Representing Confidence in Assurance Case Evidence

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Abstract. When evaluating assurance cases, being able to capture the confidence one has in the individual evidence nodes is crucial, as these values form the foundation for determining the confidence one has in the assurance case as a whole. Human opinions are subjective, oftentimes with uncertainty—it is difficult to capture an opinion with a single probability value. Thus, we believe that a distribution best captures a human opinion such as confidence. Previous work used a doubly-truncated normal distribution or a Dempster-Shafer theory-based belief mass to represent confidence in the evidence nodes, but we argue that a beta distribution is more appropriate. The beta distribution models a variety of shapes and we believe it provides an intuitive way to represent confidence. Furthermore, there exists a duality between the beta distribution and subjective logic, which can be exploited to simplify mathematical calculations. This paper is the first to apply this duality to assurance cases.

Keywords: Opinion triangle · Beta distribtion · Subjective logic

1 Introduction

Certain safety critical systems must be demonstrated to be safe and certified or approved by some regulatory body before they are allowed to be taken into operation or sold to the general public. Typical examples are avionics software for civil aviation and complex medical devices. Developing an assurance case (of which a safety case is a subset) is one approach to documenting and demonstrating that a system has been adequately analyzed and is free from critical hazards (i.e., the system is adequately safe). The UK Ministry of Defence describes a safety case as *"A structured argument, supported by a body of evidence that provides a compelling, comprehensible and valid case that a system is safe for a given application in a given operating environment"* [1].

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For an assurance case, the confidence (and uncertainty) that the reviewers—as well as creators—have in the evidence and the case itself is crucially important; how much trust can we put in the assurance case? To address this issue, researchers have proposed different approaches. Hawkings et al. proposed the use of a separate confidence case arguing why the assurance case can be trusted [2]. Others used Bayesian (Belief) Networks (BN) where nodes representing confidence are quantified using a doubly-truncated normal distribution [3,4] that then can be used to compute the confidence in the various claims in the case. Finally, Ayoub et al. used a belief mass based on Dempster-Shafer theory [5] that can be used similarly to the truncated normal distribution mentioned above.

Although these approaches allow the exploration of confidence and uncertainty in assurance cases, we in this paper argue that there may be a more intuitive way to capture the confidence and uncertainty associated with evidence and compute the confidence and uncertainty associated with claims relying on that evidence. The beta distribution, a more versatile distribution, allows for a better representation of human opinion. The beta distribution can also be tied to the idea of subjective logic [6] to aid in the quantification of confidence. Finally, the beta distribution can be represented as a point on an opinion triangle (and vice versa) [6] to allow an alternate way of capturing and visualizing the concept of confidence and uncertainty. Like the doubly-truncated normal distribution approach, the beta distribution with subjective logic approach allows for the combination of confidence in various evidence nodes in an assurance case, ultimately arriving at the confidence in the top-level claim. We are the first to propose using the beta distribution, with its correspondence to the opinion triangle, to represent confidence in evidence and compute the resultant confidence in claims supported by this evidence in an assurance case.

The remainder of the paper is organized as follows: Sect. 2 gives relevant background information and briefly touches upon some related work. Section 3 shows, through a few examples, how subjective logic operators and the beta distribution can be used to represent confidence in assurance cases. Section 4 offers some closing thoughts and anticipated future work.

2 Background and Related Work

An assurance case is a structured logical argument. Generally, it has a top-level claim supported by evidence and the arguments that connect the two. Confidence in an assurance case can viewed as confidence of two separate components—the confidence one has in the individual evidence nodes and the confidence one has in the argumentation used to combine the evidence nodes to ultimately demonstrate the validity of a top-level claim. Hawkins et al. took a qualitative approach through the use of a separate, but associated, confidence case [2]. Previous approaches to quantification of confidence and uncertainty have used the doubly-truncated normal distribution for the nodes in a Bayesian Network (BN) [3,4] or a Dempster-Shafer theory based triple of (belief, disbelief, and uncertainty) [5,7]. Duan et al. provide a general survey that summarizes various approaches to confidence in assurance cases [8]. Whether implied or explicitly stated, calculations are prudent and can aid in assessing confidence for a top-level claim. There has been debate among law scholars (in the US) about whether or not "probable cause" can and should be quantified. Kerr argues that it should not be [9], since quantification can, ironically, lead to less accurate values. However, his argument is for the legal domain and assumes the use of a single probability value for probable cause.

Bayesian Network Approaches. A Bayesian Network (BN) or Bayesian Belief Network (BBN) is a directed acyclic graph, usually similar in structure to an assurance case. BNs provide an easy to read solution to combining qualitative and quantitative data [10]. The qualitative information is encoded in the graphical connections between nodes (links) that indicate the flow of information. The graphical connections aid in informing users how information "nodes" are connected with each other and how they may be combined during evaluation. The quantitative information is encoded in the nodes themselves. Though the nodes of a BN when used for assurance cases are usually the evidence nodes, they also can include elements that are usually found in the links of an assurance case—e.g., whether or not the arguments are well developed, or how much trust one has in the manufacturer. One possible approach to quantifying such information is through the use of a probability value. How one determines this probability value is an area of active research and a non-trivial issue.

The popular AgenaRisk software [11] quantifies the confidence of a node in an assurance case by modeling the confidence using a doubly-truncated normal distribution, truncated to the interval $[0, 1]$ [4]. This method allows for the modeling of a variety of shapes of distributions, from an (approximate) uniform distribution, to the standard Gaussian distribution, to a narrow spike, or, if the mean were near the extremes (0 or 1), a sloped shape. However, there are a couple of shapes that the truncated normal cannot approximate, such as a curve where the mean and mode are not equal (a skewed Gaussian), a true uniform distribution, or a true power distribution.

Hobbs and Lloyd use AgenaRisk to quantify and combine trustworthiness in nodes of an assurance case [12]. They use logical-OR and logical-ANDs, as well as the more realistic Noisy-OR and Noisy-AND [13], among others. Denney et al. also have looked at quantifying confidence in assurance cases with a doubly-truncated normal distribution, extending the work of Fenton and Neil [3]. Since these researchers are using AgenaRisk, they are still using the truncated normal distribution and are subject to the same limitations.

Dempster-Shafer Approaches. The Dempster-Shafer theory based approach starts with the idea of an opinion, represented by a mass. As our opinion increases positively, mass increases. This opinion can be bounded by a lower bound, belief, and an upper bound, plausibility. An opinion can fall anywhere in this range. Dempster-Shafer differs from traditional probability in that it has a separate value for uncertainty. In traditional probability, there is a view that if one has 0.8 confidence, then one has 0.2 uncertainty. Dempster-Shafer might look at this as, for example, one has 0.8 confidence, 0.1 lack of confidence, and 0.1 uncertainty, taking the view that lack of confidence is not necessarily the same thing as uncertainty. Dempster-Shafer theory also provides a variety of methods to combine evidence based on different situations. A Dempster-Shafer opinion can be applied to an evidence node in an assurance case. The methods for combining disparate evidence also can be used to combine opinions in an assurance case, ultimately arriving at an opinion for the top level claim.

Cyra and Gorski developed their own plot of opinion versus confidence based on linguistics and mapped their plot onto Jøsang's opinion triangle [7]. They used Toulmin's argumentation structure [14] to combine the confidence nodes. Their approach was adapted into a tool [15] which has been adopted by over 30 institutions in areas of healthcare, security, and public administration self-assessment standards [16].

Beta Distribution. The beta distribution is a continuous version of the binomial distribution. When one has two options (e.g., heads or tails in a coin flip, or trust or distrust for an assurance case node), the binomial distribution is generally used. When one desires a continuous distribution for the binomial distribution, the beta is used. The beta distribution has finite range, most often between 0 and 1, which makes it ideal when dealing with probabilities. The beta distribution is a second order distribution, so it is used to describe a probability of probabilities. In statistics, the beta distribution is a popular choice for prior information, due to its scalability, variety of shapes, and finite boundaries [17].

The doubly-truncated normal distribution does not allow for situations where the mean and mode are different, and only can approximate the uniform and power distributions. By using only a doubly-truncated normal distribution, previous researchers are committing themselves to the distribution of every opinion being symmetrical. For instance, if the peak of a doubly-truncated normal distribution is at 0.8, the probability of an opinion at 0.7 and 0.9 would be exactly equal. While this may be true some of the time, one cannot say it will be true all of the time. Additionally, the doubly-truncated normal distribution can never truly equal 0 at a confidence value of 100 %. In some circumstances, such as with testing, it is not realistic to ever have 100 % confidence.

Merkle represents confidence using mixtures of beta distributions [18]. His approach seeks to model confidence that has been elicited, and represents a realistic view of what real confidence values would look like. His use of a beta distribution to represent confidence supports our view of the same.

The beta distribution is not a new concept in the realm of assurance cases. Bishop et al. use it in their work [19] to represent a "typical distribution" about an expert's belief. They, however, turn their focus to estimating conservative claims about dependability.

Subjective Logic and the Opinion Triangle. In standard logic, there is either true or false, with no ambiguity. There is absolute certainty and thus probability is an appropriate measure for situations such as flipping a coin or

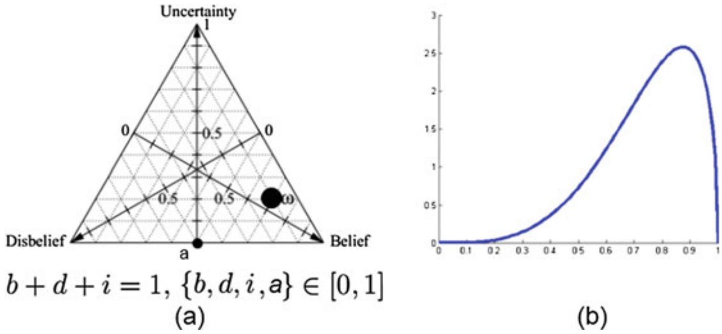

Fig. 1. Jøsang's opinion triangle

throwing a pair of dice. Jøsang argues that when humans are a factor, there is never full certainty [6]. As such, we should use subjective logic, which deals with the realm of opinions.

An opinion in subjective logic is represented by a four element tuple: belief (b), disbelief (d), uncertainty (u), and relative atomicity (a). The first three are located on the vertices of an opinion triangle (see Fig. 1(a)) and are constrained by the boundaries of that triangle and each other. The three must have values between 0 and 1 and must sum up to 1. The relative atomicity, representing the *a priori* belief, is a known quantity with no uncertainty, so it is bounded to the base of the triangle. In Fig. 1(a), the opinion is $(0.7, 0.1, 0.2, 0.5)$. Jøsang's work offers a direct mapping between his opinion triangle and the beta distribution, making it appropriate for use in assurance cases [6]. In Fig. 1(b), we see an example of how the opinion in Fig. 1(a) would be represented by a beta distribution. When one has multiple opinions, one can combine them in a variety of ways using addition, multiple, and subtraction.

Jøsang has continued working on and expanding the uses of subjective logic, but not in the assurance case area. Specifically, he has looked at multi-nomial opinions via the Dirichlet distribution [20], trust networks using subjective logic [21], and, with Whitby, reputation systems using the beta distribution [22]. Ettler and Dedecius apply subjective logic to a hierarchical model derived from a condition monitoring system [23]. The hierarchical model has a structure similar to assurance cases and consists of similar components—leaf nodes that can be evaluated and combined to ultimately arrive at the top level. How their work continues will be of interest to us as the two areas share some commonalities. Han et al. use subjective logic and the beta distribution to fuse evidence that has a subjective bias or uncertainty [24]. Their work, though not related to assurance cases, represents another use for subjective logic and the beta distribution.

3 Application to Assurance Cases

Jøsang's subjective logic deals with opinions held by a person. We argue that a person's level of confidence can be viewed as an opinion, and thus Jøsang's opinion triangle is an appropriate way of representing the confidence one has in an evidence node of an assurance case. Jøsang provides a direct, easy, and intuitive mapping from the opinion triangle to the beta distribution, as well as multiple operators for combining opinions based on different situations.

Subjective logic intuitively makes more sense than standard logic when one is describing human opinions. The idea of uncertainty being a separate entity in subjective logic, different from belief and disbelief, is also intuitively appealing. A logical question would be—what does full uncertainty mean? One could answer "knowing nothing." One also could answer "being fully split between two options." Both might be viewed as full uncertainty. Jøsang specifies a difference. The former would be represented by an opinion of $(0.0, 0.0, 1.0)$, meaning one has no opinion whatsoever. For an assurance case, we can think of this as a situation where a reviewer has no experience or knowledge of anything—a completely blank slate. This opinion would be represented as $beta(1.0, 1.0)$, a uniform distribution where every value is equally likely. The latter would be represented by an opinion of $(0, 5, 0.5, 0.0)$, or having exactly equal arguments for both belief and disbelief. For an assurance case, we can think of having exactly equal and opposite information to contribute to a split opinion. This opinion would be represented in a beta distribution with a spike, or discontinuity, at 0.5. Such an example highlights exactly the importance of treating uncertainty—the lack of information—as a separate entity. Cyra and Gorski took the view that when one has high uncertainty, no decision can be made [7]. When one has high disbelief, one can reject a piece of evidence. But when there is high uncertainty, that uncertainty can be belief or disbelief. As such, no action can or should be taken.

Realistically, though, it is unlikely that either opinion will exist in the real world, which is part of the appeal of using a distribution, specifically the beta distribution, to represent confidence. The beta distribution can accommodate a variety of shapes (Fig. 2) while Jøsang's work ties the beta distribution into subjective logic. For future work, operators in subjective logic then can be used and represented as a beta distribution. The beta distribution parameters also can be used and manipulated to better represent confidence.

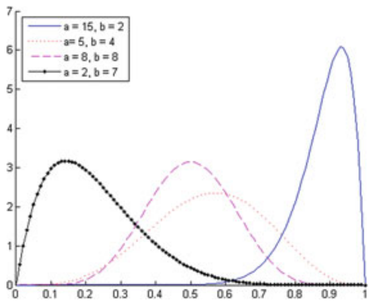

Fig. 2. Sample beta distribution shapes

3.1 Node Example

Elicitation of opinions from domain experts is still an active area of research. It is our view that distributions should be used when representing confidence instead of a single probability value. Human opinion is subjective in nature, and fraught with uncertainty. A single probability value cannot be expected to encompass all the nuances that comprise an opinion. Thus, a distribution more accurately represents a person's beliefs. A distribution models a probability of probabilities—at each confidence value, what is the probability that this confidence value is the one true confidence value for this person? When there is no uncertainty, we have a single value. When we have uncertainty, we have a distribution.

It makes intuitive sense to be able to provide an opinion triangle and have an expert simply point to where his/her opinion lies on such a triangle. This opinion then can be mapped onto a beta distribution to confirm that the distribution is an accurate representation of their opinion. Going in the other direction is possible with the aid of a parameter finder/best-fit program for the beta distribution. An expert can be asked to draw out a plot that best represents their opinion, and this plot then can be mapped onto the opinion triangle to see if it matches up to what the expert expected.

Suppose we want to quantify the confidence for an evidence node, specifically, software testing results. The software has been tested (and the test passed) by two different companies to the same test adequacy criterion, such as MC/DC [25]. This criterion is rigorous, but not perfect, so intuitively one expects the "peak" of the beta distribution to be fairly high, for example, around 0.8. The standard of testing, in this case, would affect where the peak belief or disbelief would be; however, the companies themselves would affect the variance of the distribution. Company A has documented and accounted for all of their testing meticulously, and has communicated all information clearly. Company B has had poor documentation and communication, increasing our uncertainty in their work. So intuitively, we would expect the beta distribution representations of our confidence in these companies' testing to have similar peaks, but one has a wider spread than the other. A sample plot is seen in Fig. 3—Company A's distribution is represented with a "–o" line while Company B's distribution is represented with a "–+" line. The two curves have peaks approximately at the same confidence value, as we would expect since both companies have tested to the same criterion; however, Company B's plot has a lower peak value and a higher variance due to the higher uncertainty we have in their testing.

3.2 Assurance Example

Figure 4 shows a sample assurance case, in GSN notation, based on an x-ray backscattering machine that might be used at an airport. For illustrative and clarity purposes, this assurance case is extremely simple.

We have a top-level claim that all causes of overradiation have been eliminated. For purposes of this example, "all causes" is actually just two causes—software errors and timer interlock errors. Each cause of overradiation has two

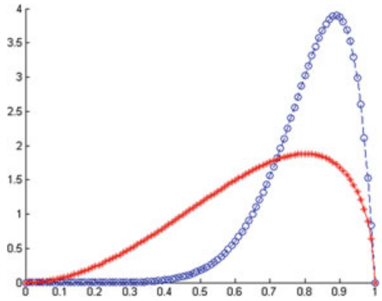

Fig. 3. Confidence distribution for two testing companies

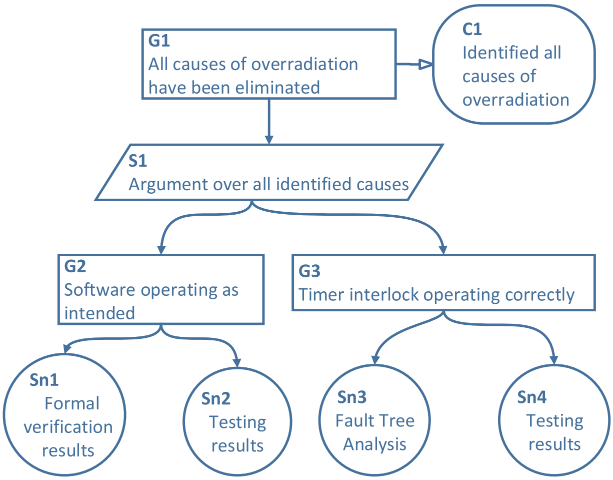

Fig. 4. Example assurance case

supporting evidence nodes. In Fig. 5, the assurance case has been modified to a fault tree analysis-based format to represent how the components could be combined via subjective logic operators in an intuitive way. Since we are dealing with *opinions* on nodes, the most appropriate operator for combining evidence is the consensus operator. Though testing results for the timer interlock or software are empirical, there are always external factors that can affect an opinion on the specific evidence node as mentioned in the previous section. When to use the empirical data by itself, versus an opinion on the result itself, will be the subject of a future work. The consensus operator for two opinions $\pi^A = b^A, d^A, u^A$ and $\pi^B = b^B, d^B, u^B$ is:

$$b^{A,B} = \frac{(b^A u^B + b^B u^A)}{\kappa},\ d^{A,B} = \frac{(d^A u^B + d^B u^A)}{\kappa},\ u^{A,B} = \frac{(u^A u^B)}{\kappa}$$

where $\kappa = u^A + u^B - u^A u^B$ such that $\kappa \neq 0$ [6]

After applying the consensus operator to an individual's opinion about the evidence nodes, we receive an intermediary opinion about whether or not

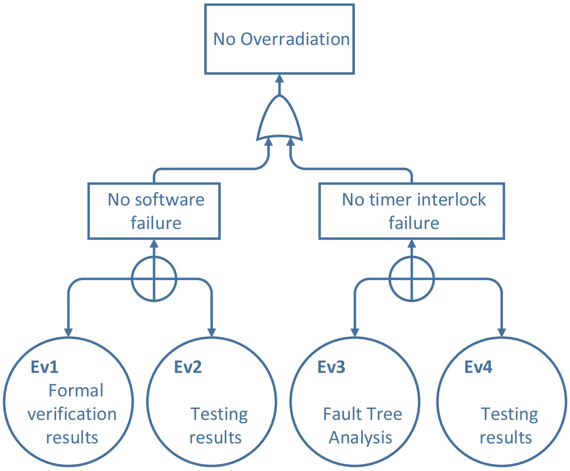

Fig. 5. Logical argument for example assurance case

software or timer components will fail. We use the logical-OR operator on our intermediary opinions to arrive at a final opinion about the claim. For overradiation to occur in a x-ray backscattering machine, both the software and the timer interlock needs to fail. Thus, for no overradiation to occur, just one of the two components needs to operate correctly—a logical-OR relationship. Such a redundancy system necessarily increases our confidence in the top level claim.

From this logical argument, the next step is to assign opinion values to the evidence nodes. There has been considerable research into the elicitation of opinions, as seen in works by Renooji [26], Druzdel and van der Gaag [10], O'Hagan [27], and van der Gaag et al. [28], but it is beyond the scope of this work to address such issues in detail. Instead, we have assigned personal opinions based on an informal survey of experts and what would give interesting and informative results (Table 1). With no prior information of any type, the relative atomicity of all nodes will be 0.5. The opinions are then mapped to their equivalent beta values based on Jøsang's work.

Table 1. Opinion and corresponding beta values.

Software Node	Opinion Values	Beta Parameters
Ev1 - Formal Verification	$\pi(0.7, 0.2, 0.1)$	$\alpha = 8.0, \beta = 2.0$
Ev2 - Testing	$\pi(0.5, 0.2, 0.3)$	$\alpha = 2.67, \beta = 1.67$
Hardware Node		
Ev3 - Fault Tree Analysis	$\pi(0.3, 0.5, 0.2)$	$\alpha = 2.5, \beta = 3.5$
Ev4 - Testing	$\pi(0.9, 0.05, 0.05)$	$\alpha = 19, \beta = 2$

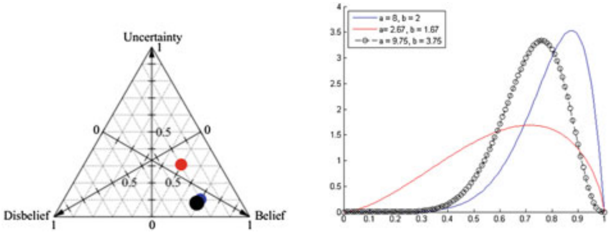

Fig. 6. Opinion triangle and beta distribution showing software node consensus

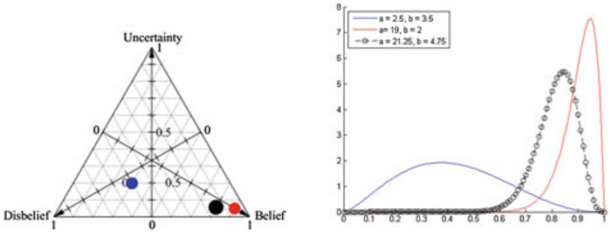

Fig. 7. Opinion triangle and beta distribution showing hardware node consensus

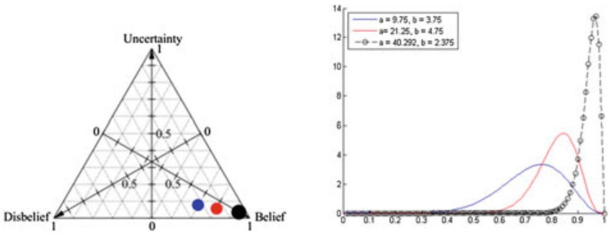

Fig. 8. Opinion triangle and beta distribution showing logical-OR for overradiation node

Figure 6 shows the opinion triangle and beta distributions for the two pieces of evidence that support the software node (Ev1 and Ev2) and the consensus of their opinions. The two smaller dots, in red and blue, represent the two opinions on Ev1 and Ev2. The larger black dot (partially covering the blue dot) represents the consensus opinion. Similarly, the red and blue lines represent the corresponding beta distribution of the opinions, while the black circled line represents the consensus beta distribution.

Figure 7 shows the opinion triangle and beta distributions for the two pieces of evidence that support the hardware node (Ev3 and Ev4) and the consensus of their opinions. Lastly, Fig. 8 shows the opinion triangle and beta distributions for logical-OR opinion of the two sub-claims—or the expected confidence for the no overradiation claim.

4 Conclusions

The use of a distribution to represent confidence in assurance cases makes intuitive sense and we claim that the beta distribution is the most appropriate one to use. The beta distribution can assume a variety of shapes and exists only on a finite range. The non-trivial mathematics that typically is associated with the beta distribution are eliminated with the use of Jøsang's subjective logic that maps the beta distribution onto an opinion triangle. The opinion triangle is not a new concept to assurance cases, but it is used in a new context here; additionally, it can be an alternative way of eliciting opinions.

We believe that such a novel use of subjective logic and the beta distribution to represent confidence will be of great benefit to assurance case evaluation and review. The next step is to explore more in depth how to combine different confidence values. We have started some of the work here with the use of the consensus and logical-OR operator, but there are many more situations and many more operators that can and will need to be used. Additionally, while subjective logic has provided a variety of operators that have been well thought out already, the assurance case domain is unique and a "pre-made" operator might not fit what we need. Such situations will need to be examined in future work.

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