Abstract – This paper proposes a discussion on the role of uncertainty in situation analysis. An overview of the principal typologies of uncertainty found in the recent literature is presented. This wide array of uncertainty conceptions is a consequence of the intrinsic richness and ambiguity of natural language, but also a consequence of the complex physical nature of information. Definitions of a limited number of concepts are proposed in order to better understand the different facets of uncertainty. The benefits sought are: (1) the avoidance of untimely uses of definitions and models of uncertainty, (2) clarifications allowing links with the already well developed logics of knowledge and belief, and (3) guidelines for the selection of the appropriate mathematical model to process uncertainty-based information.

Keywords: Uncertainty, typologies, knowledge, belief, situation analysis.

1 Introduction

This paper proposes a discussion on the role of uncertainty in situation analysis. An overview of the principal typologies of uncertainty found in the recent literature is presented. This wide array of uncertainty conceptions is a consequence of the intrinsic richness and ambiguity of natural language, but also a consequence of the complex physical nature of information. Definitions of a limited number of concepts are proposed in order to better understand the different facets of uncertainty. The benefits sought are: (1) the avoidance of untimely uses of definitions and models of uncertainty, (2) clarifications allowing links with the already well developed logics of knowledge and belief, and (3) guidelines for the selection of the appropriate mathematical model to process uncertainty-based information.

In section 2 we present definitions of situation awareness and situation analysis, cite the main applications and discuss the role of uncertainty in the situation analysis process. Section 3 is dedicated to the critical analysis general definitions, typologies and models proposed by some authors working in artificial intelligence and engineering areas. In section 4, we summarize the main facets of uncertainty based on four items of particular interest (meanings, epistemic interpretations, types and mathematical representations) highlighted in the previous section. We conclude in section 5 with some recommendations and guidelines for future works on uncertainty processing in Situation Analysis.

2 Situation Analysis

2.1 Definitions

In this section we propose definitions found in the recent literature, in order to clarify concepts and circumscribe the scope of this paper.

Situation awareness - For Endsley [5], situation awareness (SAW) is a knowledge state involving the perception, the comprehension and the projection of the situation elements. SAW is defined in [20] as “the active mental representation of the status of current cognitive functions activated in the cognitive system in the context of achieving the goals of a specific task”.

Situation analysis - Roy [15] defines Situation Analysis (SA) as “a process, the examination of a situation, its elements, and their relations, to provide and maintain a product, i.e. a state of SAW for the decision maker”. For a given situation the SA process creates and maintains a mental representation of the situation.

Situation model - The SA process relies on the integration of internal and external representations of the situation. Internal representations model the awareness of the process about itself, while external representations cope with awareness about the environment. The situation model represents the elements of the situation and their relationships in order to help a given system in a problem-solving situation to grasp the situation. A complete situation model must take into account the following tasks of [15]: A. Situation perception composed of Situation Element Acquisi-

2.2 Main applications

There are many applications to SA. Endsley [5] recalls that the interest for this field of research is not new, since it can be traced back to Clausewitz’s four main frictions and WWI aircraft aces performances. If in the recent area the domain of fighter aircraft was chiefly concerned with SA, the interest for this topic grew in fields where complex systems operate in close interaction with humans, such as: Vehicle driving, human-machine interfaces, weather monitoring, medicine, emergency fleet management, nuclear power plant operation, natural language processing, database theory, counter-terrorism, and battlefield management systems. References for these applications are given in [12].

2.3 Situation Analysis and uncertainty

Situation Analysis is the process of reaching Situation Awareness. Since situation awareness is a state of knowledge, in situation analysis the different tasks involved aim all at providing the observer with a state of knowledge about the situation (and its elements) such that he/she will be able to act, take decisions. Among the different tasks carried out by this process, the analysis of belief plays a central role. In the different subprocesses leading to belief (perception, consciousness, testimony, memory, reasoning) [1], uncertainty appears as an unavoidable feature showing many facets (meanings, types, interpretations, mathematical theories).

The methods for modeling and processing uncertainty naturally differ from one scientific community to another. For example concerning perception, probability theory is adopted by most of electrical engineers. In the case of reasoning, logical approaches are rather used by the artificial intelligence community (logical AI), philosophers and logicians. Testimony is associated with the notion of credibility which can be modeled by evidence theory [16] in legal studies.

Consequently, in a situation analysis context, the need for manipulation of numerous theoretical frameworks of different natures rapidly becomes a problem. Traditionally, this problem is tackled using two means: (1) A first approach consists in making the different theoretical frameworks “communicate” between each other. For example within the same system of SA, one module can process information using probability theory whereas another parallel (or serial) module can use fuzzy set theory. The difficulty becomes then to define algebraical transformations such that the modules can coherently communicate. (2) A second approach aims at using “general” frameworks, and two tendencies appear then: (2-a) Use a single formalism, such as random sets theory for quantitative information or autoepistemic logic for logical information. (2-b) Directly process two conceptually distinct pieces of information through a single formalism. This latter approach is proposed in [6] using modal logics and possible worlds semantics to reason on both knowledge and uncertainty. A related approach defines a semantics based on the random worlds in order to integrate statistical data processing and reasoning on knowledge [2]. Therefore, as outlined by several authors including Pearl [14] “Extensional (syntactic) systems are computationally convenient but semantically sloppy, while intensional (semantic) systems are semantically clear but computationally clumsy.” It seems, that much of difficulty encountered in the formalization of approaches dealing with computation and reasoning under uncertainty lie in the reconciliation of the syntactic and semantic aspects of the problem.

Another category of problems arise when dealing with uncertainty in distributed systems, which corresponds to the general case of SA. A classical example in epistemic logic is the problem of the coordinated attack [6]. Indeed, this problem has no solution unless an amount of uncertainty is voluntarily introduced in the system. Intentional introduction of uncertainty is also useful in order to reduce the scope of investigation or perception and thus focus on a specific area. One voluntary accept to ignore anything appearing outside this area and that seems to be a basic operation in SA. An example of a logical formal framework based on the use of such awareness operator is given in [7]. This corresponds to Bronner’s situation of type III (section 3.2).

Dynamic systems where information must be updated yield another class of problems. Information or knowledge updating is a task corresponding more or less to the level 4 of the JDL data fusion model. Very often in SA a conclusion previously accepted must be debated in the light of new evidence. Having this capability, an agent could be allowed to reason more safely on incomplete information since untimely conclusions could be withdrawn. A general framework allowing such defeasible reasoning capabilities is provided by nonmonotonic logics.

These problems should be addressed by the situation analysis community. However, uncertainty in itself appears naturally differ from one scienti-
3 What is uncertainty?

Uncertainty is a widely used term in the artificial intelligence and engineering communities. However, the authors in these fields of application and research do not always agree on the meaning of uncertainty, on its different types, on the possible sources, on the synonyms, on possible classifications, on representations, … In this paper, we would like to clarify the concept of uncertainty and related concepts such as imperfection, imprecision, vagueness, ambiguity, incompleteness, ignorance, …

Through a review of the main typologies proposed in the literature, we access the problems regarding the different types of uncertainty, the different epistemic interpretations, the different mathematical representations, and this in order to better understand and use the existing mathematical formalisms for reasoning under uncertainty. We start with general definitions of uncertainty, as well as a sociological point of view (G. Bronner [4]), before describing different visions of uncertainty over the fifteen last years, by some authors working in the artificial intelligence and engineering areas: M. Smithson [18], P. Krause and D. Clark [11], B. Bouchon-Meunier and H. T. Nguyen [3], G. Klir [10] and P. Smets [17].

3.1 General definition

Uncertainty has two main meanings in most of the classical dictionaries:

**Meaning I** Uncertainty as a state of mind;

**Meaning II** Uncertainty as a physical property of information.

The first meaning refers to the state of mind of an agent, which does not possess the needed information or knowledge to make a decision; the agent is in a state of uncertainty: “I’m not sure that this object is a table”. The second meaning refers to a physical property, representing the limitation of perception systems: “The length of this table is uncertain”. In theories of uncertain reasoning, uncertainty is often described as imperfection of information, as errors on measures for example, and does not depend on any kind of state of mind. However, an uncertain information (meaning II) can induce some uncertainty in our mind (meaning I).

3.2 Bronner’s sociological point of view

As a sociologist, Gérald Bronner [4] considers uncertainty as a state of mind, this state depending on our power on the uncertainty, and our capacity to avoid it. He distinguishes two types of uncertainty: *uncertainty in finality* (or material uncertainty) and *uncertainty of sense*. Uncertainty in finality is “the state of an individual that, wanting to fulfill a desire, is confronted with the open field of the possibles” (ex.: Will my car start?). Whereas uncertainty of sense is “the state of an individual when a part, or the whole of its systems of representation is deteriorated or can be”. Uncertainty in finality corresponds to the uncertainty which lies our understanding of the world, while uncertainty of sense bears on the representation of the world. Bronner classifies uncertainty in finality into three types, according to one’s power on uncertainty, and the capacity to avoid it:

- Situation of type I: Uncertainty does not depend on the agent and can not be avoided;
- Situation of type II: Uncertainty does not depend on the agent but can be avoided;
- Situation of type III: Uncertainty is generated by the agent and can be avoided.

In situation analysis, agents are confronted to uncertainty of sense (data driven) from the bottom-up perspective and to uncertainty in finality (goal driven) from the top-down perspective.

3.3 Smithson’s taxonomy of ignorance

In 1989, Smithson proposed a taxonomy of ignorance where uncertainty appears as a kind of ignorance, indeed “one of the most manageable kinds of ignorance” [18]. This taxonomy is reproduced on figure 1. Smithson [18] separates ignorance in two categories: the state of ignorance (error) and the act of ignoring (irrelevance). The latter corresponds to a deliberate action to ignore something irrelevant to the problem-solving situation, whereas the first category is a state (of ignorance) resulting from different causes (distorted or incomplete knowledge). For Smithson, uncertainty is incompleteness in degree (compared to absence which is incompleteness in kind), and is subdivided into three types: probability, vagueness (being either non-specificity or fuzziness) and ambiguity.

Uncertainty as a state of mind corresponds to ignorance in Smithson’s hierarchy, while Smithson’s concept of uncertainty corresponds to Klir’s uncertainty-based information concept (see section 3.6).

Smithson’s taxonomy could be an interesting guide for SA since it accounts for different levels of processing, from
physical property of information (uncertainty) to mental state (ignorance).

3.4 Krause and Clark’s uncertainty classification

In 1993, Krause and Clark [11] proposed an alternative typology to Smithson’s, centered on the concept of uncertainty. Krause and Clark distinguish two aspects: unary (i.e. uncertainty applied to individual propositions) and set theoretic (i.e. uncertainty applied to sets of propositions). Both categories lead either to conflict (conflicting knowledge) or ignorance (lack of knowledge). As subcategories, we find vagueness, confidence, propensity, equivocation, ambiguity, anomaly, inconsistency, incompleteness and irrelevance. This model is reproduced in figure 2. Compared to Smithson’s taxonomy, Krause and Clark added the unary/set theoretic dichotomy, in order to introduce the concept of inconsistency and to remove the concept of incompleteness from the unary branch to the set theoretic one.

Krause and Clark’s classification concerns meaning II of uncertainty from a formal point of view since the distinction is based on propositions. This approach is a straightforward way to process propositional belief, a concept central to SA.

3.5 Bouchon-Meunier and Nguyen’s model

In 1996, Bouchon-Meunier and Nguyen [3], proposed a model for uncertainty (figure 3). They refer to uncertainty as “imperfection on knowledge” and denote then three main types of imperfection: (1) Probabilistic uncertainty, (2) Incompleteness in knowledge (belief, general laws, imprecision), (3)Vague and imprecise description. The scheme of figure 3 is a good way to make the distinction (and perhaps the link) between the two main general meanings of uncertainty. Reading the graph from right to left, uncertainty appears as a final state (of mind) possibly caused by belief, general laws, imprecision, vagueness or incompleteness. This refers to the meaning I, uncertainty as a mental state. Reading the same graph from left to right suggests that incompleteness, vagueness, etc, are types of uncertainty, and thus meaning II applies.

3.6 Klir’s types of uncertainty

The typology proposed by Klir [10] is built upon the different existing mathematical theories of uncertainty, and directly linked to measures of uncertainty (figure 4). Klir conceives information in terms of uncertainty reduction and introduces then the term of uncertainty-based information. For Klir, uncertainty can be either fuzziness or ambiguity (two types of uncertainty). Ambiguity can itself be either non-specificity or discord. These concepts can be related to some previously used in the other classifications: Fuzziness is close to vagueness, discord is a synonym of conflict, and non-specificity means principally imprecision or generality. In his typology, Klir integrates the main key terms used by Smithson (fuzziness, non-specificity, ambiguity) as well as the set theoretical aspect introduced by Krause and Clark (discord).

Klir does not mention knowledge and thus stays at a lower level of processing, i.e. at the information level. Its conception is closely related to quantitative theories of uncertainty such as probability, possibility, fuzzy sets, evidence theories, and leads to corresponding measures of uncertainty, i.e. of uncertainty-based information [10]. We think that this typology should replace Smithson’s uncertainty.
sufficiency subtree because it provides a more acceptable classification of types of uncertainty (see section 4.3 for details).

3.7 Smets’ structured thesaurus of imperfect information

Instead of a typology of uncertainty, Smets built a typology of *imperfection of information* [17] avoiding the confusion between the two meanings of uncertainty. The model proposed by Smets distinguishes three main categories of imperfect information (figure 5) [17]:

1. **Imprecision**: Related to the content of the statement - Informational property, external world, negligence - Several worlds satisfy the statement;
2. **Inconsistency**: No world satisfies the statement;
3. **Uncertainty**: Induced by a lack of information, by some imprecision - Ordering on the several worlds that satisfy the statement:

   (a) **Objective**: Property of the information;
   
   (b) **Subjective**: Property of the observer.”

Smets considers imperfection as a central term, uncertainty being a kind of imperfection. Uncertainty can be either *objective* (property of the information, i.e. meaning II) or *subjective* (property of the observer, i.e. meaning I).

![Figure 5: Adapted from Smets’ structured thesaurus on imperfection [17].](image)

4 Main facets of uncertainty

After this overview of uncertainty concepts, it appears that different facets of uncertainty are mixed and sometimes compared even if they should be discussed separately. We distinguish then four items of interest:

1. Definitions of uncertainty (I. state of mind or II. physical property of a piece of information);
2. Epistemic interpretations of uncertainty (objective vs subjective), i.e. ways of obtaining information (or measuring uncertainty) about the situation;
3. Types of uncertainty (vagueness, nonspecificity, discord);

Obviously, discussing separately these aspects does not mean that they do not interact with each other. Also, it is well known that a given mathematical theory can be more suitable than another to process a particular type of uncertainty (fuzzy sets theory for fuzziness, probability for randomness, . . . ). On the other hand, the ways uncertainty is evaluated could also guide the choice of a mathematical model (evidence theory for belief-based uncertainty, probabilities for relative-frequencist interpretation, possibilities for propensity, . . . ). The purpose of this part is not to identify all the links between different facets of uncertainty, but rather to look at uncertainty from different angles.

4.1 Definitions of uncertainty

This brief review of some authors’ interpretations of uncertainty, in conjunction with general definitions shows that there exits two main meanings in the definition of uncertainty: I. Uncertainty as a state of mind, II. Uncertainty as the feature of what can not be predicted, what can not be stated with exactness. As a sociologist, Bronner refers essentially to meaning I. However, facing the need for formalization in order to reduce uncertainty in finality, probabilities for example are used to represent a more physical state of uncertainty (meaning II). This more practical aspect of uncertainty is more effectively captured by the term of *imperfect information* (Smets), or *uncertainty-based information* (Klir). Smets’ subjective uncertainty corresponds to a person in uncertainty who provides an imperfect information (inducing uncertainty in another person’s mind). This subjectivity, we think, is merely a characterization of the source of information rather than the information itself, i.e. an epistemic interpretation.

4.2 Epistemic interpretations of uncertainty

By epistemic interpretations of uncertainty, we mean ways of obtaining uncertainty evaluations. The two main
interpretations for probabilities (objective and subjective) that emerged in the two last centuries can be extended to uncertainty in general. Indeed, uncertainty can either come from an experiment in order to apprehend the situation, historical records, or from one’s own internal representation of the situation. This thus clarifies the distinction between objectivity into empirical uncertainty and subjectivity which is inductive uncertainty as proposed by Smets in his thesaurus. This typology of interpretations of uncertainty is detailed on figure 6. On the one hand, the empirical uncertainty is divided into three categories: Classical, Relative frequencist, and Propensity. On the other hand, the inductive uncertainty is separated into two categories: Logical and Belief-based. The figure 6: Epistemic interpretations of uncertainty.

4.3 Types of uncertainty

Types of uncertainty refer to meaning II of uncertainty, to a physical property of the information. Although the taxonomy can differ from one author to the other, some key terms commonly appear: vagueness, fuzziness, non-specificity, ambiguity, conflict, probability (or randomness). Uncertainty can then be qualified by each of these terms (uncertainty due to vagueness, uncertainty due to randomness, . . .) providing the different types of uncertainty. Klir’s typology seems to be the most accepted one from a formal and quantitative point of view.

Let $\Theta$ be the finite set of all the possible outcomes for an experiment, the set of all the possible answers for a question, the set of all the possible worlds, the universe of discourse. Let $\theta$ be an element of $\Theta$ and let $A, B, \ldots$ be subsets of $\Theta$. We denote by $[\theta \in A]$ (also written $[\theta \in A]$) the proposition “object $\theta$ is in subset $A$” and look at the interaction between $\theta$, $A$ and $B$ in order to describe the different types of uncertainty.

Non-specificity - Non-specificity is sometimes referred to as imprecision, although the latter is wider. Non-specificity concerns the (crisp) subset $A$ itself. The position of $\theta$ relatively to $A$ is not questioned, and the proposition $[\theta \in A]$ is TRUE. However, the question is which of the elements of $A$, $\theta$ is. The uncertainty comes from our inability to decide among the elements of $A$, because of their non-specificity. The non-specificity increases as the cardinality of $A$ increases, and a set is fully specific (and hence the uncertainty disappears) whenever its cardinality is 1 ($A$ is a singleton $\theta$).

Vagueness - Vagueness can be taken as a synonym of fuzziness. Vagueness implies borderline cases, i.e. elements for which it is impossible to decide if they belong or not to $A$. Contrary to a classical set whose boundaries are well defined, a fuzzy set has not well defined boundaries. The question relates neither to the number of elements in $A$ nor the position of $\theta$ relatively to $A$, but rather to the degree of membership of $\theta$ to $A$. In other words, $\theta$ belongs more or less to $A$ or the proposition $[\theta \in A]$ is more or less TRUE. This type of uncertainty concerns a single set, and disappears as soon as the boundaries of $A$ are fixed crisp.

Discord - Discord is a synonym of strife, conflict, inconsistency. Discord concerns many propositions (sets) and the question does not concern directly the size of each set, but rather how they interact together. The uncertainty derives from many possibly TRUE propositions that do not agree. Randomness is a special case of discord, since two singletons are in complete discordance. Randomness - This type of uncertainty implies a punctual representation of information. The uncertainty concerns the element $\theta$ and more particularly its relative position to subset $A$: “Is $\theta$ or not in $A$?” In other words “Is the proposition $[\theta \in A]$ TRUE or FALSE?” The uncertainty comes from our inability to predict (or to establish) to position of $\theta$ (relatively to $A$) be-
cause of its randomness. This type of uncertainty is eliminated once \( \theta \) has been observed.

These three main types of uncertainty seem to be accepted by the quantitative uncertain reasoning community. They are characterizations of Klir’s uncertainty-based information, and corresponding measures of uncertainty (or information) are defined in the main mathematical theories of uncertain reasoning (probability, possibility, fuzzy sets, evidence theories) [10]. These measures can concern a single type of uncertainty or both, and many current studies tend to define general measures including the three types of uncertainty [22].

4.4 Mathematical theories of uncertainty

To model uncertainty, many mathematical tools have been developed, being either qualitative such as modal logics, nonmonotonic logics, or quantitative approaches such as probability theory, fuzzy sets theory, evidential theory. These approaches are often compared on the basis of their different strengths and weaknesses: their better suitability to model a particular type of uncertainty, their requirement for prior knowledge, their computational time complexity, the need for independence constraints, their reasoning capacities. Up to now, it appears that none of the available mathematical tools is a best choice, and it becomes more and more obvious that depending on the type of problem one is facing, one theory can impose itself as a better choice to solve this particular problem. Hence, in [21] for quantitative approaches and in [19] for qualitative approaches an extensive list of criteria is proposed as a guide for theory selection. Supporting this descriptive approach, Klir promotes an eclectic and constructivist point of view in [10] in regard with the ability of the quantitative theories to represent uncertainty: Fuzzy sets theory is well suited to deal with vague information, evidence theory has great capacity in ignorance modelization, possibility theory is appropriate for incomplete information, rough sets theory deals well with indiscernability. Klir’s point of view is acceptable when dealing with a single type of uncertainty, but it could fail whenever many types of uncertainty appear in the same problem-solving situation. One approach could be to choose a single formalism to model the different types of uncertainty. Adopting a general theoretical framework able to take many types of uncertainty into account, for example random sets theory which seems to be a good candidate for such a general framework since belief, probability, possibility functions and fuzzy sets are special cases of random sets. Another approach could be to model each type of uncertainty using the most appropriate formalism. In this case, we face the problem of how to switch from one theory to another without any significant loss of information.

Knowledge and belief analysis as well as uncertainty management are central to Situation Analysis and thus to the acquisition of Situation Awareness. We believe that a formal triad including nonmonotonic reasoning should be taken as a basis for the formalization of Situation Analysis. Moses and Shoham [13] proposed a formal connection between knowledge and belief logics on one hand and nonmonotonic logics on the other hand. In the same paper Moses and Shoham recall that Halpern [9] proposed a logical setting allowing the connection between knowledge (and belief) logics and probability theory, and that Geffner [8] and Pearl [14] made the formal connection between probability theory and nonmonotonic reasoning.

Many formalisms of nonmonotonic logic have been proposed in order to deal with uncertainty, such as default logic, autoepistemic logic, Truth Maintenance Systems. What makes nonmonotonic logics extremely interesting for Situation Analysis is that the different formalisms proposed can implement reasoning under uncertainty and knowledge. For example, reasoning under uncertainty can be dealt with default logic, a formalism allowing reasoning with incomplete information. On the other hand, and as the name says, autoepistemic logic allows a form of nonmonotonic reasoning about belief.

5 Conclusion

Situation analysis has to deal both with knowledge and uncertainty and thus with ignorance and information. A distinction between ignorance and uncertainty appears as a crucial point in the process. Indeed, we must not confound the state of mind of the operator being uncertain facing a decision, an act to commit (meaning I of the definition of uncertainty), and the uncertainty arising from the physical limitations of means of perception (human sensory system, sensors, measures devices), this uncertainty being of different types and easily formalizable either quantitatively or symbolically (meaning II of the definition of uncertainty).

To be able to deal with knowledge or uncertainty, a formalization is necessary, defining a framework in which knowledge, information and uncertainty can be represented, combined, managed, reduced, increased, updated. The objective is (1) to build a model of situation directly usable by the different theories of reasoning under uncertainty, (2) to be able to deal with both knowledge and uncertainty. Some theoretical frameworks available to model the SA process (or some parts) and taking account uncertainty have been identified [12], their abilities and inabilities being currently under study. These potential frameworks can be divided into two main categories: qualitative approaches (such as modal logic, non-monotonic logic, truth maintenance systems, ...) and quantitative approaches (such as probability theory, evidence theory, fuzzy sets, random sets, possibility theory, ...). Qualitative approaches seem to better suit reasoning on knowledge, while quantitative approaches are better candidates for uncertainty representation and management. Hence, a good solution for a global modelization of the situation could be an hybrid approach.

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(quantitative logics, incidence calculus, ...) mixing quantified evaluations of uncertainty and high reasoning capabilities.

Characterizing uncertainty is probably the most important and difficult task, devolving on each subprocess of situation analysis. From this characterization of uncertainty is derived the choice of the most adequate theory to be used for this subprocess. It seems intuitively that each type of uncertainty can be present during the whole process of situation analysis. Hence, the choice of one framework for a given subprocess is premature and implies a deeper study of each subprocess. The choice of the adequate theory can also be guided by some possibilities (or impossibilities) of information (or data) acquisition, which directly refers to what we called epistemic theories (or interpretations) of uncertainty.

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