Where is System Dynamics situated within Soft/hard systems and Soft/hard approaches?

Akira Uchino

School of Commerce, Senshu University ***uchino@isc.senshu-u.ac.jp***

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ABSTRACT

System dynamics needs to proceed to the new stage. Before talking about the future of system dynamics, we need to rethink what the traditional and current system dynamics is. When system dynamics was born in the late 1950s, Operations Research/Management Science (OR/MS) was in its initial stage and was not as sophisticated as today. In the 1980s, when the soft OR field came into existence in the UK, system dynamics was situated in hard OR. But the relationship between the realm of soft OR and system dynamics has been ambiguous ever since. We often use the terms such as soft systems, hard systems, soft approach, hard approach, soft perspective, hard perspective, soft OR and hard OR without a necessarily classifying and using them correctly. We naturally think a hard systems field is suitable for a hard approach and a soft systems field suitable for a soft approach. In this paper, the two-dimensional framework is defined; one is soft and hard approach to the problems, the other is soft and hard systems where the problems exist. The situation of soft OR and hard OR from the current perspective, and their relationship to one another and the relationship with system dynamics will be carefully examined. The two-dimensional framework can show where the system dynamics is situated today and where it is heading to in the future.

1. Introduction

System dynamics needs to proceed to a new stage (Sterman 2018). Before talking about the future of system dynamics, we need to rethink about what the traditional and current system dynamics is. When system dynamics was born in late 1950s, Operations research/ Management science (OR/MS) was in its initial stage and was not as sophisticated as today. In the 1980s soft OR field came into existence in the UK, system dynamics was situated in hard OR. But the relationship between the realm of soft OR field and system dynamics has been ambiguous ever since. I am an old system dynamist in Japan, and I found the clear explanation where system dynamics is situated in hard/soft systems (Uchino 1995).

You usually use ‘soft’ or ‘hard’ as “approach to the problems”. But when you use ‘soft’ or ‘hard’, if you separate “problem area” and “problem approach” clearly, you can avoid unnecessary ambiguity. I use two-dimensional separation between problem area and problem approach.

Problem area:

Soft systems area and hard systems area

Problem approach:

Soft approach and hard approach

You naturally think problems in hard systems area are suitable for a hard approach and problems in soft systems area are suitable for a soft approach. For example, Soft systems methodology (SSM) is suitable for soft problem areas and using a soft approach. But do you think system dynamics only use a hard approach to problems which only exist in hard systems problem area? In the initial stage of system dynamics, don’t you use a soft approach to define the problem structure? The relationship between system dynamics and the soft OR has been

ambiguous since soft OR concept emerged. When you think about system dynamics, you can use two-dimensional framework, soft/hard problem approach and soft/hard systems problem area (Table1). The framework is beneficial for clarity of system dynamics.

Table 1. Two-dimensional Framework

		Problem area	
		soft systems	hard systems
Approach to the problem	hard apprach		
	soft approach		

The framework that was suggested as part of "Rethinking about System Dynamics in Social Systems Modeling" (Uchino 1955) was simple, however, it was not easily disseminated among system dynamists.

In this paper, the two-dimensional framework, soft/hard approach will be used as a research perspective to analyze the soft/hard problem area. The situation of soft OR and hard OR from the current perspective, and their relationship to one another and the relationship with system dynamics will be carefully examined. The two-dimensional framework can show where the traditional and current system dynamics is situated today and where it is heading to in the future.

2. Background

System Dynamics: Soft and hard operational research was published in 2018, edited by Martin Kunc. There exist 14 system dynamics papers selected from 122 papers in the *Journal of the Operational Research Society* until 2016. At the introduction of the book, Kunc has started that:

> System Dynamics was founded by Jay Forrester at the Massachusetts Institute of Technology in 1957 (Forrester 1961). Different from other operational research (OR) tools and methods, SD can adopt two modes of operations: it can involve the use of qualitative tools (e.g. causal loop diagrams) followed by quantitative simulation (e.g. stocks and flows networks), depending on the purpose of analysis (Wolstenholme 1999). Another interesting distinction of SD modelling is that models can be developed in either isolated or perspective modes. Depending on the type of enquiry, there are two basic modes of operation. First is an essentially descriptive mode, which can be defined as soft perspective and operates in a similar fashion to problem structuring methods. Second is a predictive/perspective mode, which can be considered a hard perspective and solves problems in the same manner as forecasting and optimization. (Kunc 2018, p.1)

And he continues "The Case for the Soft Perspective in System Dynamics", "The Case for the Hard Perspective in System Dynamics", and "A historical Perspective of the System Dynamics Field in Terms of Hard and Soft Contribution from the Publications in *Journal of the Operational Research Society*.

His usage of soft perspective and hard perspective are how to approach the problem, which mainly means soft approach and hard approach in this paper. Kunc shows each selected paper which uses soft perspective or hard perspective. But the hard perspective paper doesn't always treat the problem that exists in hard systems area, and vice versa. Perspective and approach don't show the problem area.

Sterman (2018) has stated that:

> [Jay Forrester] mastered the theory and methods relevant to the problem at hand, then built upon them to create new innovations needed to solve the problem. His greatest contribution was that process, not the particular artifacts resulting from it. We do not celebrate his servo, Whirlwind, core memory, and SAGE because they are the state of the art today. We celebrate them because they were the result of a process for problem solving and innovation that was extraordinarily fruitful, time and time again. The same holds for system dynamics. Just as we would not go back to the days of core

> memory and vacuum tubes, of punch cards and DYNAMO, we should not hold fast to methods for the development and analysis of system dynamics models that have outlived their useful life and for which better methods now exist. If Jay were a young man entering the field of system dynamics today, he would not defend as sufficient nor rely on methods and tools that were once the state of the art but no longer. He would not isolate himself from what other disciplines and communities offer. Rather, ever focused on solving important problems, he would master the theories and methods now available, using them where appropriate and building on them to create now tools where needed to propel the field of system dynamics to new frontiers (Sterman 2018, pp.15-16).

He continues to criticize severely that many system dynamists stick to "system dynamics" with deterministic compartment models with continuous values for the state variables and formulated in continuous time (Sterman 2018, p.17).

> System dynamics models can be implemented using a variety of different simulation architectures. These vary in their representation of time (continuous or discrete), state variables (continuous or discrete), and uncertainty (stochastic or deterministic). Ordinary differential equations, stochastic differential equations, discrete event simulations, agent-based models and dynamic network models are common computational architectures offering different choices on these dimensions. Today many software programs are available to implement these architectures, and some allow hybrid models – for example, models that have compartments (aggregated stocks) for some state variables and individual agents for others. Both compartment and individual-level models can be formulated in continuous or discrete time, with continuous or discrete quantities, and either can be deterministic or stochastic (Sterman 2018, pp.18-19).

He concluded his paper below.

> We must master the state of the art and modern methods to develop, test, communicate, and implement rigorous, reliable and effective insights into the dynamics of complex systems, wherever they originated. Where needed, we must innovate to develop new methods to address the pressing challenge we face. We must hold ourselves to the highest standards for rigorous inquiry. The need is great. The path may be difficult. Will we take it? (Sterman 2018, p.40)

I understand what he claims. I myself have lived longer in system dynamics field. My humble contribution is that the best explanation of the traditional and current system dynamics from which the future SD expands.

3. System Dynamics as a hard approach

When system dynamics was born in late 1950s, Operations research/ Management science (OR/MS) was in its initial stage and was not as sophisticated as now. OR/MS solved problems which were well-defined and have a clear structure. Linear programming, Queueing Theory, Inventory control and so on were developed. At that time Forrester founded industrial dynamics later known as system dynamics. "He built models that could be simulated and analyzed fast enough to useful in solving specific focused problems" (Sterman 2018, p.15).

He pioneered the new world where we construct a model and simulate it by using digital computers. While computation capacity was so restricted then, he defined a basic system dynamics formulation.

> The basic structure of a formal System Dynamics computer simulation model is a system of coupled, nonlinear, first-order differential (or integral) equations. Simulation of such systems is easily accomplished by partitioning simulated time into discrete intervals of length dt and stepping the system through time one dt at a time.

The feedback concept is at the heart of the System Dynamics approach. Diagrams of loops of information feedback and circular causality are tools for conceptualizing the structure of a complex system and for communicating model-based insights.

The loop concept underlying feedback and circular causality by itself is not enough, however. The explanatory power and insightfulness of feedback understandings also rest on the notions of active structure and loop dominance.

The concept of endogenous change is fundamental to the System Dynamics approach. It dictates aspects of model formulation: exogenous disturbances are seen at most as triggers of system behavior; the causes are contained within the structure of the system itself (from "*What is SD; Introduction to System Dynamics*", https://www.systemdynamics.org/what-is-sd accessed on May 1, 2019,).

Figure 1 shows the difference between OR/MS and system dynamics. System dynamics needs define problem structure clearly as a model, and then the model is simulated dynamically.

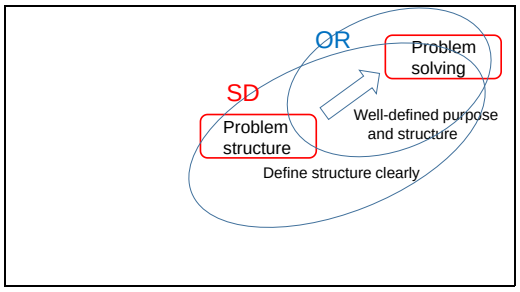

Figure 1. OR/MS vs System Dynamics

Econometrics has typical OR/MS characteristics, so we can compare Econometrics to system dynamics. Table 2 shows the typical difference between Econometrics and system dynamics.

Econometrics basically use statistical data, real data that is collected. If you use the same data, you can get the same results. Model repeatability and matching for historical data are perfect so that credibility of verification is excellent. Short-term forecasting power is strong.

Table 2. Econometrics and System Dynamics

	Econometrics	SD
model form	data dependent	structure dependent
	open system	closed system
chactaristics	short-term	long-term
	quantitative	qualitative/quantitative
merit	credibility of short-term forecasting	policy-making,
		showing critical situation
verification	matching for historical data	(matching for historical data)
	model repeatability	
		model structure have clearly responds to the real structure

System dynamics aims to understand complex problems whose structures are sometimes ambiguous. Existing OR/MS methods are not suitable for solving them. In system dynamics we define the problem structure clearly and then make the model, simulating the model to understand what elements are critical to the problem, and improve policy making. While we develop the model, model elements are depicted by stocks, flows, and other variables. Modelers do not always recognize the problem in the same way, so model repeatability is not perfect. Every so often the arbitrariness of SD models is criticized by economists. Contrarily system dynamics has explanatory power that the model structure responds to the real structure, in contrast to Econometrics model which has only data and equations. I made Figure 1 in 1995 and I add "(matching for historical data)" in SD/verification cell in this paper because of efforts to improve verification in the SD field nowadays (Sterman 2000).

4. OR/MS in the US and UK

Usage of soft OR and hard OR are used mainly in the UK. The difference between Operational research (OR) in the UK and OR/MS in the US are clearly discussed in Pauer-Caceres (2011).

The OR/MS in the UK has developed a soft and systemic approach to OR/MS practice, which has resulted in the emergence of several interactive and critical-oriented methodologies. Pauer-Caceres explores the trend in OR/MS in the US and UK during the last 25 years. They show the OR/MS history in both nations, and they examined three journals in the US, *Management Science* (MS), *Operations Research*, and *Interfaces*, and one journal in the UK, *the Journal of Operational Research Society*, and indicate how many papers about soft and systemic approach have published in four journals.

Summing up, there were only two papers on OR history in *Operational Research* and one paper in *Management Science*. There were 8 papers in *Interfaces* because *Interfaces* treated application of information systems. Contrarily, *Journal of Operational Research Society* in UK contained 1,177 papers from 1984 to 2009. The papers included "interpretative" and "critical" as the key words, that means they are written about soft OR.

OR development in UK is divided three terms by Pauer-Caceres (2011).

(1) an optimization (problem-solving) stage located between 1940 and 1970;

(2) an interactive (situation-improving) paradigm followed in the 1970s and 1980s;

(3) a critical/pluralistic paradigm (intervention-empowering) appearing in the late 1980s; and continues to date.

Jackson (2003) explains below.

(1) The optimization paradigm: problem-solving methods (1940-1960);

(2) The learning paradigm: improving-situations methodologies (1960-1980);

(3) The critical paradigm: the intervention-empowering emancipatory systems methodologies (1980-date).

Pauer-Caceres and Jackson agreed fundamentally that the development of OR/MS in the US has remained closed to the OR methods of optimization paradigm of MS. OR/MS in the UK has engaged with the systems thinking community and developed a much wider methodological scope than the US.

5. Soft OR and System Dynamics

Rosenhead (1989) arranged the problem structuring methods whose area has been called soft OR. He analyzed 6 methods and additionally referred 7 methods. Flood & Jackson (1991a, 1991b) showed 13 methods as systems approach, Richardson (1994) explained 16 systems thinking fields.

Thinking about each systems approach methods apply for the problematic situation, Jackson & Keys (1984) arranged Table 3. And Flood and Jackson (1991a, 1991b) showed Table 4.

Table 3. Arrangement of Jackson & Keys

	unitary	pluralist
mechanical	classical OR	SAST
	SE SA	Interactive Planning
systemic	Cybanetics VSD Socio-tech	SSM

Table 4. Arrangement of Flood & Jackson

	UNITARY	PLURALIST	COERCIVE
SIMPLE	OR SA SE	SSD	Critical systems heuristics
	SD	SAST	
COMPLEX	VSD cybanetics GST Socio-tech Contingency theory	SSM	
		Interactive planning	

System dynamics is put in Table 4. System dynamics occasionally is in soft OR field. Historically system dynamics is usually classified in hard OR. One reason is that SD has a long history and at the time SD was born, there was no soft OR concept. And when soft OR was

born, SD already existed and seemed to be one of mathematical tools in hard OR.

Ackoff (1957) was one of the earlier critics of the excess mathematical emphasis in OR/MS. He influenced the work of 'Soft' tradition in the UK. The work of Checkland (1981, 1999), Soft Systems Methodology (SSM), especially led methodological system thinkers and practitioners in the business field in the UK.

Figure 2(a) shows the soft OR where you should recognize and find problems in social systems. And then you should define problems descriptively. Figure 2(b) shows the classic OR or hard OR in Figure 1, where well-defined problems inquire into optimization by using strict mathematical approaches.

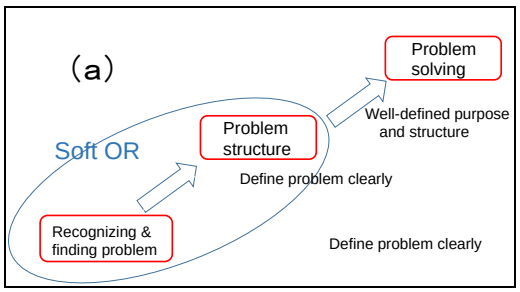

Figure 2(a). Soft OR

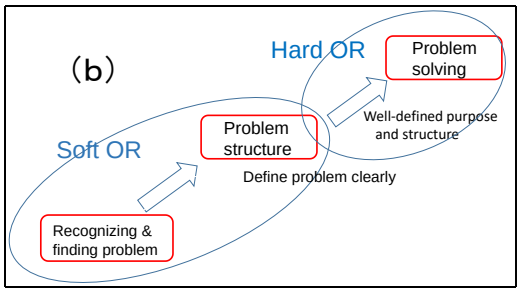

Figure 2(b). Soft OR & Hard OR

How about system dynamics in Figure 2? Where we put SD in the figure. In the third section "System Dynamics as hard OR" and in Figure 1, I treat SD, one of hard OR methods because of tradition about system dynamics. However, from outsiders they see so-called classic OR/MS, hard OR, econometrics, and statistics and so on are surely in hard approach, and others are in soft approach. Figure 3 shows the relationship between soft OR, hard OR and SD.

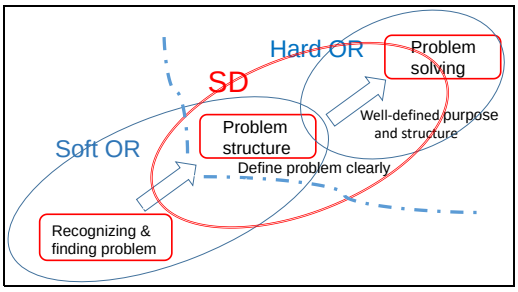

Figure 3. Soft OR, Hard OR, & SD

In traditional and current system dynamics approach;

Beginning with a problem to focus systems thinking and modeling, involving the stakeholders whose understanding and action is required to implement change.

Defining problems dynamically, in terms of graphs over time (time series), employing actual data wherever possible.

Striving for an endogenous, behavioral view of the significant dynamics of a system, a focus inward on the structures and decision rules in a system that themselves generate or exacerbate the perceived problem.

Thinking of all concepts in the real system as quantities interconnected in loops of information feedback and circular causality, a consequence of the endogenous point of view.

Identifying the key variables essential to address the problem and deciding on an appropriate level of aggregation for them. System dynamics models range from highly disaggregate representations such as individual items or agents to highly aggregated representations, and can be deterministic or stochastic, as needed to address the purpose of the study.

Formulating a richly explanatory behavioral model capable of reproducing, by itself, the dynamic problem of concern, drawing on all relevant evidence, including qualitative and

quantitative data. The model is usually a computer simulation model, but is occasionally left unquantified as a map capturing the important accumulations (stocks) in the system, the flows that alter them, and the causal feedback structure determining the flows.

Testing the structure and behavior of the model against all relevant evidence to deepen understanding and to build confidence in it, including the model's ability to replicate historical data, ensuring the model is robust under extreme conditions, exploring the sensitivity of results to uncertainty in assumptions, and diagnosing the sources of unexpected model behavior.

Designing and testing policies to address the problem of concern, testing these against data and comparing to real-world policies that have been tried in the system or similar settings.

Documenting the model and its supporting sources so that it is as transparent as possible and enabling others to critique, use, and extend the work.

Working with stakeholders and others to help translate model-based insights into implementable policies, assist in implementation, assess the results, and improve both the model and policies (from "*What is SD: Introduction to system dynamics"*, https://www.systemdynamics.org/what-is-sd accessed on May1, 2019).

Traditional and current system dynamics approach uses causal-loop diagrams in the first stage previously mentioned, then understand the problem clearly, formulate stock-flow diagrams and create formal model. In real social problems, stakeholders understand the problem structure using diagrams, they often start talking about solving the problem, or trying to improve problematic situation, not developing a formal simulation model.

We call developing a formal model and simulating it is "Quantitative analysis". We call using causal-loop diagram to analyze the problem is "Qualitative analysis" or sometimes "System Thinking". We use "System Thinking", in a part of system dynamics approach or a standalone method of Soft OR. "System Thinking" casually use in social systems and in business.

Critical difference between descriptive soft OR methods and system dynamics is that system dynamics can create dynamic simulation models. So that not only qualitative analysis but also quantitative analysis always needs to system dynamics. Dynamic computer simulation is a vital element in system dynamics. I understand that we sometimes omit the quantitative analysis in order to save time and effort in the real world, but it is exceptional situation in theory.

Compensating for descriptive soft OR, for example, Lane (1994) and Lane & Oliver (1998) insist on combining SSM and system dynamics use. There have been many discussions between soft OR and system dynamics so far. (See the Special Issue of *System Dynamics Review* Vol.10, No.2-3, 1994 and *Journal of Operational Research Society*Vol.50, No.4, 1999).

6. Soft/hard systems and soft/hard approach

Table 5 shows terms and concepts using this paper. If the soft approach applies for soft systems and the hard approach applies for hard systems, the problem in our hand is where we put system dynamics in soft approach or hard approach. Because system dynamics includes both side (Figure 3 and Table 5).

Table 5. Soft Approach & Hard Approach

	Soft Approach	Hard Approach
SD	Soft perspective	Hard perspective
	Qualitative analysis	Quantitative analysis
	Systems Thinking	
Soft OR	Systems Thinking	Hard OR
	Soft OR	
	Program Structuring Methods (PMS)	

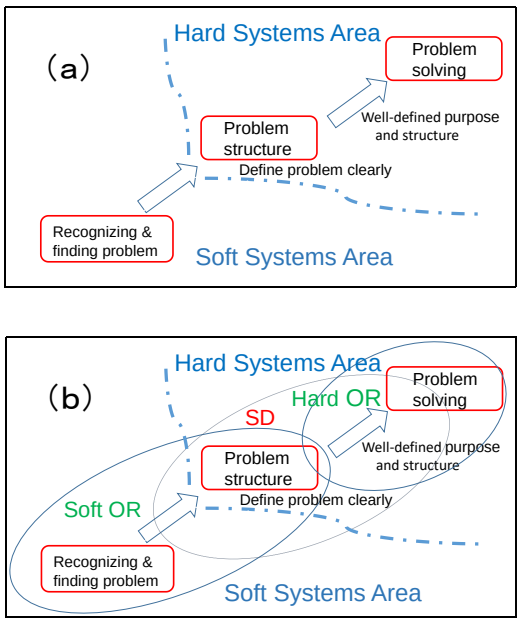

Figure 4. Soft Systems/ Hard systems

It is true that in most cases we use the soft approach for problems in soft systems area, and the hard approach for problems in hard systems area (figure 4(a)). However, we have been confusing where we put system dynamics in the hard approach, or the soft approach (figure 4(b)). Because system dynamics surely use both soft approach and hard approach. Were the problems Jay Forrester first treated in industrial dynamics in the soft systems area? Of course not. But are complex problems now we treat always in the hard systems area? Nowadays we cannot explain correctly what type of problems they are, particularly not yet formulated. While we settle the complex problems and complex approaches, we are blurring the distinction between hard approach, soft approach, soft systems and hard systems.

If we distinguish between "how to approach the problems" and "what kind of problems we treat", we can draw the picture. Apparently, there are two kinds of approaches, soft and hard. We have two kinds of problems, soft and hard. Soft problems are in soft systems area, and hard problems are in hard systems area. If we use two-dimensional framework, soft/hard approach as research perspective and soft/hard systems as the research problems exist in, we can explain what soft OR and hard OR is in current perspective, and the relationship between the framework and system dynamics.

Table 6 depicts when soft OR emerged in the 1980s. System dynamics exists still in the hard approach but SD treats problems in the soft systems area. The two-dimensional framework can show where the traditional and current system dynamics is situated today and where it is heading to in the future.

Table 6. Two-dimensional framework

		[Soft Systems Area]	[Hard Systems Area]
Hard Approach (Hard Perspective)	analytical/ data dependent		OR/MS hard OR
	simulation / structure dependent		SD
Soft Approach $soft Perspective)	descriptive	Soft OR	

7. Conclusions

Sterman (2018) declared that system dynamics should change into a new era and "system dynamics modelers should master the state of the art and use these tools, follow new developments as the tools continue to evolve, and innovate to develop new methods appropriate for the models we build." We should master how to combine other tools such as agent-based models.

> New stage system dynamics modeler uses a variety of different simulation architectures. Today many software programs are available to implement these architectures, and some allow hybrid models. Models that have compartments for some state variables and individual agents for others. Both compartment and individual-level models can be formulated in continuous or discrete time, with continuous or discrete quantities, and either can be deterministic or stochastic. (Sterman 2018, pp.18-19)

Table 7 is the same as Table 6 but includes other simulation tools and the boundaries are expanding to be able to treat more complex and

more challenging problems. SD and other simulations in Table 7 are the new stages of system dynamics. System dynamics in Table 7 expands its area and overlap OR/MS and soft OR (Program Structuring Methods (PMS)) fields. Complex systems, complex dynamical systems are the most advanced scientific field now.

Where is System Dynamics situated? There is no correct answer because system dynamics should advance dynamically in the same way as its dynamic simulation. But the two-dimensional framework can easily show where classic system dynamics is situated, and the relationship between soft/hard approach and soft/hard system where our next target problem exists.

Table 7. Two-dimensional framework

		【Soft Systems Area】	【Hard Systems Area】
Hard Approach (Hard Perspective)	analytical/ data dependent		OR/MS hard OR Econometrics Statistics
	simulation / structure dependent		SD Other simulations
Soft Approach (Soft Perspective)	descriptive	Soft OR	

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