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INVITED ARTICLE

Dynamic modeling based on a temporal–causal network modeling approach

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Abstract
This paper presents a dynamic modeling approach that enables to design complex high level conceptual representations of models in the form of causal-temporal networks, which can be automatically transformed into executable numerical model representations. Dedicated software is available to support designing models in a graphical manner, and automatically transforming them into an executable format and performing simulation experiments. The temporal–causal network modeling format used makes it easy to take into account theories and findings about complex brain processes known from Cognitive, Affective and Social Neuroscience, which, for example, often involve dynamics based on interrelating cycles. This enables to address complex phenomena such as the integration of emotions within all kinds of cognitive processes, and of internal simulation and mirroring of mental processes of others. In this paper also the applicability has been discussed in general terms.

Introduction

This paper presents a specific complex systems modeling method which is in line with the dynamical systems perspective advocated by Ashby (1960) and van Gelder and Port (1995). But more specifically, it takes modeling through networks of temporal–causal relations as a main perspective. This perspective was inspired by the analysis of causal networks in different physical, biological, neurological, mental and social application domains, among which the domain of biochemical reactions in cell biochemistry (e.g., Jonker, Snoep, Treur, Westerhoff, & Wijngaards, 2002, 2008), the domain of causal networks of mental states as considered within Cognitive Science and Philosophy of Mind (e.g., Kim, 1996), and the domain of social networks; e.g., (Bosse, Duell, Memon, Treur, & van der Wal, 2015; Sharpanskykh & Treur, 2014). The choice for networks of temporal–causal relations makes that the modeling

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approach discussed here can be considered a generic modeling approach for dynamics in (complex) networks, suitable for networks in a variety of domains: for networks of mental states, but also for biological networks, social networks, and many other types of networks. Indeed, the method has already been applied in a variety of applications in different domains, and as such has proven is usefulness (e.g., see section 'Discussion'). The current paper gives a detailed view on the method and relates it to aspects of its historical and philosophical background.

The modeling approach has a declarative nature as, for example, often seen for approaches developed within Artificial Intelligence, such as knowledge modeling, logical modeling, causal reasoning, model-based diagnosis, or agent modeling. This means that a model description describes (assumed) relations between states (over time) within the domain addressed, and the computational methods for processing or analysis of such relations are separated from the model description itself. Through the perspective of temporal—causal networks it is relatively easy to design a model mainly at a conceptual, graphical level and to relate the model to scientific literature from a wide variety of disciplines in which such causal relations are also used as a main vehicle to express knowledge. As a particular case, in this way models of mental processes can be related to neuroscientific literature (e.g., from Cognitive Neuroscience, Affective Neuroscience or Social Neuroscience) in which networks formed by connections between neurons are used as a basis for causal relations between the activations of these neurons. However, the networks of temporal—causal relations perspective chosen as a point of departure, and discussed in more detail in this paper, is much more general and in principle applies to all domains, as causal relations are commonly used as a way to describe processes.

Nevertheless, technically spoken the developed modeling approach also has similarities to approaches taking inspiration directly from recurrent neural networks studied in the neural network modeling area, as, for example, described in Hirsch (1989), Hopfield (1982, 1984), and Beer (1995). More specifically, the computational modeling approach adopted here fits in the scope of small continuous-time recurrent neural networks; this approach is advocated by Beer (1995), and was inspired, for example, by earlier work in Grossberg (1969), Hopfield (1982, 1984), and Funahashi and Nakamura (1993). In Beer (1995) it is claimed that they are an obvious choice for modeling because.

(1) They are the simplest nonlinear, continuous dynamical neural network model.
(2) They are universal dynamics approximators in the sense that, for any finite interval of time, they can approximate the trajectories of any smooth dynamical system on a compact subset of IR^n arbitrarily well (Funahashi & Nakamura, 1993).
(3) They have a plausible neurobiological interpretation.

These three advantages indeed apply to the temporal—causal network modeling approach, but in a generalized way:

(1) Temporal—causal network models are simple, nonlinear, continuous dynamical network models.
(2) They are universal dynamics modelers in the sense that, any smooth dynamical system (which by definition is a state-determined system) can be modeled as a temporal—causal network model (see section 'Applicability of the modeling perspective in a wide variety of domains'; see also item 6. in the list of desiderata below).
(3) They have a plausible interpretation in relation to scientific knowledge (from any domain) commonly described by causal relations.

The dynamic modeling approach was developed with a number of more specific desiderata in mind. In this paper these desiderata are discussed in different (sub)sections. A brief overview of them is:

1. *Modeling dynamics of complex cyclic patterns in real continuous time.*The approach models *dynamics* of processes and their often *circular or cyclic patterns* according to *continuous time*, where points and intervals at the time axis are represented by real numbers that correspond to real time points and real time durations
2. *Models at high conceptual level but with relations to physical and biological mechanisms.*The models are described at a *high conceptual* (cognitive, affective, social) *modeling level*, but can be *related* in a transparent manner *to physical and biological mechanisms* underlying the modeled processes, from biologically oriented disciplines, such as (Cognitive, Affective and Social) Neurosciences.
3. *Networks of temporal—causal relations as central element.*By using *networks of temporal—causal relations* as a central modeling element it is facilitated to make use of the large amount of scientific literature in a wide variety of disciplines with knowledge explaining complex processes in terms of *causal relations* between different states.
4. *Design of a conceptual representation as a basis for systematic generation of a detailed numerical representation of a dynamical model.Design* of a model can mainly be done at a conceptual level, for example, using *a graphical representation*. On the basis of the conceptual representation of the model a numerical representation can be generated in a systematic manner, or even automatically, and used for simulation experiments and further analysis. This generation of a numerical representation from the conceptual representation involves either specification of own chosen combination functions to aggregate the impacts of multiple states on a given state, or only specification of values for parameters of standard combination functions that can be used for this purpose.
5. *Applicability of multiple computational methods on a given model representation.*The model representations are declarative and have no built in computational methods with them. There is a free choice to apply any computational method on given model descriptions. Such computational methods applied to the model can address different types of tasks such as simulation, or analysis,