Trust-based Negotiation in Multiagent Systems: A Systematic Review

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Abstract. In this work, we conducted a systematic review on trust-based negotiation in Multiagent Systems (MAS), through a bibliometric analysis over the past 25 years of research publications, on three of the most popular scientific databases (Google Scholar, Scopus, and Web of Science). Our analysis reveals that this research topic is regaining interest, after some oscillating years, and the impact of its contributions is equivalent to other equally important research variants like ontology and argumentation (in a negotiation scenario). Discarding the human-to-agent trust challenges, we only focus on agent-to-agent trust concepts, and we performed an analysis of the different types of trust dimensions, using the findings and concerns of past review works, as we identify and select the dimensions that, in our opinion, have the most potential to lead the research advances on the topic of trust in MAS. Furthermore, we discuss the current challenges and open issues associated with those trust dimensions, and how current advancements in the literature could provide insights for the solution of those challenges, or even the finding of new research paths.

Keywords: Trust · Negotiation · Multiagent Systems.

1 Introduction

It is difficult to pinpoint the exact first negotiation in history, as negotiations have been a part of human interaction since the beginning of civilization, but we can assume that could be related to some form of basic transaction (an exchange of goods) between two actors. The question is, how did they trust each other without a previous history of interaction between them? How could they know that the other party would fulfil their part of the agreement? They simply trusted each other, as one should expect that trust (in a negotiation context) to be defined as the expectation that the other party will act in a way that is mutually beneficial and will not take any type of advantage. Some definitions of trust include keywords like positive expectations or willingness to be vulnerable, and even the Oxford Dictionary classifies trust as "to have confidence in somebody", perhaps the most commonly used definition is given by Rousseau et al. [22] that

classifies trust between humans as "a psychological state comprising the intention to accept vulnerability based upon positive expectations of the intentions or behaviour of another". As for negotiation the most acceptable definition is given as "the process by which a joint decision is made by two or more parties. The parties first verbalize contradictory demands and then move towards agreement by a process of concession making or search for new alternative" [20].

Through the years, several authors have suggested different main types of trust, three to be specific [15]: (1) deterrence-based trust: the basic form of trust that states that actors must trust the other will follow through with promises made during the negotiation; (2) calculus-based-trust: where the trustor should rationally decide to trust the other party, not because of fear of negative consequences, but to achieve positive consequences; (3) knowledge-based trust: a form of trust beyond trusting that the other party will follow through with their promises, that resides in the ability that one actor could understand the others so well, to accurately predict their behaviour during a negotiation process.

With the emergence of autonomous agents, the capability to engage in a negotiation and argue about its outcome was quickly recognized as a challenge. As result, three broad topics for research on negotiation where defined: (1) negotiation protocols; (2) negotiation objects; (3) reasoning models [5,13,14]. An agent is described as an entity that senses the environment and acts on it, performing a task continuously, with a strong autonomy, in a shifting environment, while coexisting with other entities and processes. Multiagent Systems (MAS) aim to provide both principles for construction of complex systems involving multiple agents and mechanisms for coordination of independent agent behaviour [25]. MAS, which consists of multiple autonomous agents with distinct goals, that communicate with each other and with the environment with a focus on understanding the latter and reason upon intelligent models, coordinating their efforts to achieve their goals and the one of the ecosystem where they are inserted in, and negotiating their preferences [2, 17]. To achieve that, each agent must be equipped with trust mechanisms, that can be based on mathematical principles or extracted from cognitive characteristics that mimic their human counterpart.

Intrigued by the current state of this research field, in this work we conduct a bibliometric analysis over three of the main research databases, looking to understand the evolution of research interest towards trust in negotiation-based scenarios in MAS. Additionally, we address past review works to discuss the different types of dimensions that can be associated with trust and the current challenges and open issues in modeling trust in a negotiation scenario. Despite trust having two meanings in this context, namely trust of humans in the agent that represent them, and agent trust in other agents, we will be focused on the latter.

The remainder of this work is structured as follows. In Section 2 we present an empirical quantitative analysis based on a bibliometric analysis to obtain insights regarding the research interest of the subject of trust in negotiation in MAS over the past 25 years; Section 3 contains an analysis of some review documents on this subject, with a focus on some mentioned trust dimensions,

namely, paradigm type, information sources, trust semantics, trust preferences, initial trust, and open environments; Section 4 complements the previous section with an elaboration on the challenges and open issues associated with each trust dimension described previously, including the mentioning of some possible research paths. This work concludes (Section 5) with a discussion of the actual state of research regarding trust-based negotiation in MAS, its strengths, limitations, and a reflection over possible future research paths.

2 An empirical quantitative analysis

To understand the research activity regarding the subject of trust in negotiation between agents in multiagent system, we conducted a bibliometric analysis, a quantitative method used to evaluate and measure scientific literature and research activity in a particular field or discipline.

Such quantitative analysis was conducted according to the guidelines presented by the work of Donthu et al. [7], that defines the required steps, namely: (1) define the scope; (2) choose the techniques; (3) collect the data; (4) run the bibliometric analysis and report the findings.

As the scope of this analysis, we have interest in examining the growth in publication rates (and impact of those publications) over time in this field, and analysing the evolution of research topics. We intend to obtain a general overview on the scientific interest for this field, and understand if that interest has shifted through the years.

For the techniques we have selected a combination of performance analysis and science mapping techniques, namely: publication-related metrics; citation-related metrics; citation-and-publication-related metrics; and co-word analysis. The performance analysis techniques are the most common type of analysis, with number of publications and citations per year being the most prominent measures. Regarding the science mapping analysis, a co-word analysis is focused on words and examines the actual content of the publication itself. Those words can be found in the title, abstract, author keywords, index keywords, or the full text.

The data collection set can be divided into subtasks. We first need to select the data sources (the scientific databases), then we need to define the queries to conduct such research, and finally we want to automate this data gathering process using external tools. For the scientific databases we have selected:

- Google Scholar[1]: being one of the most popular scientific databases, this platform provides a search across many disciplines and sources. Such characteristic means that the results present on this platform are often found in others, which can lead to the duplication of data;
- Scopus[2]: a widely used bibliographic database that indexes scientific research output from a broad range of disciplines. It provides a comprehensive plat-

[1] https://www.scholar.google.com
[2] https://www.elsevier.com/

form for tracking citations and analysing research impact, as well as for identifying emerging trends and collaborations in specific fields of study;
– Web of Science[3]: this scientific database platform, now maintained by the Intellectual Property and Science business of Thomson Reuters, was originally produced by the Institute for Scientific Information as comprehensive citation search across multiple databases.

As for the search query, it is a combination of title keywords and co-word analysis. Each search result must contain the words 'negotiation' and 'agent' in the title of the document, and the keyword 'trust' must be present in the corpus. To better evaluate any existing trend, we selected a period of 25 years (from 1998 to 2023 (at the time of this publication)), divided into five-year intervals. To execute this search, and collect the data, we have selected the 'Publish or Perish' tool developed by Harzing [11]. This tool also provides key metrics that will be used on our analysis, namely:

– Total Publications (TP): total number of results returned by the search;
– Total Citations (TC): total number of citations returned by the search;
– Citation Years (CY): number of years from the earliest year found in the currently selected results to the year of the search. Is given by a subtraction of the current year (i.e. 2023) by the year of the older publication in the search result (e.g. 1998);
– Total Citations per Year (TC/Y): average number of citations per year, given by TC/CY;
– Total citations per Paper: the sum of the citation counts across all papers, divided by the total number of papers. Given by TC/TP.
– g-index: Egghe's g-index, returning the g number of publications receiving at least g^2 citations (measure of impact).

Finally, our findings (represented by Table 1) allow us to conclude that the topic of trust in negotiation between agents in a MAS has been losing quantitative interest along the years. By looking at the results obtained from the GS database, we can observe that the TP has peaked in the 2008-2013 year interval, but the overall impact of those publications were more prominent in the 2003-2008 interval. Although the results obtained from the SC and WoS platform are expressive low for an efficient bibliometric analysis, they allow us to understand that such tendency is also replicated in those platforms. With an expectable decreasing tendency in the TC metric (because each consequent interval has less CY), we note a small inversion of this descending tendency in interest found in later years (namely the last year interval of the data) that contains a small increase in TP. However, such event cannot invert the decrease in impact of such publications, observable by the decreasing value of the *g-index* metric.

Curious about how this topic of research is comparable to others, we conducted another bibliometric analysis, following the same methods and sequence as before, with the following alterations: the query maintains the 'negotiation'

[3] https://apps.webofknowledge.com/

Table 1. Bibliometric analysis result for publications with 'negotiation' and 'agent' keywords present in the title of the document, and the keyword 'trust' present on its corpus, across different scientific databases (GS - Google Scholar; SC - Scopus; WS - Web of Science), over the past 25 years, contextualized with specific year intervals.

	Year Interval														
	1998 - 2003			2003 - 2008			2008 - 2013			2013 - 2018			2018 - 2023		
Metrics	GS[a]	SC	WoS	GS[a]	SC	WoS	GS[a]	SC	WoS	GS[a]	SC	WoS	GS[a]	SC	WoS
TP	28	6	4	68	10	7	80	15	12	38	6	3	47	10	4
TC	1,251	135	86	1,344	51	115	909	41	69	464	53	23	166	27	9
CY	25	23	22	20	20	16	15	15	15	9	9	6	4	5	4
TC/Y	50.04	5.87	3.74	67.20	2.55	6.76	60.60	2.73	4.31	51.56	5.89	3.29	41.50	5.40	1.80
TC/P	44.68	22.50	21.5	19.76	5.10	16.43	11.36	2.73	5.75	12.21	8.83	7.67	3.53	2.70	2.25
g index	28	6	-	36	7	-	28	5	-	21	6	-	11	5	-

[a] The nature of this particular platform means that it can contain search results that are equally present on other platforms

and 'agent' keywords in the title of the document, but the co-word analysis is based on the keywords 'trust', 'protocol', 'ontology', and 'argumentation'; instead of getting five-year intervals result, we search for results in a single 25-year interval (from 1998-2023).

The findings reported on Table 2 allow us to understand that, contrarily to what could be anticipated, with an exception to the research performed on 'protocol', the research interest on 'trust' is comparable to other research topics. Despite a smaller TP count, the results on 'trust' show us a comparable TC values, and this tendency is also found in the TC/Y metric. More important, when excluding the 'protocol' results, we can observe a comparable overall impact measurement between results.

3 Types of trust in negotiation

Our analysis is initially based on the finds on the work of Granatyr et al. [8], which itself is a compilation and extension of previous reviews on this subject [1, 6, 9, 12, 16, 19, 21, 23].

In their review work, authors define the trust and reputation models in a set of dimensions, which can have a set of values. Focusing on the existing dimensions presented by the Granatyr et al. work [8] we have selected six dimensions to be the focus of our analysis, and seven sub-dimensions. As for the dimensions we will address the paradigm type, information sources, trust semantics, trust preferences, initial trust, and open environment. For the sub dimensions we have select the sub-dimensions of the paradigm type: numeric; cognitive; and

Table 2. Bibliometric analysis result for publications with 'negotiation' and 'agent' keywords present in the title of the document, and a specific keyword present on its corpus, across different scientific databases (GS - Google Scholar; SC - Scopus; WS - Web of Science), from 1998-2023 (25 years).

	Keyword											
	Trust			Protocol			Ontology			Argumentation		
Metrics	GS[a]	SC	WoS	GS[a]	SC	WoS	GS[a]	SC	WoS	GS[a]	SC	WoS
TP	65	41	30	882	200	211	248	78	53	322	53	43
TC	4,061	299	300	12,310	3,442	1,642	3,266	588	295	4,976	575	497
CY	25	23	25	25	25	25	25	22	25	25	22	21
TC/Y	162.44	13.00	10.07	492.40	137.68	79.42	130.64	26.73	15.05	199.04	26.14	23.67
TC/P	15.20	7.29	13.13	13.96	17.21	9.03	13.17	7.54	5.96	15.45	10.85	11.56
g index	57	16	-	83	49	-	49	21	-	60	23	-

[a] The nature of this particular platform means that it can contain search results that are equally present on other platforms

hybrid. And four sub-dimensions of information sources: direct interaction; direct observation; witness information; and certified reputation. We have selected those dimensions, as we believe that they can be the most influential for future advances and development in this research path.

Paradigm type

This dimension, composed of numeric, cognitive, and hybrid sub-dimensions, is the most commonly found in literature. The numerical paradigm is vastly the most researched variant of this dimension, and the majority approaches are based on statistical methods to compute trust, including Bayesian probabilities, probability distribution, Dempster-Shafer functions, and machine learning. They are based on a numerical aggregation of past interactions, and produce a set of objective probabilities that agents will, correctly, execute a given task, and share close to none characteristics to human behaviour.

On the other hand, the cognitive paradigm is built to equip agents with human behaviours through the usage of cognitive processes to calculate trust. They are strongly related to beliefs and mental states that agents have, and trust is a measurement of these beliefs and the decision to trust, or not trust, another agent. Such characteristics link this approach to cognitive architectures, like BDI agents.

There is a possibility for both sub-dimensions to coexist in the same MAS, and this resulted in hybrid models based on beliefs (cognitive) and use numerical aggregations (numerical).

Information sources

Agents extract data from other agents, or environment, and use it to calculate trust and reputation values. Using the most simple form of transaction/negotiation as a global example, where A gives x to B, and B gives y to A in exchange (a simple trade of goods), there are several ways to extract data.

Direct interaction is considered the most relevant information source, requiring several interactions to be useful (which can be a challenge in MAS). Is one of the first computation trust models and occurs when A needs a historical set of interactions with B to evaluate the trust in the next transaction/negotiation process.

Direct observation removes the necessity for a history of past interactions between agents, since an agent can observe other agent behaviour in past or current interactions to decide about engaging with it (most applicable to MAS). Some observation characteristics include feedback provided by the agent, percentage of positive reviews, prior actions, and the results of contracts.

Witness information occurs when an agent does not own direct information, and have a necessity to 'ask' other agents. Agent A needs to interact with agent B, but query agent C to obtain its opinion about B. The trust (or reputation) value is then calculated through the aggregation of opinions who had some interaction with the trustee.

The usefulness of certified reputation is shown in first interaction scenarios between agents. To evaluate agent B, agent A will perform a direct query to B regarding his evaluations (a recommendation letter like behaviour). Sharing a similar concept to witness information, this approach can be an answer to its performance problems of due to a low computation cost to find witnesses, only if the model is able to deal with the dishonest manipulation of the list of witnesses.

Trust semantics

While most models measure trust in a single value, this dimension relies on ontologies to define trust as a composite measure. Instead of defining the outcome of a negotiation process as 'my trust in you is 0.7 on a 0-1 scale', we can specify their trust in the capability to deliver a product/service, and their trust in the (perceived) quality of such product/service. Meaning that instead of relying on a single generalist trust metric, each agent is capable of deciding which feature is the most important according to its needs, and even defining weights for each feature (e.g. a weight of 0.4 for product delivery and 0.6 for product quality) (i.e. trust preferences).

Initial trust

Like the first ever negotiation in history, a negotiation process can start without a previous definition of an initial trust. When a model assumes that trust is already present at any given, it is neglecting an important step in the initial set up of trust, and obstructing the entrance of new agents in the environment by mitigating their possibilities for success.

To address this major difficulty in building trust for newcomers, some authors have using machine learning models to predict trust values based on expectation, recommender systems, or alter the range of reputation values by including a

negative dimension expanding its possibilities to any value between -1 and 1 where newcomers enter the network with an initial value of reputation set to zero.

Open Environments

When agents are allowed to enter and leave a MAS environment as they please, this generates uncertainty about the environment, and the concept of trust becomes a greater challenge. Knowing that, authors [12] have stated relevant characteristics for a model to address this type of environments: information sources can be replaced, but their historical data must be persisted to avoid the comeback of an agent being mistaken by a newcomer and delete their past behaviour; must be decentralized to allow each agent to have its own evaluation mechanism; and be robust and secure against intrusive and cheater agents. Although many suggestions where made to solve those issues, the approach with most potential relies on the usage of digital certification to correctly recognize agents.

Granatyr et al. review over the most significant trust and reputation models published over the past two decades [8], concluded that the majority of the significant results (those with characteristics of MASs) are related to negotiation (51%), and the remaining are related to coalition, argumentation, and recommendation. The report addresses the increase in number of cognitive and hybrid models (16%), but the mathematical models are still predominant in the literature. A possible explanation for that growth tendency can be associated with a growth of the interest in applications closest to human behaviour, that consider cognitive aspects like argumentation or reasoning.

As for the information sources dimension, they concluded that most models employ direct interaction and witness information. This is explained by the necessities of the majority of scenarios where negotiation is used (e-commerce), and those models are the most common approaches to extract information from other agents, with direct interaction considered to be the most valuable information source. Nonetheless, they reported an increase in the number of models that employ different information sources, including certified reputation, which indicate a growing interest in finding new ways to extract information from agents and from an environment.

They also noted an increase in open environment dimension, that is motivated by the open characteristics of MAS models. Such growth can represent a direct proportionality between open MAS and trust and reputation models. If such argument is representative of the future reality, we can expect further developments in this dimension.

Regarding the trust semantics dimension, it shares a relationship with trust preferences, and this tendency would accompany further developments in this research subject. Contrary to previous reviews that report the lack of interest for further develop those dimensions [16], more recently several models are starting to incorporate them.

Finally, they conclude that despite the implementations of different dimensions in a single model is not common practice, this scenario only exists due to

the efforts of contribution to a specific dimension rather than the trust concept as a whole. There is no correlation between the number of scenarios per model and the quality of it, meaning that the usage of fewer dimensions are not necessary worse than the inclusion of a wide variability of dimensions, and vice versa. This means that the identification of the best model or the best combination of dimensions is still an open question.

4 Challenges and open issues in modeling trust in negotiation

While the representation of trust between agents in a MAS can be a simple concept to understand and apply (in its simple version is a numerical value between zero and one), further developments in trust-based negotiation in MAS, and its dimensions, are still facing some challenges. This is not a novel concern, since authors are notorious for indicate that user trust and trust between agents are essential for the success of MAS systems [3].

The fact that most trust and reputation models are domain and context specific, introduces an initial barrier to the development of MAS since it is not clear which model would be indicated for that environment, since most models often use particular variables. While noting the efforts related to the development of tools and frameworks regarding the selection and construction of a model for a MAS, there is still no framework capable of dealing with the most recent approaches to trust and reputation models [8]. This is also accompanied by a growth in open environments where agents can enter and leave an environment at any time, which represents a challenge for the initial trust dimensions. However, recent works have emerged with possible solutions to the problems identified by those dimensions through the usage and implementation of a blockchain [10, 18, 24].

While this challenges occur when addressing a simple negotiation scenario like a trade of goods between two agents, agent loses opportunities with other agents by interacting with just one agent at a time, cutting itself from information which it might have been generated during that negotiation. As result, such implementations become even more complex when the agent holds simultaneous negotiations, and could add an n-fold complexity in modeling trust in large-scale MAS [14].

While the developments in cognitive approaches diminish the virtual distance between humans and agents, such link to cognitive architectures can also inherit some existing problems regarding trust in negotiation between humans. As such, further developments could be slowed down by a lack of development regarding the subject of trust between humans and being limited by a close relationship and emulation of human to human negotiation.

As for other dimensions, they share a similar challenge: the need to trust a third party. Even direct interaction and observation still requires the existence of an enforcer that will guarantee the execution of the negotiation, which represents a recursive trust problem since, in most cases, each agent is always bound to trust

a third-party entity (the enforcer). The same can be said for witness information dimension, where each agent needs to trust the opinion of other agents to even start to formulate their trust values regarding a specific agent that intends to negotiate with. However, some advances have been made in this direction with works trying to offer a solution to the need to trust third entities, by replacing them with more reliable and trustworthy environments [4].

5 Conclusion

Despite a recurrent lack of mentioning discussing the subject of negotiation in MAS, trust is an implicit constant that could dictate the success, or failure, of such models and implementations. This topic has accompanied the initial definitions of concepts needed to have a successful negotiation between agents in a MAS, alongside with negotiation protocols, negotiation objects, and reasoning models.

Although it had an oscillation in quantitative metrics through the research years, data suggests that this topic of research is currently on an ascending tendency and, overall, it has been on par with other fields of research like protocol, ontology, and argumentation, on impact metrics (*g-index*), number of total citations, total citations per year, and total citations per paper. This quantitative comparison suggests that, despite an apparent decrease in publications on the past decade, there is still significant research interest for this subject and new findings are emerging that could solve the challenges with current research (e.g. new machine learning models, or even the usage of blockchain to reinforce the concept of trust between agents, and removing recurrent trust challenges associated with the usage of third-party actors that enforce the outcome of a negotiation).

While we do believe that the dimensions of paradigm type, information sources, trust semantics, trust preferences, initial trust, and open environment (and some of its sub-dimensions) have the potential to lead the research advances in the future and change the tendency of single dimension scientific contributions even when the model contains more than one dimension (as we believe that the application of these dimensions can generate a solid base framework). However, even if those dimensions would be successfully applied in a single model, we would still not find a solution to some current challenges.

As we keep narrowing the gap between agent cognition and humans, and emulate and mimic human behaviour in agents, we are distancing ourselves from possible research paths that could offer more insights about the limits of trust-based negotiation in MAS. For example, by shifting the focus of trust from agent-to-agent to a trust in the environment, we could have potential solutions to the issues regarding open environments, or even the management of first interaction negotiation between new agents. We already have physical examples of this type of trust in the process, like the European Accident Report Form, that allow complete strangers to negotiate and reach an agreement without previous history of interaction between them, by having trust in the environment, that

will enforce the outcome of the negotiation. As result, we strongly believe in a research path where the allocation of trust to the environment, instead of agents, can contribute to the success and advancements of this research subject, and offer some solutions to challenges that MAS are currently facing.

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