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On recent applications of paraconsistent logic: an exploratory literature review

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ABSTRACT

This paper aims to empirically explore the state of practical applications of paraconsistent logics. To this end, we performed an exploratory literature review, analysing papers published between the years 2015 and 2018. Paraconsistent formalisms based on annotated logics are practically the sole type of approach we found to be applied in engineering applications. The engineering problems solved by paraconsistent approaches were mainly in the fields of signal and image processing and decision support. The results of our exploratory review indicate that recent developments in the theory of paraconsistency have not yet been adopted for applications.

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1. Introduction

Real-world information is inescapably imprecise, and in many cases even inconsistent. Handling such information in general, and reasoning with it in particular, is one of the major challenges of our big data era. Classical logic, as well as its most famous rival, intuitionistic logic, both suffer from a serious drawback when it comes to reasoning with inconsistent information. According to the principle of explosion, also known as 'ex contradictione sequitur quodlibet', every inconsistent theory or knowledge base is totally trivial, which makes these logics practically useless for reasoning with inconsistencies. As a result, alternatives to classical logic that do not have this drawback have evolved, called 'paraconsistent' approaches.

The foundations of paraconsistent reasoning in modern times can be traced to the beginning of the twentieth century, the Russian logician Vasiliev and the Polish philosopher Łukasiewicz, offering new interpretations to formal systems in which contradictions could make sense. Other paraconsistent systems were later introduced independently by Jaśkowski (1949), Nelson (1959), Anderson and Belnap (1962) and da Costa (1974).

One particularly useful formalism in the context of engineering applications is Subrahmanian's *annotated logics*.[1] It was introduced as a foundation for paraconsistent logic programming (Blair & Subrahmanian, 1988). These ideas were closely related

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to the logic APC for reasoning with inconsistency later proposed by Kifer and Lozinskii (1992), further extended by Kifer and Subrahmanian (1992). The foundations and applications of these logics were further investigated by da Costa, Abe and others (Abe, Akama, & Nakamatsu, 2015; da Costa & Subrahmanian, 1989; Lu, Henschen, Subrahmanian, & da Costa, 1991). Annotated logics, as well as logic programming paradigms based on these logics, have been widely used for applications in knowledge representation and databases (Arenas, Bertossi, & Kifer, 2000; Subrahmanian, 1994).

However, the above-mentioned applications have been studied about two decades ago. Since then the field of mathematical and philosophical investigations of paraconsistent logics was significantly expanded (see, e.g.Abe, 2015; Batens, Mortensen, Priest, & Van Bendegem, 2000; Béziau, Carnielli, & Gabbay, 2007; Béziau, Chakraborty, & Dutta, 2015; Carnielli, Coniglio, & D'Ottaviano, 2001; Holger & Verdée, 2016; Berto Mares Paoli, 2010; Tanaka, Berto, Mares, & Paoli, 2013 for some surveys), with books (like Anderson & Belnap, 1975; Anderson, Belnap, & Dunn, 1992) and recently also comprehensive textbooks introducing new theory (Avron, Arieli, & Zamansky, 2018; Carnielli & Coniglio, 2016; Kamide & Wansing, 2015).

While paraconsistent logic is recently flourishing in mathematical and philosophical contexts, this paper aims to turn the spotlight on their *practical applications*. Indeed, the practical motivation behind paraconsistent logic made it seem very promising already decades ago. Béziau (1999) has referred to it as 'logic of the future', and Decker (2005) has called for adopting paraconsistency as a foundational concept for future information systems engineering. Has paraconsistent logic lived up to these promises by now? Moreover, in Akama and da Costa (2016), Akama and da Costa claim that annotated logic remain one of the most attractive paraconsistent logics, which also have many engineering applications. Is it the case also in recent years?

This paper empirically explores the current trends in *applied* paraconsistent logics by means of an exploratory literature review (Fink, 2005), aiming to identify papers discussing *concrete practical applications* of paraconsistent logic in recent years (between 2015 and 2018). By concrete and practical applications, we mean here works where paraconsistent logic is used for a solution of some concrete engineering problem. Our results show that annotated logics are still the leading formalism in terms of usefulness for engineering problems. Furthermore, we found no indication of impact recent advances in paraconsistent logics may have had on their practical applications. This shows there exists a gap between theory and practice of paraconsistent logics, which should be addressed by the logical community.

2. Literature review methodology

Following Fink (2005), we provide a precise, reproducible description of the procedure we followed when performing the review. However, it should be noted that the review is of an exploratory nature and does not intend to cover exhaustively all possible papers on applications of paraconsistent logic. Rather, we aim to provide an exploratory mapping, which will serve as basis for further, more systematic investigations.

We used the following criteria for including papers in our review. We searched Google Scholar for all papers between the years 2015 and 2018 which included the

word 'paraconsistent' or 'paraconsistency' in their title. Google Scholar can be a valuable source for such efforts, see, e.g. Halevi, Moed, and Bar-Ilan (2017) for a discussion on its suitability. Our assumption here was that if paraconsistent logic is an important tool in the studied solution, one of these words will be mentioned in the title.[2]

Our search resulted in 244 results for 'paraconsistent', and 57 results for 'paraconsistency'. Out of these, five were books on paraconsistent logic, which were excluded. We then went over the remaining results, excluding papers, which addressed mathematical properties of existing logics or introduced new extensions of paraconsistent formalisms. This process filtered out the majority of the results, ending up with 64 papers. Out of these, publications in unindexed[3] journals and conference proceedings were also excluded. This led to a final list of 24 papers, the details of which are presented in the appendix. It should be noted that five of these papers were published as book chapters in the book 'Paraconsistent Intelligent-Based Systems: New Trends in the Applications of Paraconsistency' (Abe, da Silva L., & Anghinah, 2015) was published in 2015.

3. Literature analysis results

We started by classifying the papers to domains of the solved problem. The classification results are presented in the table in the appendix. The domains we identified included signal analysis (where signals do not include images which got a category of their own), decision support systems (abbreviated below as DSS), image processing, process control, network analysis and multi-agent communication. One paper Gao, Fodor, and Kifer (2016) addressed word puzzles, which we found too specific to include in Figure 1, which shows the distribution of the papers over the problem domains. As can be seen, most papers address signal analysis (7), DSS and image processing come second (4), followed by process control (2), network analysis (2) and agents (2).

We then continued the analysis by identifying the paraconsistent formalism used in each paper. These results also appear in the table in the appendix. The striking observation is that all but two papers use a formalism based on some form of *annotated logic*. This includes four-valued and two-valued annotated logics (da Silva Filho, Torres, & Abe, 2010; Dill, da Costa Jr, & Santos, 2014) (abbreviated by EPAL and PAL2v respectively in the table), paraconsistent neural networks based on annotated logics (da Silva Filho et al., 2010) (abbreviated by PANN in the table) and APC (another version of annotated logics introduced by Kifer and Lozinskii (1992)).

The two papers that were an exception were both on artificial agents, and applied other formalisms: the query language 4QL (Maluszyński & Szalas, 2011) and 3-valued paraconsistent logic programming system QMPT0 (Goto, Fujita, & Nide, 2018).

4. Discussion and summary

Our results indicate that the leading paraconsistent formalisms in practical applications in the recent 3 years are those based on annotated logics. This needs to be further validated by expanding the rather limited scope of the current literature review. One aspect that needs to be better addressed is ideas borrowed from various paraconsistent formalisms that may not be referred to as 'paraconsistency' per

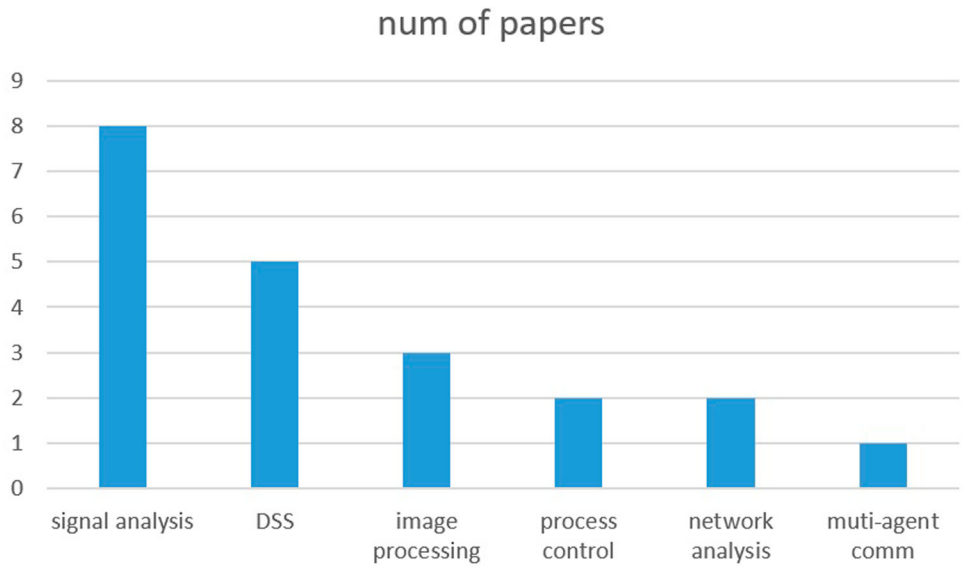

Figure 1. The papers divided into problem domains.

se. For instance, one of the main ideas behind the paraconsistent family of Logics of Formal (In)consistency (LFIs, Carnielli, Coniglio, & Marcos, 2007) is that the metatheoretical notions of consistency/inconsistency are expressed at the object language level, practically introducing explicit marking for inconsistent formulae. Analogous ideas are used, e.g., for handling consistency violations in databases: in Geppert and Dittrich (1995), e.g., one of the proposed strategies for managing database constraint violations is *marking*: inconsistent elements of query results are annotated with information about constraint violations. Thus, although no explicit reference to 'paraconsistency' is made in such approaches, this could be thought of as implementing ideas from paraconsistent formalisms and would be missed in any search looking explicitly for mentions of paraconsistency. This could be addressed, however, by looking for reference to '(in)consistency management' or 'handling', as it is referred to in the requirement engineering literature (Hadar & Zamansky, 2015; Nuseibeh, Easterbrook, & Russo, 2000).

The fact that annotated logics were practically the sole formalism used in the context of engineering applications raises some questions. First, the formalism of annotated logics is not among the popular or investigated ones in the logical community. This can be explained by the fact that their logical properties are traditionally considered not as elegant as those of their rivals: e.g. their mixing semantic and syntactic notions (Arieli & Avron, 1994) or the lack of structurality (i.e., closure under substitutions) of their consequence relations (Lewin, Mikenberg, & Schwarze, 1997). For instance, logics based on bilattices (Arieli & Avron, 1994) are referred to as a more 'logically elegant' alternative approach to annotated logics (McGinnis, 2003). The popularity of annotated logics in practical applications, however, calls for further understanding of the connections between them and related, better known, logical formalisms, which could perhaps be better exploited.

The second interesting question is the reasons behind the uptake of annotated logics for engineering applications. One important consideration is the availability of the theory for practical use: e.g. annotated logics have been established as foundations of logic programming, as well as of artificial neural networks. Such investigations for other paraconsistent formalisms have not yet been undertaken. It is an interesting challenge for the logical community to see which of the well-studied paraconsistent formalisms can be extended to such contexts. Another aspect is that, analogously to other logical fashions (e.g. tableaux vs. Gentzen-type proof systems), the uptake in the academia is affected by particular research groups or schools of paraconsistent reasoning: indeed many of the papers in our survey were authored by a research group who has been promoting annotated logics for applications for more than a decade (Abe et al., 2015). The question is, therefore, how the discourse between the different schools of paraconsistency, and between paraconsistent logicians and practitioners be stimulated to allow for a more efficient uptake of different existing formalisms in paraconsistency.

In any case, the paraconsistent community should be concerned about the fact that the gap between theory and practical applications of paraconsistent logics still makes the latter seem more as 'logics of the future' (Béziau, 1999), at least with respect to engineering problems, and perhaps make more efforts for making such logical tools more readily available for practitioners in need of them.

Notes

1. Logics based on bilattices, studied in Arieli and Avron (1994), are sometimes seen as more logically elegant alternative approach to annotated logics; their connections further explored in McGinnis (2003).
2. This of course presents a limitation of our approach, however, to keep the manual analysis feasible we chose to limit our search in this way. A immediate direction for future work is to extend our search using less strict criteria (e.g. the word 'paraconsistent' appearing anywhere in the paper, considering years later than 2015, etc.).
3. We used Scimago Journal Rank for journals, and CORE portal for conferences.

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Appendix A. Papers included in the literature review

Table A1. Selected papers.

#	Title	Domain	Source	Formalism	Publ	Year	Refs.
1	Paraconsistent extractor of mammographic images applied in the process of diagnosis of breast cancer assisted by computer	Image processing	2018 Innovations in Intelligent Systems and Applications (INISTA)	PANN	IEEE	2018	do Amaral, de Castro T., Abe, Nakamatsu, Ungaro (2018)
2	Evaluation of adherence to the Model Six Sigma using paraconsistent logic	DSS	Innovations in Intelligent Systems and Applications (INISTA)	EPAL	IEEE	2018	Kirilo et al. (2018)
3	Paraconsistent logic used for estimating the gait score of broiler chickens	Image processing	Biosystems Engineering	PANN	Elsevier	2018	Nääs, Lozano, Mehdizadeh, Garcia, Abe (2018)
4	An analyser of computer network logs based on paraconsistent logic	Network analysis	Journal of Physics: Conference Series	EPAL	IOP Publishing	2018	Mario et al. (2018)
5	Implementation of 3-Valued Paraconsistent Logic Programming Towards Decision Making System of Agents	Agents	Journal of Systems Science and Systems Engineering	$QMPT_0$	Springer	2018	Goto et al. (2018)
6	Anomaly detection using the correlational paraconsistent machine with digital signatures of network segment	Network analysis	Information Sciences	PAL2v	Elsevier	2017	Pena, Carvalho, Barbon Jr, Rodrigues, Proença Jr (2017)
7	Paraconsistent analysis network applied in the treatment of Raman spectroscopy data to support medical diagnosis of skin cancer	Signal analysis	Medical and biological engineering and computing	PAL2v	Springer	2016	Da Silva Filho et al. (2016)
8	Applying the paraconsistent annotated evidential logic $E\tau$ in a solar tracker for photovoltaic panels: an analytical approach	Signal analysis	IFIP International Conference on Advances in Production Management Systems	EPAL	Springer	2016	Prado, Nogueira, Abe, Machado (2016)
9	Novel method to characterise upper limb movements based on paraconsistent logic and myoelectric signals	Signal analysis	Engineering in Medicine and Biology Society (EMBC), 2016 IEEE 38th Annual International Conference of the	PANN	IEEE	2016	Favieiro, Moura, Balbinot (2016)
10	Determination of operating parameters and performance analysis of computer networks with paraconsistent annotated evidential logic $E\tau$	Network analysis	IFIP International Conference on Advances in Production Management Systems	EPAL	Springer	2016	Junior, Abe, Silva (2016)
11	Paraconsistent artificial neural network for structuring statistical process control in electrical engineering	Process control	Towards paraconsistent engineering	PANN	Springer	2016	Da Silva Filho et al. (2016)
12	ERP software quality using paraconsistent logic	Software quality	FIP International Conference on Advances in Production Management Systems	EPAL	Springer	2016	Tavaves, Abe, Silva, Pimenta (2016)

(*continued*)

Table A1. Continued.

#	Title	Domain	Source	Formalism	Publ	Year	Refs.
13	Effectiveness of production planning and control (PPC) in a Baby Fashion Cluster, Under the Prism of Paraconsistent Logic	DSS	IFIP International Conference on Advances in Production Management Systems	EPAL	Springer	2016	de Lima, Papalardo, Sacomano, Tavares, Barboza (2016)
14	Production planning in intra-organizational network – A study under the point of view of annotative paraconsistent logic	DSS	IFIP International Conference on Advances in Production Management Systems	EPAL	Springer	2015	Papalardo, de Carvalho, Sacomano, Machado (2015)
15	Improving photovoltaic applications through the paraconsistent annotated evidential logic $E\tau$	Signal control	International Conference on Computational Science and Its Applications	EPAL	Springer	2016	Prado, Nogueira, Abe, Machado (2016)
16	Paraconsistency and word puzzles	Word puzzles	Theory and Practice of Logic Programming	APC	Cambridge University Press	2016	Gao et al. (2016)
17	Application of paraconsistent artificial neural network in statistical process control acting on voltage level monitoring in electrical power systems	Process control	Intelligent System Application to Power Systems (ISAP), 2015 18th International Conference on	PANN	IEEE	2015	da Cruz et al. (2015)
18	An algorithmic method supported by paraconsistent annotated logic applied to the determination of friction factors for turbulent flow in smooth pipes	Signal analysis	Paraconsistent Intelligent-Based Systems	PAL	IEEE	2015	Mário et al. (2015)
19	Paraconsistent logic study of image focus in cylindrical refraction experiments	Image processing	Paraconsistent Intelligent-Based Systems	EPAL	IEEE	2015	Masotti de Mesquita (2015)
20	Paraconsistent logic in decision making: paraconsistent decision method (PDM)	DSS	Paraconsistent Intelligent-Based Systems	EPAL	IEEE	2015	da Silva Filho, F. Pontes, Mario, Abe, Giordano (2015)
21	Paraconsistent logic algorithms applied to seasonal comparative analysis with biomass data extracted by the fouling process	Signal analysis	Paraconsistent Intelligent-Based Systems	EPAL	IEEE	2015	da Silva Filho et al. (2015)
22	Paraconsistent neurocomputing and biological signals analysis	Signal analysis	Paraconsistent Intelligent-Based Systems	EPAL	IEEE	2015	Abe et al. (2015)
23	Paraconsistent multi-party persuasion in TalkLOG	Agents	International Conference on Principles and Practice of Multi-Agent Systems	4QL	Springer	2015	Dunin-Kplicz, Strachocka, Szałas, Verbrugge (2015)
24	Paraconsistent artificial neural network applied in breast cancer diagnosis support	image processing	Software & IFIP International Conference on Advances in Production Management Systems	PANN	Springer	2015	do Amaral et al. (2015)