Metadata of the chapter that will be visualized in SpringerLink

Book Title	Enric Trillas: A Passion for Fuzzy Sets
Series Title	
Chapter Title	A Survey of Contributions to Fuzzy Logic and Its Applications to Artificial Intelligence at the IIIA
Copyright Year	2015
Copyright HolderName	Springer International Publishing Switzerland

Corresponding Author	Family Name	**Mantaras**
	Particle	**de**
	Given Name	**Ramon Lopez**
	Prefix	
	Suffix	
	Division	Artificial Intelligence Research Institute (IIIA)
	Organization	Spanish National Research Council (CSIC)
	Address	Campus UAB, 08193, Bellaterra, Spain
	Email	mantaras@iiia.csic.es
Author	Family Name	**Godo**
	Particle	
	Given Name	**Lluis**
	Prefix	
	Suffix	
	Division	Artificial Intelligence Research Institute (IIIA)
	Organization	Spanish National Research Council (CSIC)
	Address	Campus UAB, 08193, Bellaterra, Spain
	Email	godo@iiia.csic.es
Author	Family Name	**Plaza**
	Particle	
	Given Name	**Enric**
	Prefix	
	Suffix	
	Division	Artificial Intelligence Research Institute (IIIA)
	Organization	Spanish National Research Council (CSIC)
	Address	Campus UAB, 08193, Bellaterra, Spain
	Email	enric@iiia.csic.es
Author	Family Name	**Sierra**
	Particle	
	Given Name	**Carles**
	Prefix	
	Suffix	
	Division	Artificial Intelligence Research Institute (IIIA)
	Organization	Spanish National Research Council (CSIC)
	Address	Campus UAB, 08193, Bellaterra, Spain

Email	sierra@iiia.csic.es

Abstract	The Artificial Intelligence Research Institute (IIIA) is a public research centre, belonging to the Spanish National Research Council (CSIC), dedicated to AI research. We focus our activities on a few well-defined sub-domains of Artificial Intelligence, positively avoiding dispersion and keeping a good balance between basic research and applications, and paying particular attention to training PhD students and technology transfer. In this article, we survey some of the most relevant results related to Fuzzy Logic and Fuzzy AI Systems that we have obtained since the initiation of our research activities in 1985.

Keywords (separated by '-')	Artificial intelligence - Fuzzy logic - Fuzzy systems - Multiple-valued logics - Similarity logics - Knowledge-based systems - Case-based reasoning - AI applications

A Survey of Contributions to Fuzzy Logic and Its Applications to Artificial Intelligence at the IIIA

Ramon Lopez de Mantaras, Lluis Godo, Enric Plaza and Carles Sierra

Abstract The Artificial Intelligence Research Institute (IIIA) is a public research centre, belonging to the Spanish National Research Council (CSIC), dedicated to AI research. We focus our activities on a few well-defined sub-domains of Artificial Intelligence, positively avoiding dispersion and keeping a good balance between basic research and applications, and paying particular attention to training PhD students and technology transfer. In this article, we survey some of the most relevant results related to Fuzzy Logic and Fuzzy AI Systems that we have obtained since the initiation of our research activities in 1985.

Keywords Artificial intelligence · Fuzzy logic · Fuzzy systems · Multiple-valued logics · Similarity logics · Knowledge-based systems · Case-based reasoning · AI applications

1 Introduction

It all started in 1985 when Professor Enric Trillas, then President of the Spanish National Research Council (CSIC), asked Prof. Ramon Lopez de Mantaras to found an AI department at the newly established Centre of Advanced Studies located in

R.L. de Mantaras (✉) · L. Godo · E. Plaza · C. Sierra
Artificial Intelligence Research Institute (IIIA), Spanish National Research Council (CSIC), Campus UAB, 08193 Bellaterra, Spain
e-mail: mantaras@iiia.csic.es

L. Godo
e-mail: godo@iiia.csic.es

E. Plaza
e-mail: enric@iiia.csic.es

C. Sierra
e-mail: sierra@iiia.csic.es

L. Magdalena et al. (eds.), *Enric Trillas: A Passion for Fuzzy Sets*,
Studies in Fuzziness and Soft Computing 322, DOI 10.1007/978-3-319-16235-5_6

332870_1_en_6_chapter ☑ TYPESET ☐ DISK ☐ LE ☑ CP Disp.:28/2/2015 Pages: 13 Layout: T1-Standard

Blanes, a village on the Mediterranean coast about 70 km north of Barcelona. With the collaboration of Dr. Jaume Agustí, from the Autonomous University of Barcelona, Prof. Josep Aguilar-Martin, from the CNRS, and Professor Settimo Termini, from the CNR, the AI research activities started at this centre. The group grew fast and in 1994 we became the Artificial Intelligence Research Institute (IIIA) and moved to a new building located in the campus of the Autonomous University of Barcelona. The IIIA is now one of the leading AI research centers in Europe. Since then, well over 2000 papers have been published by IIIA members, 80 PhDs have been completed, and over 100 research projects—including 24 European projects—and contracts with industry have been done. The total funding of these projects is approximately 20 million Euros which is about 40 % of the total IIA budget for all this period of time. IIIA researchers have received over 40 international awards and recognitions, including 15 best paper awards at international conferences, 6 outstanding PhD thesis awards, the 2012 "EUSFLAT Best PhD Dissertation" award, the 2011 "IFAAMAS Victor Lesser Distinguished Dissertation" award, and the 2011 "AAAI Robert S. Engelmore". In addition, many IIIA senior members are, or have been, members of the editorial boards of more than 30 international journals, have participated in hundreds of program committees, and are on the board of several governing bodies of international AI organizations such as IJCAI, IFAAMAS, ACP and EUSFLAT.

Intensive collaborations take place with academic institutions from numerous countries and particularly from France, UK, Italy, Australia, USA, Germany, Argentina, Czech Republic, Japan, Israel, Brazil, and Austria. As a result of this collaborations, about 50 % of our publications have international co-authorship.

Our research has been and is always guided by concrete and challenging applications in fields such as health, e-commerce, automated negotiation, conflict resolution, music, tourism, logistics, supply chain management, transport, energy, data privacy, and social networks, among others. Several of our systems, tools and applications have been distributed outside the institute and in some cases have been commercialized. Among the many AI applications developed, the most recent ones are: Prediction of energy demand in intelligent buildings; early detection of potential failures in windmill turbines for electrical power generation; improving the customers shopping experience in supermarkets; managing safe personalized tourism for disabled persons; AI tools for social networks-based music education; on-line digital games that are worth playing by older people for active and positive aging; social networking using autonomic software agents to enrich, encourage, and enliven online cultural experiences in virtual visits to museums; recruitment intelligent matching system to improve online job searching; and automatic generation of audiovisual narrative such as summaries of soccer matches or other types of TV events.

Our focus is on a few well-defined sub-domains of Artificial Intelligence, positively avoiding dispersion and keeping a good balance between basic research and applications, and paying particular attention to training PhD students and technology transfer.

The existence of the Technological Development Unit (UDT) provides technological support to our research activities and improves our technology transfer capabilities by channeling contacts with industry. In particular, we keep strong ties with our three spin-off companies: iSOCO (http://www.isoco.com), STRANDS (http://strands.com), and COGNICOR (http://cognicor.com).

Our first spin-off, ISOCO, was set up in 1999 dedicated to the design of intelligent software components for Internet-related applications. Today, ISOCO is a leading company within its sector in Spain. STRANDS, was started in 2004 dedicated to recommendation Systems particularly in the finances sector that nowadays is also a leading company in Spain. COGNICOR was founded in 2011 based on the results of a large, over five million Euros, project called "Agreement Technologies". This company develops software products for the automatic resolution of customers' complaints using machine learning and case-based reasoning techniques. COGNICOR has received several awards, including the prestigious "2012 European Union Tech All Stars Competition".

At present, our research activities are structured around three departments: Learning Systems, Multi-agent Systems, and Logic, Reasoning and Search. However, in what follows we will focus on the activities related to the area of Fuzzy logic and Fuzzy systems, area in which Prof. Enric Trillas was the pioneer in Spain. We have structured these activities in three periods: The first 10+ years from 1985 to 1995, then the next 5+ years, from 1996 to 2001 and finally from 2002 till now. For additional information regarding all our contributions to AI we refer the reader to the "History" section of our website: www.iiia.csic.es/en/about_iiia/history.

2 The Beginnings: 1985–1995

2.1 Knowledge Based Systems

AQ1

The research on Knowledge Based Systems has been one of the initial interests of the group that has had continuity till today. Motivated by several real applications, we created, formalized and implemented languages to better represent uncertainty and imprecision, based on fuzzy and multi-valued logics. These languages have been integrated in a two-generation tool (MILORD and MILORD II) on top of which most of the applications to real domains have been built.

MILORD [32] was an expert system building tool developed between 1985 and 1989 within the framework of Carles Sierra's Ph.D. thesis [49]. It allowed to perform different calculi of uncertainty on an expert defined set of linguistic terms expressing truth degrees. Each calculus corresponded to specific conjunction, disjunction and implication operators. The internal representation of each linguistic truth value was a fuzzy subset of the interval [0,1]. The different calculi of uncertainty applied to the set of linguistic terms, resulted in a fuzzy subset that was approximated to a linguistic truth value belonging to the set of linguistic terms. This linguistic approximation kept the calculus closed. This had the advantage that, once the linguistic truth values had been defined, the system computed, the conjunction, disjunction and implication operations for all the pairs of linguistic truth values in the term set off-line, and stored

332870_1_en_6_chapter ✓ TYPESET DISK LE ✓ CP Disp.:28/2/2015 Pages: 13 Layout: T1-Standard

the results in matrices. Therefore, when MILORD was run, the propagation and combination of uncertainty was performed by simply accessing these pre-computed matrices. This tool also used a meta-level language to represent the strategies of execution of modules containing domain rules. This meta-control language was the inspiration of some work done in Case-Based reasoning as well. MILORD has been used in the development of several real applications. The first application was the expert system PNEUMON-IA, on the diagnosis of community-acquired pneumoniae. This problem required extensive research in the area of uncertainty, to satisfactorily represent the lack of precise diagnostic procedures of the domain. It took two years to complete it. In 1988 it was validated, and the results presented in 1989 in Albert Verdaguer's M.D. thesis [52]. In 1987 we started another application in the area of rheumatological diseases and colagenosis [10]. The more heterogeneous nature of the set of diseases included in this application forced us to develop more complex and declarative control structures to represent the dynamics of the reasoning that the expert needed to model the diagnostic processes. The application was validated in 1989 and the results published in Miquel Belmonte's M.D. thesis [9].

We had also been involved in applications to industrial problems. In particular, from 1988 to 1992, we developed a successful diagnostic system for defects in TV screens manufactured by PHILIPS. This research was done in the framework of two projects (IPCES-I and IPCES-II) funded by the ESPRIT I and ESPRIT II European research programs. IPCES-I was one of the very first European projects funded in Spain. The diagnostic system was connected to a vision system capable of detecting different categories of defects, and to an information system that provided data from the process plant. Using this combination of information a ranking of the most plausible causes of the defect was generated as output [53]. The work around the MILORD expert systems building tool had a very significant international impact and was awarded the Digital Equipment European Artificial Intelligence Research Award.

MILORD was improved and extended, becoming MILORD II [1], an architecture for Knowledge Base Systems that combined reflection and modularization techniques, together with an approximate reasoning component based on many-valued logics, to be able to define complex reasoning patterns at large. Its development started in 1989 and constituted the main component of Josep Puyol's Ph.D. thesis [46]. A Knowledge Base in MILORD II consisted of a set of hierarchically interconnected modules. Each module contained an Object Level Theory and a Meta-Level Theory interacting through a reflective mechanism. From the logical point of view, MILORD II made use of both many-valued logic and epistemic meta-predicates to express the truth status of propositions.

An application that was developed and validated using MILORD II was Spong-IA, an automatic classification tool for marine sponges. It covered all the atlanto-mediterranean taxonomy up to the level of family and a part of it up to the level of species. It passed an international experts validation process with great success. The main results of this work were presented in Marta Domingo's Ph.D. in Biology [15].

Another industrial application using MILORD II was the supervision of production in pig farms. The results of this work were transferred to several farms thanks to a grant from the Spanish Ministry of Industry.

2.2 Fuzzy and Multiple-Valued Logics

According to Zadeh, the Fuzzy logic term is used, at least, with two different meanings. Fuzzy Logic in broad sense refers to methodologies involving Fuzzy Sets and Possibility theories, whereas in narrow sense it refers to the various formal logical calculi underlying Fuzzy Set Theory. The theoretical research done in our group on Fuzzy Logic has covered both aspects. The main contributions have been in the following two subjects:

Fuzzy truth values

The work on modeling inference in Fuzzy Logic using the Fuzzy Truth Values formalism started quite early in the IIIA with the PhD thesis of Lluís Godo [30]. This formalism allowed the implementation of some inference patterns without the need to specify particular possibility distributions to represent the fuzzy statements involved in such inference patterns. It was shown that Fuzzy Truth Values play the same role that classical truth-values do in classical or many-valued logic. In this direction, we also studied the closure system of inference operators in the above formalism as well as a semantic formalization of fuzzy logic as logic with fuzzy truth-values.

Multiple-valued Logic

The investigation of different fuzzy (or many-valued) logics, in the narrow sense, was motivated by a fruitful cooperation since 1993 with the Institute of Computer Science of the Czech Academy of Sciences, led by Prof. Petr Hájek. This collaboration resulted in a number of significant publications [35–37] about different systems of many-valued logic and their relation to main uncertainty calculi, such as probability theory or possibilistic logic.

2.3 Similarity Logic

Similarity relations, as generalizations of equivalence relations, were defined by Zadeh in the late sixties. Most of the early work dealt with the application of these relations to cluster analysis. In the eighties Enric Trillas introduced a generalization of Zadeh's definition [50] and Trillas and Valverde related similarity relations to equivalence connectives in fuzzy logic [51]. In the nineties this type of fuzzy relations started to be used in order to obtain a semantics for fuzzy logic and to build a logical setting for dealing with sentences like "close to p", "not far from p" or "similar to p" being p a proposition. In both issues the contribution of our research group was very relevant.

In the early 90s Ruspini published his studies on a semantics for fuzzy logic based on similarity relations [47]. Based on this, Esteva, Godo and García proposed a definition of a similarity logic as a propositional logic based on similarity relations [22]. A complete analysis of the relations between this logic and the fragment of necessity-valued possibilistic logic and fuzzy-truth-valued logic was also achieved.

On the other hand, the concept of similarity was also used by researchers of the Institute, in cooperation with the D. Dubois and H. Prade, to define graded consequence relations corresponding to different levels of approximation [18]. The main idea underlying this approach was to approximate every classical proposition p by a fuzzy set of interpretations in such a way that the alpha-cuts of this fuzzy set provide a set of approximations of p. As expected, approximation in degree 1 coincides with p and approximation in degree 0 coincides with the classical set of all interpretations. In this setting, p entails q to the degree alpha if p classically entails the alpha-approximation of q. The results of the work done along this research line were both theoretical and practical. From the theoretical point of view, we studied the properties, a syntactical characterization, and a formalization, in a multi-modal and a multi-valued setting, of these graded entailment relations. From the practical point of view our results were also of interest. A framework for interpolative reasoning based on graded entailment was developed [18] and applications to case-based reasoning, as well as to analogical reasoning, were developed, being the first to incorporate fuzzy techniques within a Case-Based system [45]. Another result of our activities in this early case-based research was the BOLERO system [39], developed from 1990 to 1993 by Beatriz López within her PhD [38]. It was an important contribution to both case-based and rule-based expert systems. The object level knowledge of BOLERO was represented by rules and the meta-knowledge were the solved instances of problems conveniently organized in the memory of cases. The added value of such hybrid system was the capability to learn meta-knowledge by experience. BOLERO was integrated within the MILORD System and was successfully applied in a complex medical diagnosis problem using the rules for diagnosing pneumonias of the PNEUMON-IA expert system previously developed at our Institute as object knowledge. This research yielded important insights into the integration of learning and problem solving.

2.4 Fuzzy Logic for Mapping Unknown Environments Using Autonomous Mini-Robots

An interesting application of Fuzzy Logic, undertaken in our Institute within the framework of the PhD work of Maite López-Sánchez [40], was to the problem of the acquisition of maps of unknown environments by means of a group of autonomous mini-robots [42, 43]. The problem of collective map generation is to obtain the most plausible position of walls and obstacles based on the perception of several mini-robots. The mini-robots detected portions of walls or obstacles with different degrees of precision depending on the length of the run and the number of turns they have done. The main problem was to decide whether several detected portions, represented by imprecise segments, were from the same wall or obstacle or not. If two segments were from the same wall or obstacle, a segment fusion procedure was applied to produce a single segment. This process of segment fusion was followed by a completion process in which hypothesis were made with respect to non-observed regions. The completion process was achieved by means of hypothetical reasoning based on declarative heuristic knowledge about the orthogonal environments in which the mini-robots evolve. Finally, an alignment process also took place so that, for example, two walls separated by a doorway were properly aligned. All these operations were based on modeling the imprecise segments by means of fuzzy sets. More concretely, the position of the wall segment was a fuzzy number and the length a fuzzy interval. The main advantage of using fuzzy techniques was that the position and imprecision of the resulting fused segments could be very easily computed. Furthermore, using Fuzzy sets to model the imprecision about the position of obstacles was very appropriate.

3 The Take-Off: 1996–2001

3.1 Foundations of Mathematical Fuzzy Logic

Fuzzy logic until very recently lacked a formal basis. We have done significant research on fuzzy logic "in the narrow sense" with remarkable results, due in part to the already mentioned fruitful collaborations with Prof. Petr Hájek and, more recently, with Prof. Montagna and Prof. Cignoli. The main results obtained concern the axiomatization of several t-norm based residuated logics: product logic [36], completeness of Hájek's basic fuzzy logic BL [14], residuated logics with involutive negation [25], Lukasiewicz Product logic LΠ [26] and Monoidal t-norm based logic MTL [24]. Another important result has been the modelling of probability in the fuzzy logic setting [35] and the expression of fuzzy inference as deduction in some of these types of logic [31].

3.2 Similarity-Based Reasoning

The notion of similarity among knowledge states plays an important role in different inference patterns of approximate reasoning. Two relevant examples are the reasoning mechanisms used in fuzzy rule-based systems and in case-based reasoning. A fuzzy rule-based system interpolates rule consequents according to the degree of match between actual variable values and those in the rule premises. In doing so, the system extends the domain of application to system's states that are similar to those described in the fuzzy rule base. On the other hand, case-based reasoning techniques follow an analogy principle which states that similar problems have similar solutions, leading—naturally—to a formalization using similarity-based reasoning. Research on similarity-based reasoning, in close collaboration with the group of Profs. D. Dubois and H. Prade, has focused on two major issues:

Logical foundations of similarity-based reasoning

We have addressed several fundamental problems ranging from semantic to syntactic considerations, one being based on two graded similarity-based consequence relations [16, 18], which allow an interpolation mechanism to be defined, and another on graded logics, both classical [23] and many-valued [33], for which completeness results were obtained. Their relation to other types of graded logical formalism, like possibilistic logic, have also been considered [22].

Similarity-based reasoning and case-based reasoning and decision

We have used fuzzy set techniques, based on fuzzy similarity relations, to formalize some common problems which appear in case-based reasoning, such as retrieving the most relevant cases, or getting a more flexible adaptation of past solutions by interpolating them [16, 17]. A logical modeling of the inference patterns involved in case-based reasoning, using the similarity-based consequence relation formalism, has also been introduced in [44]. Regarding case-based decision theory, Gilboa and Schmeidler [29] have recently proposed a new approach to decision theory based on similarity, rather than probability, where the utility function is defined on partially described situations in terms of their similarity with previously experienced decision. Using fuzzy similarity relations and possibility theory, a new qualitative decision model was proposed, closely related to Dubois-Prade's possibilistic decision theory, and with an axiomatic basis [17, 21]. Extensions to this latter model were also investigated [34, 54].

3.3 Case-Based Reasoning Application to Expressive Music Synthesis

One of the most successful and widely cited CBR system developed at our institute is an application to the synthesis of expressive music performances [7, 8]. The problem solving task of the system is to infer, via imitation, and using case-based reasoning, a set of expressive transformations to be applied to every note of an inexpressive musical phrase given as input. To achieve this, it uses a case memory containing human performances and background musical knowledge. The score, containing both melodic and harmonic information, is also given. The expressive transformations to be decided and applied by the system affect the following expressive parameters: dynamics, rubato, vibrato, articulation, and attack. The similarity reasoning capabilities provided by CBR allow the system to retrieve those notes in the case base of expressive examples (human performances) that are, musically speaking, similar to each current inexpressive note of the input. We developed a fuzzy approach to combine a set of solutions from several retrieved cases into a single solution to be applied to every note of the inexpressive input in order to render it expressive. The system is connected to software for sound analysis and synthesis based on spectral modeling as pre- and post-processor. This allows the obtained results to be listened to. These results clearly show that a computer system can indeed play expressively. In our experiments, we have used Real Book jazz ballads. This work has been awarded the "Swets & Zeitlinger" prize of the International Computer Music Association. This is the most prestigious award in the field of computer music.

3.4 Automated Deduction in Generalized Possibilistic Logic

Possibilistic logic is a logic of uncertainty that has many applications to plausible reasoning under incomplete information. Automated proof techniques were also developed for a classical first order language. Things become much more complex (both semantically and syntactically) when one allows the language to deal with imprecise or fuzzy constants, a very natural extension. Therefore, a line of research was en developed in order to provide both semantic foundations and efficient and sound proof methods. Some interesting results were obtained [4–6, 48], where two different extended possibilistic logic programming systems PLFC and PGL were proposed and fully investigated.

4 The Consolidation: 2002–2013

During this last period we have continued to play a key international role in the definition and development of Mathematical Fuzzy logic and we have obtained important results in the following topics: (1) General and deep results for completeness of fuzzy logics either propositional or first order with respect to different semantics (real, hyper-real, rational and finite) that cover and significantly extend previous results in the field. Our results have been possible as a consequence of a fruitful collaboration with researchers from different leading institutions on the topic; (2) Formalization of t-norm based logics dealing with partial degrees of truth, with algebraic semantics, and axiomatization and completeness results, both for propositional and first order languages [27], which have high applicability in modeling graded notions [12]; (3) Development of different systems of fuzzy modal logic [11], with applications to reasoning under different forms to uncertainty on non-Boolean algebras of events [28]; and (4) Development of a new hierarchy of Fuzzy Description logics, along with new complexity results based on results of Mathematical Fuzzy Logic [13].

Moreover, in this last period, in collaboration with leading international researchers in the area of computational argumentation, we have also extended the computational argumentation of Defeasible Logic Programming (DeLP), with the treatment of possibilistic uncertainty at object level, allowing to stratify defeasible rules in a DeLP program according to their strength [3] and by defining a new recursive semantics which avoids some undesired side effects of the original semantics based on dialectical trees [2].

5 Conclusions

This paper has briefly surveyed the most relevant results obtained at the IIIA in the area of Fuzzy Logic and Fuzzy AI Systems from 1985 till today. We have structured the paper in three time periods: The beginning, the take-off, and the consolidation. We believe that the IIIA has played and is playing a major role in both the mathematical foundations and applications of Fuzzy Logic and Fuzzy AI Systems.

Acknowledgments It is fair to say that the IIIA exists thanks to the vision of Professor Enric Trillas that, as mentioned in the introduction, in 1985 he commissioned Ramon Lopez de Mantaras to found the AI department within the Centre of Advanced Studies of Blanes of the CSIC that later became the Artificial Intelligence Research Institute. As early as 1985, Professor Trillas already saw the importance of including the field of Artificial Intelligence among the activities of the Spanish National Research Council (CSIC). This paper is in homage to him, to his wisdom and his vision.

References

1. Agustí, J., Esteva, F., García, P., Godo, L., López de Mántaras, R., Sierra, C.: Local multi-valued logics in modular expert systems. J. Exp. Theor. Artif. Intell. **6**(3), 303–321 (1994)
2. Alsinet, T., Béjar, R., Godo, L., Guitart, F.: RP-DeLP: a weighted defeasible argumentation framework based on a recursive semantics. J. Log. Comput. (In Press)
3. Alsinet, T., Chesñevar, C., Godo, L., Sandri, S., Simari, G.: Formalizing argumentative reasoning in a possibilistic logic programming setting with fuzzy unification. Int. J. Approx. Reason. **48**(3), 711–729 (2008)
4. Alsinet, T., Godo, L.: A Complete Calculus for Possibilistic Logic Programming with Fuzzy Propositional Variables. Uncertainty in Artificial Intelligence Conference (UAI'2000). Morgan Kaufmann, San Francisco (2000)
5. Alsinet, T., Godo, L.: Towards an automated deduction system for logic programming with fuzzy constants. Int. J. Intell. Syst. **17**(9), 887–924 (2002)
6. Alsinet, T., Godo, L., Sandri, S.: On the Semantics and Automated Deduction for PLFC. Uncertainty in Artificial Intelligence Conference (UAI'99), pp. 1–12. Morgan Kaufmann, San Francisco (1999)
7. Arcos, J.L., de Mantaras, R.L.: An Interactive CBR approach for generating expressive music. J. Appl. Intell. **27**(1), 115–129 (2001)
8. Arcos, J.L., de Mantaras, R.L., Serra, X.: SaxEx: A case-based reasoning system for generating expressive musical performances (Swets & Zeitlinger Award from the International Computer Music Association). J. New Music Res. **27**(3), 194–210 (1998)

332870_1_en_6_chapter ☑ TYPESET ☐ DISK ☐ LE ☑ CP Disp.:28/2/2015 Pages: 13 Layout: T1-Standard

9. Belmonte, M.A.: RENOIR: un sistema experto para la ayuda en el diagnóstico de colagenosis y artropatías inflamatorias. Ph.D. thesis, Universitat Autònoma de Barcelona (1990)
10. Belmonte, M.A., Sierra, C., de Mantaras, R.L.: RENOIR an expert system using fuzzy logic for rheumatology diagnosis. Int. J. Intell. Syst. **9**(11), 985–1000 (1994)
11. Bou, F., Esteva, F., Godo, L., Rodríguez, R.: On the minimum many-valued modal logic over a finite residuated lattice. J. Log. Comput. **21**(5), 739–790 (2011)
12. Casali, A., Godo, L., Sierra, C.: A graded BDI agent model to represent and reason about preferences. Artif. Intell. **175**(7–8), 1468–1478 (2011)
13. Cerami, M., García-Cerdaña, A., Esteva, F.: On finitely-valued fuzzy description logics. Int. J. Approx. Reason. (In Press)
14. Cignoli, R., Esteva, F., Godo, L., Torrens, A.: Basic fuzzy logic is the logic of continuous t-norms and their residua. Soft Comput. **4**, 106–112 (2000)
15. Domingo, M.: An Expert System Architecture for Taxonomic Domains. An Application in Porifera: The Development of Spongia. Ph.D. thesis, University of Barcelona (1995)
16. Dubois, D., Esteva, F., Garcia, P., Godo, L., de Mantaras, R.L., Prade, H.: Fuzzy modelling of case-based reasoning and decision. In: Second International Conference on Case-Based Reasoning. Lecture Notes in Artificial Intelligence, vol. 1266, pp. 599–610 (1997)
17. Dubois, D., Esteva, F., Garcia, P., Godo, L., de Mantaras, R.L., Prade, H.: Fuzzy set modelling in case-based reasoning. Int. J. Intell. Syst. **13**(4), 345–373 (1998)
18. Dubois, D., Esteva, F., García, P., Godo, L., Prade, H.: Similarity-based consequence relations. Lect. Notes Artif. Intell. **946**, 171–179 (1995)
19. Dubois, D., Esteva, F., García, P., Godo, L., Prade, H.: A logical approach to interpolation based on similarity relations. Int. J. Approx. Reason. **17**(1), 1–36 (1997)
20. Dubois, D., Godo, L., Prade, H., Zapico, A.: Making decisions in a qualitative setting: from decision under uncertainty to case-based decision. In: Cohn, Schubert, Shapiro, (eds.) Sixth International Conference on Principles of Knowledge Representation and Reasoning (KR'98). Morgan Kaufmann (1998)
21. Dubois, D., Godo, L., Prade, H., Zapico, A.: On the possibilistic decision model: from decision under uncertainty to case-based decision. Int. J. Uncertain. Fuzziness Knowl.-Based Syst. **7**(6), 631–670 (1999)
22. Esteva, F., Garcia, P., Godo, L.: Relating and extending semantical approaches to possibilistic reasoning. Int. J. Approx. Reason. **10**(4), 311–344 (1994)
23. Esteva, F., Garcia, P., Godo, L., Rodriguez, R.: A modal account of similarity-based reasoning. Int. J. Approx. Reason. **16**, 235–260 (1997)
24. Esteva, F., Godo, L.: Monoidal t-norm based logic: towards a logic for left-continuous t-norms. Fuzzy Sets Syst. **124**(3), 271–288 (2001)
25. Esteva, F., Godo, L., Hajek, P., Navara, M.: Residuated fuzzy logics with an involutive negation. Arch. Math. Log. **39**, 103–124 (2000)
26. Esteva, F., Godo, L., Montagna, F.: The L and L logics: two complete fuzzy systems joining Lukasiewicz and product logics. Arch. Math. Log. **40**(1), 39–67 (2001)
27. Esteva, F., Godo, L., Noguera, C.: First-order t-norm based fuzzy logics with truth-constants: distinguished semantics and completeness properties. Ann. Pure Appl. Log. **161**(2), 185–202 (2009)
28. Flaminio, T., Godo, L., Marchioni, E.: Logics for belief functions on MV-algebras. Int. J. Approx. Reason. **54**(4), 491–512 (2013)
29. Gilboa, I., Schmeidler, D.: Case-based decision theory. Q. J. Econ. **110**(3), 607–639 (1995)
30. Godo, L.: Contribució a l'estudi de models d'inferència en els sistemes possibilistics. PhD thesis. Universitat Politècnica de Catalunya (1990)
31. Godo, L., Hajek, P.: Fuzzy inference as deduction. J. Appl. Non-Class. Log. **9**(1), 37–60 (1997)
32. Godo, L., de Mantaras, R.L., Sierra, C., Verdaguer, A.: MILORD: the architecture and the management of linguistically expressed uncertainty. Int. J. Intell. Syst. **4**(4), 471–501 (1989)
33. Godo, L., Rodriguez, R.: A fuzzy modal logic for similarity reasoning. In: Chen, G., Ying, M., Cai, K.-Y. (eds.) Fuzzy Logic and Soft Computing, pp. 33–48. Kluwer (1999)

34. Godo, L., Zapico, A.: On the possibilistic-based decision model: characterization of preference relations under partial inconsistency. J. Appl. Intell. **14**, 319–333 (2001)
35. Hajek, P., Godo, L., Esteva, F.: Fuzzy logic and probability. In: Besnard, P., Hanks, S. (eds.) Uncertainty in Artificial Intelligence Conference, pp. 237–244. Morgan Kaufmann Publisher (1995)
36. Hajek, P., Godo, L., Esteva, F.: A complete manyvalued logic with product conjunction. Arch. Math. Log. **35**(3), 191–208 (1996)
37. Hájek, P., Harmancova, D., Esteva, F., García, P., Godo, L.: On modal logics for qualitative possibility in a fuzzy setting. In: López de Mántaras, R., Poole, D. (eds.) Uncertainty in Artificial Intelligence, pp. 278–285. Morgan Kaufmann (1994)
38. López, B.: Aprenentatge i generació de plans per a sistemes experts. Ph.D. thesis, Universitat Politècnica de Catalunya (1993)
39. López, B., Plaza, E.: Case-based planning for medical diagnosis. Lect. Notes Artif. Intell. **689**, 96–105 (1993)
40. López-Sánchez, M.: Approaches to Map Generation by means of Collaborative Autonomous Robots. Ph.D. thesis, Universitat Autònoma de Barcelona (1999)
41. López-Sánchez, M., Esteva, F., de Mántaras, R.L., Sierra, C., Amat, J.: Map generation by cooperative low-cost robots in structured unknown environments. Auton. Robot. J. **5**, 53–61 (1998)
42. Lopez-Sánchez, M., de Mantaras, R.L., Sierra, C.: Incremental map generation by low cost robots based on possibility/necessity grids. In: 13th International Conference on Uncertainty in Artificial Intelligence pp. 351–357 (1997)
43. Lopez-Sanchez, M., de Mantaras, R.L., Sierra, C.: Possibility theory-based environment modelling by means of behaviour-based autonomous robots. In: European Conference on Artificial Intelligence (ECAI'98), pp. 590–594 (1998)
44. Plaza, E., Esteva, F., Garcia, P., Godo, L., de Mantaras, R.L.: A logical approach to case-based reasoning using fuzzy similarity relations. J. Inf. Sci. **106**, 105–122 (1998)
45. Plaza, E., de Mántaras, R.L.: A case-based apprentice that learns from fuzzy examples. In: Ras, Z., et al. (eds.) Methodologies for Intelligent Systems-5, pp. 420–427. North-Holland (1990)
46. Puyol, J.: Modularization, Uncertainty, Reflective Control and Deduction by Specification in MILORD II, A Language for Knowledge-Based Systems. Ph.D. thesis, Universitat Autònoma de Barcelona (1994)
47. Ruspini, E.H.: On the semantics of fuzzy logic. Int. J. Approx. Reason. **5**(1), 45–88 (1991)
48. Sandri, S., Godo, L.: Treatment of temporal information in possibilistic logic with fuzzy constants. In: Proceedings VIII Fuzzy Systems Association World Congress (IFSA'99), pp. 561–565 (1999)
49. Sierra, C.: MILORD: Arquitectura multinivell per a sistemes experts en classificació. Ph.D. thesis, Universitat Politècnica de Catalunya (1989)
50. Trillas, E.: Assaig sobre les relacions d'indistingibilitat, In: Proceedings of the First Catalan Congres on Mathematical Logics, Barcelona, pp. 51–59 (1982)
51. Trillas, E., Valverde, L.: An inquiry on indistinguishability operators. In: Skala, H. et al. (eds.) Aspects of Vagueness, pp. 231–256. Reidel, Dordrecht (1984)
52. Verdaguer, A.: PNEUMON-IA: desenvolupament i validació d'un sistema expert d'ajuda al diagnòstic mèdic. Ph.D. thesis, Universitat Autònoma de Catalunya (1989)
53. Vila, L., Sierra, C., Martínez, A.B., Climent, J.: Intelligent process control by means of expert systems and machine vision. Lect. Notes Comput. Sci. **604**, 185–194 (1992)
54. Zapico, A., Godo, L.: Representation of preference relations induced by lattice-valued, generalised possibilistic utility functions. Int. J. Uncertain. Fuzziness Knowl.-Based Syst. **6**(8), 719–734 (2000)

Author Queries

Chapter 6

Query Refs.	Details Required	Author's response
AQ1	Please confirm if the section headings identified are correct.	
AQ2	References [19, 20, 41] are given in list but not cited in text. Please cite in text or delete from list.	

MARKED PROOF

Please correct and return this set

Please use the proof correction marks shown below for all alterations and corrections. If you wish to return your proof by fax you should ensure that all amendments are written clearly in dark ink and are made well within the page margins.

Instruction to printer	*Textual mark*	*Marginal mark*
Leave unchanged	• • • under matter to remain	Ⓥ
Insert in text the matter indicated in the margin	⋏	New matter followed by ⋏ or ⋏ⓧ2
Delete	/ through single character, rule or underline or ⊢⊣ through all characters to be deleted	∂/ or ∂/ⓧ2
Substitute character or substitute part of one or more word(s)	/ through letter or ⊢⊣ through characters	new character / or new characters /
Change to italics	— under matter to be changed	⌴
Change to capitals	≡ under matter to be changed	≡
Change to small capitals	= under matter to be changed	=
Change to bold type	~ under matter to be changed	~
Change to bold italic	≂ under matter to be changed	≂
Change to lower case	Encircle matter to be changed	≢
Change italic to upright type	(As above)	⊹
Change bold to non-bold type	(As above)	⊹
Insert 'superior' character	/ through character or ⋏ where required	Y or X under character e.g. Y or X
Insert 'inferior' character	(As above)	⋏ over character e.g. ⋏
Insert full stop	(As above)	⊙
Insert comma	(As above)	,
Insert single quotation marks	(As above)	Y or X and/or Y or X
Insert double quotation marks	(As above)	Y or X and/or Y or X
Insert hyphen	(As above)	⊢=⊣
Start new paragraph	⌐	⌐
No new paragraph	↩	↩
Transpose	⊔⊓	⊔⊓
Close up	linking ⁐ characters	⁐
Insert or substitute space between characters or words	/ through character or ⋏ where required	Y
Reduce space between characters or words	| between characters or words affected	⊤