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Reasoning in BDI agents using Toulmin's argumentation model

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A B S T R A C T

The theory of argumentation pervades several fields of knowledge, and it has gained significant space in multiagent systems because it provides a way for modeling reasoning over conflicting information in intelligent agents. This work proposes the development of an argumentation-based inference mechanism for BDI agents based on Toulmin's model of argumentation. The philosopher Stephen Toulmin claimed that arguments typically consist of six parts: data, warrant, claim, backing, qualifier, and rebuttal. This argumentation structure allows arguments to be described through separated components, making it easier to define and to evaluate the inference process. By presenting and discussing some case studies, this paper shows how this mechanism supports the inference of new beliefs based on available evidence within BDI agents programmed in an agent-oriented programming language.

1. Introduction

The theory of argumentation is studied in different fields of knowledge such as Rhetoric, Law, Communication, Philosophy, and Artificial Intelligence (AI). In AI, argumentation has constantly evolved, being used to provide a reconciliation between information and decision-making. Some models of argumentation that are influential in AI appear in [1–3].

Agents can be defined as virtual entities that act in an environment in which they interact and collaborate with other agents motivated by *goals* [4]. Agents can act in isolation or in groups, forming multiagent systems [5,6]. Along the years, several architectures for intelligent autonomous agents were developed, but perhaps the best known is the architecture for rational agents called BDI [7], which is based on the model proposed in [8], allowing agents to explicitly represent the following mental attitudes: *Beliefs*, *Desires*, and *Intentions*.

In recent years, argumentation has become an important focus of research within the multiagent systems community, because it provides an agent with the ability to reason about available information, to reason about conflicting information, to reason about information acquired through perception of the environment, and to reason about information obtained from various agents through communication. In the literature, there are many papers involving argumentation and multiagent systems, e.g. [9–22].

In multiagent systems, argumentation can be divided into two main lines of research: (i) Argument-based reasoning, which is used on incomplete, conflicting, or uncertain information, where arguments for and against a conclusion (e.g., a

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belief or a goal) are constructed and compared; (ii) Argument-based dialogues where agents interact by exchanging arguments (e.g., providing justifications to support claims).

This paper presents an argumentation-based inference mechanism for BDI agents, which aims to provide a model that supports agent reasoning about beliefs. The mechanism proposed in this work has its structure defined in accordance with the main ideas introduced by Stephen Toulmin in [23,24]. Stephen Toulmin presented a model of argument that has as a key point the structural analysis of an argument.

Toulmin's model defines six components for constructing an argument: data, which are facts and evidence used to prove an argument; warrants, which are general statements that serve as bridges between the claim and the data; qualifier, which is a statement that limits the strength of an argument; rebuttals, which are counter-arguments or statements indicating circumstances where the general argument does not hold true; and backing, which are statements that serve to support the warrants (i.e., statements that do not necessarily help to prove the main point being argued, but which do prove that the warrants are true).

The mechanism proposed in this paper allows agents to build new claims (beliefs) based on five components of Toulmin's model; the backing component is not currently used in the mechanism. The mechanism is also helpful when agents have to justify a certain claim by taking advantage of the decomposition of the various aspects of an argument into those components.

This paper is an extended version of the work presented in [25]. In this extended version, we added a more sophisticated and detailed case study, which is based on a healthcare scenario. We also include details of its implementation on the Jason platform, a well-known agent-oriented programming platform. Also, the topics related to this work were discussed in more detail, new related research was added and a background section was added to introduce the concepts that served as the theoretical basis of our study.

This paper is structured in 8 sections. In Section 2, some basic concepts about agents, such as the BDI architecture and argumentation, are provided. In Section 3, Toulmin's model is presented in details. Section 4 describes how Toulmin's model was mapped and adapted to the BDI model. Section 5 shows how the mechanism was implemented in AgentSpeak [26], the BDI agent programming language on which Jason is based. In Section 6, two case studies and their analysis using the proposed mechanism are presented. Section 7 discusses some related work and, finally, Section 8 concludes the paper.

2. Background

2.1. Agents and BDI agents

Agents are computational entities with autonomous behavior (i.e., able to make decisions and act without direct human intervention on unexpected circumstances). These computational entities are situated in an environment that they are able to sense (through sensors), act upon it (through effectors), and communicate with each other through message passing [6].

One of the most studied architectures for cognitive agents is the BDI (*Beliefs-Desires-Intentions*) architecture, which provides a particular structure for agent internal states based on "mental attitudes". The internal state of a BDI agent is formed by (i) *Beliefs* that represent the information about the world (including itself and other agents) available to that agent; (ii) *Desires* representing the motivations of the agent, i.e., the states of the environment that the agent would like to reach; and (iii) *Intentions* which are desires that the agent is committed to achieving by following particular *plans* of action [7].

The BDI architecture gives some support to the challenge of modeling commonsense reasoning. This kind of reasoning almost always occurs in the face of incomplete and potentially inconsistent information [27]. Argumentation is a possible approach to improve the BDI architecture to deal with such issues. Within agents, argumentation can be used as the inference process within a single agent, or a dialogue mechanism to allow agents to have advanced communication skills [19,18].

2.2. Argumentation in multiagent systems

In recent years, interest in research in the area of argumentation theory has grown considerably [14], where it appears as a way to represent the reasoning of agents for decision making and exchange of information through dialogues. Argumentation strengthens interaction to obtain agreements in negotiations where agents do not share the same goals, in order to allow agents to deal with incomplete information and to agree with the other agents in the same system [10]. According to [14], an argument can help solve two main problems in the field of multiagent systems: formation and revision of beliefs and decisions, as well as rational interaction.

- **Formation and revision of beliefs and decisions**
  Argumentation provides a principled basis for resolving conflicts between different arguments. In this way, arguments allow agents to make decisions and generate beliefs based on uncertain, conflicting and incomplete information.
- **Rational interaction**
  As already mentioned, an essential feature in multiagent systems is communication to help agents achieve their individual and collective goals. Arguments put forward in communicative exchanges provide a means to structure dialogues between agents with different points of view, aiming at interaction between agents respecting certain principles.

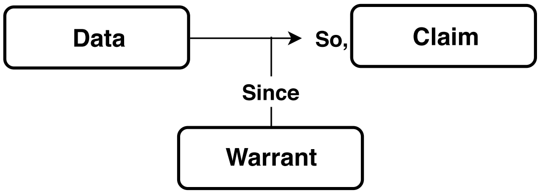

Fig. 1. Toulmin's model with components Data, Warrant, and Claim [23].

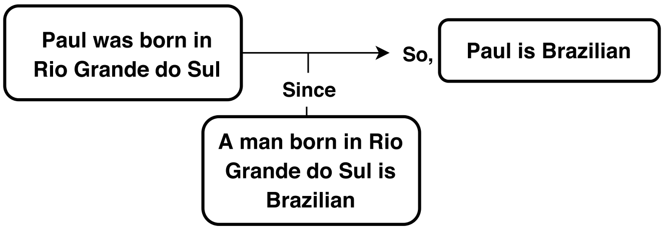

Fig. 2. Example of Toulmin's model with components Data, Warrant, and Claim.

The first aspect above has its focus on reasoning (non-monotonic reasoning in particular) about conflicting and incomplete information, where arguments are constructed against and in favor of certain conclusions aimed at decision making. On the other hand, when the focus is on communication and interaction between agents, arguments can be used to justify and defend claims, beliefs, or objectives, enabling agents to question the validity of claims and allowing them to persuade other participants in the dialogue to accept their claims.

3. Toulmin's model

In 1958, Stephen Toulmin presented an alternative model of argumentation to the traditional syllogism [23], specifying the structure of an argument and detailing the components of an argument. That model is not restricted to a discussion involving two or more individuals; it can be used for individual reasoning, where an individual draws conclusions based on available knowledge [28].

According to Toulmin [23], there should be facts that support a claim, provided that claim was not made in an irresponsible manner. In Toulmin's model, a claim is the conclusion of an argument. In order to establish such a claim, an individual needs information to justify it. Such information is called *data* in Toulmin's model. In order to support the relation between the data to the claim, there should be at least one warrant, see Fig. 1.

An example that illustrates how argumentation works in Toulmin's model is as follows. An individual receives the information that "Paul was born in Rio Grande do Sul", and the individual knows that "A person born in Rio Grande do Sul is Brazilian" (both are data in the model), so the individual can claim that "Paul is Brazilian".

In the above example, there is a proposition that grounds the data as support for the claim. These propositions are called warrants, which are used as explicit assumptions that act as a bridge between data and claim (Fig. 2).

According to [23], there may be different types of warrants, which provide different degrees of strength for a claim. Thus, it is necessary to qualify the confidence of the claim based on a pair (data, warrant). Also, there may be facts that challenge the claim. So Toulmin's model has two other components, called qualifier and rebuttal that are used to represent such aspects of an argument. The qualifier stands next to the claim, indicating the strength of the claim, and it relates to the warrant and the rebuttal components.

The complete Toulmin's model for argumentation has another component called *backing*, which represents the source of a warrant (i.e., a law, a specialist, etc.). As mentioned before, this concept is not currently used in our implementation of the model. Fig. 3 shows the complete version of Toulmin's model and Fig. 4 extends the example presented above.

In the field of Artificial Intelligence (AI), Toulmin's model began to gain visibility in the 1980s, when nonmonotonic logics began to draw the attention of those who at the time sought alternatives to traditional logic. Those nonmonotonic logical systems evaded the rigidity of classical logics and allowed formal logical systems to reach new conclusions from new facts as they arise, which could be additional or contradictory information. The main idea that motivated that AI research was to allow the analysis of real life arguments. From the 1990s onwards, from research on nonmonotonic logics emerged what might called the logic of argumentation [24].

4. A mechanism for argumentation-based reasoning in BDI agents based on Toulmin's model

In this section, a mechanism for argumentation-based reasoning in BDI agents based on Toulmin's model is presented. This mechanism allows BDI agents to infer new claims based on their beliefs. This kind of behavior is desirable because

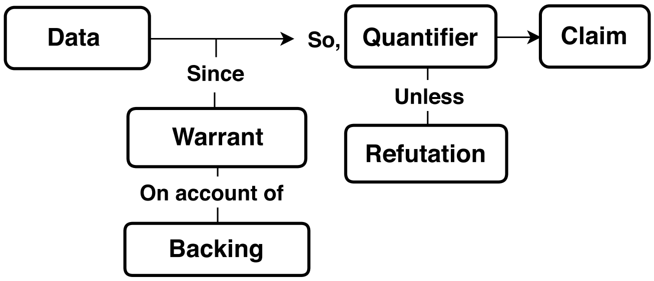

Fig. 3. Toulmin's model with all six components.

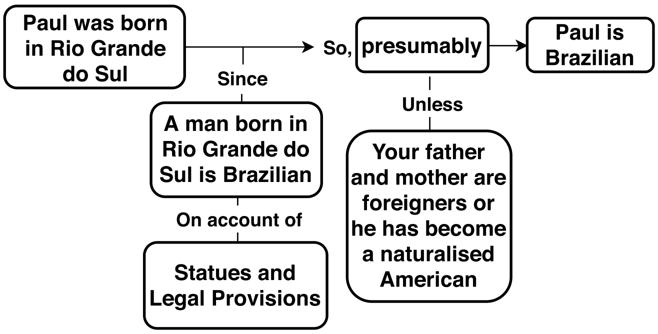

Fig. 4. Example of argument following Toulmin's model with all six components.

Table 1
Mechanism components.

Component	Description
Data	Beliefs that the agent may have at the time of its creation, or acquired from perception of the environment, or received through communication with other agents, or through communication with human users.
Warrant	Beliefs supporting a claim.
Rebuttal	Beliefs disproving a claim.
Claim	A new conclusion supported by the evidence currently believed by the agent.
Qualifier	A numeric or a symbolic value that represents the strength of a claim.

an agent can reason about its beliefs facing incomplete and potentially inconsistent information, as well as use it to make claims when communicating with other agents.

Based on the Toulmin's model, the mechanism is composed of five components: `Data` (`D`), `Warrant` (`W`), `Rebuttal` (`R`), `Qualifier` (`Q`), and `Claim` (`C`). The backing component from the Toulmin's model is not currently used in our approach, but we aim to include it in future work. The components of the mechanism are described in details in Table 1.

Fig. 5 shows a BDI agent architecture based on the Procedural Reasoning System (PRS)[1] changed to mark explicitly the components of the inference procedure we propose here. Note how the Data, Warrant, Rebuttal, and Claim components are *beliefs*, while the Qualifier component is located in the *plan library* instead.

Fig. 6 illustrates the functioning of our inference mechanism. A plan based on agent's beliefs (data, warrants and rebuttals) generates a new belief (claim) with an associated value (qualifier) as a way to express the relative strength of the claim. To compute the qualifier, the plan uses a qualify function. This qualify function can be implemented in several ways, depending on the application (more details on this are discussed later in this paper).

[1] The original model was proposed by [29].

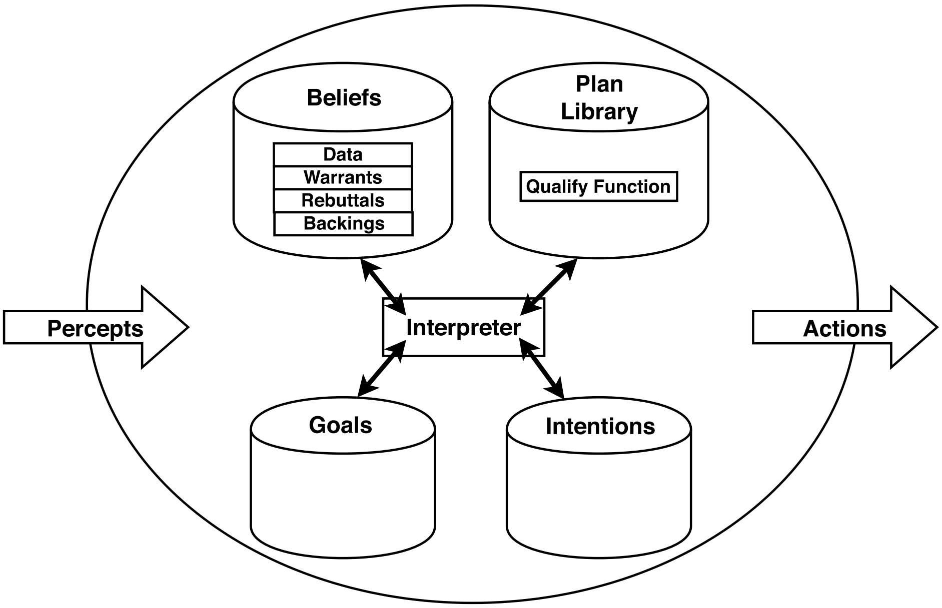

Fig. 5. Agent Architecture.

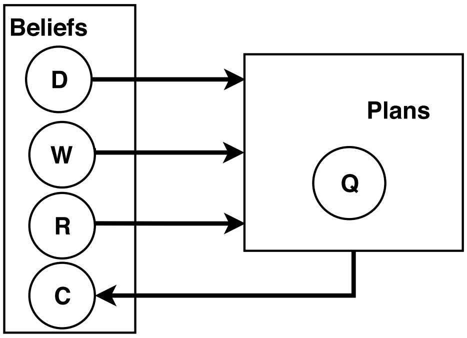

Fig. 6. Toulmin's reasoning model for BDI agents.

4.1. *The Qualify Function*

In order to express the relative strength of a claim, i.e., to establish the *Qualifier* component of an argument, it is necessary to evaluate the relationship between data, warrants, and rebuttals. This process is made by a *qualify function* that receives as input three sets of beliefs that are the Data (D), the Warrants (W) and Rebuttals (R) for a particular claim, and computes the Qualifier (Q) for a particular argument towards that claim. This qualifier value can be numeric or symbolic. Using **B** for the set of all beliefs and **S** the specific domain used to assign a strength value to an argument, the signature of the qualify function (QF) is as follows:

$$QF : (\mathcal{P}(\mathbf{B}) \times \mathcal{P}(\mathbf{B}) \times \mathcal{P}(\mathbf{B})) \longrightarrow \mathbf{S}$$

and, for example, $QF(D, W, R) = Q$ means that in a particular argument the strength assigned by the qualifier function to that argument's claim C, given data D, warrants W, and rebuttals R for C, is Q.

The qualify function can be implemented in various ways according to the application and, therefore, can be adapted to different domains. An example is given in the next section.

5. Implementation of the mechanism in AgentSpeak

To evaluate the proposed mechanism, the model presented in the previous section was implemented in the Jason platform [26]. Jason is a platform that enables the development of multiagent systems using Java and AgentSpeak. AgentSpeak is an agent-oriented programming language based on logic programming and the BDI architecture for (cognitive) autonomous agents.

Listing 1 Belief components.

```
data(data1).
data(data2).
data(data3).
warrant(claim, warrant1, weight1).
warrant(claim, warrant2, weight2).
warrant(claim, warrant3, weight3).
rebuttal(claim, rebuttal1, weight1).
rebuttal(claim, rebuttal2, weight2).
rebuttal(claim, rebuttal3, weight3).
```

Listing 2 A plan in AgentSpeak for forming claims.

```
/* Plan */
+!reasoning(Claim)
    <- .findall(data(Data), data(Data), ListData);
       .findall(warrant(Warrant,Weight),
                warrant(Claim,Warrant,Weight), ListWarrant);
       .findall(rebuttal(Rebuttal,Weight),
                rebuttal(Claim,Rebuttal,Weight), ListRebuttal);
       .qualifyFunction(ListData,  ListWarrant,
                        ListRebuttal, Qualifier);
       +claim(Claim, Qualifier).
```

5.1. Beliefs

The components `Data`, `Warrant`, and `Rebuttal` are represented as agent beliefs. Listing 1 shows an abstract example of how we model `Data`, `Warrant`, and `Rebuttal` in an agent program.

And they can be interpreted as follows:

- `data` are facts available to an agent, and may be relevant for forming arguments supporting various different claims.
- `warrant` beliefs are information that combined with data will support a particular claim. Each warrant has a support weight for a claim. This weight can be represented in several ways, depending on how the qualify function will be implemented.
- `rebuttal` beliefs are information that discourage a claim. They also have an associated weight.

The `Claim` component is also a belief, but it is created by a plan that combines all other components and the `Qualify Function`.

5.2. Plans

The reasoning process is implemented as a plan that creates a new claim (belief) with an associated qualifier. An agent will use this plan to check all its relevant beliefs (data, warrants, and rebuttals), compute a qualifier through the qualify function, and create a claim. A template of the code for this reasoning process can be seen in Listing 2.

In Listing 2, `.findall()` is an internal action of Jason that builds a list of all instantiations of a term that make the query a logical consequence of the agent's belief base. Also, `.qualifyFunction()` is a function to compute the strength value of the claim. As mentioned before, the `qualify` function can be implemented as required for each application. An example is presented below.

It is important to mention that this is a preliminary implementation aimed to test the mechanism based on Toulmin's model. There are several improvements that can be done in future work. For example, one possible future direction is to use separate Jason modules for each claim the agent may need to make.

5.3. The Qualify Function

The Qualify Function (QF) is a function that returns the strength of confidence on a claim. In this work, each warrant or rebuttal has an associated weight value between 0.0 and 1.0 for a certain claim. The value of these weights increases according to the level of certainty that the warrants and the rebuttals influence the claim with which they are associated.

As described above, the qualify function receives three inputs: Data (D), Warrants (W), and Rebuttals (R). It then computes a symbolic value:

"$CertainlyNot$", "$Hardly$", "$Maybe$", "$Presumably$", "$Certainly$".

In this function, the first step is to select only warrants and rebuttals matching the data. In other words, some data must correspond to a warrant or a rebuttal for it to be considered valid. There may be any number of valid warrants and rebuttals.

If there is any data that matches warrants and/or rebuttals with maximum weights (1.0), the qualify function will consider only the warrant and/or rebuttal with that weight, as shown in Equation (1).

$$QF(D,W,R) = \begin{cases} 1.0 & \text{if } \exists(Warrant \text{ with } Weight = 1.0) \\ 0 & \text{if } \exists(Rebuttal \text{ with } Weight = 1.0) \\ 0.5 & \text{if } \exists(Warrant \text{ with } Weight = 1.0) \\ & \quad \text{and } \exists(Rebuttal \text{ with } Weight = 1.0) \\ QF'(D,W,R) & \text{otherwise} \end{cases} \tag{1}$$

If there is any input data that matches a warrant with value 1.0, the confidence value that qualifies the claim will also be 1.0, generating a symbolic qualifier of "Certainly". The symbolic qualifiers are explained below. If there is any data that matches a rebuttal with weight 1.0, the confidence value that qualifies the claim will be 0, generating a symbolic qualifier of "Certainly not" for the claim. However, if there is data matching both warrants and rebuttals with values 1.0, this results in a confidence of 0.5, generating a symbolic qualifier of "Maybe" for the claim, because the agent should be completely ambivalent about it.

Otherwise, QF' is computed; to do so, the Sum of the Weights of the Warrants (SWW) is computed, as well as the Sum of the Weights of the Rebuttals (SWR), according to Equations (2) and (3) respectively.

$$SWW = \sum_{i=1}^{nvw} WW_i \tag{2}$$

$$SWR = \sum_{i=1}^{nvr} WR_i \tag{3}$$

In Equation (2), nvw stands for the number of valid warrants and (WW_i) is the weight of each valid warrant (as mentioned before, valid here means that it matches some data). Equation (3) does the same as Equation (2), but summing over the data matching the set of rebuttals. In Equation (3), nvr stands for the number of valid rebuttals and WR_i is the weight of each valid rebuttal.

An intermediate value is generated by a function q which, subsequent to the computing of the sums of weights, normalizes those values and subtracts $SWR_{normalized}$ from $SWW_{normalized}$, as shown in Equation (4).

$$q(D,W,R) = SWW_{normalized} - SWR_{normalized} \tag{4}$$

After calculating q according to Equation (4), QF' is computed using Equation (5), which is the final numeric confidence level on the claim.

$$QF'(D,W,R) = \begin{cases} q(D,W,R) & \text{if } SWW > SWR \\ 1 - |\, q(D,W,R) \,| & \text{if } SWR > SWW \end{cases} \tag{5}$$

The qualify function (QF) above determines a numeric confidence level for a claim as a value between 0.0 and 1.0. To be easily interpreted, this numerical value is mapped into a symbolic value accordingly to the following rules:

- $[0, 0.2) \rightarrow$ "Certainly not";
- $[0.2, 0.4) \rightarrow$ "Hardly";
- $[0.4, 0.6] \rightarrow$ "Maybe";
- $(0.6, 0.8] \rightarrow$ "Presumably";
- $(0.8, 1.0] \rightarrow$ "Certainly".

6. Case studies

This section presents two case studies used to evaluate the proposed reasoning mechanism based on Toulmin's model. The first case study, in Section 6.1, shows how an agent is able to use the argumentation-based inference mechanism in order to reason about a person's nationality. This example is originally proposed by Toulmin.

Table 2
Case study – Paul's nationality.

Component	Information
Data	Paul lives in Rio Grande do Sul. Paul's parents are Brazilian. Paul's wife was born in Rio Grande do Sul. Paul has a sister who lives in London. Paul has a Brazilian son. Paul works in Rio Grande do Sul. Paul studied in London.
Warrants	Paul was born in Rio Grande do Sul, 1.0. Paul lives in Rio Grande do Sul, 0.2. Paul's parents are Brazilian, 0.2. Paul has a Brazilian son, 0.3. Paul works in Rio Grande do Sul, 0.2. Paul's wife was born in Rio Grande do Sul, 0.1. Paul has a sister who lives in Rio Grande do Sul, 0.2.
Rebuttals	Paul was born in London, 1.0. Paul lives in London, 0.2. Paul's wife was born in London, 0.1. Paul has a sister who lives in London, 0.2. Paul studied in London, 0.1.

The second case study, in Section 6.2, shows how an agent can be implemented, using the argumentation-based inference mechanism, in order to classify the risk of patients with dengue diseases.

6.1. First case study – determining nationality

This case study was adapted from [23] and aims to answer whether a person named Paul is Brazilian or not. In the study, the warrants act as supporters of the claim "*Paul is Brazilian*" and the rebuttals act to reduce the confidence of the claim. Table 2 presents the data, warrants, and rebuttals used in this case study, and Listing 3 shows the code in AgentSpeak of the information contained in Table 2.

In Table 2, there are five warrants and two rebuttals matching the data. Therefore, they are the only values used to generate the qualifier.

The first step in the qualify function is to check for data that matches a maximum weight warrant and/or rebuttal. In this case, there is none, so the qualify function computes the sum of the valid warrants and rebuttals:

$$SWW = (0.2 + 0.2 + 0.3 + 0.2 + 0.1) = 1.0$$

$$SWR = (0.2 + 0.1) = 0.3$$

Subsequently, Equation (4) is applied using the normalized values of SWW and SWR:

$$q = (1.0 - 0.3) = 0.7$$

After the calculation of Equation (4), QF is computed using Equation (5), which is the final confidence level of the claim.

$$QF = q = 0.7 \qquad \text{because } SWW > SWR.$$

In this example, QF has value 0.7. This value is between 0.6 and 0.8, thus the symbolic qualifier for the claim is "Presumably".

If we have the same warrants and rebuttals, but different data, the QF value would be different, and the symbolic qualifier for the claim could be different too. For example:

- If the agent believes that "Paul was born in Rio Grande do Sul", the symbolic qualifier would be "Certainly", since data "Paul was born in Rio Grande do Sul" matches a maximum weight warrant.
- If the agent believes that "Paul was born in London", the symbolic qualifier would be "Certainly not", since data "Paul was born in London" matches a maximum weight rebuttal.
- If the agents believe that "Paul's wife was born in London" rather than "Paul's wife was born in Rio Grande do Sul", the symbolic qualifier would be "Maybe", since the sum of the weights of the warrants and the rebuttals would be very similar.

Listing 3 Nationality case study in AgentSpeak.

```
/* Beliefs */
data("Paul lives in Rio Grande do Sul").
data("Paul's parents are Brazilian").
data("Paul's wife was born in Rio Grande do Sul").
data("Paul has a sister who lives in London").
data("Paul has a Brazilian son").
data("Paul works in Rio Grande do Sul").
data("Paul studied in London").

warrant("Paul is Brazilian","Paul was born in Rio Grande do Sul", 1.0).
warrant("Paul is Brazilian","Paul lives in Rio Grande do Sul", 0.2).
warrant("Paul is Brazilian","Paul's parents are Brazilian", 0.2).
warrant("Paul is Brazilian","Paul has a Brazilian son", 0.3).
warrant("Paul is Brazilian","Paul works in Rio Grande do Sul", 0.2).
warrant("Paul is Brazilian","Paul's wife was born in Rio Grande do Sul", 0.1).
warrant("Paul is Brazilian","Paul has a sister who lives in
                             Rio Grande do Sul", 0.2).

rebuttal("Paul is Brazilian","Paul was born in London", 1.0).
rebuttal("Paul is Brazilian","Paul lives in London", 0.2).
rebuttal("Paul is Brazilian","Paul's wife was born in London", 0.1).
rebuttal("Paul is Brazilian","Paul has a sister who lives in London", 0.2).
rebuttal("Paul is Brazilian","Paul studied in London", 0.1).

/* Goal */
!reasoning("Paul is Brazilian").

/* Plan */
+!reasoning(Claim)
    <- .findall(data(Data), data(Data), ListData);
       .findall(warrant(Warrant,Weight),
                warrant(Claim,Warrant,Weight), ListWarrant);
       .findall(rebuttal(Rebuttal,Weight),
                rebuttal(Claim,Rebuttal,Weight), ListRebuttal);
       .qualifyFunction(ListData,  ListWarrant, ListRebuttal, Qualifier);
       +claim(Claim, Qualifier).
```

Table 3
Risk classification according to patients' signs and symptoms.

Dengue Group A	Care according to the order of arrival
Dengue Group B	Non-urgent priority
Dengue Group C	Urgency, provide care as fast as possible
Dengue Group D	Emergency, patient needs immediate care

6.2. Second case study – risk classification for patients with dengue fever

This case study aims to classify patients according to the severity of their disease, in particular dengue fever. Dengue fever is a mosquito-borne tropical disease caused by the dengue virus, and it is a major public health problem worldwide and continues to increase in incidence [30]. By classifying patients according to the severity of their disease, it is possible to reduce the waiting time for health care, prioritizing those patients who require immediate care.

This case study was based on the document created by the Brazilian Ministry of Health – Department of Surveillance of Communicable Diseases [31], which indicates that a patient, when arriving in a hospital, should be classified into four levels of dengue fever severity: A, B, C, or D. Table 3 shows the risk classification for dengue fever, according to patients' signs and symptoms.

According to that document [31], the types of dengue are characterized by having the following symptoms in each group:

- Group A
  - Fever or history of acute fever, lasting 2-7 days, with two or more unspecific signs and symptoms (headache, prostration, retro-orbital pain, exanthema, myalgia, arthralgia), supportive serology or occurrence at the same location and time as other confirmed cases of dengue fever.
  - Without warning signs.

Table 4
Warrants and rebuttals – Group A.

	Group A
Warrants	Fever for more than seven days + headache and/or prostration and/or retro-orbital pain and/or rash and/or myalgias and/or arthralgias, 0.3. Absence of warning signs, 0.8. Proof of negative loop and absence of spontaneous hemorrhagic manifestations, 0.8. No comorbidities, risk group or special clinical conditions, 0.9.
Rebuttals	With spontaneous (petechial) or induced skin bleeding (positive loop test). Special clinical conditions, 0.8. Presence of any of these warning signs: severe and continuous abdominal pain; persistent vomiting; postural hypotension and/or lipothymia; hepatomegaly, painful; bleeding from the mucosa or bleeding (hematemesis and/or melena); drowsiness and/or irritability; decreased diuresis; sudden decrease in body temperature; hypothermia; sudden increase in hematocrit; abrupt platelet loss; respiratory distress, 1.0. Signs of shock, respiratory distress or severe organ dysfunction: shock; convergent arterial pressure (differential BP ≤ 20 mmHg); cold extremities, cyanosis; Weak and filiform pulse; slow capillary filling (>2 seconds); hypotension, 1.0.

  - Proof of negative bond and absence of spontaneous hemorrhagic manifestations.
  - No comorbidities, risk group, or special clinical conditions.
- Group B
  - Fever for more than seven days, accompanied by at least two nonspecific signs and symptoms (headache, prostration, retro-orbital pain, rash, myalgia, arthralgia) and compatible epidemiological history.
  - Without warning signs.
  - With spontaneous (petechial) or induced skin bleeding (positive loop test).
  - Special clinical conditions and/or social risk or comorbidities: infants (under 2 years of age), pregnant women, adults over 65 years of age, hypertension or other serious cardiovascular diseases, diabetes mellitus, chronic obstructive pulmonary disease, chronic hematological diseases (mainly anemia sickle and purpura), chronic kidney disease, peptic acid disease, liver disease and autoimmune diseases.
- Group C
  - Fever for more than seven days, accompanied by at least two nonspecific signs and symptoms (headache, prostration, retro-orbital pain, rash, myalgia, arthralgia) and compatible epidemiological history.
  - Presence of any of these warning signs:
    * severe and continuous abdominal pain;
    * persistent vomiting;
    * postural hypotension and/or lipothymia;
    * painful hepatomegaly;
    * drowsiness and/or irritability;
    * decreased diuresis;
    * sudden decrease in temperature;
    * hematemesis and/or melena;
    * sudden rise in hematocrit;
    * abrupt platelet loss;
    * respiratory discomfort.
- Group D
  - Fever for more than seven days, accompanied by at least two nonspecific signs and symptoms (headache, prostration, retroorbital pain, rash, myalgias, arthralgia) and compatible epidemiological history.
  - Signs of shock, respiratory distress or severe organ dysfunction:
    * shock;
    * convergent arterial pressure (differential BP ≤ 20 mmHg);
    * cold extremities, cyanosis;
    * Weak and filiform pulse;
    * slow capillary filling (>2 seconds)
    * hypotension.

6.2.1. Modeling

This case study is more complex than the *Nationality* case study, given that it involves more information, and it generates more claims. In this case study, we use claims for each of the above dengue severity groups.

Tables 4, 5, 6, and 7 show the model we developed for this case study, translating the information from each group to warrants and rebuttals. For example, warrants for Group A, which are not warrants for Group C, become rebuttals for Group C.

Table 5
Warrants and rebuttals – Group B.

	Group B
Warrants	Fever for more than 7 days + headache and/or prostration and/or retro-orbital pain and/or rash and/or myalgias and/or arthralgias, 0.4. With spontaneous (petechial) or induced skin bleeding (positive loop test), 0.8. Special clinical conditions, 0.9.
Rebuttals	No warning signs. 0.9. Proof of the negative loop and absence of spontaneous hemorrhagic manifestations, 0.8. No comorbidities, risk group or special clinical conditions, 0.8. Presence of any of these alarm signals: severe and continuous abdominal pain; persistent vomiting; postural hypotension and/or lipothymia; hepatomegaly, painful; bleeding from the mucosa or bleeding (hematemesis and/or melena); drowsiness and/or irritability; decreased diuresis; sudden decrease in temperature; body or hypothermia; sudden increase in hematocrit; abrupt platelet loss; respiratory distress, 1.0. Signs of shock, respiratory distress or severe organ dysfunction: shock; convergent arterial pressure (differential BP $\leq$ 20 mmHg); cold extremities, cyanosis; Weak and filiform pulse; slow capillary filling ($>$ 2 seconds); hypotension, 1.0.

Table 6
Warrants and rebuttals – Group C.

	Group C
Warrants	Fever for more than seven days + headache and/or prostration and/or retro-orbital pain and/or rash and/or myalgias and/or arthralgias, 0.2. Presence of any of these alarm signals:severe and continuous abdominal pain; persistent vomiting; postural hypotension and/or lipothymia; hepatomegaly, painful; bleeding from the mucosa or bleeding (hematemesis and/or melena); drowsiness and/or irritability; decreased diuresis; sudden decrease in temperature; body or hypothermia; sudden increase in hematocrit; abrupt platelet loss; respiratory distress, 0.9.
Rebuttals	No warning signs, 1.0. Proof of negative loop and absence of spontaneous hemorrhagic manifestations, 1.0. No comorbidities, risk group or special clinical conditions, 1.0. With spontaneous (petechial) or induced skin bleeding (positive loop test), 0.8. Special clinical conditions 0.8. Signs of shock, respiratory distress or severe organ dysfunction: shock; convergent arterial pressure (differential BP $\leq$ 20 mmHg); cold extremities, cyanosis; Weak and filiform pulse; slow capillary filling ($>$ 2 seconds); hypotension, 1.0.

Table 7
Warrants and rebuttals – Group D.

	Group D
Warrants	Fever for more than seven days + headache and/or prostration and/or retro-orbital pain and/or rash and/or myalgia and/or arthralgia), 0.2. Signs of shock, respiratory distress or severe organ dysfunction: shock; convergent arterial pressure (differential BP $\leq$ 20 mmHg); cold extremities, cyanosis; Weak and filiform pulse; slow capillary filling ($>$ 2 seconds); hypotension, 0.9.
Rebuttals	No warning signs, 1.0 Proof of negative loop and absence of spontaneous hemorrhagic manifestations, 1.0 No comorbidities, risk group or special clinical conditions, 1.0 With spontaneous (petechial) or induced skin bleeding (positive loop test), 0.8 Special clinical conditions, 0.8 Presence of any of these warning signs: severe and continuous abdominal pain; persistent vomiting; postural hypotension and/or lipothymia; hepatomegaly, painful; bleeding from the mucosa or bleeding hematemesis and/or melena); drowsiness and/or irritability; decreased diuresis; sudden decrease in body temperature; hypothermia; sudden increase in hematocrit; abrupt platelet loss; respiratory distress, 0.9

In this case study, there are four goals, and each goal will generate a claim with a strength qualifier for each group (Dengue A, B, C, and D). The implementation of this example in *AgentSpeak* language can be seen in Listing 4.

6.2.2. Results and discussion

In this section, we discuss some results of the case study on dengue fever severity classification. The goals in Listing 4 are reached through the `+!reasoning(Claim)` plan. This plan implements the practical reasoning an agent performs in order to reach the qualifier for each dengue classification. As explained in the other case study, this plan searches for all

Listing 4 Second case study – classification of dengue severity in AgentSpeak.

```
/* Beliefs */
// ...

/* Goals */
!reasoning("Dengue Group A").
!reasoning("Dengue Group B").
!reasoning("Dengue Group C").
!reasoning("Dengue Group D").

/* Plan */
+!reasoning(Claim)
  // ...
  // Exactly as in the previous case study
```

Listing 5 Excerpt of the beliefs for the "Dengue Group A" claim in AgentSpeak.

```
/* Beliefs */
...
warrant("Dengue Group A",
        "Fever for more than seven days + two symptoms", 0.2).
warrant("Dengue Group A","No warning signs", 0.2).
warrant("Dengue Group A",
        "Proof of negative loop and absence of spontaneous
        hemorrhagic manifestations", 0.4).
warrant("Dengue Group A",
        "No comorbidities, risk group, or special clinical
        conditions", 1.0).

rebuttal("Dengue Group A","With spontaneous (petechial) or induced skin
                          bleeding (positive loop test", 0.4).
rebuttal("Dengue Group A","Special clinical conditions", 0.4).
rebuttal("Dengue Group A","Presence of any warning signs", 1.0).
rebuttal("Dengue Group A","Presence of shock signals", 1.0).
...
```

data, warrant and rebuttal. Then the qualify function is applied and the claim is generated. This plan is generic and used in all applications of our argumentation approach.

However, each type of dengue has specific warrants and rebuttals. Listing 5 shows an excerpt of the information from Table 4 translated into the implemented code in *AgentSpeak*, which provides the warrants and rebuttals for an agent to generate the appropriate qualifier for "Dengue Group A", using goal `!reasoning ("Dengue Group A")`.

It is possible to see that the beliefs (warrant and rebuttal) of this class of dengue severity are described and each one has a weight. For example, the belief `rebuttal("Dengue Group A", "Presence of any warning sign", 1.0)` will completely refute that claim, i.e., the qualify function will assign value 0 ("Certainly not").

Below, we give some examples, showing how distinct outputs (symbolic qualifiers) are generated depending on the input information (data). Furthermore, in the last scenario, we show a detailed example, including the complete calculation of the qualifier.

- Data: "Fever for more than seven days + two symptoms", "Negative loop test and absence of spontaneous hemorrhagic manifestations":
  - Group A: "Certainly yes", given that the data is compatible with the warrants for this group, and there is no rebuttal matching the input data.
  - Group B: "Probably not", given that it contains some information compatible with the warrants, but the weight for the rebuttals is higher than the warrants.
  - Group C: "Certainly not", given that the rebuttals matching the data have higher weights.
  - Group D: "Certainly not", given that the rebuttals matching the data have higher weights.
- Data: signs referred to in "Presence of warning signs" (see full description in the definition of each dengue group):
  - Group A: "Certainly not", given that the rebuttals matching the data have higher weights.
  - Group B: "Certainly not", given that the rebuttals matching the data have higher weights.

- Group C: “Certainly yes”, given that the warrants matching the data have higher weights.
- Group D: “Certainly not”, given that the rebuttals matching the data have higher weights.

• Data: any signs referred to in “Presence of shock signs” (see full description in the definition of each dengue group):
  - Group A: “Certainly not”, given that the rebuttals matching the data have higher weights.
  - Group B: “Certainly not”, given that the rebuttals matching the data have higher weights.
  - Group C: “Certainly not”, given that the rebuttals matching the data have higher weights.
  - Group D: “Certainly Yes”, given that the warrants matching with data have higher weights.

• Data: “Fever for more than seven days + headache and/or prostration and/or retro-orbital pain and/or rash and/or myalgia and/or arthralgia”, “Presence of any warning signs”:
  - Group A:
    Initially, the function checks the existence of data matching warrants and/or rebuttals with maximum weight (1.0). In this group, there is one data matching a rebuttal with weight 1.0, thus the following condition is used:

$$QF = \begin{cases} 0.0 & \text{, because } \exists(Rebuttal \text{ with } Weight = 1.0) \end{cases}$$

    Therefore, the generated qualifier for this claim is “Certainly not – Dengue Group A”.
  - Group B:
    Initially, the function checks the existence of data matching the warrants and/or rebuttals with maximum weight (1.0). In this group, there is one data matching a rebuttal with weight 1.0, thus the following condition is used:

$$QF = \begin{cases} 0.0 & \text{, because } \exists(Rebuttal \text{ with } Weight = 1.0) \end{cases}$$

    Therefore, the generated qualifier for this claim is “Certainly not – Dengue Group B”.
  - Group C:
    Initially, the function checks the existence of data matching the warrants and/or rebuttals with maximum weight (1.0). In this group there are no warrants or rebuttals with maximum weight. Thus, the qualify function computes values for Equations (2) and (3):

$$SWW = (0.2 + 0.9 + 0.3) = 1.4$$
$$SWR = (0.0) = 0.0$$

    Afterwards, it applies Equation (4) with the normalized values of SWW and SWR.

$$q = (1.0 - 0.0) = 1.0$$

    Then QF is computed, representing the confidence value for that particular claim, based on the conditions presented in Section 4.

$$QF = q = 1 \qquad \text{because } SWW > SWR$$

    For this particular case, QF has a value of 1.0, given that the data matching the warrants, which support the claim, have high weights. Considering that the value of QF is in the interval between 0.8 and 1.0, the generated qualifier for this claim is “Certainly yes – Dengue Group C”.
  - Group D:
    Initially, the function checks the existence of data matching the warrants and/or rebuttals with max weight (1.0). In this group, there are no warrants or rebuttals with maximum weight. Thus, the qualify function computes Equations (2) and (3):

$$SWW = (0.2 + 0.3) = 0.5$$
$$SWR = (0.9) = 0.9$$

    Afterwards, it computes Equation (4) with the normalized values of SWW and SWR.

$$q = (0.55 - 1.0) = -0.45$$

    After the calculation using Equation (4), QF is generated, representing the confidence value for that particular claim, based on the conditions presented in Section 4.

$$QF = 1 - |q| = 1 - |-0.45| = 0.55 \qquad \text{because } SWR > SWW$$

    For this particular case, QF has a value of 0.55, given that the warrants and rebuttals matching the data have similar weights. Considering that the QF value is in the interval between 0.4 and 0.6, the generated qualifier for this claim is “Maybe – Dengue Group D”.

7. Related work

This work proposes a new approach for argumentation-based reasoning in BDI agents. Different approaches to argumentation-based reasoning can be found in the literature, for example [3,32,11,13,12,33,34,17,16,18,19,35]. None of them is based on Toulmin's Model of Argumentation. This model is interesting because it decomposes an argument into components, detailing the reasoning and thereby facilitating its explanation.

The work presented in [17] uses a practical approach for the construction of argumentative BDI agents and is based on the abstract framework of [1], which is used to develop a module to be integrated into the Jason platform. The author has developed a module that is decoupled from the traditional BDI model since it only operates on the beliefs of agents and there is no interference in the execution of plans, goal adoption, or agent commitments. The main objective of that paper is to allow the agents to query the argumentation module to obtain suggestions for attacks or justifications based on arguments for accepted or rejected beliefs.

In [18,16], the authors have developed an argumentation-based reasoning mechanism in an agent-oriented programming language, which has its properties defined according to the BDI model. The argument-based mechanism developed by the author has its foundation in the mechanism of defeasible logic and enables agents to reason about uncertainty and to argue to support their claims by exchanging messages with other agents. The authors used the AgentSpeak language to implement their approach.

In [19], the authors presented the implementation of an argumentation system for participatory management of protected environmental areas, specifically modeling a park management agent. This implementation was based on the BDI architecture, using the AgentSpeak language. The authors modeled an argumentation system through different layers in the knowledge base and the relation of attacks between arguments, in order to generate a basis for selecting more viable arguments. The authors present a case study where the proposed architecture was tested, modeling a park management agent in a serious game for participatory management of protected areas. The park management agent aims to make decisions about conservation types by examining and arguing about the situation and issues of the protected area.

Compared with our work, other recent work on argumentation, such as [21,22], have different approaches. In [21], it was introduced a new argumentation-based formalism called Statement Graph that represents rule applications as "statements" with attack and support relations (i.e., edges) between them. The authors analyzed different variants of defeasible reasoning (ambiguity propagating or blocking with or without team defeat) for argumentation. However, that work did not consider BDI agents, although the authors claim that the approach is generic.

In the work of [22], a sequent-based argumentation framework is defined with modular formalisms for representing arguments and reasoning. It could be used on different kinds of languages and logics, it also could be used to model different kinds of attacks. According to the authors, once the priorities have been decided, different orders may be defined for making preferences among the underlying arguments. Again, the BDI architecture is not used.

In [20], the authors introduced an approach for single-agent decision making based on the Dynamic Argumentation Framework [36], which is a specialization of Dung's argumentation framework [1] to handle evidence that changes dynamically. In that work, conclusions are supported by warranted arguments that are constructed using a set of evidences that support those particular conclusions. Then, those arguments are used by agents to make decisions. An interesting idea from [20] is that the evidence can change dynamically, which means arguments are dynamically activated, defining a set of the so-called working arguments. Although the decision component from [20] has similar components to the Toulmin's model, in which the authors use warranted conclusions from a dynamic argumentation framework as precondition and constraints for decision rules that agents use to make decisions, they are conceptually different. While in [20] the authors proposed an approach in which agents use arguments (their conclusions) to support their decision making, which is part of their practical reasoning, we propose an approach for argumentation-based reasoning based on the Toulmin's model, which allows agents evaluating a particular conclusion, which can be used as part of their theoretical or practical reasoning.

The main difference of the mechanism proposed in this paper in relation to the work in [17,18,16,19,21,22], is the use of Toulmin's model to make inferences in BDI agents, so an argument is decomposed into components, thereby facilitating its modeling and, if necessary, allowing a deeper analysis of how the reasoning was performed and, consequently, how to argue about it.

8. Conclusion

The central objective of this work was the development of an argumentation-based mechanism for reasoning in BDI agents. The proposed mechanism has its foundation on the model presented by Toulmin, which decomposes an argument in various components. The mechanism enables not only the generation of claims, but it also qualifies the level of confidence of a claim.

The advantage of using the developed mechanism is to allow a modular analysis of an argument, making it possible to analyze each component of the mechanism separately. In this way, it becomes possible to check which argument had a determinant weight in a conclusion. Our approach also adapts to different areas of application, given customizing features such as the qualify functions, while we maintain a fixed structure for the mechanism according to the foundations laid out by Toulmin, providing general support regardless of application area.

As future work, we intend to improve the qualify function, adding new metrics and exploring more complex functions specific for other domains. Furthermore, we hope to experimentally compare the resulting mechanism with alternative approaches to reasoning under conflicting and uncertain information. We also aim to experiment with machine learning, particularly multiagent reinforcement learning, combined with our approach, so agents can improve and adapt their reasoning and dialogue skills over time.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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