45=0.13
4	*Systems Research and Behavioral Science*	4/56=0.07	4/45=0.09
5	*Technological Forecasting and Social Change*	7/35=0.2	7/45=0.16
6	*Systemic Practice and Action Research*	3/12=0.25	3/45=0.07

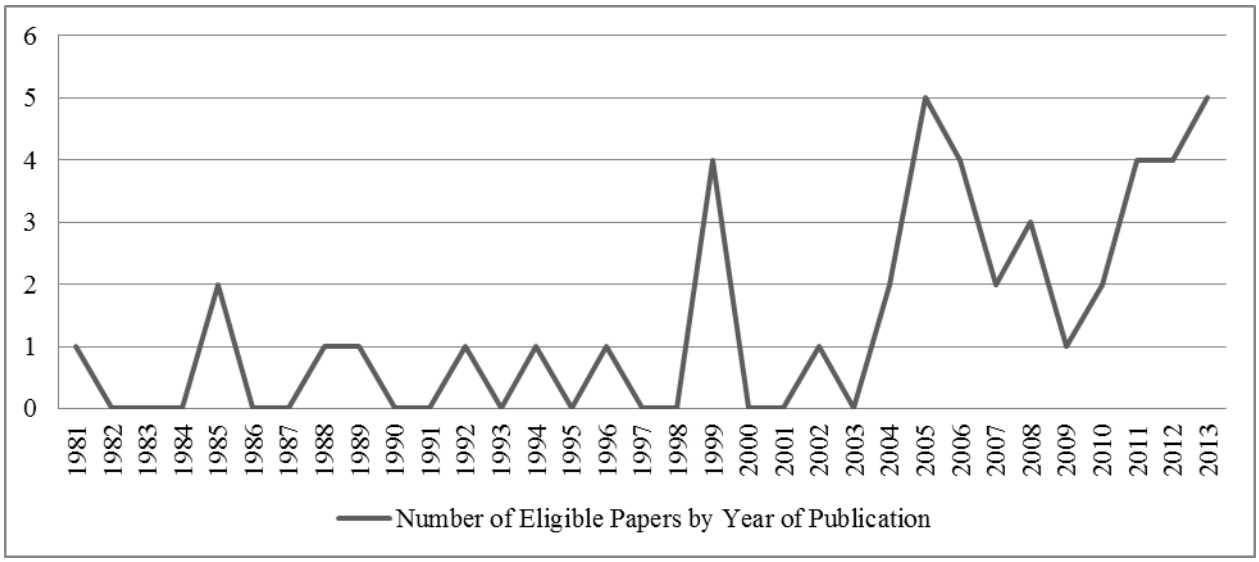

Figure 1: Number of eligible paper by year of publication

FINDINGS

As we mentioned before, there is a lack of studies of when and how SD is combined with other methodologies, methods and techniques. The systematic review approach outlined in the previous section serves to address this gap in the literature. In this regard, we read all selected articles, in order to find answers to the following set of related questions: (1) which methodologies, methods and techniques are combined with system dynamics modeling; (2) what are the problems areas and main characteristics of the research questions motivating the study; (3) what are the largest benefits of combining SD with other methods; (4) which phase(s) of the SD modeling process is/are enriched during such combination: conceptualization and/or simulation; and finally (5) do the authors consider any theoretical debates and challenges on combining methods or not. The remainder of this paper is dedicated to a synthesis of the individual answers extracted from reviewing each article. A detailed report on the analysis of each paper can be found in Appendix I.

Methods combined with system dynamics

Based on our review, the methods combined with SD in the selected papers can be categorized in five main groups, that somewhat overlap each other:

1. Mathematical methods that covers statistical methods, simulation approaches and optimization methods:
   a. Fuzzy approach; Conjoint analysis; Taguchi method; Econometrics; Control model (optimization); Modal control theory; Linearization; Loop eigenvalue elasticity analysis (LEEA); Dynamic decomposition weights (DDW); Multivariate regression analysis, Tree-based regression analyses, CART and CHAID; Queuing model; Bifurcation analysis.
   b. Agent-based modeling; Exploratory modeling and analysis (EMA); Qualitative simulation.
   c. Multiple-criteria decision analysis (MCDA); Multi-objective optimization; Reference model (optimization nonlinear model); co-evolutionary approaches: Recurrent neural network (RNN), Genetic algorithms (GA).
2. Systems methodologies:
   Viable systems modeling (VSM); Soft systems methodology (SSM); Qualitative system dynamics approach as QPID (Qualitative Politicized Influence Diagrams).
3. Research methods and techniques:
   Grounded theory.
4. Other methods
   Social fabric matrix (networked representation); Event map of scenarios (networked tools); Patent analysis; Bibliometrics; Analogies; Scenarios; Growth curves; Decision tree analysis.

As can be seen, we can locate all these methods on the spectrum between completely quantitative and qualitative approaches.

Areas of the case studies

Of the reviewed articles, 23 take a problem-oriented perspective. In these articles, the authors combined SD with other methods in order to be able to understand and model a

particular problem more deeply and effectively. The remaining 22 papers first propose their methodological contribution on combining SD with other methods, and then use case studies to illustrate their ideas.

Within the category of "management" or "business", the focal areas of our review, we identified seven main threads (or sub-areas) where the combination of SD and other methods were frequently used: Business & Operations, Health, Public Policy, Resources, Information & Knowledge, Economics, and Security. Table 4 provides an overview of the problems modeled in the papers we reviewed.

Characteristics of the problems addressed

Generally, the goal of the research project as well as specific characteristics of the data requirements in terms of source, content and context constitute the main motivations for combining SD with other methods. Based on our review, we also identified four primary features in the research problems addressed in the selected articles:

1. Characteristics related to the nature of the problems: The complex, multi-level, multi-aspect, multi-disciplinary and ambiguous nature of these problems motivated authors to combine SD with other methods.
2. Characteristics related to the variables and formulations of causal relations: Existence of a level of uncertainty, fuzziness, linguistic, qualitative and intangible variables compounded by the difficulty in formulation of causal relations are located in this class.
3. Characteristics related to the agents involved and their divergent views: Involving multiple agents, stakeholders and groups with different subjective views are among the sources in this category that motivated the authors to avoid stand-alone SD.
4. Characteristics related to the contexts of the problematic situation: Politicized systems, auspices of the central government, and public concerns over the problematic situation are some of the contextual factors that along with the above characteristics influenced the adoption of other methods besides SD.

The coding procedure for finding these characteristics is described in the Appendix II. In practice, one or a set of the above features derived the researchers and practitioners to enrich SD thorough combination with at least one other methodology, method or technique. It is worth mentioning that some of the reviewed problems do not have any special characteristics. Yet demonstrating special characteristics for some problems does not mean that the applied methods are only dedicated to the problems with those features.

Most important benefits of enhancing SD modeling

Our review suggests that an enhanced SD approach has one or more of the following benefits:

1. *Improved capabilities of SD in eliciting, obtaining and quantifying non-objective information*. For example, Seth (1994) combined SD with fuzzy set theoretic to incorporate subjective beliefs and perceptions easily in an objective, scientific and rational manner using the concepts of fuzzy sets. Also, Kim and Andersen (2012) used grounded theory to identify problems, key variables, and their structural relationships from purposive text data.
2. *Added confidence, rigor, precision and flexibility* in the components of SD modeling, especially in the form of added firmness, rigorous and robust policy exploration, design and analysis. For example, Van Ackere and Smith (1999) combined SD with

econometrics to obtain a more secure estimate of the related equations, and Duggan (2008) used a genetic algorithm to allow for the varying of policy equations in order to discover the best strategies for a given problem.

3. *Inclusion of multiple attributes and perspectives of agents in SD modeling*. Concerning this issue, Schwaninger (2004) used viable systems modeling to bring the multiple actors together and help actors at different levels to achieve the requisite variety.
4. *Developing structures and processes that support SD intervention and implementation*. For example, Rodríguez-Ulloa et al. (2011) used soft systems methodology to orchestrate and implement change in social systems, based on a multimethodological and a multiparadigmatic approach.

Appendix II depicts the coding procedure that served to analyze and then synthesize our findings in these four generic benefits.

Enriched phases of SD modeling

In order to better understand the benefits of combining methods, we divided the enrichment benefits to SD into two main phases: *conceptualization* (whether in problem articulation or policy design) and *simulation* (including formulation, testing and policy analysis) phases. The review reveals that in 26 papers (58 percent), combining methods serves to enrich the simulation phase of SD modeling process, while in 12 articles (26 percent) the conceptualization side of SD has been improved. In seven papers (15 percent), the combination of SD with another method promotes both phases of the SD modeling process.

Theoretical considerations in combining SD with other methods

In the multi-methodology literature, there is ongoing controversy about the paradigmatic and conceptual status of mixing methods. These debates can be placed on the spectrum between pursuit stances that state paradigms guide and direct how research studies are conducted, and the a-paradigmatic stance that states paradigms are unimportant to many studies conducted within real world especially in applied fields (Tashakkori and Tedlie, 2010: 12-16; 69-95; Mingers and Brocklesby, 1997). However in this section, we have just determined for each article whether there is a mention on the theoretical stance of the authors or not. As reported generally in multi-methodology practices, just six out of 45 selected papers include comments and notes on theoretical challenges of multi-methodology, while the remaining 39 papers do not refer to any ongoing debates or stances of the authors on this subject. Absolutely, it does not necessarily imply that these articles slected the a-paradigmatic stance.

Table 3: Main threads of the problems studied in the reviewed studies

Main threads of the reviewed problems	Addressed problem
Business and operation	1. A company with two departments: distribution and manufacturing 2. A simple model of unstable inventory dynamics 3. A small hypothetical company which deals in a non-durable consumer good 4. A company that becomes a target for a group of activists who have threatened to adulterate its products in support of their agenda and who have, in a few cases, actually succeeded in doing so 5. A simplified version of the inventory-workforce model 6. Linear supply chain network, four-agent Beer game example 7. Long-term capacity planning in the reverse channel of a two-product closed-loop supply chains (CLSCs) with remanufacturing activities, under a high cost setting regarding investment decisions in remanufacturing facilities. 8. The beer distribution game: a multi-sector SD structure 9. Product development resource allocation 10. Sales and service model 11. Field service dynamics 12. Corporate planning: the market evolution module
Health	1. Misuse of personal protective equipment that results in health risk among smallholders in Columbia 2. Improving patient access to general practice 3. Measurement and improvement of performance in radiotherapy departments 4. The AIDS treatment-free incubation period distribution: epidemiology of AIDS 5. Healthcare: improving the cost-effectiveness of chlamydia screening with targeted screening strategies 6. Dynamics of National Health Service waiting lists
Public Policy	1. The future of transportation 2. Regional Innovation and Technology Transfer System (RITTS) 3. Urban dynamics of POBSON model 4. Conventional world dynamics model 5. Management of urban and industrial solid waste 6. A technology foresight case study in the Chinese information and communication technologies (ICT) industry 7. Forecasting technologies in optical storage technologies
Resources	1. Policy assessment in the natural gas industry 2. Wind power industry 3. Forecasting technologies in fuel cell 4. The renewable energy market in the U.K.'s electric power grid 5. Copper scarcity 6. Plausible dynamics for mineral and metal scarcity 7. Ecological systems: predator-prey and the Kaibab plateau models 8. Forecasting technologies in food safety 9. Adoption of seed from improved maize varieties in Malawi 10. Development of the Australian pollination services market 11. A small Peruvian company dedicated to commercialize national and imported steel products
Information and Knowledge	1. The phenomena of market penetration or diffusion of new products in Segmented Populations 2. Exploring pricing strategies for the company's existing product and analyze a variety of NPD options 3. Technological innovation risk decision-making in an entrepreneurial team for typical enterprises 4. Three case studies from the domains of organizational change and entrepreneurial studies
Economics	1. Economic system 2. One of the most common macroeconomic models 3. Design a coherent and efficient strategic plan for a CO2 tax scheme over a medium-term horizon. 4. Policy design in the Australian Taxation Office
Security	1. Naval command and control systems effectiveness assessment 2. Citizen insecurity in the Province of Mendoza, Argentina

Table 4: Enriched phases of SD modeling in the reviewed papers

Enriched phase	Simulation phase	Conceptualization phase	Conceptualization and simulation phase	SD as a dependent methodology

Number of articles	26	12	7	2
Percentage in relation to the reviewed articles	58	26	15	4

DISCUSSION

Over the last years, there have been concerns and debates among the members of system dynamics community about linking SD with other systems methodologies and problem structuring methods (Paucar-Caceres and Rodriguez-Ulloa, 2005). However, there is not much explicit (codified) knowledge on when and how SD is combined with other methods, or what were the results of the combination attempts. In this paper, we have tried to shed light on this situation and consolidate a main body of papers using SD along with at least one other methodology, method or technique; in the field of "management" or "business".

Our findings serve to close the identified gap in the literature by addressing several sub-questions. We think that the answers to these specified questions assist in providing valuable information on when and how SD is combined with other methods. As such, our findings inform SD modelers regarding the opportunities of using a broad range of methodologies, methods and techniques in order to enhance the capabilities of SD in the conceptualization as well as simulation phases of the research cycle. Also, given the benefits of a multi-method approach toward SD, we hope that this review will motivate more SD modelers to combine SD with other methods. They should especially take great care in using stand-alone SD when addressing a problem with the characteristics we described earlier in this paper.

All in all, this review demonstrates that the extant literature on SD multi-methodology is fragmented, poorly grounded in theory, and open for further research. Similar to most multi-methodology practices, it is not so clear why a modeler adds a particular method rather than another to the SD modeling process. It seems most of the authors prefer to use an approach within the "bush of methods[2]" which they are more familiar with, irrespective of the promised benefits. It can be claimed that there is a lack of a framework or guidelines that describes the mechanisms for selecting the optimum or most satisfied methods to be combined with SD modeling process. Furthermore, a wide range of combined methods with SD has made it apparent that SD could be a platform for combining other methodologies, methods and techniques. As such, ascribing SD as an "umbrella for integrating problem structuring methods" (Kaempf and Ninios, 1998) maybe an intriguing idea that deserves more attention and research.

Limitations of the research and future research

The main limitation of this review is associated with the articles we surveyed. First of all, our findings are based on (a selected sample of) the past experiences in how and when SD is combined with other methods. Any prescription for effectively combining SD modeling with other methodologies, methods, and techniques also needs to draw on other conceptual and methodological knowledge (e.g., in conceptual work on multi-

[2] It seems to be early to use "Jungle of Methods" metaphor as Koontz (1961) used "The Management Theory Jungle". However, "Bush of Methods" could be considered as a guiding metaphor that can describe the plenty of methods from different origins for conceptualization and policy analysis of complex problems.

methodology). Our analysis is restricted to papers published in a relatively small, albeit important, number of selected journals, and is also limited to the area of "management" or "business". Future work in this area may serve to extend the scope of our review.

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