Towards Multi-Perspective Modeling and Simulation for Complex Systems

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Abstract

This conceptual paper discusses the role of hierarchy in complex systems modeling and simulation and discusses the difficulty of subsuming a complex system into a model having a unique hierarchical decomposition. After elaborating on the potential of multi-perspective modeling and simulation, a first formalization of multi-perspective models is proposed.

1. INTRODUCTION

Modeling and simulation is increasingly being applied in biology and human sciences after having been mainly restricted to purely physical systems. The higher intrinsic complexity in these new areas of application brings new challenges both in terms of theory and methodology. Complex systems show multiple levels of organization corresponding to different time and space scales [1]. Hierarchical modeling formalisms [2, 3] would seem well equipped to represent such systems, but close scrutiny shows that their multi-level expressiveness is limited; behavior generation is always specified at the leaves of a unique decomposition tree (atomic models in DEVS). This form of reductionism where higher levels merely result from the composition of entities at the immediately lower levels makes it difficult to represent notions such as upward and downward causation which are ubiquitous in complex systems [4].

When we want to make sense of a complex system, there does not seem to be any alternative to the hierarchical decomposition[1] strategy, and this naturally translates into modeling formalisms. However, by breaking a system down into sub-systems, an abstraction is made; a unique perspective is adopted about the decomposition and its atomic units of behavior generation. This abstraction process is only possible through disregarding some features of the system, making the experimenter blind to some of the system's properties [5]. Modeling being objective-driven, this attitude is normal, but, for some classes of systems, a unique decomposition can lead to a model overlooking important aspects of its source system, and consequently, unable to replicate or predict some phenomena of interest. If used to steer decision-support, such a model could lead to undesirable side-effects.

This problem is not salient when current simulation formalisms are applied to simple systems. In such systems, all relevant abstractions/decompositions tend to have structures that are isomorphic in relation to each other [6]. The issue becomes more obvious when we target complex biological or socio-technical systems where neat hierarchical decomposition seems to break down as we go higher in levels [7].

The problem of a unique compositional hierarchy and that of multi-level representations have already been posed in various ways in modeling and simulation. For example, recently, Dalle and colleagues [8] proposed to introduce shared components in DEVS coupled models. In the field of Systems Biology, Uhrmacher discussed the difficulty of representing complex multi-level biological systems in DEVS, pinpointing the formalism's intrinsic reductionism [9]. As a result, an extension to the formalism was introduced, which, among other interesting features, provides coupled models with their own behavior specification constructs [10]. By adding an organizational level hierarchy to the classic compositional hierarchy of DEVS, this approach tackles the reductionism problem but sticks to the unique decomposition paradigm, whereas it can be shown that, some systems, for example, complex social systems, exhibit tangled hierarchies (the unit of behavior can be the individual, the family, the company, or the neighborhood. The higher level behaviors are not simple aggregates of lower level behaviors, and one individual part can simultaneously be part of different hierarchies) [7].

Winther's concept of a *partitioning frame* [11] and other related concepts in philosophy of science and theoretical biology [12] underline the existence of a *de facto* theoretical unit guiding the investigation and decomposition of a system of interest. Furthermore, considering the role of theories, as stated by Poppers' famous statement that "… *Theories* [were] *nets cast to catch what we call* '*the world'…"* [13], we realize that any theory, and any decomposition in modeling results from a choice of abstraction and leaves out something of the world. This is also consistent with Wimsatt's statement that the number of relevant alternative perspectives for a system's description is positively correlated with its complexity.

To enable modelers to catch more of the world's complexity in hierarchical modeling and simulation formalisms, we will investigate the opportunity of using several of Popper's proverbial nets together in a model. More concretely, we introduce the basis for a modeling and simulation framework for multi-perspective models with multiple alternative decompositions of a system of interest, each from a specific perspective, which are simulated in parallel and can influence each other. The proposed framework is rooted in Zeigler's theory of modeling and simulation to which it blends Wimsatt's concepts descriptive and interactional complexity [12]. We expect this approach to yield more robust system descriptions in the sense of Levins [5]. In Yilmaz and Oren's taxonomy of multi-models, the proposed concept is fits in the class of multi-aspect model [14].

Beyond the management of alternative hierarchical decompositions, the challenge is in the definition of the relations that have to be specified between those alternative system representations. These relations are not of the same nature as state transitions or coupling relations found in single perspective specification of hierarchical systems. They rather form a another level of system specification, on top of the coupled component level, which defines how system specifications can be obtained through mapping sets of components pertaining to different system decompositions.

The rest of the paper is organized as follows. Section 2 discusses the role of hierarchy in complexity and further argues the necessity of multiple hierarchies in the description of some classes of systems. Section 3 introduces multi-perspective modeling through examples and shows the proposed formalism. Finally, section five concludes and discusses future directions.

2. HIERARCHY AND COMPLEXITY

Hierarchy has been a recurring theme in complexity science. Much has been said about its role in the nature of systems and in our ability to make sense of complexity. Herbert Simon's famous *"Architecture of complexity"* [1] places the concept of hierarchy at the center of the discussion. His oft repeated definition of a complex system as a system consisting of a *"large number of parts that interact in a non-simple way"* already shows the importance of such notions such as composition and interaction. One first step towards understanding hierarchy and its relation with complexity is to recognize the polysemy of the term. In different contexts, hierarchy can cover different meanings. Lane [7] makes a salutary distinction between four, distinct, yet overlapping, meanings associated with the term: (*order, inclusion, control, and level hierarchies*). For our purpose, inclusion and level hierarchies are the most relevant meanings we will consider. Inclusion hierarchy is best described with the metaphor of *Chinese boxes* or *Matryoshka dolls* where an entity contains smaller entities, with the latter smaller entities containing even smaller entities, and so forth. Level hierarchy describes the notion that entities in nature exist at different levels of organization characterized by distinct time and space scales [7]. One such hierarchy of levels in the biological realm could be: *cells, tissue, organ, and organism*. We can already see the overlap between inclusion and level hierarchies since organisms are made of organs, organs are made of tissues, and tissues are made of cells. However, the hierarchy between levels is often considered richer than a mere inclusion relation, phenomena such as emergence, upward, and downward causation are believed to hold in a hierarchy of levels of organization.

The concept of hierarchy has been used in both epistemological and ontological claims about systems. Some authors consider that systems, either engineered or natural, are fundamentally hierarchical. For example, Simon uses the famous watchmakers' metaphor to explain the importance of hierarchical construction in the evolution and stability of complex systems. Other authors explain the importance of hierarchy more as a simplification strategy to overcome the human cognitive inability of holding more than a few concepts in working memory [15].

Hierarchical organization has very close links with the notions of modularity and near-separability of system components. Parts are behaviorally nearly independent and interact through their interfaces. The recognition of this property of the objects surrounding us made the reductionist (Cartesian, Newtonian) research program so efficient. With this near-separability heuristic, one can gain much knowledge about an object by breaking it down into subsets of reasonable complexity and studying them independently. System Theory challenges this view but remains faithful to the central role of hierarchy (major inductive system frameworks are hierarchical [3, 2]), while emphasizing the importance of interactions between parts. Indeed, as Klir himself puts it, systemhood is more about the relation between parts than about the parts themselves.

However, the notion of system hierarchy has had its contradictors. The concept of a level hierarchy is clearly established in the physical realm but becomes difficult to maintain as we rise towards the realms of life, cognition, and society [7]. As we go up in complexity, the neat levels of organization, observed in physical systems tend to break down [12]. Besides, it seems that, the more complex a system is, the more difficult it is to represent it completely within a single hierarchical decomposition. This fact is well described by Levin's distinction between aggregated, engineered, and evolved systems. Unlike the former two types, evolved systems tend to violate the near-separability property. In Wimsatt's terms, such systems have a high degree of both descriptive and interactional complexity. Complexity can thus be seen as the property of systems to have multiple alternative and non-isomorphic decompositions [12,6].

3. MULTI-PERSPECTIVE REPRESENTATION OF COMPLEX SYSTEMS

We just saw that hierarchy is a decisive feature for the expressiveness of modeling and simulation formalisms. In DEVS, the coupled specification of hierarchical models through modular components and message based communication through ports provides a clean and rigorous way of expressing the dynamics of composite systems. A DEVS coupled model results from pruning a System Entity Structure, choosing one aspect and one specialization for each entity, in a pragmatic, problem-oriented way. As Wimsatt states, however, complex systems are systems which have problems that cannot be tackled from a unique perspective, but rather require blending several of the latter with well defined bridges from one to the other. This situation can be intuitively understood with a couple of real life examples: Some severe diseases require the joint diagnosis and intervention of various specialists who actually are working collaboratively with complementary mental models, each with a partial representation of the patient's condition. In the domain of urban planning, a city can be seen from various functional perspectives which need to be conciliated if a good design is to be reached. These and many more problems in real life require multi-perspective thinking and would largely benefit from a modeling and simulation theory and methodology providing conceptual support for the process. The classic works on multi-models [14], dynamic structure [10, 16, 17], experimental frames [2], and systems entity structures [18] show that descriptive complexity has always mattered in modeling and simulation research. Descriptive complexity refers to the propensity of complex systems to be describable in various alternative and non-isomorphic decompositions. Interactional complexity refers to the extent of the relations between those alternative system decompositions. These relations result from two components in the two decompositions sharing a *common referent* [12], like a parameter in one perspective being a variable in another perspective, or an atomic model in the first perspective having an aggregation/disaggregation relation with a coupled model in the second perspective such a that the atomic model constrains the structure of the coupled model through a trans-perspective relation, and the coupled model's components output summary are used in the transition functions of the atomic model.

To discuss the two extremes of descriptive and interactional complexity, let us consider a system entity S, with two aspects, p1 and p2. If p1 and p2 are isomorphic and if each component in one of the decompositions has a unique referent in the other decomposition, the system is both descriptively and interactionally simple. A DEVS model can be built subsuming both decompositions in a single hierarchical structure p3. An example of this class of system is given by Wimsatt in [12]. A piece of granite decomposed into subregions of roughly constant chemical composition and crystalline form, under the perspectives of electrical conductivity, thermal conductivity, and density, is descriptively simple. Figure 1 abstractly depicts such a system entity and the resulting simplification.

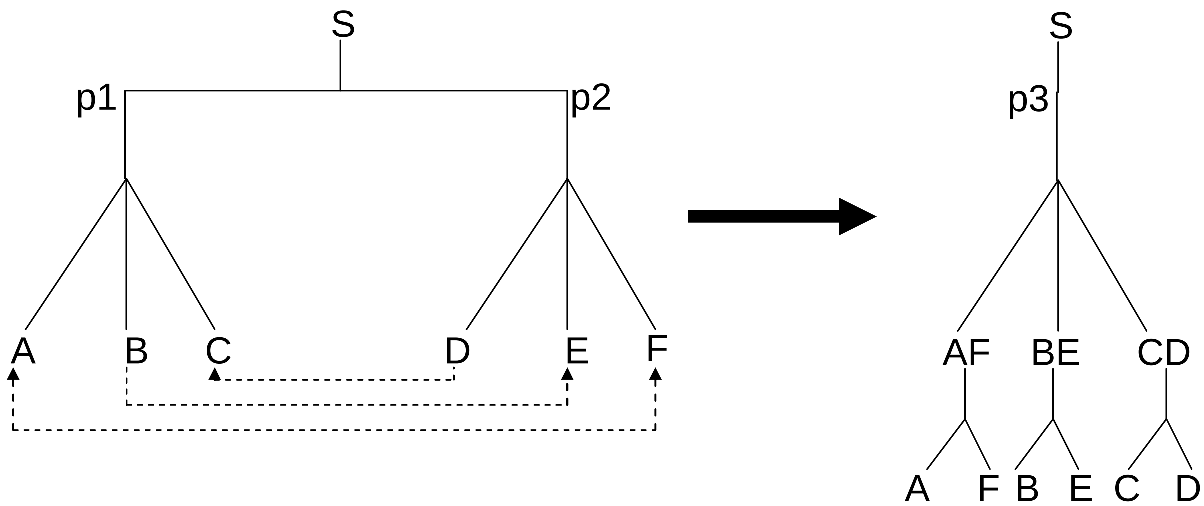

Figure 1: SES of a descriptively simple system

If p1 and p2 are not isomorphic and an entity in one of the aspects can have multiple referents in the same level or referents in another aspect at a lower or higher level of the hierarchy, the system is then descriptively and interactionally complex. Most complex systems are of this type [12]. A unique DEVS model subsuming both decompositions in a single hierarchical structure cannot be trivially built. An example of this class of system is given by Wimsatt in [12]. A differentiated multi-cellular organism decomposed under anatomical, physiological, biochemical etc., perspectives is descriptively and interactionally complex. Figure 2 depicts abstractly such class of a complex system.

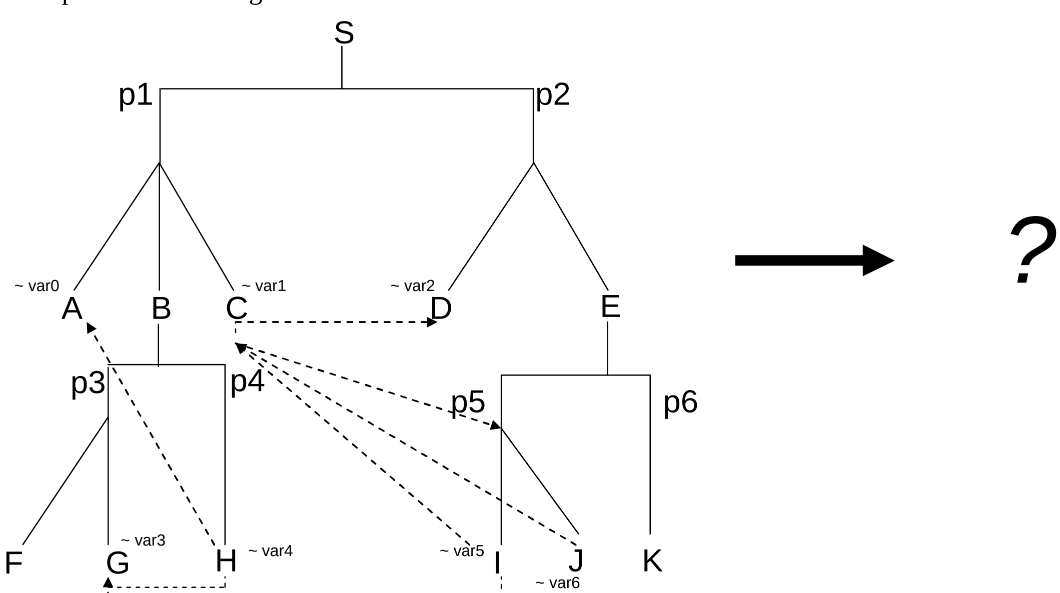

Figure 2: SES of a descriptively complex system

Defining the relations between the components pertaining to different perspectives offers extra expressiveness in the specification of complex systems. Besides the DEVS coupling relations existing between entities within a single aspect (omitted in Figures 1 and 2), a multi-perspective modeling formalism should allow specifying couplings between the values of variables pertaining to components in different aspects. For example, one should be able to specify a function mapping the influence of the value of var1 of entity C in the aspect p1 on var2 of entity D in the aspect p2. This would allow specifying inter-perspective influences. One could consider the coupling of var5 and var6 of p5 to var1 of entity C in p1 as an instance of upward causation, while the coupling of var1 with p5 would represent an instance of downward causation. If p5 is a dynamic structure coupled model, its executive should select the relevant structure depending on the value of var1.

For a more concrete example, let's envision analyzing a conflict situation through simulation from three distinct perspectives. The first perspective relates to the behavior of the factions in presence. The second perspective deals with the economic activity during the conflict, and the third perspective reflects the social class effects of the conflict. In the first perspective, we want to study the effect of peacekeeping policies on the conflict. Thus, this perspective breaks the conflict into one component per faction, for example, *FactionA*, *FactionB*, *TerroristOrganizationX*, and *PolicingForce*, with coupling relations between them. In the second perspective, the system is broken down into economic sectors, *Agriculture, Industry, and Commerce*. From a social class perspective, we want to know how the conflict affects the long-term repartition of the population into social classes: *Poor*, *WorkingClass*, *MiddleClass*, and *Rich*. These perspectives on the same issue will rely on different theories. These theories will generally focus on their aspect of interest and suppose that everything else remains constant. The time scales can also be very different. For example, the actions and interactions between the factions (attacks, demonstrations, riots, etc.) happen at a faster scale than drastic economic changes. It is very clear however that these perspectives are not independent. One can make the hypothesis that the behavior of the factions is affected by the current economy, but also by the group's composition in terms of social class. The intensity of the groups' actions will have an impact on the economy, etc. Specific knowledge can also be specified, if for example, it is a known fact that FactionA is mostly active in agriculture, while FactionB is a mostly made of traders. Through multi-perspective modeling, one can obtain a conceptually cleaner and more powerful grasp of a complex system under the systems paradigm. A multi-perspective conflict model could have the structure represented on figure 3.

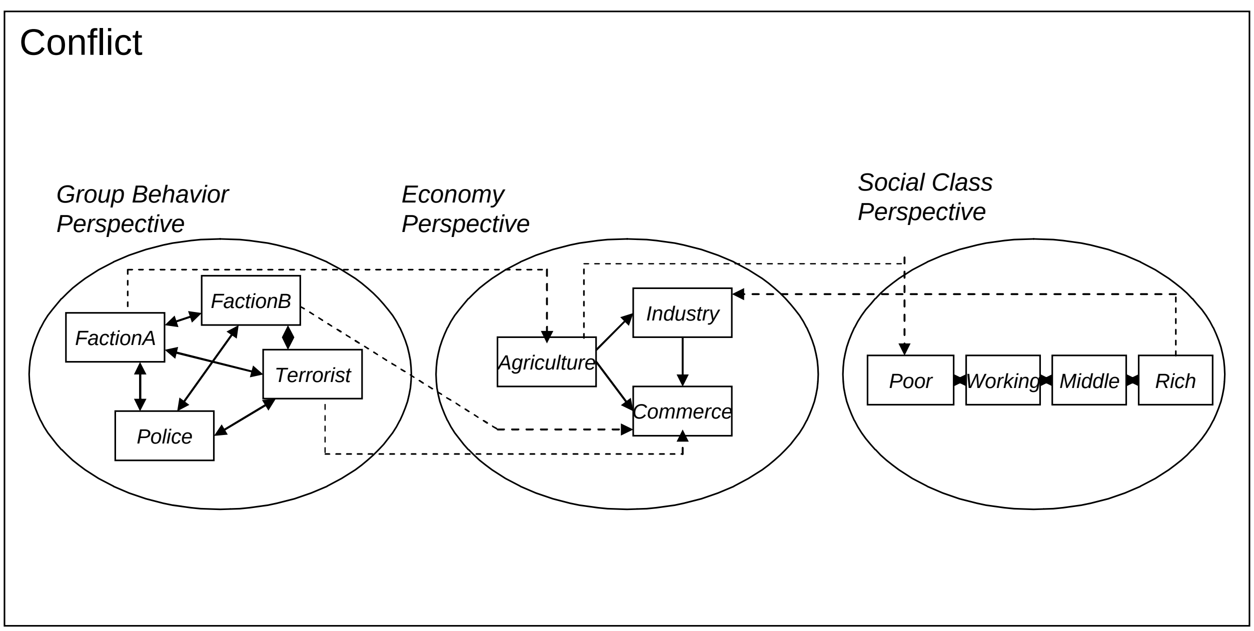

Figure 3: Multi-Perspective Conflict Model

A preliminary specification of a multi-perspective model can be given as follows.

A multi-perspective model is a tuple :
MPS = <A, E, V, VIF, SIF, VC, SC >

A is the set of SES aspects (perspectives)
E is the set of SES entities (atomic or coupled models)
V is the set of variables (each variable is part of an entity)
VIF is the variable influence functions mapping the influencing variable's range into the influenced variables values.
SIF is the structure influence function mapping the influencing variable's range into aspect compositions.

VC: V x VIF -> V, specifies the coupling of variables between perspectives
StructureCoupling: V x SIF -> A, specifies the coupling between a variable in one aspect and the structure of another aspect.

If two variables varA and varB are referents of each other in two distinct aspects, a variable coupling can be defined such that
AspectB.EntityB.varB = VC (AspectA.EntityA.varA, VIF(VarA,VarB)). It must be checked that AspectA and AspectB are distinct; otherwise a DEVS internal coupling should be built between the two entities. VIF(VarA,VarB) specifies the influence of variable varA on varB.

If variable varC influences the structure of aspect AspectD, the structure coupling relation is specified such that the variable can modify the structure of the aspect.
AspectD = SC (AspectC.EntityC.varC, SIF(varC, AspectD)).
SIF(varC, AspectD) is the structure influence function for AspectD.

On the simulation side, all perspectives have to be synchronized. Each relevant state change in one perspective has to be reflected in the other perspectives.

4. CONCLUSION

This paper has discussed the importance and limitation of hierarchy in complex systems modeling and simulations. It has argued that a unique decomposition is unable to capture the complexity of certain systems, especially, living and social system. An approach for multi-perspective representation of complex systems has been proposed, extending the DEVS and SES formalisms and based on Wimsatt's concept of descriptive and interactional complexity.
In the next steps of this research, the proposed modeling approach will be applied on a complex social simulation scenario involving various perspectives such as religion, social status, collective and individual behavior.

References

[1] Simon, H.A., 1962, 'The Architecture of Complexity', reprinted in Simon (1969), pp. 84-118.
[2] Zeigler, B. P. and Praehofer, H., 2000. Theory of Modeling and Simulation. Academic Press.
[3] Klir, G. (1985). Architecture of Systems complexity. Sauders, New York, USA.
[4] Kim, Jaegwon. "Epiphenomenal and Supervenient Causation." Midwest Studies in Philosophy 9 (1984): 257–270.
[5] Levins, R. 2007. Strategies of Abstraction Biol. Philos. 1 (5): 741-755.
[6] Kauffman, S. A., 1971, 'Articulation of Parts Explanations in Biology', Boston Studies in the Philosophy of Science , ed. R. C. Buck and R. S. Cohen, vol. 8, pp. 257-272.
[7] Lane, D. (2006), "Hierarchy, complexity, society," in D. Pumain, ed., Hierarchy in Natural and Social Sciences (Springer-Verlag: Berlin), 2006, 81-119.
[8] Dalle, O. Zeigler, B. P., Wainer G.A., Extending DEVS to support multiple occurrence in component-based simulation. Winter Simulation Conference 2008: 933-941
[9] Uhrmacher, A. M., Multi-Level Modeling and Simulation in Systems Biology -- Promises and Challenges. DS-RT 2006: 95
[10] Uhrmacher, A.M., 2007, Combining micro and macro-modeling in DEVS for computational biology. Winter Simulation Conference 2007
[11] Winther, R. G., 2006. Parts and Theories in Compositional Biology. Biology and Philosophy 21 (4).
[12] Wimsatt, W.C., 1972, Complexity and Organization, in K. F. Schaffner and R. S. Cohen, eds., PSA-1972 (Boston Studies in the Philosophy of Science, volume 20), Dordrecht: Reidel, pp. 67-86.
[13] Popper, K. R., 1959, The Logic of Scientific Discovery, New York: Harper Torchbooks.
[14] Yilmaz, L. and Oren T.I. (2005). Discrete-Event Multimodels and their Agent-Supported Activation and Update. In Proceedings of the Agent-Directed Simulation Symposium of the Spring Simulation Multiconference (SMC'05), San Diego, CA, April 2005, pp. 63-70.
[15] Cowan, N., 2005, Working memory capacity. Hove, East Sussex, UK: Psychology Press.
[16] Barros, F. J., 1997, Modeling formalisms for dynamic structure systemsACM Transactions on Modeling and Computer Simulation (TOMACS) archive Volume 7 , Issue 4 (October 1997) table of contents Pages: 501 - 515
[17] Hu, X., Zeigler, B., and Mittal, S. (2005).Variable structure in devs component-based modeling and simulation. Simulation, 81(2):91–102.
[18] Zeigler, B. and Hammonds, P.,2007. Modeling and simulation-based data engineering: introducing

pragmatics into ontologies for net-centric information exchange. Academic Press.

Biography

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