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Using fuzzy logic to implement decision policies in system dynamics models

Daniel Cardoso de Salles[1], Armando Celestino Gonçalves Neto[1], Lino Guimarães Marujo*

Department of Industrial Engineering, Polytechnic School, Universidade Federal do Rio de Janeiro, Av. Athos da Silveira Ramos 149, PO Box 64548, Cidade Universitária, Rio de Janeiro 21941-909, Brazil

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A B S T R A C T

This paper aims to show how the use of fuzzy systems can enhance the application of system dynamics (SD), with the construction of virtual worlds, for organizational learning. By doing so, the main contribution is to propose a fuzzy-SD integrated methodology that allows a natural language modeling of decision policies. At first it will be revised the recent literature with practical and theoretical fuzzy-SD integration showing that the motivation and purpose of this article have not been explored yet. Following, it will be scrutinized the origin of system dynamics to theoretically justify the proposed fuzzy-SD integration for organizational learning. Finally, it will be presented a hypothetical case study based on the balance scorecard model to illustrate the methodology in action.

1. Introduction

Almost simultaneously, two revolutionary knowledge fields were developed: Systems Dynamics, created by Jay Forrester at Massachusetts Institute of Technology in the 50's (Forrester, 1961), and Fuzzy Logic created by Lotfi Zadeh in the 60's (Zadeh, 1975a). Both arose from the perception that the tools of their times were unable to deal appropriately with real problems (Sterman, 2000; Ross, 2005).

System Dynamics (SD) can be defined as the branch of control theory that deals with socioeconomic systems and the branch of science that deals with management issues' controllability (Coyle, 1996). Forrester perceived the deficiency in our decision-making process when dealing with the complexity of dynamic systems. To overcome this deficiency, he proposed modeling tools that allowed discussion, refining and simulation of mental models exposed to different policies. His greatest contribution was the Stock and Flow Language that allowed the creation of virtual worlds, controlled experimental laboratories to enhance learning.

Fuzzy Logic (FL) and related Fuzzy Sets Theory have been created with the purpose of adapting the mathematical tools of logic to types of uncertainty such as vagueness and approximation, characteristics of natural language and of human mental models. By doing so, FL enables a representation of human knowledge by linguistic IF-THEN expressions, characteristic of approximate reasoning (Zadeh, 1975a, b).

Besides the Introduction, this article will be structured as it follows: on Section 2 it will be revised all FL-SD integrations proposed in the literature; on Section 3 it will be introduced a theoretical discussion on learning in SD environment showing how the use of FL could enhance its potential; on Section 4 it will be properly presented the FL-SD integrated methodology; on Section 5 it will be presented a case study exemplifying the methodology application; and finally Section 6 contains the discussion and conclusion remarks.

2. Review of literature

Traditionally, literature uses the FL approach especially for natural language processing and inaccurate knowledge in expert systems, process control and pattern recognition (Karavezyris, Timpe, & Marzi, 2002). At the other extreme, the literature of dynamic systems permeates many areas of study, especially socioeconomic and administrative, basically applicable to any system we wish to study.

The first authors to integrate these two approaches were Pankaj and Sushil (1994), who proposed a method for qualitative analysis of causal loops using fuzzy linguistic uncertainties to incorporate the perceptions and beliefs of the modeler. As in most of later integration proposals their motivation was the perception that variables' relationships in humans' mental models are best expressed in natural language.

* Corresponding author.
E-mail addresses: daniel_cardoso@poli.ufrj.br (D.C. de Salles), armandoneto@poli.ufrj.br (A.C. Gonçalves Neto), lgmarujo@poli.ufrj.br (L.G. Marujo).
[1] Tel.: +55 21 3938 8065.

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Most of the available researches integrate FL to SD models in order to consider fuzzy variables (their relations and arithmetic, or soft descriptions) when data was unavailable, with low credibility or because specific variables presented fuzziness uncertainty. Examples of such motivation and practical integrations can be seen by Campuzano, Mula, and Peidro (2010); Kunsch and Springael (2008) and Karavezyris et al. (2002). In these applications, FL was not used to define policies to control the model but to deal with uncertainty in some variables of the model. The control of their models was presented in a classical way (mixed in the model and with crisp parameters).

Others like Song, Song, and Zhang (2015), and Orji and Wei, 2015a, 2015b) used SD models to simulate alternative scenarios that were subsequently ranked by multi-objective programming (MOP), which embedded FL. In a similar application, Xu, Deng, and Yao (2014) used fuzzy to model uncertain parameters and a MOP to select alternative policies that were individually evaluated in a SD model.

In a more elaborated extension of this application, Chang and Ko (2014); Xu and Li (2011) and Wu and Xu (2013) used the MOP to control each step of the SD model. This proposal is in a sense similar to the proposed methodology because the controller is totally dissociated from the model to be controlled. However, the focus was not on the learning throughout development and testing of politics, since the control was "automated" by a MOP controller that searched for optimization.

Another different FL-SD integration can be found by Sabounchi, Triantis, Sarangi, and Liu (2014), who used FL to model a decision rule inside their SD model (user's preference on transportation). As discussed in the article, the specific decision is naturally fuzzy which demands the introduction of a Fuzzy Inference System (FIS) (Mamdani & Assilian 1975). In a sense this article presented a practical application of the currently proposed FIS controller; however, there is a main difference that should be highlighted: the model decision policies were not transferred to the FIS controller since the stakeholders' policy decision was still mixed into the model ("classically"). The FIS was introduced only to model a specific variables' relation that was, by nature, fuzzy. However, although not very different in a practical way, there is a considerable theoretical difference since the complete dissociation of control policies proposed in this present article is the main aspect to reinforce virtual world's learning.

Baradaran and Keshavarz (2015) also used a FIS (specifically a Sugeno type) in part of their model to express specific relations between variables that are naturally fuzzy. As in the previous article, the application was conceptually different from the proposed in this article since the decision policies are still provided "classically" inside the SD model.

Finally, another recent integration proposal is found by Arasteh and Aliahmadi (2014); Nasirzadeh, Khanzadi, and Razaie (2014) and Khanzadi, Nasirzadeh, and Alipour (2012). These articles mix in their SD models crisp variables, whose relations were obtained from historical data, and fuzzy variables (imbedding expert knowledge), whose relations were obtained by fuzzy systems (simulating mental models of experts). Since not all the control decisions were disaggregated in a FIS (that could provide crisp commands to govern the model), these applications had to extend the model's arithmetic to deal with fuzzy numbers. In all these articles, their goals were to use the SD model to simulate a specific output of the models (a fuzzy output considering the extension principle). Because of that, there was no focus on the modeling and testing of different decision policies, which in all these cases was stated once in the construction of the model.

After the revision of the theoretical and practical FL-SD integrations in the literature, it can be seen that there are no applications focused on virtual worlds' learning. Consequently, the main contribution of this article will be to propose a FL-SD integration methodology specifically to enhance learning with the use of virtual worlds. Since the proposal and testing of policies are the basis of learning throughout experimentation in virtual worlds models, it is essential to built "white-box models", which means according to Wieland and Gutzler (2014): simple enough to be understood by stakeholders; constructed with mutual collaboration of experts and stakeholders; and fast-prototyping to support fast interactive modeling. Before presenting and exemplifying the methodology, it will be introduced a theoretical discussion on system thinking and learning to justify the integration proposal.

3. Theoretical discussion on system thinking and learning

Systems Dynamics (SD) is a methodological approach derived from systems thinking, aiming to facilitate learning in the complex, feedback, multi-loop, multi-states and non-linear systems in which we live (Forrester, 1961).

According to Sterman (2000), SD was originally developed to promote and enhance the double loop learning. He stated that the key to circumvent the difficulties is the so-called virtual worlds, thus encouraging the explicit and ongoing discussion of mental models, which are not limited by analytical tractability. They are based on realistic assumptions about human behavior and use all types of data, available for specifying and estimating relationships (Forrester, 1987).

However, some of the practical barriers to the double loop learning cannot be overcome simply by virtual worlds' applications. In fact, Sterman (2000) pointed out that the use of virtual worlds has some pitfalls, e.g., not being able to develop the ability to scientific reasoning and to overcome deficiencies in group learning processes and the commonly verified video game syndrome (closely related to the lack of scientific method).

Another barrier to learning in virtual worlds, mentioned by Sterman (2000), is that an individual's mental model is fuzzy, incomplete, loosely defined and variable in terms of time. Therefore, each individual interprets certain content differently and adapts his or her model particularly.

Scholars agree that, for effective group learning with SD, it is necessary to declare and efficiently test the assumptions, and to communicate their results in a standardized manner (that way reaching a group learning consensus). Otherwise, efforts would be diffuse, and learning could be lost through some practices, such as video game syndrome.

A primary cause of these problems is the fact that in most SD models, decisions are either parameterized in a classical logic or provided directly (manually) by the operator of the experiment. The first option is inconsistent with our real decision-making process (as mentioned, fuzzy by nature), and therefore, has little practical value. In this sense, nearly three decades ago, Morecroft (1988) predicted that the biggest and most challenging possible collaboration in SD, would focus on using policy-maker knowledge at a symbolic/conceptual level.

The second option, manual parameterization, is the main origin of the lack of scientific method and video game syndrome problems, because the user (even if he or she does not change) by not declaring explicitly his decision-making process (i.e., the policy hypothesis) can easily lose the learning focus. Another cause for these problems stems from the inability to communicate (to the group) in ordinary language the hypothesis of each experiment and its results (Oliva, 2003).

We believe that the use of fuzzy logic, with clearly-stated linguistic rules, is the perfect solution to externalize all the hypotheses and decision-making under development. As highlighted by Ross (2005), natural language is one of the most powerful ways of conveying knowledge and information that