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ScienceDirect

Fuzzy Sets and Systems 269 (2015) 1–29

FUZZY sets and systems

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Linguistic composition based modelling by fuzzy networks with modular rule bases

Alexander Gegov [*], Farzad Arabikhan, Nedyalko Petrov

University of Portsmouth, School of Computing, Buckingham Building, Portsmouth PO1 3HE, United Kingdom

Received 16 March 2012; received in revised form 22 June 2014; accepted 23 June 2014

Abstract

This paper proposes a linguistic composition based modelling approach by networked fuzzy systems that are known as fuzzy networks. The nodes in these networks are modules of fuzzy rule bases and the connections between these modules are the outputs from some rule bases that are fed as inputs to other rule bases. The proposed approach represents a fuzzy network as an equivalent fuzzy system by linguistic composition of the network nodes. In comparison to the known multiple rule base approaches, this networked rule base approach reflects adequately the structure of the modelled process in terms of interacting sub-processes and leads to more flexible solutions. The approach improves significantly the transparency of the associated model while ensuring a high level of accuracy that is comparable to the one achieved by established approaches. Another advantage of this fuzzy network approach is that it fits well within the existing approaches with single rule base and multiple rule bases.

Keywords: Fuzzy models; Decision analysis; Large-scale systems; Transport management; Retail management; Linguistic models

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1. Introduction

Complexity is a versatile feature of existing systems that cannot be described by a single definition. In this context, complexity is usually associated with a number of attributes such as uncertainty, dimensionality and structure, which make the modelling of systems with these attributes more difficult. Therefore, the complexity of a given system can be accounted for by identifying the complexity related attributes that are to be found in this system.

Fuzzy logic has proved itself as a powerful tool for dealing with uncertainty as an attribute of systemic complexity. In this context, fuzziness is quite suitable for reflecting non-probabilistic uncertainty such as imprecision, incompleteness and ambiguity [1–3].

More recently, fuzzy logic has also become more effective in dealing with dimensionality as a systemic complexity attribute by means of rule base reduction and compression. Dimensionality in rule base reduction is associated with the number of rules, which is an exponential function of the number of system inputs and the number of linguistic terms per input [4–7]. In rule base compression, dimensionally is associated with the amount of on-line operations required during fuzzification, inference and defuzzification [8].

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[*] Corresponding author.

http://dx.doi.org/10.1016/j.fss.2014.06.014

However, as far as structure is concerned, fuzzy logic is still unable to reflect adequately any interacting modules within a modelled process. This is due to the black-box nature of most fuzzy models that cannot take into account explicitly any interactions among sub-processes [9–12]. In this respect, the following paragraphs discuss some of the main approaches in fuzzy modelling and their ability to deal with structure as a systemic complexity attribute.

The most common type of fuzzy system is the one with a single rule base [13–15]. This type of system is referred to here as Standard Fuzzy System (SFS). The latter is characterised by a black-box nature whereby the inputs are mapped directly to the outputs without the consideration of any internal connections. The operation of SFS is based on a single Fuzzification–Inference–Defuzzification (FID) sequence and it is usually quite accurate for output modelling as it reflects the simultaneous influence of all inputs on the output. However, the efficiency and transparency of SFS deteriorate with the increase of the number of rules. Therefore, as the number of rules increases, it not only takes longer to simulate the model output but it is also less clear how this output is affected by the model inputs.

Another type of fuzzy system is the one with multiple rule bases [16–19]. This type of system is often described by cascaded rule bases and it is usually referred to as Chained Fuzzy System (CFS) or Hierarchical Fuzzy System (HFS). Both CFS and HFS are characterised by a white-box nature whereby the inputs are mapped to the outputs by means of some internal variables in the form of connections. The operation of CFS and HFS is based on multiple FID sequences whereby each connection links the FID sequences for two adjacent rule bases.

CFS has an arbitrary structure in terms of subsystems and the connections among them [20–22]. In this case, each subsystem represents an individual rule base whereas each interaction is represented by a connection linking a pair of adjacent rule bases. This connection is identical with an output from the first rule base and an input to the second rule base in the pair. CFS is usually used as a detailed presentation of SFS for the purpose of improving transparency by explicitly taking into account all subsystems and the interactions among them. Also, efficiency is improved because of the smaller number of inputs to the individual rule bases. However, accuracy may be lost due to the accumulation of errors as a result of the multiple FID sequences.

HFS is a special type of CFS that has a specific structure [23–27]. Each subsystem in HFS has two inputs and one output. Some connections represent identical mappings, which may propagate across parts of the system. HFS is often used as an alternative presentation of SFS for the purpose of improving transparency by explicitly taking into account all subsystems and the interactions among them. Efficiency is also improved by the reduction of the overall number of rules, which is a linear function of the number of inputs to the subsystems and the number of linguistic terms per input. However, these improvements are often at the expense of accuracy due to the accumulation of errors as a result of the multiple FID sequences.

A third type of fuzzy system is the one with networked rule bases. This type of fuzzy system has been recently introduced as a theoretical concept in [28]. This concept is referred there as Networked Fuzzy System (NFS) and it has been further extended in this work by more generic descriptions in the form of generalised Boolean matrices. NFS is characterised by a white-box nature whereby the inputs are mapped to the outputs by means of connections. Subsystems in NFS are represented by nodes and the interactions among subsystems are the connections among these nodes. NFS is a hybrid between SFS and CFS/HFS. On one hand, the structure of NFS is similar to the structure of CFS/HFS due to the explicit presentation of subsystems and the interactions among them. On the other hand, the operation of NFS resembles the operation of SFS as the multiple rule bases are simplified to a linguistically equivalent single rule base. This simplification is based on the linguistic composition approach that is described further in this work. As a hybrid concept, NFS has the potential of providing a trade-off between SFS and CFS/HFS.

Properties of fuzzy systems such as accuracy, efficiency and transparency are directly related to attributes of systemic complexity such as uncertainty, dimensionality and structure. In this respect, uncertainty is an obstacle to accuracy as it is harder to build an accurate model from uncertain data [29–32]. Furthermore, dimensionality represents an obstacle to efficiency because it is more difficult to reduce the amount of computations in a FID sequence for a large number of rules [33–36]. Finally, structure is an obstacle to transparency as it is harder to understand the behaviour of a black-box model that does not reflect the interactions among subsystems [37–40].

This paper introduces an advanced theoretical framework for NFS as a novel type of fuzzy system. The framework facilitates the validation of NFS as a modelling tool with respect to SFS and CFS/HFS. For clarity and simplicity, NFS is referred to as Fuzzy Network (FN) further in this paper whereby NFS and FN are equivalent in terms of performance. Besides this, the paper addresses several attributes of systemic complexity including uncertainty, dimensionality and structure and the associated properties of the above fuzzy systems such as accuracy, efficiency and transparency. This