Towards an orientation framework in multi-paradigm modeling

Aligning purpose, object and methodology in
System Dynamics, Agent-based Modeling and Discrete-Event-Simulation

Tobias Lorenz
University of Stuttgart
DaimlerChrysler AG, Research and Technology
System Dynamics Group Bergen
Nordbahnhofstr. 179, 70191 Stuttgart, Germany
Tobias.Lorenz@gmail.com

Andreas Jost
DaimlerChrysler AG, Research and Technology Strategy
Andreas.Jost@daimlerchrysler.com

Keywords: Agent-based Modeling, Discrete-Event-Simulation, Paradigmata, Multi-Paradigm-Modeling, Hybrid Modeling

Abstract

Methodologies are built upon fundamental assumptions (called paradigms) which are rarely questioned within a respective community. When applying a methodology without being aware of these assumptions we risk accepting wrong conclusions (abduction risk). Therefore this paper proposes that the development of valuable simulation models strongly depends on the sound alignment of purpose, object and methodology. In order to align these dimensions and in the light of upcoming tools capable of multi-paradigm-modeling a clear conception of the available methodologies, their differences and suitability becomes a necessity. In the context of modeling and simulating of socio-technical systems three methodologies seem reasonable. Next to System Dynamics (SD) these are Agent-based Modeling (ABM) and Discrete-Event-Simulation (DES). The following paper analyzes and compares all three approaches in order develop an initial concept idea for an orientation framework which aligns purpose, object characteristics and methodology for choosing and/or combining suitable modeling approaches.

Introduction

Reviewing System Dynamics literature, a clear problem definition or model purpose is the initial starting point of a successful modeling process.[1] Only with a clear purpose the modeler is able to focus on key aspects, define adequate model boundaries and choose an appropriate level of abstraction. Mostly overlooked however is the fact, that also the choice of a suitable modeling and simulation approach is an essential success factor that needs to be integrated in the early stages of the modeling process. Due to familiarization and (early) association with a specific modeling paradigm modelers tend overlook other paradigms or simply are not able to adequately differentiate and apply alternative approaches. The latter is about to change with the availability of tools capable of multi-paradigm modeling. However, the ability to differentiate is still a success factor these tools simply cannot provide.

Purpose – Object – Methodology

Based on the fact that any given methodology comes along with a set of (implicit or explicit) assumptions (called paradigms[2]) it is the central hypothesis of this paper that only by finding the best fit of the three dimensions: purpose, object and methodology, a suitable modeling approach can be found.

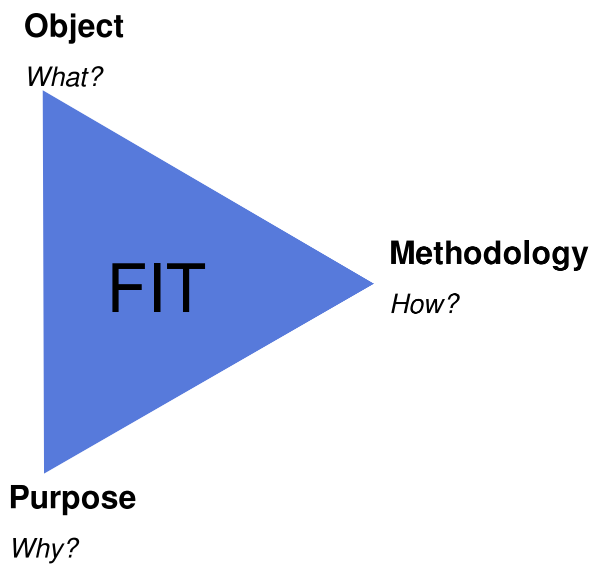

Figure 1: Purpose - Object - Methodology

Purpose refers to the motivation of the intended modeling effort which can include solving a given problem or finding effective leverages to change or optimize a given behavior. Let alone the fact that a correct problem definition already includes a clear

[1] Compare Sterman, Business Dynamics. Systems Thinking and Modeling for a Complex World, Boston, 2000, page 89 "A clear purpose is the single most important ingredient for a successful modelling study"

[2] Compare Meadows, The unavoidable A Priori, p. 24 in Randers, Elements of the System Dynamics Method, Cambridge/ London, 1980, "Different modeling world views, or in Thomas Kuhn's terminology, paradigms (Kuhn, 1970), cause their practitioners to define different problems, follow different procedures, and use different criteria to evaluate their results."

purpose, a modeling purpose can also be to gain insight into a broader not yet understood problem context. Therefore the term purpose is not equal to a problem definition but can and should nevertheless lead to an exact problem definition. Both purpose and/or problem definitions are not only important for the identification of adequate model boundaries but also hold key aspects for the selection of a suitable modeling methodology.

Object refers to the real world context under investigation. Since models refer to selected aspects of the real world, examining the characteristics of the respective real world objects provides important indications for the selection of an appropriate modeling approach. E.g. the structure and level of detail of available information about investigated objects can already favor certain modeling approaches.

Methodology is defined as „a comprehensive, integrated series of techniques or methods creating a general systems theory of how a class of thought intensive work ought to be performed“[3]. Therefore a methodology consists of a set of individual methods and/or techniques. In the example of SD the methodology includes methods and techniques such as boundary diagrams, causal loop diagrams and stock & flow diagrams. In other approaches techniques such as state charts, workflow diagrams are applied. Through its set of methods a modeling and simulation methodology defines how the object is being approached in order to achieve the intended purpose. As no model can reflect a one-to-one representation of reality, choices of what aspects to include are to be made. Since all methods come along with strengths and weaknesses, the application of a certain methods already presets a tendency which aspects are likely to be included and which are likely to be left out. This effect is frequently associated with the paradigm of a modeling methodology. Different paradigms favor different object and purposes. Therefore the methodology needs to be chosen in accordance with the real world objects and the purpose of the modeling effort.

Paradigms

The term "paradigm" has been frequently used to capture the aforementioned set of assumptions and is characterized by the fact that it is to a large extent not questioned within its scientific community. Meadows and Robinson for example postulate that "Different modeling paradigms cause their practitioner to define different problems, follow different procedures, and use different criteria to evaluate the results."[4] Some concepts from theory of science may clarify the problems that come along with preliminarily accepting paradigms.

Generally, three distinct methods are discriminated in scientific research. These are induction, deduction and abduction. If we conceptualize science as consisting of causality statement about observable phenomena, these statements have the logical form:

$$C \longrightarrow E \; \textit{(If C then E)}$$

[3] „Standard Glossary of Software Engineering Terminology“ of the Institute of Electrical and Electronics Engineers (IEEE) defines methodology as „a comprehensive, integrated series of techniques or methods creating a general systems theory of how a class of thought intensive work ought be performed“ [IEEE 1990] -> therefore a methodology consists of individual methods and/or techniques.“ IEEE Standard Glossary of Software Engineering Terminology. IEEE Computer Society. IEEE Std 610.121990. New York 1990.

[4] Meadows/Robinson, The electronic oracle, Chichester, 1985, p. 20

Induction finds validated regularities by the observation of a certain number of regularities between causes and effects and the abstraction of a general statement (Having observed a glass break when hitting the ground with a certain impulse for several times one could postulate: If "glass hits the ground with a certain impulse" then "glass breaks").

Deduction builds upon existing regularities in order to deduce the effect for observed causes (given the aforementioned regularity and observing a glass hitting the ground, one could postulate that "it will break").

Abduction on the other hand, attempts to explain an observed effect with a given regularity (Observing a broken glass and assuming that it had fallen by referring to the aforementioned regularity). Acknowledging that there might be other reasons which might cause a glass to break (e.g. $C_1 \rightarrow E$) this is logically a relative weak method of reaching conclusions. Abduction finds causes for a certain effect by assuming a specific regularity (e.g. $C \rightarrow E$) to be adequate. Therefore this logical weakness persists no matter how certain the assumed regularity ($C \rightarrow E$) is for itself, because it arises out of the uncertain application of the regularity to an observed effect ($C \rightarrow E$ where $C_1 \rightarrow E$ might as well be applicable).

Coming back to modeling and simulation we argue that methodologies already build upon certain $C \rightarrow E$ statements, which are implicitly accepted within a certain paradigm. Therefore by approaching a problem with a given methodology without confirming inherent assumptions already holds the risk of uncertain conclusions (abduction risk). Looking at simulation models themselves, they add numerous assumptions on top of these fundamental statements, adding up to a complex system of $C \rightarrow E$ statements.[5] But fortunately (and in contrary to underlying assumptions of a paradigm) the assumptions in a simulation model are mostly (and ideally) stated explicitly. Therefore they can be questioned, which reduces the risk of drawing uncertain conclusions. The lower level of a modeling paradigm on the other side include statements that are understood to be generally relevant. These include the expected dominant sources of complex system behavior as well as methods and techniques how these underlying concepts are to be transformed into computable models.

Core assumptions of SD, DES and ABM

In the following the assumptions of the three competing simulation modeling techniques (Agent-based Modeling, System Dynamics and Discrete-Event-Simulation) will be discussed. This discussion is based on the idea that major difference can be found in the abduction of assuming underlying causes for complex system.[6] Morecroft and Robinson formulate this as follows: "Rather than focus on technical and conceptual differences, we compare the nature of explanations and insights these two approaches have to offer about puzzling dynamics. Our premise is that the modeling style you choose affects the way you represent and interpret phenomena from the real world"[7]

a) Differences between Discrete-Event-Simulation and System Dynamics

---

[5] Compare Magnani, Model-Based Creative Abduction in Magnani/ Nersessian/ Thagard, Model-based reasoning in scientific discovery, New York, 1999

[6] Also compare Morecroft, John/ Robinson, Stewart, Explaining Puzzling Dynamics: Comparing the Use of System Dynamics and Discrete-Event Simulation, Proceedings of System Dynamics Conference 2005,

[7] Morecroft, John/ Robinson, Stewart, Explaining Puzzling Dynamics: Comparing the Use of System Dynamics and Discrete-Event Simulation, Proceedings of System Dynamics Conference 2005, p.5

Morecroft and Robinson deliver an exquisite analysis of the different worldviews held by System Dynamicists and Discrete-Event-Modelers respectively. Before we turn towards the main issue - the assumed roots of behavior - some technical details will be regarded en passant. System Dynamics is generally viewed to be computed continuously whereas DES is computed discretely. A model can be called discrete if "[…] the state variable(s) change only at a discrete set of points in time"[8]. Taking a closer look SD models are also computed in a series of discrete time steps, nevertheless the focus lies on continuous policies in contrast to the focus on individual events in DES. A DES-model consists of entities, attributes and activities, which constitute defined states and can be changed by events. The focus lies on the entities in contrast to the focus on aggregates in System Dynamics. "An entity is an object of interest in the system. An attribute is a property of an entity. An activity represents a time period of specified length."[9]

Whereas in System Dynamics aggregates are linked through aggregated mechanisms implemented as flows, in DES the activities of the individual entities are modeled and then linked through interconnecting events.[10]

The perspective in DES is on multiple events, where an event is an "[…] instantaneous occurrence that may change the state of the system."[11], whereas the perspective in SD is again an aggregated one, where these multiple events are aggregated into rates. Nevertheless, we need to keep in mind, that in reality there are also discrete events within a SD model when the system does react with a sudden state change e.g. upon the introduction of a new control policy. This fact is once in a while forgotten within SD through the attempt to smooth everything out and look at the system from a highly aggregated view.

Typical applications of DES are so-called queuing models, where "[…] customers arrive from time to time and join a queue, or waiting line, are eventually served, and finally leave the system. The "term" customer can be transferred to any type of entity that is requesting "service" from a system. Therefore, many service facilities, production systems, repair and maintenance facilities, communications and computer systems, and transport and material handling systems can be viewed as queuing systems."[12]

The main difference has been assumed to lie in different assumptions regarding the roots of complex behavior. Whereas in System Dynamics these are assumed to "[…] arise from endogenous, deterministic and structural properties of the system […]"[13], in DES behavior is assumed to "[…] arise from the interaction of (random) processes coupled together by endogenous structure."[14]

Another approach has been to claim that the methodologies pursue different kinds of complexity, which is "dynamic complexity" in the case of SD, and "detail complexity"

---

[8] Banks, Carson, Nelson, Nicol, Discrete-Event System Simulation, New Jersey, 3rd edition, p.12
[9] Banks, Carson, Nelson, Nicol, Discrete-Event System Simulation, New Jersey, 3rd edition, p.10
[10] "In order to build a model suitable for discrete event simulation, it is necessary to: Identify the important classes of entity; Consider the activities in which they engage; Link these activities together." (Michael Pidd, Computer Simulation in Management Science, Chichester, 2004, 5th edition, p.66)
[11] Banks, Carson, Nelson, Nicol, Discrete-Event System Simulation, New Jersey, 3rd edition, p.10
[12] Banks, Carson, Nelson, Nicol, Discrete-Event System Simulation, New Jersey, 3rd edition, p.204
[13] Morecroft, John/ Robinson, Stewart, Explaining Puzzling Dynamics: Comparing the Use of System Dynamics and Discrete-Event Simulation, Proceedings of System Dynamics Conference 2005, p.7
[14] Morecroft, John/ Robinson, Stewart, Explaining Puzzling Dynamics: Comparing the Use of System Dynamics and Discrete-Event Simulation, Proceedings of System Dynamics Conference 2005, p.7

in the case of DES: "Detail complexity arises from the existence of multiple variables, which may have many different attributes and which therefore give rise to an enormous number of possible inter-connections and effects. Such detail can swamp users wishing to grasp its ramifications and is a central concern of DES. Dynamic complexity arises because variables influence each other in ways which involve non-linearities, delays and accumulative or draining relationships. Such complexity produces counterintuitive behavior which can confuse problem owners and is the focus of SD."[15] Lane proposes the following table for discrimination:

	DES	SD
Perspective	Analytic, emphasis on detail complexity	Holistic, emphasis on dynamic complexity
Resolution of models	Individual entities, attributes, decisions and events	Homogenized entities, continuous policy pressures and emergent behavior
Data sources	Primarily numerical with some judgmental elements	Broadly drawn
Problems studied	Operational	Strategic
Model elements	Physical, tangible and some informational	Physical, tangible, judgmental and information link
Human agents represented in models as	Decision makers	Boundedly rational policy implementers
Clients find the model	Opaque/ dark, grey box, nevertheless convincing	Transparent/ fuzzy glass box, nevertheless compelling
Model outputs	Points predictions and detailed performance measures across a range of parameters, decisions rules and scenarios	Understanding of structural source of behavior modes, location of key performance indicators and effective policy levers

Table 1: Comparison of Discrete-Event-Simulation and System Dynamics[16]

Applying a given Methodology (accepting a certain set of general assumptions) also leads to a different perspective on a system. E.g. looking for structure within a system requires a longer time horizon, whereas a collection of events can be discussed within shorter periods.[17]

b) Differences between Agent-based Modeling and System Dynamics

Both System Dynamics and Agent-based Modeling are regularly utilized to explain socio-technical phenomena but differ significantly in the way they approach their explanandum. Whereas System Dynamics typically looks for a reference mode for a

---

[15] Lane, David, You just don't understand me: Modes of failure and success in the discourse between system dynamics and discrete event simulation, LSE OR Working Paper 00.34, 2000, p. 16

[16] Lane, David, You just don't understand me: Modes of failure and success in the discourse between system dynamics and discrete event simulation, LSE OR Working Paper 00.34, 2000, p. 16

[17] Compare also: "Thus, events have a short, possibly immediate, timescale whereas system behaviour represents the observed fluctuations over a longer time period." (Michael Pidd, Computer Simulation in Management Science, Chichester, 2004, 5th edition, p.250)

central variable (which is to be reproduced and explained), Agent-based Modeling takes a contrary approach. It models an agent with individual behavior and observes the emergent behavior out of the interaction of a population of those agents. Due to the complications arising in tracing back the emerging behavior to the agents properties, which don't arise in the tighter causal linkage of a SD model, the Agent-based approach might be called explanatory. The approach of SD might be called exploratory. Phelan uses the descriptions confirmatory and exploratory[18] to discriminate System Theory from Complexity Theory, but Systems Theory is capable of more than consistency checking as it normally integrates several theories into one model and implements the assumptions of the modeler through the links. Nevertheless both techniques can be described as "abductive", since they attempt to develop models to explain given effects.

In Agent-Based Modeling, "the individual members of a population such as firms in an economy or people in a social group are represented explicitly rather than as a single aggregate entity."[19]. "This massively parallel and local interactions can give rise to path dependencies, dynamic returns and their interaction."[20]

By focusing on the individual entity, three characteristics of Agent-based approaches can be identified. They are suitable to

a) describe and demonstrate how the interaction of independent agents create collective phenomena;

b) identify single agents whose behavior has a predominant influence on the generated behavior;

c) identify crucial points in time, at which qualitative changes occur.[21]

Schieritz and Milling developed the following table in order to pin down some distinct differences between System Dynamics and Agent-Based Modeling.

	System Dynamics	Agent-based Simulation
Basic building block	Feedback loop	Agent
Unit of analysis	Structure	Rules
Level of modelling	Macro	Micro
Perspective	Top-down	Bottom-up
Adaptation	Change of dominant structure	Change of structure
Handling of time	Continuous	Discrete
Mathematical formulation	Integral equations	Logic
Origin of dynamics	Levels	Events

Table 2: Comparison of System Dynamics and Agent-Based Modeling[22]

---

[18] Phelan, Steven, A Note on the Correspondence Between Complexity and Systems Theory, Systemic Practice and Action Research, Vol. 12, No. 3, 1999

[19] Sterman, Business Dynamics. Systems Thinking and Modeling for a Complex World, Boston, 2000, p. 896

[20] Grebel/ Pyka, Agent-based modelling – A methodology for the analysis of qualitative development processes, 2004 in: Lombardi/ Squazzoni, Saggi di economia evolutiva , Franco Angeli, Milano, Italy (forthcoming). p. 10

[21] Grebel/ Pyka, Agent-based modelling – A methodology for the analysis of qualitative development processes, 2004 in: Lombardi/ Squazzoni, Saggi di economia evolutiva , Franco Angeli, Milano, Italy (forthcoming).

[22] Schieritz/ Milling, Modeling the Forest or Modeling the Trees, Proceedings of the 21st International Conference of the System Dynamics Society, 2003

These points of departure between the two methodologies seem to be a good starting point for the analysis of the underlying assumptions. Nevertheless, a central point in our conception, the primary hypothesized cause of the problem to be explained, is missing.[23] Other directions to discriminate both methodologies can be found in the diverging approach to individuals and observables[24] or the concept of emergence[25].

As hypothesized above, we regard the assumed origins of dynamic behavior as the central difference inherent to the two methodologies. This set of assumptions is central for the explanation of a problem, whereas the practices of the methodology (e.g. if a model is implemented in continuous or discrete time) are technical details following from the choice of the basic assumptions. As those assumptions are crucial, they will be made more explicit in the following as a clear perception of them might lead to refined discussion. Two assumptions are regarded as central in System Dynamics:

a) Feedback is central in generating behavior ("All dynamics arise from the interaction of just two types of feedback loops, positive (or self-reinforcing) and negative (or self-correcting) loops."[26]; "…the concept of feedback is central to system dynamics."[27])

b) Accumulations are central in generating behavior ("Stocks and flows, along with feedback, are the two central concepts of dynamic systems theory."[28]; "To capture disequilibria in a system, however, stocks must be explicitly represented since they accumulate the imbalances between inflows and outflows."[29])

Analyzing Agent-Based Modeling, we find a different set of basic assumptions:

a) Micro-Macro-Micro feedback is central in generating behavior

b) Interaction of the systems elements is central in generating behavior. ("In its broadest perspective, the work can be seen as part of the study of emergent organization through "bottom-up" processes. In such "bottom-up" processes small units interact according to locally defined rules, and the result is emergent properties of the system such as the formalization of new levels of organization."[30]; "At the simplest level, an agent-based model consists of a system of agents and relationships between them. Even a simple agent-based model can exhibit complex behavior patterns and provide valuable information about the dynamics of the real-world system that it emulates"[31], "One of the basic premises of complexity theory is that much of the apparently complex aggregate

---

[23] For a detailled critique of the Schieritz/ Milling approach compare Lorenz/ Bassi, Comprehensibility as a discrimination criterion for Agent-Based Modelling and System Dynamics: An empirical approach, in Sterman et al., Proceedings of the 23 rd International Conference of the System Dynamics Society, Boston, 2005

[24] Parunak/ Savit/ Riolo, Agent-Based Modeling vs. Equation-Based Modeling: A Case Study and Users' Guide, Proceedings of Workshop on Modeling Agent Based Systems, 1998

[25] Compare Casti, Would-Be Worlds: How simulation is changing the frontiers of science, New York, 1997, p. 91, "A surprise-generating mechanism dependent on connectivity for its very existence is the phenomenon of emergence. This refers to the way the interactions among system components generates unexpected global system properties not present in any of the subsystems taken individually."

[26] Sterman, Business Dynamics. Systems Thinking and Modeling for a Complex World, Boston, 2000, p. 12

[27] Radzicki, Michael/ Sterman, John, Evolutionary Economics and System Dynamics in England, Richard, Evolutionary Concepts in Contemporary Economics, p. 67

[28] Sterman, Business Dynamics. Systems Thinking and Modeling for a Complex World, Boston, 2000, p.191

[29] Radzicki, Michael/ Sterman, John, Evolutionary Economics and System Dynamics in England, Richard, Evolutionary Concepts in Contemporary Economics, p. 68

[30] Axelrod, A model of the emergence of new political actors, in Gilbert/ Conte, Artificial Societies, London, 1995, p. 19

[31] Bonabeau, Eric, Agent-Based modeling: Methods and techniques for simulating human systems in PNAS, 2002, Vol. 99

behavior in any system arises from the relatively simple and localized activities of its agents."[32])

Purpose-oriented modeling

Having identified some major differences between these three paradigmata, the crucial question remains how to deliver sound models. As recommended above one of the first steps of modeling after having defined a problem context should be a reflection upon which modeling paradigm and methodology suit purpose and object best. At this stage the modeler has two options: he can either focus on one paradigm gaining the advantage of a stringent set of methods of one established methodology, or he can try to combine suitable methodologies and turn towards multi-paradigm modeling. The latter tend to be closer to reality as they can combine best-fit methods of different methodologies but may lose some explanatory power. In both cases practitioners need criteria that provide orientation for when to apply which methodology.

In order to find the most suitable method for a modeling project it seems useful to identify the impact of different causes to the problem. The most important impacts need to be categorized into the main assumptions of the available methods.

This idea has already been addressed against System Dynamics in a very early critique of Ansoff: "Another major characteristic in determining areas of application of Industrial Dynamics is the specific model structure incorporating concepts of levels and flows built around the concept of tight loop information feedback. Forrester, in his book, makes a point that industrial systems are inherently information feedback systems. Granting the point, it does not necessarily follow that all aspects of the firm are best studied by means of information feedback systems. This suggests that the appropriateness of the information feedback viewpoint should be determined on the basis of the relative influence of the feedback information on the decision in any given situation."[33]

The main point is, if the feedback of a system (and it is argued that there is feedback almost everywhere) has only a minor effect on the problem to explain then of course the importance of this feedback should not be overstated by using System Dynamics methodology. If a system is characterized by discrete jumps, which form the core problem, then these jumps should not be smoothed out by a SD model. If the problem seems to be caused by the interaction of heterogeneous agents, then ABM seems most suitable. Of course if several effects interact a mix of methodology can be useful. Nevertheless it has to be considered, that a clear focus on a small number of interrelations is the differentiating advantage of computer simulation in approaching "messy systems". The major problem seems to be found in comparing the strengths of the different causes in order to identify the most suitable method. Up to now (if alternative methodologies are considered at all) this is mostly done intuitively. A method or framework in order to determine the most suitable modeling methodology is still missing.

[32] Phelan, Steven, A Note on the Correspondence Between Complexity and Systems Theory, Systemic Practice and Action Research, Vol. 12, No. 3, 1999, p. 239
[33] Ansoff, Igor/ Slevin, Dennis, An appreciation of Industrial Dynamics, in Management Science, Vol. 14, No. 7, 1968, p. 392

A final list of criteria for the choice of the right modeling paradigm seems out of reach. Nevertheless there are criteria at hand that might serve as rules of thumb. Some criteria for the usage of Agent-based Modeling have been proposed by Bonabeau[34]:

- When the interactions between the agents are complex, nonlinear, discontinuous, or discrete
- When space is crucial and the agents' positions are not fixed
- When the population is heterogeneous, when each individual is (potentially) different
- When the topology of interactions is heterogeneous and complex
- When the agents exhibit complex behavior, including learning and adaptation

Discrete models seem appropriate if the discreteness of the object has some reflection in the purpose. "Discrete-event models are appropriate for those systems for which changes in system state occur only at discrete points in time."[35]

Considerations regarding the application of Agent-Based Simulation seem to be driven predominantly by the object-side of the triangle (spatialty and heterogeneity can not be modeled very elegantly in SD). The criterion for choice between SD and DES on the other hand seems to lie more on the purpose-side. For DES-models it seems to be more short-term, operational logistics problems, which are to be optimized and require a shorter time horizon. The discussion of long-term strategic policies favors SD: "Hence, most discrete event simulations are microscopic in their focus and involve considerable detail. They may include appropriate probability distributions if the system behavior is stochastic. It is, though, possible and often useful to model system behavior at the rather more macroscopic level. This is the usual focus of the system dynamics approach […]. System Dynamics is less concerned with detail than discrete event simulation and focuses, instead, on the ways in which system structures affect system behavior."[36] In accordance with the criteria that Lane proposes in his table which seem to reflect more upon the purpose side than onto the object-side the thesis defended here would be that the choice of the modeling paradigm depends upon the purpose if it is to decide between SD and DES. If the decision has to be taken between SD and AB, the object-side becomes more relevant. Then the key-indicator would be whether the problem is caused by feedback or interaction between heterogeneous elements.

Some authors propose "uncertainty" and "probability" as a key criterion for the choice of modeling a paradigm:

"For example, SD is particularly well suited to studying systems containing a complex web of feedback loops, while discrete system simulation is preferred when the system contains a high degree of uncertainty. A key strength of ABS is its ability to incorporate spatial as well as probabilistic aspects of the system."[37]

---

[34] Bonabeau, Eric, Agent-Based modeling: Methods and techniques for simulating human systems, in PNAS, 2002, Vol. 99, page 7287

[35] Banks, Carson, Nelson, Nicol, Discrete-Event System Simulation, New Jersey, 3rd edition, p.163

[36] Michael Pidd, Computer Simulation in Management Science, Chichester, 2004, 5th edition, p.249

[37] Wakeland/ Gallaher/ Macovsky/ Aktipis, A comparison of System Dynamics and Agent-Based Simulation Applied to the Study of Cellular Receptor Dynamics, Proceedings of the 37th Hawaii International Conference on System Science, 2004, p.1

Nevertheless stochastic elements can be included in SD-models as well. Another rule might suggest itself in that context: With an increase in uncertainty in the available data, the degree of aggregation should increase aswell.[38]

An approach to choose the right paradigm which takes into account only "idiosyncratic combinations of factors to do with the personal styles and preferences of analysts and clients, the time available, gross characteristics of the 'perceived issues', past experiences of all concerned, organizational cultures, financial and academic pressures inhibiting or encouraging collaborative working, and so on"[39] seems inappropriate and tends to result in the loss of credibility.

Multi-Paradigm Modeling

In addition to the selection of suitable paradigms a next step would be to build multi-paradigm-models consisting of interacting modules orientated at best-fit paradigms for the respective sub-problems. This effort makes the preliminary task to identify the right methodology for a sub-problem even more necessary in order to avoid unnecessary work by trying different methodologies. Experiments with models integrating ABM and SD have already been studied. Main areas were the Bass model[40] and the modeling of supply chains[41].

For the integration of the two methodologies it is necessary to clearly identify possible links. In this context two main approaches for implementing SD into Agent-based modeling are reasonable. The first possibility is to create entities out of SD structures. The second possible way includes creating a dynamic environment for the agents, which would be provided by an SD model. In this context three categories of environments can be distinguished in an Agent-based model:

Alternative environments in AB-modeling

a) "Zero" environment
   - Environment does not effect agents in any way
   - Environment may just hold some aggregate values
b) Passive environment
   - Agents only interact with some variables or structures in the environment
   - Environment does not have any inherent dynamics
c) Active environment
   - Environment has its own dynamics and therefore is an active player in the AB model

Table 3: Alternative environments in Agent-based Modelling[42]

---

[38] Compare Rahmandad/ Sterman, Heterogeneity and Network Structure in the Dynamics of Diffusion: Comparing Agent-Based and Differential Equation Models (to appear), downloadable from http://web.mit.edu/jsterman/www/Heterogeneity.html, p. 24, "The results suggest extensive disaggregation may not be warranted unless detailed data characterizing network structure are available, that structure is stable, and the computational burden does not limit sensitivity analysis or the inclusion of other key feedbacks that may condition the dynamics."
[39] Bennett, Ackermann, Eden, Williams: Analysing Litigation and Negotiation: Using a combined methodology, in Mingers, Gill: Multimethodology, Chichester, 1997, page. 86
[40] Borshchev/ Filippov, From System Dynamics and Discrete Event to Practical Agent Based Modeling: Reasons, Techniques, Tools, Proceedings of the 22nd International Conference of the System Dynamics Society, 2004
[41] Schieritz/ Groessler, Emergent Structures in Supply Chains – A Study Integrating Agent-Based and System Dynamics Modeling, Proceedings of the 36th Hawaii International Conference on System Sciences, 2001; Akkermans, Henk, Emergent Supply Networks: System Dynamics Simulation of Adaptive Supply Networks, Proceedings of the 36th Hawaii International Conference on System Sciences, 2001
[42] Agent Based Modeling in AnyLogic downloadable from http://www.anylogic.jp/download/any5agentbasedmodeling.pdf, p.11

In the case of the zero environment clearly no SD structure is necessary, neither in the case of a passive environment. In the case of an active environment on the other hand it seems very useful to use System Dynamics as the dynamics are constituted by aggregate values gained out of the Agent-based model.

It remains questionable how useful this approach is after all. Two ways of generating dynamics, first by interaction of individual entities and second by feedbacks are combined, which leaves the analysis of the evolving model even more challenging. Whether this approach is beneficial strongly depends on the model purpose. In any case the combination leads to a higher flexibility as the stock-and-flow-notation is enriched with additional syntax. This would hint towards the idea that stocks can easily be disaggregated into individual agents without the loss of information (Nevertheless possibly loosing computational speed).

One of the major advantages that can be gained through the integration of Agent-based Modeling into System Dynamics models is the spatiality which is easily implemented by giving each agent a distinct x and y variable. There are different types of concepts in ABM in order to add information of space. One is the concept of discrete space which could also be represented within stock and flow notation. However it remains unanswered whether this would still be consistent with the traditional concept of stock and flow.

Interaction of paradigms

"While the conventional wisdom suggests that reality is causally prior to theories that attempt to explain it, it is clear that causality runs in both directions. Theories and beliefs, once widely accepted, shape behavior in ways that make reality consistent with the theory, even when it was not initially the case."[43]

As discussed above methodologies assemble a distinct set of hypothesis regarding the underlying sources of dynamic in a system. Repenning[44] illustrates that it is risky to assume those sets for a given problem unreflectively. The challenge is to stay aware of those sets and to apply them adequately.

The most promising approach of a reflection upon the underlying assumptions of a modeling paradigm is a lively discussion with experts of the other fields (in this case Agent-Based Modeling or Discrete-Event Simulation). In addition it seems valuable to foster the integration with Agent-Based Modeling as it is increasingly being integrated into the social sciences. Two fields which are particular interesting are the so-called socionic, which evolves out of sociology, based on the first steps made by Axelrod[45] and the Agent-Based computational economics, promoting the application of Agent-Based Modeling to economic questions. As those fields are both still relatively young, they might profit from the insights gained in System Dynamics. Once the assumptions of both methodologies have been clearly formulated as assumptions, which is a legitimate process, a collection of arguments for these assumptions could be started within the fields. A starting point might be Phelan:

[43] Repenning, Nelson, Selling system dynamics to (other) social scientists, System Dynamics Review, Vol. 19, No. 4, p.325
[44] Repenning, Nelson, Selling system dynamics to (other) social scientists, System Dynamics Review, Vol. 19, No. 4
[45] Axelrod, The evolution of cooperation, London, 1984

"It is something of an article of faith with systems theorists that a combination of positive or negative feedback (including self-referential behavior) is a useful way of characterizing interactions in a system. One of the weaknesses of the approach is that stocks and flows invariably refer to the quantity rather than to the quality (or any other characteristic) of an element (or its attributes)."[46]

Conclusion

Based on the basic principles of how to reach conclusions in science theory it must be acknowledged that by crude application of modeling methodologies we risk wrong conclusions through the implicit acceptance of underlying assumptions in established paradigms (abduction risk). Therefore this paper proposes to integrate the discussion and selection of suitable modeling methodologies into the early stages of any modeling process.

By discussing and comparing underlying assumptions as well as technical differences of the three paradigms (SD, ABM and DES) this paper provides important indications which aspects need to be taken in account. These aspects can be categorized in the dimensions purpose, object and methodology.

Purpose refers to the initial motivation of the modeling effort and can include aspects such as:

- Tracking individual behavior[47]
- Understanding aggregate values
- Gaining insight in a specific (not yet understood) problem context
- Reproducing a given system behavior
- Optimizing specific system values
- Evaluation of long term policies
- Etc.

Object relates to the real world characteristics of the problem context and includes aspects such as:

- Level of detail of available information
- Uncertainty of available information
- Continuous or discrete system behavior
- Number of relevant entities
- Importance of interaction
- Differentiability of entities (individual properties such as entity history and spatiality)

---

[46] Phelan, Steven, A Note on the Correspondence Between Complexity and Systems Theory, Systemic Practice and Action Research, Vol. 12, No. 3, 1999, p. 240

[47] Compare Sterman, Business Dynamics. Systems Thinking and Modeling for a Complex World, Boston, 2000, p.208, "When the purpose of the model requires tracking the individual people, for example modeling the behavior of people entering the line at the supermarket to determine the optimal number of checkout counters, then people can be modeled as discrete individuals arriving at discrete points; this is a classic modeling paradigm in queuing theory."

- Etc.

Methodology refers to the general approach, the underlying assumptions and suggested methods and techniques of a given modeling paradigm. Methodology aspects include:

- Perspective (top down vs. bottom up)
- Predominant source of dynamics (e.g. feedback, coupled events, interaction of agents, …)
- Perception of time (discrete events, time slicing, continuous, etc.)
- Available methods and tools
- Validation techniques
- Etc.

This paper argues that only by aligning these three dimensions (purpose, object and methodology) the best suitable methodology for a given problem or sub-problem can be identified. This argumentation of course also applies to the combination of methodologies for different sub-problems in multi-paradigm modeling efforts. The ability to link purposes and objects with alternative methodologies will hopefully overcome a typical phenomenon that practitioners of a specific methodology "define different problems, follow different procedures, ..."[48]. Our vision is to select the most suitable methodology for a given purpose and object.

[48] Meadows, The unavoidable A Priori, p. 24 in Randers, Elements of the System Dynamics Method, Cambridge/ London, 1980

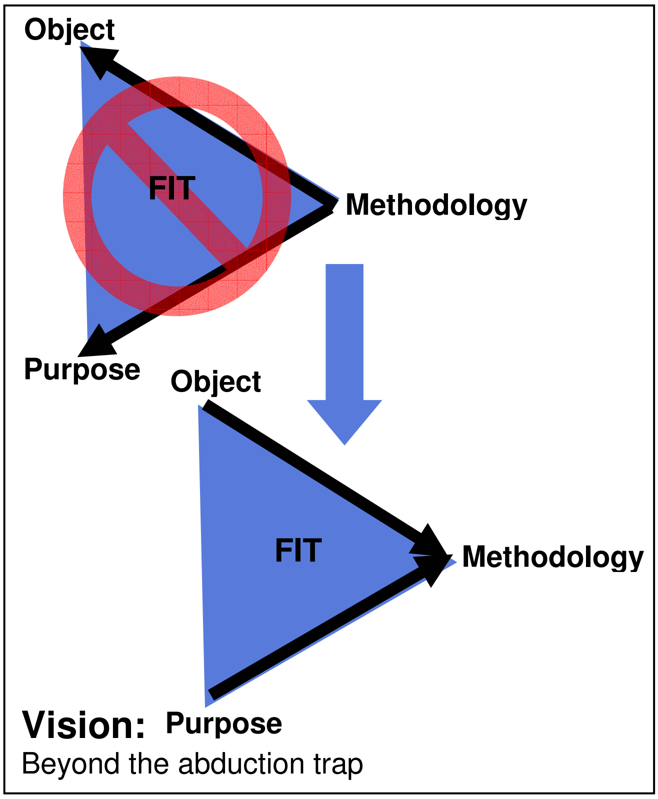

Figure 2: Vision of Multi-Paradigm Modeling

Concluding the discussion of this paper it must be admitted, that there is still a way to go in order to provide the wanted orientation framework that can be applied by modeling practitioners independently. First steps will now be made in the form of criteria hinting towards a specific methodology, which is proposed for discussion. These criteria correspond to the underlying assumptions of the methodologies and form guidelines to the choice of the adequate methodology in a specific modeling task.

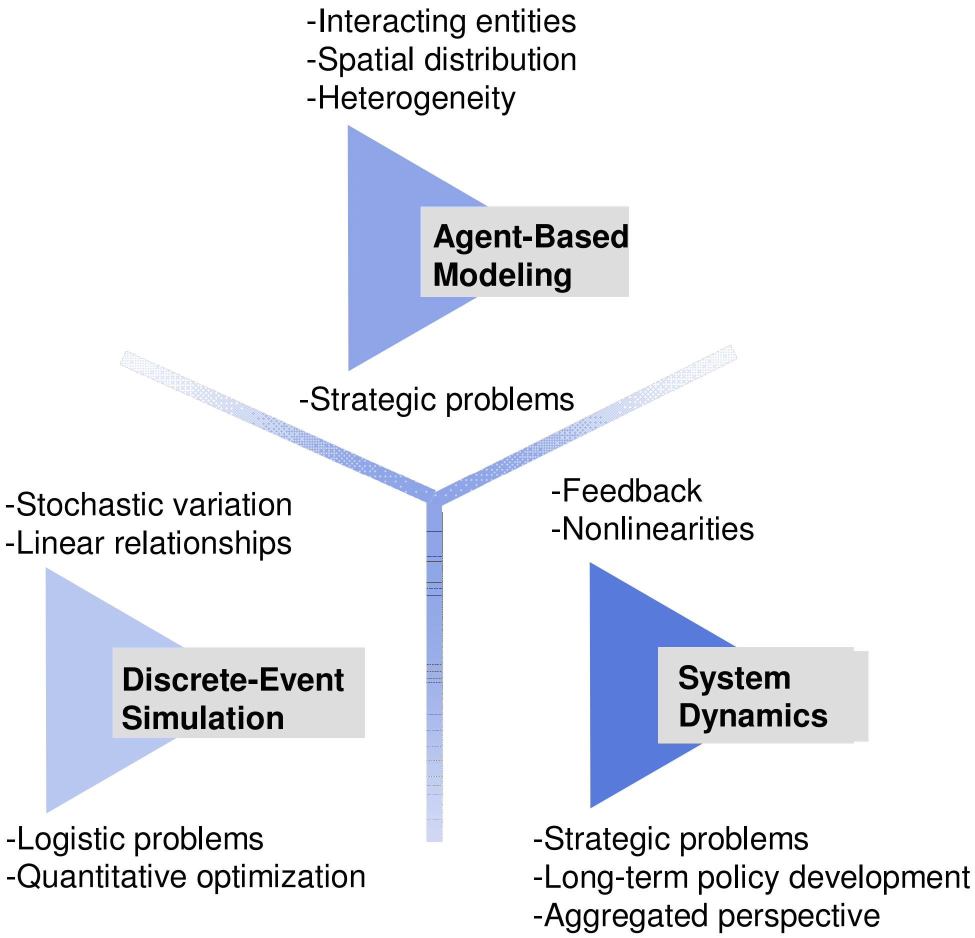

Figure 3: Criteria for adequate modeling methodologies

Together with the developed categories and the discussion above these criteria form a first step towards an orientation framework in multi-paradigm modeling. Further research is necessary in subsequent steps in order come closer to this declared goal.

Literature:

Agent Based Modeling in AnyLogic downloadable from http://www.anylogic.jp/download/any5agentbasedmodeling.pdf

Akkermans, Emergent Supply Networks: System Dynamics Simulation of Adaptive Supply Networks, Proceedings of the 36th Hawaii International Conference on System Sciences, 2001

Ansoff/ Slevin, An appreciation of Industrial Dynamics, in Management Science, Vol. 14, No. 7, 1968

Axelrod, A model of the emergence of new political actors, in Gilbert/ Conte, Artificial Societies, London, 1995

Axelrod, The evolution of cooperation, London, 1984

Banks, Carson, Nelson, Nicol, Discrete-Event System Simulation, New Jersey, 3rd edition

Bennett, Ackermann, Eden, Williams: Analysing Litigation and Negotiation: Using a combined methodology, in Mingers, Gill: Multimethodology, Chichester, 1997

Bonabeau, Agent-Based modeling: Methods and techniques for simulating human systems in PNAS, 2002, Vol. 99

Borshchev/ Filippov, From System Dynamics and Discrete Event to Practical Agent Based Modeling: Reasons, Techniques, Tools, Proceedings of the 22nd International Conference of the System Dynamics Society, 2004

Casti, Would-Be Worlds: How simulation is changing the frontiers of science, New York, 1997

England, Evolutionary Concepts in Contemporary Economics, 1994

Gilbert/ Conte, Artificial Societies, London, 1995

Grebel/ Pyka, Agent-based modelling – A methodology for the analysis of qualitative development processes, 2004 in: Lombardi/ Squazzoni, Saggi di economia evolutiva , Franco Angeli, Milano, Italy (forthcoming)

Lane, You just don't understand me: Modes of failure and success in the discourse between system dynamics and discrete event simulation, LSE OR Working Paper 00.34, 2000

Lorenz/ Bassi, Comprehensibility as a discrimination criterion for Agent-Based Modelling and System Dynamics: An empirical approach, in Sterman et al., Proceedings of the 23 rd International Conference of the System Dynamics Society, Boston, 2005

Magnani, Model-Based Creative Abduction in Magnani/ Nersessian/ Thagard, Model-based reasoning in scientific discovery, New York, 1999

Magnani/ Nersessian/ Thagard, Model-based reasoning in scientific discovery, New York, 1999

Meadows, The unavoidable A Priori, in Randers, Elements of the System Dynamics Method, Cambridge/ London, 1980

Meadows/Robinson, The electronic oracle, Chichester, 1985

Mingers/ Gill, Multimethodology, Chichester, 1997

Morecroft/ Robinson, Explaining Puzzling Dynamics: Comparing the Use of System Dynamics and Discrete-Event Simulation, Proceedings of System Dynamics Conference 2005

Parunak/ Savit/ Riolo, Agent-Based Modeling vs. Equation-Based Modeling: A Case Study and Users' Guide, Proceedings of Workshop on Modeling Agent Based Systems, 1998

Phelan, A Note on the Correspendence Between Complexity and Systems Theory, Systemic Practice and Action Research, Vol. 12, No. 3, 1999

Pidd, Computer Simulation in Management Science, Chichester, 2004, 5th edition

Radzicki/ Sterman, Evolutionary Economics and System Dynamics in England, Richard, Evolutionary Concepts in Contemporary Economics

Rahmandad/ Sterman, Heterogeneity and Network Structure in the Dynamics of Diffusion: Comparing Agent-Based and Differential Equation Models (to appear), downloadable from http://web.mit.edu/jsterman/www/Heterogeneity.html

Randers, Elements of the System Dynamics Method, Cambridge/ London, 1980

Repenning, Selling system dynamics to (other) social scientists, System Dynamics Review, Vol. 19, No. 4, p.325

Schieritz/ Groessler, Emergent Structures in Supply Chains – A Study Integrating Agent-Based and System Dynamics Modeling, Proceedings of the 36th Hawaii International Conference on System Sciences, 2001;

Schieritz/ Milling, Modeling the Forest or Modeling the Trees, Proceedings of the 21st International Conference of the System Dynamics Society, 2003

Sterman, Business Dynamics. Systems Thinking and Modeling for a Complex World, Boston, 2000

Sterman et al., Proceedings of the 23 rd International Conference of the System Dynamics Society, Boston, 2005

Wakeland/ Gallaher/ Macovsky/ Aktipis, A comparison of System Dynamics and Agent-Based Simulation Applied to the Study of Cellular Receptor Dynamics, Proceedings of the 37th Hawaii International Conference on System Science, 2004