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Uncertainty modelling for threat analysis

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Abstract

Accurate modelling of information and knowledge is central to the modern command and control (C2) process. Without models and a language for describing them, it is impossible to collaborate on C2. All information which enters a C2 system will be uncertain, and hence it is important to be able to model the uncertainty in a way that makes it possible for us to understand it. Some kinds of knowledge can be embedded into reasoning systems designed to help humans sense-making. In order to do this, it is necessary to obtain the relevant knowledge (from humans, sensors and databases of background information), to model it in an appropriate way, and to design computer tools that use these models. In this paper, we describe some aspects of knowledge and information that are important both for understanding the C2 process and for constructing computer tools that help humans achieve situation awareness. We describe positive and negative information, and the concept of indicators as well as how they can be used in a computer tool for threat analysis.

Introduction

For military commanders and analysts, it is important to have an adequate understanding of the situation they are in. This is sometimes referred to as having *situation awareness*, meaning "the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning and the projection of their status in the near future" (Endsley, 1988)

It is important to realize that situation awareness cannot be created by tools: it is a process that resides inside a human's brain. However, it is possible and necessary for the human to have access to various computer tools and processes that help them achieve situation awareness.

In this paper, we discuss human information processes and their relation to situation awareness, focusing on how to use analysis tools to deal with uncertainty and in particular on how to predict future events and outcomes. Along the way, we describe the concept of negative information and briefly discuss how it can be used in computer tools for situation awareness.

Most everyday situations follow routine patterns that require little attention or understanding. Therefore, when problems or threats arise, situation awareness (SA) must adapt to deal with the components of the new situation. Whether attention is data- or model driven, the first step of SA is to build a description of the processes in the environment, leading into an analysis of these processes (Endsley, 1995). Such diagnosis combined with background knowledge enables prediction – with more or less accuracy - of future situations. That prediction may in turn enable intervention in the situation development.

With recent decades' information technology, sociotechnical systems have emerged that allow humans, sensors and computers to share information, including information for situation awareness. Military C2-systems are examples of sociotechnical systems, in which prediction of situation developments are central. Much effort has been spent on new functionality in these systems, a development that alternately has enhanced, altered, and ignored human capabilities.

This paper is outlined as follows: First we present, general requirements for decisionmaking, namely the background knowledge and the expectations of the decisionmaker, as well as information within the situation picture. The concept of negative information is often forsaken, and therefore further elaborated in this article. We then describe some concepts of uncertainty management, beginning with conditions where knowledge is lacking, to the utilization of different types of indicators, from which the decision maker (helped by computer tools) can make diagnoses and prognoses. The relationship between decision making over time, uncertainty, and insecurity is then discussed, illustrating how these concepts together limits freedom of action and pointing to the need for decision aids. Finally, we briefly describe a tool, Impactorium, that attempts to use the concept of indicators and Bayesian inferencing to help commanders make prognoses about the future.

Information processes

Knowledge

In order to understand information requirements and the impact of information uncertainty, the level of knowledge of the information user is central. Hence, the following section discusses various aspects of decision makers' knowledge.

The environment for C2 has changed from the horseback, to underground bunkers, to mobile headquarters, to distributed functions and authority within network enabled defence. Each arena develops with respect to technology and tactical developments. What then is the decision maker's knowledge in general?

Since ancient times, strategy and tactics have been guided by principles of survival, such as speed, strength, protection, mobility, and impact. In addition, the commander's role includes leading the organization with its functions, personnel, and social aspects.

Without going deeper into leadership or specific operational tasks, a distinction can be made between know-how and know-what. Know-what includes understanding facts and meanings. Know-how includes practical knowledge but also, more specific to the topic, the analytic skills for dealing with information (Table 1).

Table 1 Distinction between know-how and know-what, further categorized in facts, understanding, ability, and expertise with definitions and type of learning from Swedish doctrine (Försvarsmakten, 1998)

Form of knowledge		Definition	Learning
Know-what	Facts	Knowledge of isolated phenomena	Memorizing
	Understanding	Insight into relationships and knowledge of meaning and consequences in what is experienced	Interpretatation and analyzing
Know-how	Ability	Practical or intellectual capability to perform actions	Training/Doing
	Expertise/ Familiarity	Achieved competence such that in dealing with phenomena, having quick understanding of situation and the consequences of intervention alternatives.	Participation and acquiring experiences

If appropriate knowledge is lacking, the decision maker is unable to make use of any information, whether that information by itself is certain or not. Hence, in order to make decisions and plan future activities, the basic "know-how" requirement is the ability to perceive, understand, reason and create new combinations of information components. Experience is the single most important factor in this process, since it enables evaluation of current and new combinations of information.

Acquiring knowledge

When an observer arrives at a mission area he is often unacquainted with a situation and wants to learn it and its dynamics, and begin to gather the explicit facts on objects, states and events he observes (Positive Information, PI). Maybe he also put attention to something he expected, but does not see

(Negative Information, NI), simply by comparing the present situation to some other he already knows and that appears to be similar. But in the first phase PI is most important, and his reasoning is mainly *data-driven*.

In due time, he begins to form a “normal picture” of the situation which in principle means that he has a mental model of the typical situational elements that are present in this normal picture, ranging from the typical amount of people in the bars in the evenings of the different weekdays to the kids playing soccer in the streets, and the routine power cut between 21:00 and 06:00 or similar. From then he can also more easily pay attention to NI simply by comparing with what is typical in the normal picture: Where are all the children that usually play soccer here… The street is empty! His reasoning is now not just data driven, but also *model-driven*.

Having a model of what “is normally” or “should be” the case is often necessary to state, or use, NI as something absent from what was expected. If the situation changes, he might eventually have to change his mental model to one that reflects the new situation

To generalize: In the short-term, decision makers are guided by basic principles and doctrines and may be limited to decisions based on available (positive) information only. Long-term time perspectives (planning or prepared execution), allows for acquiring new knowledge (learning) which can enable better interpretation of new situations. The long-term perspective also makes it possible to think about what negative information might be present that should influence the decisions made.

Knowledge can be acquired in different ways. While first-hand experience is most useful to people, knowledge can be transferred on higher levels by studying models of phenomena. Descriptive and explanatory knowledge models can be extracted from empirical data-sets, but they also incorporate theoretical concepts. Computational models extends human mental models with predictive models and simulation models (Figure 1).Such models help a decision maker interpret the information in new situations.

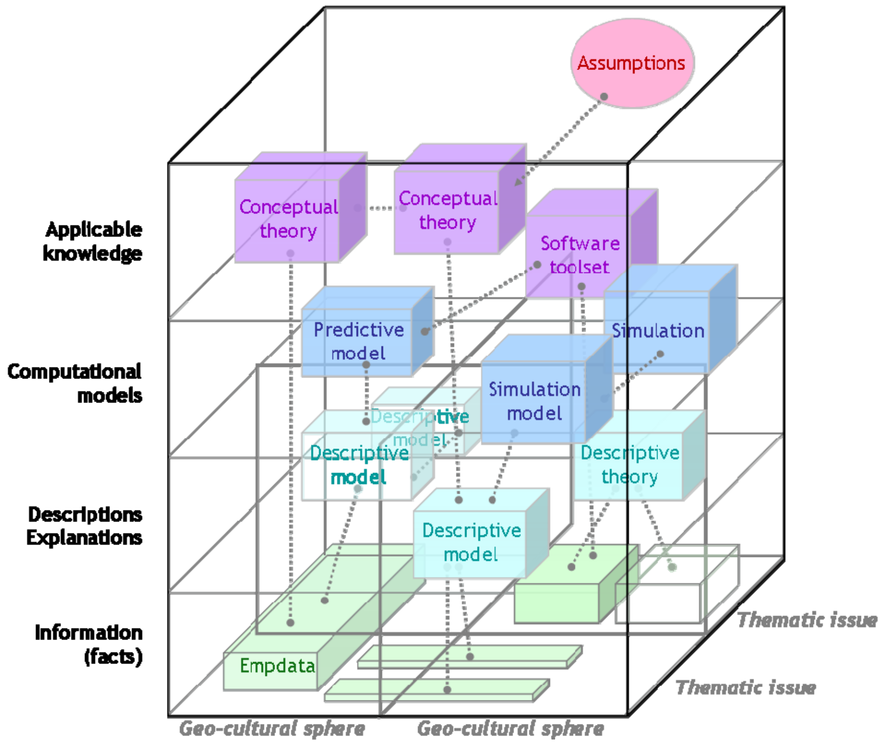

Figure 1 Descriptive and explanatory knowledge models (cyan boxes) can be extracted from empirical data-sets (green boxes), but they also incorporate theoretical concepts (violet boxes). Extending human knowledge in mental models (facts and understanding, green and cyan boxes), are computational models (blue boxes) which encompass both predictive models and simulation models.

Mental models can be based on descriptions of previous experiences, but also grounded in general mechanisms, accepted theory, and experiments. Expert knowledge can be simplified, but yet retain its applicability for the range of situations which the decision maker will face.

For instance, quantum mechanics may be simplified in Newton's laws of classical physics, which may be further specified in rules of thumbs and approximations, which determines operational guidelines concerning time, mass, speed, impact, etc.

Another example would be general principles of human motivation, which may be simplified in Maslow's model of hierarchy of needs (e.g., Simons, 1987). An instance of this model can be specified for a target group in a particular operational area, thereby limiting their probable courses of actions.

Expectations

After knowledge has been acquired, whether in the form of facts or models or experience, this background knowledge will guide the building of situation awareness. For instance, a "model of terrorists" may help directing search towards specific organizations rather than any angry crowd.

Also, within the situation picture alone components will trigger simple or more complex expectations of situation developments. For instance, a vehicle on a road can be expected to stay on that road (not turning) if its speed is fairly constant. This information, in combination with weather and road conditions, and a "sharp curve" ahead, may lead to expectation of an accident. While there is background knowledge also in these cases, the expectations rise during the experience of this particular situation.

Whole or parts of situations may be meaningless to a decision maker or sensor, to the extent that no form of background knowledge is applicable. What is then expected? Such circumstances can still be anticipated by expecting no deviations of measured *normality*. In an open landscape, a deviation from normality could be "movement of an animal" (PI), but also "no movement of an animal" (NI), all depending on what is most often occurring in a given timeframe. In a week's timeframe, animal movements in dusk and dawn but at no other time, may become the normal picture. Normal distributions of events can therefore construct and inform future models.

Positive information

For the purpose of this text, positive information (PI) or simply *information* is defined as "meaningfully processed data". *Data* is defined as distinguished units available to senses or sensors. Information can be created from conscious processing which can be as simple as adding a label to the data, or more complex like editing the data. Pieces of information, from sensors or human observations, are thereafter combined in *intelligence reports*, which takes a context, question, operation, mission, or task into account. Table 2 provides some examples. A *fact* is similar to information but also associated with a truth value and usually a context.

Table 2 Descriptions, relationships and examples of data, information, and intelligence reports in the context of military C2-systems.

Data	Information	Intelligence report
Registered or percieved distinguished units	*Like data but with some degree of meaningful processing*	*Like information, but with interpretation within an explicit or implicit context*
A randomly snapped photo	A composed portrait	A composed portrait of suspects in a criminal investigation
A recording of a speech made by mistake	The same recording with a label (e.g., “Speech of Olof Palme, Spring 1973)	The same recording, labeled, and attached to an analysis of the Israeli-Palestinian conflict
A report containing meaningless symbols in unfamiliar combinations	A report describing a scientific experiment	A report describing a scientifc experiment and its implication for a type of operation

From this definition follows that information is constantly created during perception, when sense data in the environment is attached to a meaning. The produced information, which depends both on the subjective observer and the objects of attention, can thereafter be directly communicated in speech or gestures, or recorded in handwriting, illustrations, even movies. Since human memory is limited, most perceived data is lost, in contrast to data recording procedures by information technology (sensors, computers, databases).

Negative information

For the purpose of this text, negative information (NI) can be defined as the *absence of any sensed data corresponding to expected information*. If animals are expected to be moving in the sunset, any instance of sensed data corresponding to the category animals would produce information. Unless that sense (or sensor) data is present, there is *negative information* on animals in the terrain.

What is NI?

At low, “physical object” level, it is easy to define what meaningful NI to report about is: Not observed physical objects in a surveilled space-time volume. They were, from earlier measurements, expected to be present, but now found not to be. This is a definition used in, i.e., robotics, and target tracking (Koch, 2004).

Formally, one can report on everything possible one does not observe but also does not expect, such as "I do presently not see a Brontosaurus pass the crossroads XY where I stand here outside Stockholm", which (at least today) is a rather useless statement. It is necessary to put negative information in relation to what one expects, or has assumptions about, to obtain a reasonably manageable quantity of (useful) NI. Concerning the Brontosaurus, however, it would be so odd to observe it that it would certainly result[1] in a report simply because it was probably not expected to pass the crossroads. That is, a strong PI deviation from what is expected does also feel natural to report about.

Hence, it is only meaningful to report PI or NI that changes the receivers’ model of the situation or if there is a reason to report something that what was expected in order just to corroborate the model. In this case we certainly had an odd identity or type of object. If we saw a Morris Minor car accelerate 0-100 km/h in 3 seconds, we would probably also like to report it because it deviates from the expected kinetic behaviour of such a vehicle.

The semantic definition of “Expect” could here be formulated as: “Based on knowledge, experience and measurements: Setting up one (or several) hypotheses on the expected outcome of future observations”. The outcome could be the position of objects, that an event of some kind is likely or not

[1] Unless the reporter refrains from doing so, in order not to appear to be crazy.

likely to occur, that a certain state should be achieved within a certain time span, or similar. If the hypothesis is corroborated, we are still in an expected or “normal” state. For both lower and higher level Situation Understanding, the concept of a "Normal Picture" (NP) is an analogy to the system model in a target tracking filter, where the model is, if needed, modified using new measurements, where the obtained PI, or NI, lead us to dynamically modify the model by combining model and measurements in a filtering process. A simple change in characteristics of an object, such as an object that is normally blue and suddenly changes its color to red, could formally be reported by PI on red color and NI on blue color, referring to the same object.

NI on higher levels

Now, NI on a well defined physical object is simple: either it is present or not, based on an observation. The observed results of course have varying reliability because of the sensor sensitivity and discrimination, occlusion by other objects, the object's ability to camouflage itself or maybe conceal its identity. But what is "higher-level" NI? Going to the data fusion level 2 (Situation Assessment or SA, see Bossé, et al., 2007) we have to include "Expected, but not observed, relations between objects".

In the case of tracking a group of objects that, based on their types, are expected to move together, one could create NI from the observation that an object is suddenly missing, or deviates from the joint behaviour. More generally, we can talk about a team as a system of actors that, based on our experience of previous observations, tend to interact. If we think we know that a more or less important component of the group suddenly is not active or present in the system, it can help us to draw conclusions about the group's ability or assumed change of plan. SA could as well include information about the cluster or group membership at large, such as those that tend to hang out, talk on the phone, etc.

Is NI on situations meaningful? For the above case, the situation, perhaps described in some knowledge base of typical situations, is defined by the type of actors and their relative behaviour. But what if one actor is missing (or being hidden) or there is one extra (maybe just by coincidence, not involved with the others)? We do not have the same situation, but rather a similar one. To say that there is NI on the first situation description would be misleading; that situation is the case to a certain extent. Here we have PI on that situation *combined with* NI on one of its parts (the not observed actor) or PI on another extra actor, respectively.

For SA in general we could generalize further from objects with their relations, to the Situation to be characterized by one or a set of “States”, such as “It is rather windy”, or “It is cold, but the children are playing soccer in the street as usual”. A state is present at a definite time and might change. An Event, on the other hand, is extended in time. Larger “events” could cause, or constitute, a transition between states, and thus “Indicate” that such a state transition is likely to occur, or is already going on[2]. Smaller events could simply be typical (hence: expected) for a state itself, and be regarded as “indicators” for that state being the present one.

Concerning a normal state we could expect both the situation observed to be in a certain state, or we could expect some typical events (Indicators) to happen within some time, or with some frequency. If they occur too scarcely, or are not observed at all, we have NI on them. If too frequent, we get PI. This might indicate that the state has changed. Otherwise we are, as far as we know, still in the normal state. Similarly, a large-scale event is built up (or defined) by typical smaller scale events that tend to be present, but sometimes are questionable or absent. These smaller events might have a typical time ordering, often simply being pairs of cause – consequence.

At data fusion level 3 (Threat Assessment or TA) one assesses the threat against oneself or some people, object(s) or infrastructure one is set to protect. This also limits the “search space” to hypotheses about adversary actions available that have negative consequences regarding this

[2] Compare our discussion of indicators below.

protection. This also means a cueing of search for information (PI as well as NI) to limit the number of hypotheses about adversary future courses of action. It will guide in the staffs formulation of the different Requests For Information (RFIs) that have to be answered by observers in the field. Basically, RFI's could of course be defined as "RF PI" as well as "RF NI".

Discerning states and events

With what certainty is PI or NI at a higher level true? That a certain state is present, or that a certain event is happening or has happened can be difficult to judge. If a physical object is at a specific location or not is easier to elaborate on since physical objects are more "discrete" in nature and an inherent unique identity, even if you might not know it in detail. If an event we recognize really is happening or not is more difficult, a number of characteristic features for the event should be met (á la Case Based Reasoning or a medical diagnosis). Furthermore, events are limited in time scope and states can make transitions to other states. They both are often more or less localized in space. Physical objects involved in events tend to be persistent. If we know it exists, and we know that it is not located in a certain region, the consequence of this NI is that it has to be somewhere else; it seldom just "fades out" and disappears.

How about subjectivity? Shall we give NI on an expected event when we only see something similar happen? And what does "similar" mean? Here it is natural to rely on subjectivity and intuition, which are difficult to formalize. There may be a risk of being "biased" or "subjective" if you beforehand have a certain expectation. If you do not observe some of what you thought were important components of this expectation, you report that you did not see what was expected. There are a lot of other NI (and PI of course) that are also present and is perhaps relevant but not reported. But that's always the case, there are always "unknown indicators" in a situation you do not know well enough.

There is also a problem with bias; being a member of a reconnaissance patrol, you might have been asked to look for certain indicators. You do not see what was expected or asked for and, therefore, you look a little extra for it, or wait for it to happen (meaning you had not waited otherwise). Different observers may have different biases. If an observer refrained from reporting something that happened he thought was too "common" or "trivial", then perhaps the recipient of the information does not have the same bias and expectation and interprets it as NI that none of this was reported, and act accordingly.

So, is the absence of reports in some cases to be interpreted as NI? Subjectivity could probably be handled by letting some expert define, a priori, a set of "standard" indicators to look for, and then objectively report PI only on the ones observed. This would be a more formal way to indirectly use high level NI by Closed World reasoning (see below, everything not explicitly mentioned is false, that is NI for everything else)[3].

Formalizing events and states

The discussion on NI in earlier sections tries to show that reasoning with NI on higher levels is meaningful if it can be done relative to some expectation. But how can we define an event, and, more precisely, how should it be formalized to be stored in a Knowledge Base (KB) in a C2 system? Databases, for instance, are usually assuming the "Closed World (CW)" (everything not explicitly mentioned to be true in the database is false, that is NI for everything else), "Domain Closure (DC)" (everything that can be described is known by the database, true or false by CW) and "Unique Names (UN)" (Everything known to the database is distinct, and non-overlapping) assumptions.

Concerning PI, one usually wants to store as exact information as possible on what is observed. For NI it would be the opposite; Storing as general as possible NI will automatically mean that all it includes is also not the case. The CW assumption however, automatically means that everything except what is explicitly mentioned in the DB as PI is NI by default. It makes storing of NI redundant. Hence,

[3] We elaborate further on different "flavors" of uncertainty later in this article.

storing PI as well as NI requires (in order to be meaningful) an Open World assumption: What is not explicitly stored as PI or NI, or can be logically derived from it, is Unknown.

Concerning *states*, in a linguistic sense, it is common to have notions for a state and its opposite, such as “war – peace”, “hot – cold” or simply “presence of – absence of”. PI on one of them implies NI of the other and has to be handled as such, when reasoning. One has to take care semantically here; this implication is only true if we have word pairs truly meaning a state and its complement: If the complement name X used is a bit more specific, i.e., less general, in some sense than the true complement of a state, using X to report NI on the state might give the false impression that there is less NI reported than intended.

What about *events*? An event is in some sense always unique, but can be categorized more or less clearly, depending on the actual state in which it typically happens, what events that usually precede it, are parts of it, or happen after it. Furthermore, it depends on what types of objects and actors are involved, the relationships they tend to have, when and where the event tends to happen, etc. But one has to be careful; events must hang together in a logical way, not only happen at the same location and at the same time, in which case they are more likely different parallel non-related events. Events and states are, as mentioned earlier “nondiscrete” in nature, making typical KB solutions unsuitable for storing and reasoning with them. “Crisp” concepts, like CW, DC and UN are rather meaningless here since they require sharp boundaries between the different elements (here: situations, events and states) that are to be contained in the KB, something that is most often not the case.

Most events are, however, dependent on the physical objects that interact in them. The objects might have been identified and related at data fusion levels 0, 1 and 2 (Bossé, et al., 2007). How well the identification succeeded will of course affect how well we can make predictions about events at a higher level. If we know that a particular warlord stands behind a certain militia, we can, to some extent, predict their behaviour if we know the warlords strategy.

Taxonomies and ontologies

One way that has been tried to formalize situations, events and states is by using description logic (Description Logic) to describe them as taxonomies or ontologies on different levels of detail (Matheus et al, 2005, Vistology). However, most of what has been done is still on a research-level. There is often much work associated with building such ontologies even if many of them are intended to be re-useable and extendable. Lower level, and detailed, ontologies that are intended to be applicable to specific areas (logistics, disaster relief, criminal investigation, etc.) might also be very situation dependent, and have to be built by specialists on these matters. If these specialists do not yet exist (a similar enough situation might not have been experienced) when facing the new situation, one even has to build the ontology while learning the characteristics of the situation.

Taxonomies intend to categorize a certain class or domain hierarchically in higher and higher detail. Ontologies also add attributes to the components in the taxonomy, as well as relations between them. A well structured ontology could of course guide an inexperienced observer what to look for in a situation, and report PI or NI on components observed or not observed. One would then, as mentioned above, report PI on an as detailed as possible component when present, and an as general component as possible as NI when not present, in order to cover up for as much NI as possible. Or simply assume Closed World reasoning; everything not reported as PI is by default NI.

Also, when using taxonomies or ontologies, one has to be careful not to use an ontology for understanding a situation for which it is not applicable. To determine this can be difficult since different domains (here: situations, states or events) can smoothly overlap and be more or less similar.

Dealing with uncertainty

In this section, we describe some different aspects of uncertainty that are relevant for C2 systems. We describe the concept of indicators to be used for predicting events, outline some important aspects of various mathematical models for describing uncertainty, and place the uncertain information presented to a decision-maker in context by discussing decision-making and how it limits the freedom of action of the decision-maker.

Origin of information requests

The core qualities enabling any self-chosen human action are courage and hope. With only fear and anticipated failures, people wouldn't start enterprises, children wouldn't try to walk, and a decision maker in a military C2-system wouldn't take any decision, even less act, no matter how much information was available. It is not before a decision maker possesses these qualities that a discussion of the quality of decisions and risk-calculation can begin.

Information superiority provides the decision maker with the potential to maximize decision utility and minimize risks. Hence, there are good decisions and bad decisions! The information provided may require additional tasks to achieve successful outcomes (e.g., learning new skills, acquiring supplies, communicating, and so on), while in other cases information alone is sufficient to decide and act (route selection, identification, calibration, word translation, etc.).

Information requests arise from problem solving in which information gaps are identified. The problem itself may be anything from an external threat to an internal order to mobilize. Assume a situation where a decision maker is in charge of safe transportation for a convoy moving from A to B. Knowledge requests may be[4] "How much fuel is available?", "How far from the road are enemies located?", "What type of weapons do they have?", "What are road conditions?", "What are weather conditions?", and so on.

Conditions for knowledge requests

Information requests are rooted in the (lack of) background knowledge and experiences of the decision maker, but concerns the current situation. Information requests can be broad, such as "identify all enemy vehicles", or specific, such as "identify the vehicle at coordinate x, y". Clearly, one information request will provide information with better quality than another request. The quality of information requests depends on the decision makers current state of knowledge, regarding 1) the situation, 2) the task or problem, and 3) the selected problem solving method. The states of knowledge indicated in Table 3 exists to different extents for any decision maker .

Table 3 Knowledge states with respect to awareness and aquisition

	Knowledge acquired	**Knowledge gap**
Aware	(3) What we know that we can do	(2) What we know we can not do
Unaware	(4) What we don't know that we can do	(1) What we don't know that we can not do

These states not only illustrate general states of knowledge. They also illustrate a stepwise transition from the worst condition (1) to a suboptimal but much better condition (4). Decision makers with courage and hope may step into situations where they don't know what knowledge will be lacking (1). Soon they find out what they need to know (2), acquire the necessary knowledge, which then is active (3) and later is automated or inactive (4).

From the table above we can conclude that knowledge support is optimal under condition (2), whereas communication of the knowledge (teaching) is optimal under condition (3). Condition (4) can also

[4] These examples are taken from an experiment with another decision support tool that we perfomed in collaboration with the Swedish Armed Forces in 2008.

refer to something never tried and seeming impossible while in an active situation demands little from the decision maker.

The often quoted statement "Know your enemy, know yourself" (Sun Tzu) applies to modern information systems as well. Hence, an important instance of Table 3 concerns own knowledge acquisition potential: What do we know that we can ask about? This is central because of the following relationship:

Knowledge of own system → Quality of questions → Quality of info requested → Quality of decisions

Of course there are nuances in Table 3. A decision maker may know where to direct own fire and also know how to fire, but not know how much to fire. Likewise, information may be enough to make decisions about activities, but not enough for guiding sufficient performance of those activities.

Uncertain information and prediction

All information that enters a military C2 system will be uncertain. We might be uncertain about the quality of the information or about the details contained within it. When we want to use the information to do prediction, an additional layer of uncertainty is added: since we are dealing with the future, it is in practice impossible to predict what will happen. By extracting knowledge from subject matter experts of constructing expert systems using machine learning, we might in some cases be able to construct models that allow us to predict the future in various restricted setting. For example, given measurements about the position and velocity of an aircraft, it is possible to predict its location in the next seconds. However, the longer the time-perspective of interest, the more difficult it is to make the prediction.

In this section, we will briefly describe some aspects of both mathematical and psychological uncertainty, and also describe how the concept of indicators could be used to estimate the likelihoods of future events.

Indicators

One type of uncertain information exists in the form of *indicators*. An indicator can be defined as a *sign of something that will happen, is happening, or has happened*. For an indicator to be active means that it points to an expected outcome, but does not completely confirm this outcome. For instance, a piece of snow on a rooftop is an indicator that snow soon will fall down on the street from the moment the snow begins to move and until the moment is starts falling. Hence, indicators are the first signs that may only vaguely reveal information about events that currently are unknown, such as forgotten, undocumented, consciously hidden, or not yet existing (future) events.

At the end of the 19^{th} century Pierce invented *semiotics*, a science of signs (Chandler, 2001). From the beginning a study of written signs, expanding linguistics, semiotics can be extended to indicators as well. Pierce distinguished between the observed signifier (sign) and the signified concept in his breakdown of types of signs:

- **Symbols:** Representing the signified concept by conventional meanings (e.g., English words signifying items)
- **Index:** Directly linked (causally or physically) to the signified concept (e.g., handwriting signifying the person writing the text)
- **Icons**: Resembling or imitating the signified concept (e.g., a cartoon signifying a real person, Roman numerals)

Symbols, icons, and indexes are signs that can be experienced directly with the senses, from precise visual inspection to subtle vibrations in the ground. Symbols and icons enable communication of meaning and can be used not only to signify observable phenomena, but also thoughts, feelings, and other abstract phenomena. Such meanings can be keys to understanding a situation by revealing an intention or state of affairs. A decision maker searching for this meaning (perhaps in an unknown language) should therefore send a request for information.

While symbolic and iconic meanings are *indirect indicators* for situation development, indexical meanings may also be *direct indicators*. An active indexical indicator provides some degree of positive information, while inactivity of a functioning sensor provides negative information. Consider the following example: Some prisoners are digging a tunnel from a prison camp, but the guards are unable to observe any prisoner doing this (NI). Perhaps there are instruments registering sounds from underground. Such sounds would be a *direct effect* of the current situation (PI). Perhaps the prisoners never mention the project (NI), but an air of hope and ambition in their expression is visible, a *manifestation* (PI). We may know the ground is made of sand and conclude that if a tunnel is built there must be somewhere to hide this sand. Sand that is found is a historical indicator of a situation, a *trace* (PI).

This example shows the multitude of indexical indicators in the environment. Apart from direct perception, sensors may be useful for indication of situations or events. Sensors may passively react to something in the environment (such as a thermometer) or require specific methods and repetition (such as precipitations in chemical analyses). Sensors may also intervene in situations, such as a radar being detected and therefore one tries to avoid it.

Sensor indicators may contain different amounts of information. An experienced stock market analyst may see patterns in the values of multiple stocks simultaneously. The information may also be combined in single variables, such as wind, humidity and temperature in combination indicating risk for cooling injuries.

Usually measurements and methodologies are associated with sensors, while estimates and evaluations are associated with human perception. The sources of error become higher with more complex instruments. The accuracy of sensors therefore may differ with respect to handling, as much as the sensitivity and accuracy of human senses differ individually.

Mathematical methods of handling uncertainty

There are very many different methods of expressing uncertainty mathematically. For a given problem, it is not self-evident which specific mathematical model to use. Klir and Yuan (1995) have formulated a typology of uncertainty that attempts to describe various aspects of uncertainty and that maps closely to different mathematical models. In their model, uncertainty is divided into either fuzziness or ambiguity. Their typology [5] divides uncertainty into either fuzziness (lack of definite or sharp distinctions) and ambiguity (one-to-many relationships). Fuzziness is further sub-divided into vagueness, cloudiness, haziness, unclearness and indistrinctness. For ambiguity, the sub-division is into discord (with further refinements conflict, dissonance, incongruity, and discrepancy) and non-specificity (imprecision, variety, diversity, generality).

Fuzziness can be handled by the mathematical theory of fuzzy mathematics (fuzzy sets, fuzzy logic). Fuzzy mathematics is most simply understood by considering set theory and introducing the characteristic function $f_A(x)$ of a set A. In classical set theory, $f_A(x)$ is either 1 (if x belongs to the set) or 0 (otherwise). In fuzzy set theory, we allow $f_A(x)$ to take any value between 0 and 1, and interpret $f_A(x)$ as the degree to which x belongs to the set A.

Non-specificity can be handled by evidence theory (Shafer 1976), where we allow mathematical statements about non-specific sets. For example, instead of having to specify whether a vehicle is a

[5] There are several other typologies or classifications of uncertainty, see for example Bosse, et al (2008) for a discussion of some of them.

tank or a truck, we can mathematically express, and reason probabilistically with, the statement that the vehicle is “either a truck or a tank”.

Imprecise probabilities is a general framework for expressing second order uncertainty. In this framework, it is possible to reason not only about the probability of an event, but also about how uncertain we are about our probability calculation.

When constructing a C2 system, it is important to take account of several aspects of uncertainty. How does the uncertainty change when data is processed? A very important aspect is how to display the uncertainty to the user (see Riviero, 2007 for an overview). Negative information, as described above, can also be associated with uncertainty, which adds further complications.

Related to the problem of trying to predict future events, C2 systems will have to deal with opponents that are trying to deceive us. How can we separate uncertainty due to bad sensors or signal processing from that which is due to deception? We also need to handle bias in information. For example, information that is supplied to us from third partied (non-governmental organisations or media) will be biased towards the goals of the organisation.

Freedom of action – Uncertainy in context

Decision-making over time

Decision making in C2 staffs revolves around achieving SA and using this to decide on activities that lead to a pre-defined goal (from a strategy, plan, or the situation picture itself). Observation and orientation during build-up of SA presents alternatives for decision making about actions to execute (Observe, Orient, Decide, Act; OODA-loop, see Boyd, 1996). While this is a schematic abstraction and equally important parallel processes (such as continuous learning, goal shifting, and preparations for action) are omitted, it illustrates how decisions are made with respect to awareness of the current situation and it’s most likely predicted development (Figure 2).

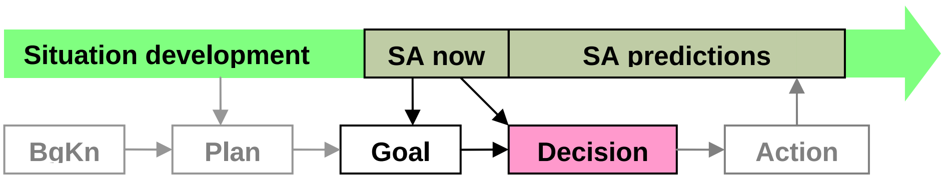

Figure 2 Situation development over time (green) must be taken into account in decision points (pink). Decisions are made both with respect to goals as well as SA now, and SA future (transparent pink). Goals can appear more or less directly in the situation picture (e.g., the goal of preventing an unidentified approaching vehicle to enter an area of responsibility) or with respect to a plan where goals are defined (no unidentified vehicles are allowed in the area of responsibility). Plans, in turn, may be based on previous mission and hence part of background knowledge (BgKn in figure).

Depending on the decision maker’s role and performance within the C2 system, together with the task and the dynamics of the environment, the OODA loop works at different speeds. During execution of specific tasks, minimal planning or learning may occur and actions are continuously executed almost instinctively. For strategic decision making staffs, planning and monitoring may take months or years and clear *decision points* can be identified. Intermediate levels in C2 systems must fuse these decision-making loops, strategic above, tactical below. One key to organization agility may be found in continuous adaption of all these processes with regards to the multi-dimensional dynamics of the environment. Net-centric organizations have the possibility to distribute information, therefore authority, in other ways than traditional military hierarchies. Another key to agility may be in joint awareness of time perspectives. Just like the return and risk of stock-market investments are dependent on time-frame, so is the impact of military actions.

Introducing uncertainy

Uncertainty exists in the information about the components of the situation picture (e.g., terrain, infrastructure, adversary plans, willingness to sacrifice, etc.), but also regarding own forces ability and responsibility (e.g., availability, performance, legitimacy). Both sources of uncertainty impacts the decision making and action (the latter either consequently or directly) (Figure 3). For instance, insurgents may plot to overthrow a local government whose security forces must decide how to intervene in prevention. The commander of these security forces faces, for instance, the following sources of uncertainty, (that is; vague indicators are active, some information exists, but none confirming any specific development):

- **Situation picture:** Where, how many, and what are the insurgents plotting to do this week? (Info: 50% chance of suicide attacks) Next month? (Info: 33% chance of riots near all government buildings)
- **Goal:** What intervention will best neutralize the insurgent plot? (Info: 25% Show Of Force) What interventions are the security forces trained to do? (Info: 80% Patrolling) How many of our security forces sympathize with the goal of the insurgents? (Info: 15% do so)

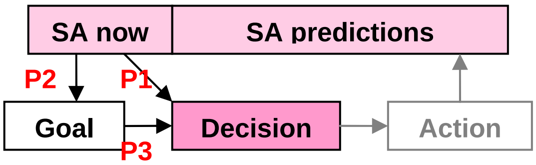

Figure 3 The uncertainties in the situation picture (including predictions of future) directly influences the decisionmaker (P1), but also makes it difficult to determine relevant goals (P2). For instance, an approaching vehicle (from previous figure text) may be from the Red Cross or from the Enemy, and the choice of response is therefore not clear. Responses may be objectively defined (according to doctrine) in also in uncertain circumstances, but may still be uncertain for a particular decisionmaker (P3) in combination with a particular team.

The commander of the security forces are now left with a couple of alternative actions. Apart from *selecting* one of them (for instance, begin patrolling around all government buildings), he must also decide *when* to begin this action. How much information is required? What defines if the situation is critical? Would it be better not to act? Are there other ongoing plots, shifting priorities of this particular task? Do some actions of the security forces meet multiple situation developments (e.g., both preventing riots and attempted murder of government executives)? While these questions may or may not be coupled with reliable analyses and clear answers, we simply leave it for specific scenarios. The remaining conclusion is that uncertainties in the diagnosis of the situation as well as in the prognosis for future developments are central when decisions have to be made, both with respect to self (e.g., own forces) and to environment (e.g., adversary).

Uncertainty and insecurity

The preceeding sections pointed out the problem of selecting the correct set of actions, given SA in different time perspectives and given levels of uncertainty. Assuming the time frame is known and certainties have been identified in the situation picture as well as own force abilities and responsibilities, are we then automatically free to act? In the context of a military C2-system, whether in the field of action or in a bunker a thousand miles away, physical insecurity of personnel may be everything from imminent to implicit. In this section, we elaborate on the relationship between uncertainty of information and insecurity. By insecurity we do not only mean life-threatening situations, but any negative impact on wellbeing (Table 4).

Table 4 Some examples of causes of insecurity and uncertainty from within the individual and from the external environment. Much debated within psychology is whether states are caused from within our outside the individual (nature vs nurture), and most conclusions end up in the importance of the meeting between the two and the continuous interaction that occurs. For instance, intelligence is dependent on both genetic configurations and a stimulating environment, and whether a person is neurotic or not, is dependent on social norms.

	Causes in the environment	**Causes within the individual**
Insecurity	Life threats, violence, theft, lies, betrayals, manipulation, sense- and concentration distortion	Inbalances or deficiencies from dependencies on: food, water, money, social bonds, stimulus level, heat, light, substances
Uncertainty	Information: Lack of, Overload in, Contradictory or incoherent, Uninterpretable, Invalid Unknown information source Unknown/unclear task or other expectations	Low situation awareness Low understanding of task Undefined identity Low intelligence (pattern matching, analytic ability, working memory. General knowledge, etc) Neuroticism (tendency of depression, paranoia, schizophrenia, etc) Specific syndroms (aphasia, AD/HD)

The psychological consequences of both concepts are often similar, namely limitations in deciding and acting. In critical situations both uncertain information and insecurity can be associated with stress. Further, at least the following two combinations exist:

1) In this paper we will refer to the first combination as *risk*, which for our purposes can be defined as *Risk = Uncertainty X Insecurity*. The uncertainty is associated with some aspect of information (too little, too much, contradictory), while insecurity can refer to undesired physical, economic, or management consequences. Sometimes there are trade-offs between the concepts, such as fixed interest rates on loans and taking the long route because we know it well (certainty gained on behalf of negative consequence), or the opposite (certainty lost on behalf of positive consequence).

2) The second combination can be referred to as decision-making under stress. The circumstances (especially in the field) may have an impact on the performance of decisionmaking usually in that stress has a degrading effect on performance. The experienced insecurity can result from either time pressure (e.g., “how to select route when escaping a threat”) or pressure from skills needed (e.g., “how to assist wounded personnel in painful but unknown conditions”) or in combination (e.g., “pulling out the right cable when disarming a time delayed bomb”). The last example also shows that decision-making under stress where the source of insecurity is also the object of concern for uncertainty is a situation that can be described as containing a risk.

Table 5 points out that situations containing uncertain information may or may not be problematic with respect to diagnosis or prognosis. This is important when formalizing situation descriptions in decision-aids where decision support should meet either diagnosis or prognosis needs.

Table 5 Different combinations of uncertainty and insecurity causing priorities for diagnosis or prognosis. The diagnosis problems stem from the fact that awareness is degraded in stressful situations. The prognosis problems stems from inability to foresee dangers in the future. When the object of uncertainty and insecurity is the same, it can also be described as containing a *risk*.

		Object of uncertainty and insecurity	
		Same	**Different**
Stressful situation	**Yes**	Diagnosis and prognosis problems (e.g. disarming an unknown time-delayed bomb)	Diagnosis problems (e.g. selecting route when escaping from a threat)
	No	Prognosis problems (e.g. adversary plan prediction)	No problem (insecurity can be dealt with since we know it, uncertainties aren't critical

Human beings prefer to be in control of situations in which they act and that entails both certainty and security. A military commander doesn't want to send soldiers to an area that certainly has minefields or that may have minefields, and either knowing or not knowing whether a mushroom is poisonous would keep a person from eating it.

Just like decision-making without any insecurity or uncertainty has a timefactor, so does insecurity and uncertainty. For instance, a threat may be present only at a certain time, an aircraft may be lost from radar coverage only in a certain time, or an own vulnerability may be tied to a specific moment in time. Illuminating these time aspects (points in time, schedules, intervals) may reduce the risks and stresses of complex missions substantially.

Freedom of action

We started by pointing out that hope and courage are the two basic requirements for decision-making and action, and then pointed out complicating circumstances such as time aspects, uncertainty and insecurity. Freedom of action also requires ability and will. Table 6 gives examples of negative issues concerning these concepts.

Table 6 Some examples of causes of unwillingness and inability from within the individual and from the external environment. Compare with examples in Table 4.

	Causes in the environment	**Causes within the individual**
Unwillingness	High costs, low benefits, conflict with other objectives or interests	Expected regrets. Belief in lack of qualities, low performance, endurance, etc
Inability	High demands, Chaos, Attack, Dangers, Physical and Mental Stress, Abnormal situations, Fast situation changes	Lacking qualities, drives, control, endurance, concentration, injuries, low performance

We're leaving out conflicting desires in this text (while people express "I want but I can't", we simply say in such case they don't want). Bringing will and ability together following model (Figure 4) is finalizing the analysis of freedom of action.

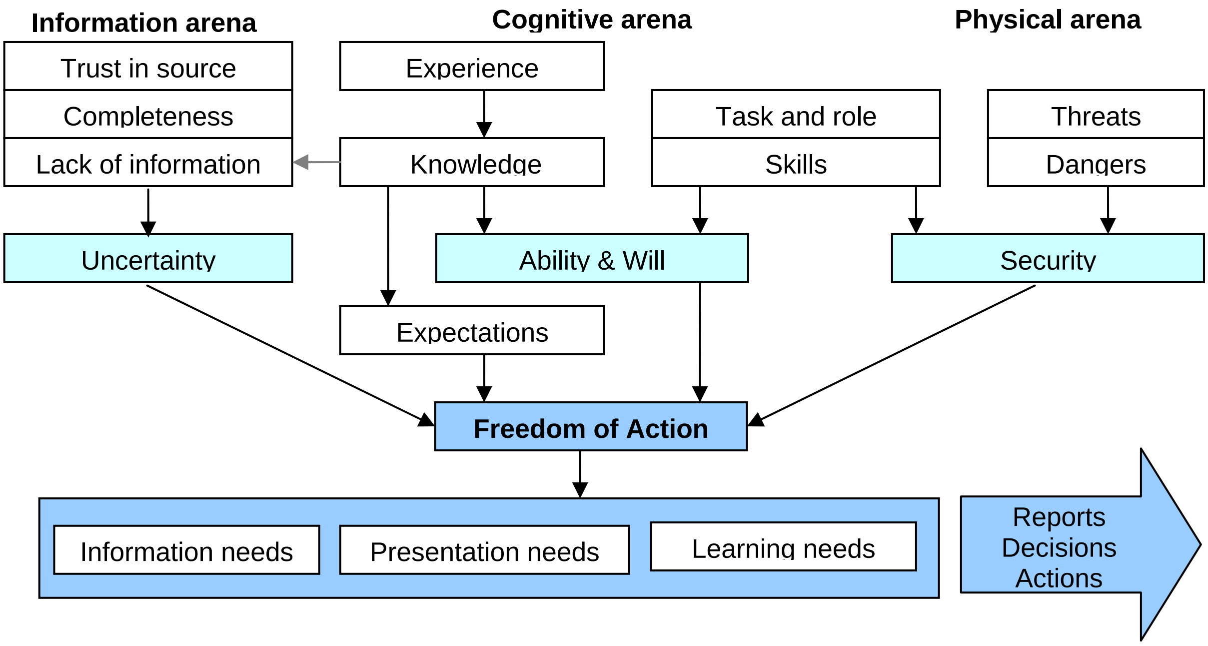

Figure 4 Factors with impact on Freedom of Action that has been discussed (Uncertainty, Ability & Will, Security) and are central in military C2-systems. Depending on the combined state of Freedom of Action, information, presentation, and learning needs are different. For instance, pedagogical tools may be required when knowledge (Ability) is low, expert tools when knowledge is high. Different man-machine interfaces (e.g haptic wests) may be required when information overload is a problem (Uncertainty).

Figure 4 illustrates the context of the insecure decision-maker dealing with uncertainty. These factors should be taken into account when designing sociotechnical systems, and concerns not only personnel in the field but also staff members.

Consider a commander just having received the report from a reconnaissance patrol in Afghanistan. The report states that villagers have said that Taliban fighters are approaching an airport with rocket launchers, at which a coalition airplane is about to land within minutes. The decision-maker has contact with the airplane all the time, but can only reach the patrol at certain times. Should the commander decide for the pilot to choose another airport? What other options are at hand? Going through the model in Figure 4, the following aspects should be considered:

Uncertainty

- Trust in source: The patrol is trusted, but what about the villagers? How was the interaction between them when they received the information?
- Completeness: The current information was complete (not scattered), but to make a decision to change airport (leading to high costs and disrupted plans) we want more precision. Where exactly are the Taliban fighters? How far from the airport?
- Lack of information: Perhaps we need to know the weapons range of the rocket launcher

Ability & Will

- Experience: The commander has no experience of rocket attacks on airplanes.
- Knowledge: The commander has some knowledge of Taliban equipment but not precise.
- Skills: The commander may be unable to picture the scenario of Taliban approaching.

Insecurity

- Threats and dangers: The commander is in no physical danger, but the airplane, with dozens of soldiers and equipment may be. A shot down airplane would be an enormous disaster in every respect.

Now consider the same scenario but with the reconnaissance patrol having direct contact with the pilot or crewmembers. How is the pilot able to make a decision based on the conversation with local villagers? How is his working situation affected? If the airplane is coming in for landing, only some nervousness may be harmful.

What if the reconnaissance patrol comes under fire? What are their opportunities to provide intelligence reports? High stress, maybe corrupt the performance severely (Wientjes, et al., 1999). Reasoning skills may be impaired. Or should we simply conclude the military personell in this situation is has an insecurities in their personality? Just like with irrational fears (like phobias) training, discipline, and medication may limit and prepare for insecure situations.

Analysis tools

Analysis tools can help the user handle uncertain information. In this section, we will briefly describe how information fusion tools can be used to manage uncertain information. Of course, no computer tool can ever reduce the uncertainty completely. For a general discussion on what computer tools can and cannot help intelligence analysts do, see (Brynielsson, et al., 2009).

In the Impactorium tool (see Brynielsson, et al., 2009 and Svenson, et al., 2007), we make use of the concept of indicators as described above in order to connect observations reports (from sensors, soldiers, or analysts) to events of interest. The tool contains software to:

- Create reports, including labelling of them.
- Manage indicators, namely associate reports to the indicators, activate and deactivate indicators, change the values on them.
- Create threat models that define the relationships between indicators and events.
- Visualize events and the likelihood that they will occur.
- Sort and filter reports, depending on criteria that the user sets, for example, that they should have to do with a given report.

For each event of interest that a decision-maker wants to monitor, we construct a threat model in the form of a Bayesian belief network, see Figure 5.

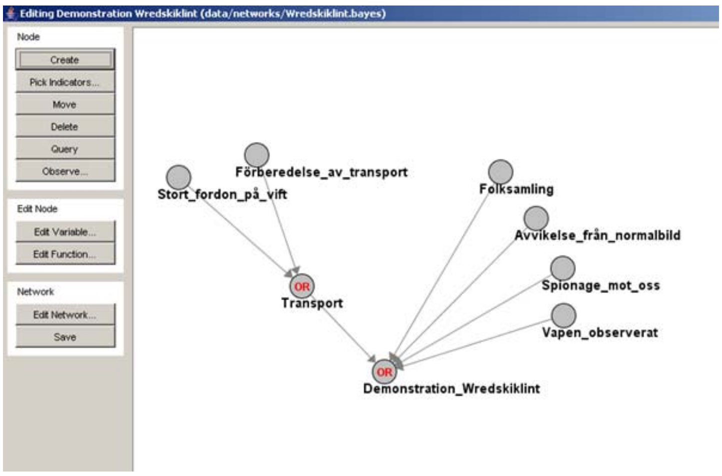

Figure 5 Exanple threat model for use in Impactorium. See text.

The Bayesian belief network consists of an event of interest (in the example above, "Demonstration Wredskiklint" denotes a demonstration to commemorate an ancient battle in a fictitious scenario that is used by the Swedish Armed Forces). The event of interest is connected to indicators (the nodes at the top of the figure). There can also be internal nodes, that act to fuse together a set of indicators (node denoted "Transport" in the figure) that belong together. For each node that has incoming arrows in the network, a conditional probability table is constructed that specifies how the probability of the target node is related to the values of the indicators and internal nodes above it. This allows the software to calculate a probability for the event of interest, given that some of the indicators have been observed. Several simplifications in the mathematical model are made in the Impactorium tool, in order to make the model more understandable for users.

The tool described can be seen as a simple form of case-based reasoning. Case-based reasoning (CBR) is a methodology from artificial intelligence that has some similarities to naturalistic decision making (Klein, 1992) from behavioural science. In CBR, a library of reference situations is compared to the current situation and the reference situation that is most similar to the current one is found. The plan of action that was used in the reference situation is then adapted to the current situation. In order to use CBR, is is necessary to have a good way of describing situations that enables comparisions to be made.

In Impactorium, the reference library of situations corresponds to the set of threat models for events of interest. Situations are described by the indicators that have been observed, and comparisons between the current situation and the library situations are made by calculating the probabilities of the events of interest.

The user is then presented with a display showing the estimated probabilities of all events of interest. The user can sort and filter observation reports according to what event of interest they are related to, and can use this to build their situation awareness.

Impactorium consists of several components: Reportorium, Indicatorium, and Impactorium, as well as the common Impact-server. Observation reports are created in Reportorium. This tool is meant to be used by anybody who reports on observed events or creates intelligence analyses. There are several basic use-cases:

- The tool is used by a sensor operator who uses signal processing methods on the sensor data to understand what the sensors observe and then writes a report about it. Example: An unmanned autonomous vechicle (UAV) operator who has a separate display where synthetic aperture radar (SAR) and infrared (IR) imagery is shown, and then inputs a report on movement of armed vehicles.
- The tool is used by a platoon commander out on patrol to report observations, for example that there are no children playing football on the field where they normally play (i.e., giving negative information about the field).
- The tool is used by an intelligence analyst who uses open source intelligence to determine that there has been a meeting between a clan leader and a religious leader.

Reports contain standard metadata (SALUTE-information[6]) as well as text written by the user. It is also possible to attach images or video to the report. A report can (but is not required to) also contain information about what indicators it is related to, and possibly even values for the indicators.

Indicators are added in the Indicatorium tool. Here, the user can activate and de-activate indicators, and link active indicators to the reports and other information used in the analysis.

We have performed user-experiments with an earlier version of the Impactorium tool (Nilsson, 2008). The addition of the Indicatorium tool to manage indicators and have a more clear distinction between indicators and reports is a result of the evaluation of the user-experiments. In order to be useful for missions that take place over an extended period of time, it is necessary to separate reports from indicators and allow indicators to, for example, change in value as time passes.

[6] SALUTE: Size, Activity, Location, Unit, Time, and Equipment

Conclusions and future work

While the concepts introduced and presented in the text all contribute to understanding and tackling problems in the decision-maker's situation, we have not operationalized them quantitatively, even less proposed a best practise for decision-making in C2-systems. Therefore, the road ahead should aim for precisely that by investigating methods and experiments to learn about the variability in knowledge and information factors, and the changes in quality of decisions, and the organizational consequences for efficiency and effectiveness.

Background factors

- Experience – How can previous experiences be formalized in terms of similarity in operation, team, operational environment? What is the impact? Can experience be a negative factor?
- Knowledge – How can different types of knowledge (e.g., facts, understanding, ability, expertise) be tested in a meaningful way? To what extent can they replace experiences from previous operation?
- Learning – From moments of reflection about the situation picture, to acquiring expert knowledge, to following the situation development over long periods, what is the role of learning in decision making?
- Expectations – How do expectations help and limit our information space? What is the exact relationship to experience and knowledge in different situations? How can we proceed more efficiently by taking our own expectations into account?

Situation factors

- Uncertainty – What is the relative importance, common ways of overcoming, and potential use-cases for decision-aids with regards to different types of uncertain information (lack of, contradictory, uninterpretable, invalid, unknown source)? How is it related to lack of knowledge? How well do we know our current organizational status?
- Negative information – What is the usability of description logic to express NI in a formalized way to store and report important NI? How can it contribute to reasoning about the situation (e.g., pruning alternative courses of adversary actions or excluding reconnaissance areas)?
- Indicators – What is the relative importance of different types of indicators? Can we overcome subjective biases and shortfalls by including model-based conclusions in a decision aid?
- Insecurity – How will stress and experienced risks change the decision quality? Can we define situations where reasoning becomes so degraded that a decision-aid should be given higher authority?

Decision and action factors

- Planning – What types of long, mid, and short term plans guides decisionmaking in a quickly changing situation? How "general" can a plan be for both meeting the challenges of a changing environment and enable preparedness and relief for the decionmaker?
- Organization design – What types of organizational structure will be most successful in agile responses, given the decision-aids that are available today and tomorrow? If authority is distributed, will decisions be made in more insecure (field) environments?
- Time factors - Are there known schedules, events and orders, intervals, and other time aspects in uncertainty and security related phenomena? To what extent can such knowledge guide information requests and change the space of opportunities for decisionmaking and acting? For instance, are perceived threats smaller or bigger, taking the time-factor into account? Further, are prognoses beyond a certain time horizon too complex? When is it better to postpone a decision?

For all these sets of factors interesting specific questions exist with respect to decision aids. Yet, perhaps most important is how the factors relate to each other and whether shortfalls in one (e.g., knowledge or certain information) can be overcome by another (e.g., automated reasoning tools). The way to proceed would need careful and deliberate investigations, in which methods may need to be developed. For instance, how can we formalize knowledge and experiences? Simple testing may be inadequate. Can we measure the effectiveness and efficiency of a single decision? Should it be compared with another decision/activity? With no decision/activity? It would also be useful to conduct experiments where as many variables as possible are controlled. This would be beneficial not only for constructing decision-aids, but also for determining how an organization should be designed and what skills, knowledge and experiences are required in that organization.Again, illuminating the interrelationships between the listed factors would an important key for unlocking the door to agile and effective organizational responses.

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