Mind the Gap:
Human Decision Making and Information Fusion
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Abstract
Information fusion, i.e., the automatic integration of information from multiple sources, is an advancing research area which can assist decision makers in enhancing their decisions. Most information fusion research so far has had a technical focus and has paid relatively little attention to human decision making processes. Hence, through both theoretical and empirical studies, the research presented in this licentiate thesis seeks to characterise the interdependencies between human decision making and information fusion. The work presented constitutes different building blocks for a framework for the information fusion community. The initial framework promotes a user (decision maker) centred perspective and is presented as an instrument with which to understand the various ways decision makers can influence information fusion systems and processes.

Keywords: Information Fusion, Decision Making, Distributed Cognition, Decision Support.

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Finally, many thanks goes to my family for always being there for me. I made it!
Publications

This licentiate thesis is based on research performed by the author of this thesis at the University of Skövde and includes the following papers:


Other publications and manuscripts written by the author outside the scope of the thesis are as follows:


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1. Introduction

This section introduces the research areas of human decision making and information fusion, the motivation for the given research problem. The overall research approach in terms of its methodology and included papers is presented.

1.1 The Gap between Human Decision Making and Information Fusion

As humans, we have extraordinary skills which help us both to interact with the surrounding environment and to interpret situations and various pieces of information we encounter on a daily basis. Decision making is a central part of this process and a cognitive capacity we constantly utilise, to some extent. As new technologies are developed and introduced into our lives, decision making becomes increasingly complex, and new challenges arise. Today, we have the possibility to access an increasing amount of information and in some cases we have to make use of all that information to be able to make an informed and successful decision.

How we actually make decisions is a research area which has been studied for centuries in various disciplines. The traditional view (i.e., classical decision making (for a definition, cf. Patel, Kaufman & Arocha (2002, p. 52)) has been that we are rational beings who can make an objective choice amongst a set of alternatives. However, many of our decision making processes do not conform to this neat logical view founded in economic theory. Therefore, more recently, the dynamic nature of decisions has been gaining increasing recognition, and is now an established research area commonly referred to as naturalistic decision making (Zsambok & Klein, 1997).

With regard to the current situation, Tien (2003) argues that we are living in the “information stage” (following the previous mechanical and electrical stages), which actually can be claimed to share many of the characteristics of naturalistic decision making. The information stage focuses on emerging services dependent on information, that is, information technology, which is mostly based on multiple data sources. While information technology, and information in particular, is a requirement for robust and timely decision making on the one hand, on the other, a common problem is that “we are awash in data but starved for information” (Tien, 2003, p. 104). The question is: How can we make effective decisions in this kind of environment?

Interestingly, information fusion (IF) has been suggested to be a solution which partly addresses the above described problem, that is, “while information technology can transform a data poor situation into a data rich environment, the fact remains that data needs to be fused and analyzed effectively and efficiently, in order to provide appropriate information for intelligent decision making” (Tien, 2003, p. 104). Due to the current development of complex information technologies, there is an increasing recognition of the power of IF. Actually, more recently, IF systems (e.g., computer systems which fuse information from multiple sources) have also received attention.
outside the defence domain, from where the concept originated. Today, IF systems can be found in various domains characterised by large amounts of data (Hall & Llinas, 2001; Hall & McMullen, 2004) such as within crisis management and automated manufacturing. More specifically, the IF research field encompasses¹:

> “the theory, techniques and tools conceived and employed for exploiting the synergy in the information acquired from multiple sources (sensor, databases, information gathered by humans etc.) such that the resulting decision or action is in some sense better than (qualitative or quantitative, in terms of accuracy, robustness and etc.) than would be possible if any of these sources were used individually without synergy exploitation” (Dasarathy, 2001, p. 75)

As stated above, the focus of IF research is on the exploitation of information from different sources in such a way that, ultimately, better decisions can be made. Even though it can be argued that users are implicitly accounted for in this definition, the traditional focus within IF research has been on the actual process of combining large amounts of, sometimes dissimilar, information in a more comprehensive and easily manageable form (Hall & McMullen, 2004). This technical focus has resulted in the development of many technological advances in areas, such as probability and statistics, decision and estimation theory, pattern and image recognition, various approximate reasoning techniques, such as fuzzy logics, and other artificial intelligence tools (Dasarathy, 2001). With the computational techniques outlined, IF can be used to support and enhance users’ decision making processes.

However, there has been little relatively little interest of performing investigations of human decision making processes or other cognitive aspects in the IF research domain so far (Hall, Hellar, McNeese & Llinas, 2007). Bearing that in mind, not only are the decision making processes of users being ignored, but also the users’ possible contribution to the success of the IF process. Although the human cognitive aspect of IF has received limited attention, it has long been indirectly recognised as an important consideration for IF research. More recently, one can see an increasing acknowledgement of the importance of the actual users and their contribution to IF. For instance, it has been argued that “without human inputs, the DFS [Data Fusion System] refinements … may be time consuming and useless” (Blasch, 2003, p. 463) or “[b]y rethinking the HCI … we may be able to re-engage the human in the data fusion process” (Hall & McMullen, 2004, p. 336).

Despite these acknowledgements and the growing interest in user aspects, no clear overall picture of the interaction between IF systems/processes and the users’ utilisation of such systems to support decision making has yet emerged from the IF community. With few exceptions (e.g., Blasch & Plano, 2003), in most IF research,

¹ Today there is no agreement on standard characteristics or a general agreed upon definition of IF (for a review of existing definitions, see Boström et al., 2007). Therefore, a broad description of the research field (presented in the International Journal of Information Fusion) has been chosen here.
users of IF systems are considered the mere receivers of fused data. In fact, it has been argued that “what is missing from previous research is that the users drive the control process, from the inception of sensor designs to fusion algorithm approval” (Blasch, 2006a, p.1). It has been argued that there are interdependencies between users’ decision making processes and IF systems (Hall et al., 2007) which are not to be underestimated. It should be understood that a fusion process utilising the previously outlined computational techniques is not more effective than its possible utilisation by users in their decision making processes. Thus, today, the focus is on the technical aspects of IF, not on how to actually support users’ decision making processes by exploiting IF in order to make better decisions.

This is a common problem not only in the IF community. For instance, in computer-supported collaborative work (CSCW), Ackerman (2000) refers to this trade-off as the social-technical gap, that is, “the divide between what we know we must support socially and what we can support technically” (p. 179), which has been identified as an important challenge for future CSCW systems. Similarly, in order to bridge the above identified gap between decision makers, on the one hand, and IF technology, on the other, we need to have a better understanding of the interaction between users’ decision making processes and IF systems which should support those processes. In fact, it has been argued that in “recognizing the need for automation [in IF] to help navigate complex and large problem spaces like those in NCW [network centric warfare], it is equally important to recognize the critical role that humans play in these decision making tasks” (Cummings & Bruni, 2005, p. 1). Furthermore, “[a]ll of the data fusion models described recognize that decision making and situation awareness are components of a complete data fusion system. However, the ability of the data fusion models to effectively represent the issues of situation assessment and decision making fall outside the traditional scope of the field” (Hall et al., 2007, p. 6).

Another limitation is that currently existing studies within IF are mostly being performed in military settings (Bossé, Roy & Wark, 2007). Due to today’s wide usage of IF systems in, e.g., manufacturing, civic security, crisis management, bioinformatics, to name a few, there is an additional need to develop theoretical frameworks which can reach beyond the military domain.

1.2 Thesis Objectives and Approach

The aim of this licentiate thesis is to analyse the gap between IF and human decision making. In other words, the aim is to answer the research question: what are the interdependencies between human decision making and IF systems/processes? Thus, from a cognitive science (human factor) perspective, the explorative research documented in this licentiate thesis seeks to contribute to IF research by providing insights concerning the possible interdependencies between users and IF systems in terms of their ability to support human decision making. More specifically, the
research approach is to iteratively combine theoretical and empirical work to identify the buildings blocks for a future framework (to be completed in the subsequent PhD thesis) which captures the interdependencies between human decision making and IF (cf. Figure 1). Hence, the focus of the thesis is to first characterise the areas of human decision making and IF research, and then, investigate the interdependencies between the two of them. The theoretical framework of distributed cognition (Hutchins, 1995a) is proposed as a way to investigate this interdependency. For more information regarding the research approach, see Section 3.

Figure 1. Schematic overview of the research approach, viewing the licentiate thesis as the first step towards developing a framework which captures the interdependencies between human decision making and information fusion.

1.3 Overview of Thesis and Included Papers

The licentiate thesis is organised as follows: this introduction has briefly described the motivation for the research. In Section 2, a literature review describing central concepts is provided, that is, covering areas of IF, human decision making, and distributed cognition. The research approach is identified in Section 3, while Section 4 contains a summary of the included papers which describes the initial studies. In Section 5, the combined results and implications of the included papers are discussed, while possible future work towards the PhD is discussed in Section 6.

The thesis includes the following papers: Paper I presents a theoretical discussion of the implications of utilising a distributed cognition perspective in IF research. Paper II provides a theoretical discussion regarding the possibilities of using IF systems for decision support. Paper III is a literature analysis characterising user interaction and the factors affecting that interaction. Paper IV comprises an empirical investigation in which a distributed cognition perspective has been applied to analyse a
semi-automated IF process. *Papers IV and V* are empirical investigations of IF systems’ implications for human decision making. The underlying approach has been to iteratively combine *theoretical* investigations with *empirical* studies to understand and characterise the interaction between users and IF systems (cf. Figure 2).

![Figure 2. Schematic overview of the included papers. The categorisation of the papers illustrates the underlying research approach. (Abbreviations IF: Information Fusion; DC: Distributed Cognition; DSS: Decision Support System; HCI: Human Computer Interaction)](image)

As illustrated in Figure 2, Paper I is part of the theoretical grounding for the empirical work reported on in Paper IV, Paper II is the theoretical grounding for the empirical research presented in Papers V and VI, Paper III consists of both a theoretical and an empirical investigation. For more details on the chosen research approach, see Section 3. The following section presents the background of the included papers.
2. Background

In order to be able to bridge the gap between IF and human decision making, and to analyse the possible interdependencies between the two, this section starts by introducing main concepts and models commonly used in IF research. A presentation of relevant insights from cognitive science in terms of human decision making and distributed cognition is then provided.

2.1 Information Fusion

As noted by Hall and McMullen (2004), the use of fusion is not new; humans and animals have used combinations of different senses since the dawn of time in order to survive. Today, due to the current expansion of complex information technology, the concept of IF is becoming increasingly important with regard to developing new technology. The main reason is the possibility of exploiting (the synergy) and integrating data from different sources (cf., Figure 3a and 3b), and thereby processing huge amounts of data from many objects, simultaneously, in order to reach a presuming, better decision (cf. description of IF, p. 2).

![Figure 3a](image)

**Figure 3a.** Illustration of the concept “fusion”. By using majority voting one could reach a better decision (cf., Condorcet’s jury theorem, Condorcet, 1785).

![Figure 3b](image)

**Figure 3b.** Illustration of the concept “fusion”. By using multiple sensors registering different aspects of a particular object, a better understanding of the object can be achieved through fusion.

Actually, empirical studies have shown that the performance of the overall system improves with the number of information sources, that is, sensors (Hall & Llinas, 2001). It has been argued that “[f]usion of relevant sensor data … has proven effective in reducing false alarm rates, increasing confidence levels in early fault detection, and reducing time to failure of degraded condition requiring maintenance action” (Roemer, Kacprzynski & Orsagh, 2001, p. 1). In this context, an IF system refers to the actual computer system that collects, processes and exploits information originating from different sources, with which users could interact and, in extension, be supported by (note that this is in line with the traditional view in IF which does not include humans as part of an IF system). There have been different attempts to characterise IF systems,
for example, Bloch and Hunter (2001), Bossé et al. (2006), and Dasarathy (2000). Actually, in the current literature, there is no general consensus of the components of an IF system, and consequently, no agreement of standard characteristics and capabilities of IF systems. This is at least partly due to the immaturity of the research domain (for instance, the annual IF conference celebrated its 10th anniversary in 2007). Despite the lack of consensus, one could claim that the basic component of an IF system is that the system needs to receive information from multiple information sources. Information sources can be, for example, active sensors (radar), passive sensors (infrared, visible, acoustic, magnetic and seismic), human sources (intelligence gathering) or data archives (weather, financial data) (Dasarathy, 2000). Alternatively, one could distinguish the different information sources by classifying them as either past (e.g., databases), present (e.g., active sensors), or future (e.g., simulations) information sources.

The core of IF systems is the actual process of integrating the information from multiple sources into a format which can support decision making, this is referred to as the IF process. The very reason for wanting an automatic IF process is the fact that information received from different sensors could be combined in such a way that generated more or better information than originally started out with (Hall & McMullen, 2004). For example, to fuse information/data from different sources one could reduce uncertainty (comparing information from different sources), increase accuracy (information from different sources complementing each other) or increase robustness (the possibility for redundant information) (Bossé, Guitouni, & Valin, 2006) (cf. Figure 3a and 3b). Hence, more or better information than originally started out with can be achieved by combining the different sources.

The IF process is most commonly captured by the so called JDL model (Hall & Llinas, 2001). The JDL model was developed in 1985 by the U.S. Joint Directors of Laboratories (hence, the name ‘JDL’) for the purpose of having a common understanding across the different application domains which use IF, thus allowing different stakeholders within the fusion community to have a common ground. In general, the model describes how information is transformed from sensor data to information which a user can use for decision making.

As illustrated in Figure 4, the process starts by collecting information via different sensors/sources (e.g., radar, sensors, databases, optic camera). The IF system can be used for many different purposes, for instance, it can include Level 1 functionality which involves locating and tracking objects, such as vessels at sea. Furthermore, the system can include Level 2 functionality, such as automated inference for finding relationships in the collected information, such as a clustering of vessels in a specific group. In addition, the system could include Level 3 functionality, such as predicting future states, while Level 4 functionality involves refining the fusion process. An IF system can be tailored towards one or several levels of the JDL model.
It has been argued that IF can be an effective tool in situations dealing with large amounts of data, that is, “this situation creates a significant information overload to the users in many operational environments, when the data is presented in a ‘raw’ form. Without advanced data/information fusion architectures and techniques, the user, often resorts to viewing that data from a single sensor or single database viewpoint” (Akita, 2002, p. 1). In addition, Steinberg, Bowman and White (1999) acknowledge the possibility of fusing IF for refining and reducing information to support humans in their decision making activities. However, one must remember to present the information in such a way that it conveys important aspects of the information and so the user can develop trust towards the system (Bisantz, Finger, Seong, & Llinas, 1999).

User aspects of IF systems should not be underestimated. It has been argued that “the purpose of a fusion system should be tailored towards supporting a decision-maker” (Bossé et al., 2006). However, this is not an easy task. Monitoring IF systems is a challenging activity for humans, not only due to the amount of information, the high number of variables involved, or the opacity and complexity of the data mining techniques used in the detection process, but also other factors, such as time pressure, high stress, inconsistencies as well as the imperfect and uncertain nature of the information. In fact, it has been suggested that a Level 5 should be added to the JDL model (Blasch, 2006a; Blasch & Plano, 2002; Hall, Hall, & Tate, 2000) to account for user (human decision making) issues. However, Level 5 is not widely acknowledged by the IF community (Hall et al., 2007), neither well explored, that is, “the fusion community has typically overlooked the role of the user by designing them out of the system” (Blasch, 2006a, p. 3).

**Figure 4.** A schematic view of typical IF systems functionalities according to the Levels of the JDL model.

<table>
<thead>
<tr>
<th>Level 1: Object assessment</th>
<th>Level 2: Situation assessment</th>
<th>Level 3: Impact assessment</th>
</tr>
</thead>
<tbody>
<tr>
<td>e.g., sensors, databases</td>
<td>e.g., tracking</td>
<td>e.g., forecasting</td>
</tr>
<tr>
<td>e.g., humans, weather, objects, other systems</td>
<td>e.g., data association</td>
<td>Predictions based on situations</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Level 4: Refinement process</th>
</tr>
</thead>
<tbody>
<tr>
<td>e.g., clustering</td>
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</table>
Examples of IF systems

The defence domain is, by far, the most developed research area to exploit IF, and it is here that you find most examples of IF systems. For instance, IF is used in the area of image processing in order to identify objects (e.g., Filippidis, Jain & Martin, 2000); IF technology is also used to track objects in order to aid surveillance (e.g., Blasch & Plano, 2002; Mevassvik & Løkka, 2000); predict the actions of the enemies (e.g., Bell, Santos Jr, & Brown, 2002); while the main purpose could also be to support the overall success of a mission (e.g., Louvieris et al., 2005).

More recently, there is promising IF research in other domains, typically characterised by large amounts of data. For instance, Dasarathy (2000) presented an overview of different industrial applications using IF technology focusing on the technical fusion process. Another domain is the manufacturing domain; Roemer et al. (2001) conducted a comprehensive study where they investigated different fusion algorithms and identified the contribution of IF within “health” management systems to be used in manufacturing. More specifically, they were able to show the benefits of combining individual vibration features (i.e. utilise fusing techniques) to aid the detection of cracked gear teeth through developed metrics. Similarly, Volponi et al. (2004) developed a system based on IF technology which could diagnose engines. Furthermore, it has been shown that IF could be used in the retail domain (Loefstroem et al., 2006).

Other examples of IF systems include those used for weather predictions (Treinish, 2001). Fan, Gordon, and Pathak (2006) used a data fusion approach in an information retrieval decision support system (DSS). Another further example is Yen et al. (2006) who developed CAST, a system which assisted teams on making critical decisions under time pressure. The idea was to support the anticipation of information needed by other team members. IF was employed especially to reduce users’ cognitive workload. Delen, Sharda, and Kumar (2005) developed a web-based decision support in which IF techniques (combining two forecast/predictions models) helped managers make better decisions regarding important movie characteristics. Fusion techniques have also been used in facilitating the prevention of cyber attacks (Mathew, Shah, & Upadhyaya, 2005).

The wide usage of IF systems implies that there is an increasing recognition of the value of IF techniques not only outside the defence domain but also outside the IF community (e.g., two of the mentioned studies are published outside the IF community, i.e., in the Decision Support Systems Journal). Notably, a common thread among the listed examples of IF systems is that they provide technological descriptions in terms of architecture and algorithms, etc. As such, user aspects have received limited or no attention. Hence, there is a need of more research that intends to capture the interaction between IF systems and users, which also goes beyond the defence domain.
2.1.1. Current Models and Frameworks in Information Fusion

Over the years, different models and frameworks have emerged from the IF community. The most influential models and frameworks are explained in this section together with an assessment of their ability to also capture the human decision maker (that is, models and frameworks mentioned in IF handbooks such as Hall and McMullen (2004), and Hall and Llinas (2001)).

**Capturing the Information Fusion Process**

The JDL model is a functional model which explains the hierarchical process of fusion, bottom-up (cf. Figure 5). The model captures the fusion process by describing how information transforms from sensor data to information which a user can apply in decision making. The model is read from left to right, beginning with readings from different sources of information, and ends with a computer interface. While these levels may be viewed in a hierarchical order, it is important to note that the JDL model should not be interpreted as a process model indicating a linear flow, unidirectional (i.e., perform Level 1 first, then Level 2), but rather as showing different categories of functions which can be used independently of each other (Hall & Llinas, 2001). Nevertheless, for simplicity, the functions are explained in their hierarchical order.

Various extensions of the JDL model have emerged over the years (Blasch & Plano, 2002; Hall & McMullen, 2004; Steinberg & Bowman, 2001). In its current state, the JDL model comprises the levels 0-5, however, it should be noted that whether or not levels 4 and 5 are actually “levels” is a discussion within the IF community (Hall & McMullen, 2004). Levels 4 and 5 could, in a sense, be treated as meta-processes, controlling/refining the previous levels (hence, not actually levels, per se). In particular, the very existence of a level 5 is not accepted by all researchers in the fusion community (Hall et al., 2007). However, for the purpose of this thesis, levels 0-3 are
first explained as different *assessment* functions, followed by levels 4 and 5 as *refinement* functions\(^2\). Firstly, the definitions of the levels 0-3 are as follows:

**Level 0 pre-processing** (*signal assessment*): this level pre-processes data at the individual sensor in order to not overwhelm the system with raw data (Hall & McMullen, 2004).

**Level 1 processing** (*object assessment*): this level involves “fusion of multi sensor data to determine the position, velocity, attributes, characteristics, and identity of an entity (such as an emitter or target)” (Hall & McMullen, 2004, p. 2).

**Level 2 processing** (*situation assessment*): this level involves “automated reasoning to refine our estimate of a situation (including determining the relationships among observed entities, relationships between entities and the environment, and general interpretation of the meaning of the observed entities)” (Hall & McMullen, 2004, p. 2). This level is sometimes referred to as threat refinement/assessment.

**Level 3 processing** (*impact assessment*): this level involves “projection of the current situation into the future or define alternative hypotheses regarding possible threats or future conditions” (Hall & McMullen, 2004, p. 2). This level is sometimes referred to as threat refinement/assessment.

All of these levels (0-3) deal with some form of assessment, for example, an estimation of the current situation. Firstly, prior to fusion, the data may be pre-processed (Level 0), which involves assessment of the signal from the sensor in order to correct for biases, standardise inputs, and extract key information, for example, functions such as image processing and signal processing. The second function is object assessment (Level 1), which concerns the combination of data from different sensors to obtain estimates of an object’s position, motion, attributes, characteristics or identity. This function involves classical techniques such as target tracking and pattern recognition. Level 2 refers to a collection of functions which assess the situation and make interpretations of objects’ relationships as well as their relationships to the environment. Typically automated reasoning and artificial intelligence techniques are used. The difference between the two levels is that Level 1 identifies objects, while Level 2 focuses on the meaning of those objects. In other words, Level 1 involves attribution-based state estimations and Level 2 fusion involves relation based state estimations (Hall & Llinas, 2001). Impact assessment (Level 3) concerns the projection of future states, that is, it assesses possible threats, risks, and impacts. A distinguishing feature is that you are

\(^2\) A similar categorisation of the JDL levels is provided by Blasch and Plano (2002).
assessing the possible reaction to your own action at this level, that is, you are dealing with a threat which can counteract.

There are attempts at these levels, to some extent, to incorporate human capabilities by exploring the ideas of cognitive modelling. Cognitive modelling is a technique (built upon human processing) which has had relatively little impact on the IF community so far. The aim of cognitive modelling is to utilise information about how humans process information and simulate it in a computer system. For instance, Jakobson, Lewis, and Buford (2004) used the concept “cognitive fusion” to address the problems at levels 2 and 3 in the JDL model. In this case, cognitive fusion refers to pattern recognition in the sense that multi-source data is being fused using cognitive processing techniques. The cognitive fusion model has three basic functional qualities (situation, decision, and knowledge awareness) where the cognitive fusion architecture is built upon real-time EC (event correlation) and CBR (case base reasoning). Another example is a cognitive assessment of a battle space which resulted in a three layered model (Looney & Liang, 2003): Fusion preparation- cluster area targets. Situation assessment- determines unit type, size and purpose using case base reasoning and databases. Threat assessment- assesses enemy intention and action using fuzzy belief networks. The study indicated that one can use a multi-stage process of IF to infer information for decision making.

In addition to the techniques used at the assessment levels (0-3) there are refinement levels. However, the refinement functions could be treated as meta-processes controlling the previous levels 0-3. Levels 4 and 5 are sometimes referred to as a part of resource and knowledge management tasks (Blasch & Plano, 2002). The assessment levels of the JDL model may seem independent of the refinement levels of the JDL model, for instance, the users’ decision making process. However, as Blasch and Plano (2002) point out, it is important to consider the higher levels of the JDL model even when developing techniques or algorithms intended for one of the lower levels (i.e., levels 0-3), because they are interdependent (i.e., the higher levels control the lower levels). In detail, one needs to incorporate the possibility of decoupling information processing algorithms and isolate particular functions in order to enable future “user refinements”. If this is not allowed, the user may not be able to use the system effectively to solve his/her particular needs, i.e. the user is not able to refine the process (activate/deactivate functions) according to the needs and goals of the current situation. More specifically, the refinement levels can be defined as follows:

Level 4 processing (process refinements): “a meta process that monitors the ongoing data fusion process to improve the processing results (namely improved accuracy of estimated kinematics/identity of entities and improved assessment of the current situation and hypothesized threats” (Hall & McMullen, 2004, p. 2).
Level 5 processing (cognitive refinements): “interaction between the data fusion system and a human decision maker to improve the interpretation of results and the decision-making process” (Hall & McMullen, 2004, p. 2). Further, level 5 has also been referred to as “user refinements” (Blasch & Plano, 2002; 2003) which, in addition to the previous definition, would incorporate functions which the user could employ in the system to manually refine the IF process.

As seen in the definition, Level 4 concerns the overall success of the fusion process. In other words, one could say that Level 4 controls the process with the goal of improving the real-time performance of the ongoing data fusion. As illustrated in Figure 4, Level 4 is situated on the border (both inside and outside the fusion process), that is, the figure acknowledges the fact that the fusion process must account for both fusion system as well as operational needs. Often these needs contradict each other and may require resolution by a human, for example, the user of the system.

As Hall and McMullen (2004) explain, Level 5 deals with “[m]onitoring the ongoing interaction between the data fusion [computer] system and a human decision-maker; optimization of displays, interaction commands, focus of attention to improve the human/computer effectiveness” (p. 40). In other words, Level 5 changes the output from the fusion process into displays and meaningful information for the user. Functions to be performed are focus of attention management, search engines, cognitive aids, and query decomposition (Hall & McMullen, 2004). In addition, Blasch and Plano (2003) developed a taxonomy which defined the interaction between users and IF systems in terms of user behaviour (neglect, consult, rely, interact) and user functions (planning, organising, coordinating, directing, controlling). The defined user behaviours are related to the degree of automation of the IF systems, while the defined user functions relate to sensor management. To be noted, the taxonomy is not explained in detail by Blasch and Plano, however, it provides an indication of the possibilities users provide.

Levels 4 and 5 are quite similar, although, there are some distinguishing features. For example, while Level 5 is interpreted as providing information in such a way that the users’ decision processes and interactions with the system could be enhanced, level 4 on the other hand, has no consideration about how to present and involve the users in an effective way. In addition, when Level 5 is viewed as user refinements, the main difference between levels 4 and 5 is the fact that in level 4 it is the system itself which refines the ongoing process whereas in level 5 it is the user who initiates and controls the refinements process, from a user’s perspective (on the basis of the particular need of the user have at the time). In this context, from a practical point of view, taking over from level 4 to level 5 means taking over control of, for instance, an individual remote sensor, tactician or vehicle from the automated system (Blasch & Plano, 2002). However, the incorporation of level 5 into the JDL model has not yet
achieved common usage within the IF community (Hall & Llinas, 2001; Hall & McMullen, 2004; Hall et al., 2007).

The JDL model is under constant revision; most recently, a Level 6 has been suggested (Blasch, 2006a). This level is defined as follows:

Level 6 processing (mission management): “Adaptive determination of spatial-temporal control of assets (e.g. airspace operations) and route planning and goal determination of support team decision making and actions (e.g. theatre operations) over social, economic, and political constraints” (Blasch, 2006a, p. 2).

In parallel to the JDL model, other models of the data fusion process have emerged and been proposed within the IF community. However, it should be noted that these models have not achieved the same popularity as the JDL model. This might be due to the fact that the JDL model was the first one created and more recent models might not provide an as holistic perspective as the JDL model. The additional models capturing the fusion process are as follows.

Firstly, the Functional Model (Dasarathy, 1994) has been developed with the purpose of categorising different fusion functions, similar to the JDL model. The model consists of a matrix of input (what is processed) and output functions (what is the result), divided into data, features and objects. The benefit of this model is that it is easy to fit different fusion techniques into the different fields of the matrix (Hall & Llinas, 2001). It should be noted that this model captures the fusion process as a data driven process (Hall & Llinas, 2001), hence, the users’ role (interaction) for the success of the fusion process can not be accommodated in it. Moreover, Steinberg and Bowman (2001) have provided a mapping between Dasarathy’s functional model and the JDL model.

The Object Oriented Reference Model (Kokar, Bedworth, & Frankel, 2000): Kokar et al. approached IF from a design process perspective. They proposed a new object oriented reference model for data fusion systems where the data fusion process is top-down (the system constraints are considered first). Within this model, they argue that human capabilities can be easily accommodated, since no distinction is made between human and computer objects until the model is viewed from the realisation perspective. However, explicit examples of how users are accommodated are yet to emerge.

The Omnibus Process Model (Bedworth & O’Brien, 2000): this model aims to capture the IF process by using a general terminology. The model includes a process flow chart, a dual perspective prescription for using it and a structured repository of fusion knowledge. In detail, the Omnibus process model combines different models,

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3The JDL model could be used for many purposes such as a tool to describe the research domain of IF as well as a tool for engineers to communicate regarding functions of IF systems.
such as the decision making model, OODA-loop (Observe-Orient-Decide-Act) (Boyd, 1987), with more data fusion process models, for example, Dasarathy’s functional model (Dasarathy, 1994), the JDL model (Hall & Llinas, 2001), and the waterfall model (system development process model). It is argued that the omnibus model enables the merging of the system-goal and the task-oriented point of view. Moreover, feedback loops are explicitly acknowledged in the model. Due to the integration of the OODA loop, one could argue that users are implicitly accounted for. However, when presenting the Omnibus model, Bedworth and O’Brien (2000) provide an extended review of different fusion process models where decision making is still regarded, in a way, as a computational process. For instance, when comparing the different fusion process models, the decision making process is equalised to JDL level 4 and the decide phase in the OODA-loop.

The TRIP Model, Transformation of Requirements for the Information Process (Kessler and Fabian (2001), as cited in Hall and McMullen (2004)): this model captures the data fusion process, although, from another point of view. The focus here is to understand the transformation of information needs/requirements to the applying sensor resources. The model is presented in a hierarchical order as follows: Human information requirements—objective stage—situation stage—information stage—object stage—collection stage—collection evaluation—Observable World. Hence, the role of the user in the fusion process is defined.

In general, “[m]odels in the field of data fusion provide a theoretical and functional representation of the data fusion process; starting from the collection of data from a sensor to the presentation of the meta-data to the user” (Hall et al., 2007, p. 2). Thus, there is an implicit assumption that the role of the user is to perceive the output of the fusion process, scaling down the user to an interface issue where the user can be viewed as an information sink (cf. Table 1). This is exemplified by the fact that interaction is most often viewed as a one-way interaction, that is, the presentation of data without any feedback loop. Also, as illustrated in Table 1, human decision making is not accommodated in the models to a great extent, most often the decision making process is viewed as a computation process in a computer. Hence, there is gap between human decision makers (decision making processes) and IF processes. Attempts have been made to accommodate for human decision making by using additional models, such as the OODA-loop, explained in the following section.
Table 1. Assessment of IF process models and their ability to capture human decision making (i.e., models cited in handbooks of IF, e.g., Hall & McMullen, 2004; Hall & Llinas, 2001).

<table>
<thead>
<tr>
<th>IF PROCESS MODELS</th>
<th>Role of users</th>
<th>Output</th>
<th>Interaction (user-technology)</th>
<th>Orientation</th>
<th>Decision making</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>JDL model (levels 0-4)</td>
<td>Receivers of info</td>
<td>One optimal decision</td>
<td>One way (computer to user)</td>
<td>Function oriented/ data driven</td>
<td>Computer automated decisions</td>
<td>Hall &amp; McMullen (2004)</td>
</tr>
<tr>
<td>JDL model (levels 0-5)</td>
<td>Active components</td>
<td>Human decision support</td>
<td>One way (user to computer)</td>
<td>Function oriented/ Goal directed</td>
<td>Human decisions</td>
<td>Blasch &amp; Plano (2003)</td>
</tr>
<tr>
<td>Dasarathy’s functional model</td>
<td>Not applicable</td>
<td>Data, features, objects</td>
<td>One way (computer to user)</td>
<td>Theoretic (function) oriented</td>
<td>Computer automated decisions</td>
<td>Dasarathy (1994)</td>
</tr>
<tr>
<td>Object oriented model</td>
<td>Integrated components</td>
<td>Decision</td>
<td>One way (computer to user)</td>
<td>Top down directed</td>
<td>Human/ computer decisions</td>
<td>Kokar et al. (2000)</td>
</tr>
</tbody>
</table>

Capturing the Decision Making Process

The most accepted and most used decision making process model within IF is Boyd’s OODA loop (Observe-Orient-Decide-Act) (Boyd, 1987), which originated from the military domain. It is the most referenced model in conference papers and handbooks of IF (cf. Hall & Llinas (2001); Hall & McMullen (2004)), and used within IF as a general model of decision making. However, the intended usage of the model was to explain why American fighter pilots were more successful than their opponents in the Korean War. The model consists of four activities (cf. Figure 6):

Observe. This is the first activity which involves observation of the environment by noting distinguishing features. Originally, this activity referred to detecting an opponent’s aircraft.

Orient. This activity positions you in the environment. It originally referred to the activity of positioning your aircraft towards your opponent’s aircraft so you were in a good position for the next step, make a decision.

Decide. This activity involves deciding what to do next, based on the information from previous stages.
**Act.** This activity basically means that you carry out and implement your decision. Originally, this referred to the actual pressing of the trigger in the aircraft which would shoot down the opponent’s aircraft.

**Figure 6.** The OODA-loop (adapted from Boyd (1987)).

The activities are positioned in a cyclic and iterative way, with the first activity being *observe* (most often, but not necessarily), and the final one being *act*, before it starts again with a new *observation*, as exemplified in Figure 7. There is no end point in the loop, however, where the loop would naturally stop due to a successful activity or when there is nothing more to observe, it stops due to a lack of input. The aim of the model is to enable faster decisions by identifying both your own decision steps and those of your opponent, thereby being able to act before your opponent. Boyd (1987) showed that the Americans were superior in all four activities of the OODA loop, enabling them to “get inside” the opponent’s decision making process (i.e., their OODA-loop) and win the battle. Despite the fact that the OODA-loop is reasonably old and simplistic, it is the most prominently used model for capturing the command and control process, and also the most commonly referenced decision making model within the IF community today (Hall & McMullen, 2004); perhaps due to the current defence heritage in IF.

More recently, Boyd developed a more general model that expands the original OODA loop to accommodate various forms of combat, not only a fight between two individual aircrafts. While the original activities in this new OODA-loop are still the same, the actual activity is outlined in more detail and the interrelationships between the activities are identified (cf. Figure 8).
As a result, it is now a process model, with multiple loops, rather than a single one, and it is implied that you always start with an observe activity. As discussed by Boyd (1987), Brehmer (2005), and Hall and McMullen (2004), the observe activity not only concerns making observations and monitoring the situation, but also about gathering information which could later be used to confirm or refute hypotheses in the subsequent decision stage. The orient activity is not only about a physical orientation in the environment (that is, to position oneself in the environment so a decision can be made about what to do). It also includes a mental orientation concerning an understanding about how the data fits with previous experience, what changes have taken place since the last time, and how does it correlate with your hypothesis? The decide activity is concerned with generating alternative hypotheses and determining which has the most severe consequences. Finally, the act activity has not changed since the original version of the OODA loop, that is, after a decision there is still a need to take action upon that decision. This may involve a military operation, collection of data, redirection of information resources, additional modelling, and so on.

In addition, Rousseau and Breton (2004) have suggested the M-OODA loop (modular OODA loop) as an extension of the original OODA loop. The new model accommodates teams (organisations) rather than individuals and instead of the concept of performing a set of activities, the model comprises of different modules, namely: data-gathering (observe), situation-understanding (orient), action-selection (decide), and action-implementation (act). The model is suggested as a response to the criticism of the OODA loop being a simplistic, non-dynamic decision process model. It is argued that there is more to a decision than can be categorised and visualised with the OODA loop.

Similarly, Brehmer (2005) argues that the original OODA loop provides a static picture of decision making, and therefore proposed the dynamic-OODA (D-OODA) loop (Brehmer, 2005) as an attempt to include the dynamic nature of the command and control process. In this version, the dynamic nature is accommodated by explicitly introducing feedback loops and acknowledges the fact that the different functions in
the model partly overlap. The model has been suggested in a military setting to capture the actual decision process made by commanders, by combining ideas from the OODA loop and cybernetic models. The model is divided into different functions as follows: information collection, command concept, sense-making, planning, decision/order, military activity, and effect.

Moreover, *Endsley’s Situation Awareness (SA) model* (Endsley, 2000) is a commonly used model within the IF community to capture situation awareness (e.g. Blasch and Plano (2002), Bossé et al. (2007), Salerno et al. (2004), Paradis et al. (1999), Hall et al. (2007)), which can be seen as a pre-stage for the decision making process. The model explains the core of human situation awareness and the various factors affecting situation awareness. The model is divided into three different mental processes, that is, *perception, comprehension, and projection*. Here, it is believed that situation awareness is a state of knowledge resulting from a process referred to as situation assessment, which is the process of achieving, acquiring, or maintaining situation awareness. In the IF community, having a certain level of SA is believed to be a requirement for making good decisions.

![Figure 8. The situation awareness model. Adopted from Endsley (2000).](image)

**Additional Models**

In addition to the IF process models and the specific decision making process models, there are others developed within the IF community which capture limited aspects of the fusion process and/or the decision making process. The additional models exemplify the current development within IF where user aspects are gaining increasing attention. The most promising models with respect to the users and their decision making processes are listed below. However, it should be noted that these models are not extensively used within the fusion community apart from those who developed the models.

Firstly, the *Task/human/technology Triad Model* (Paradis, Breton, & Roy, 1999) was intended to facilitate the development of command and control systems built on data fusion technology. The model was created due to a typical lack of cognitive fit in IF systems design, that is, “[t]here is a tight link between this mental model used to structure and express situation elements and the cognitive process involved in achieving the levels of awareness. This link is known as the cognitive fit...
and requires an understanding of how human perceives a task, what processes are involved, what are the human needs and what part of the task can be automated or supported”. Hence, the triad model emphasises the relationship between users, the task to be performed and the technology executing the task. In other words, the model represents the relationship between the technology (the system designers who need to develop the technology) and humans (human factors specialists have knowledge about the limitations/capabilities of users), as well as the task which needs to be accomplished. An important aspect of the model is that it specifies when to develop requirements. Although it is a good tool when developing new IF systems, it does not detail the actual interaction (interdependency) between the decision maker and the IF system in the final product.

The User Dominant/Machine Dominant Model (Blasch & Plano, 2003) is developed similarly. This model specifically targets the relationship, thus, the interdependencies between users and IF systems. The model specifies different degrees of dominance within IF systems, from user dominant to machine dominant. On the one hand, a system can be user dominant when the user tells the system what to do; there is no freedom for automatization. On the other hand, machine dominant means the “sensor manager” (as similar to process refinement, level 4 in the JDL model) makes the decisions from the information available (fully automated). Apart from these extremes, the system can be somewhere in between. More specifically, the model consists of specific attributes which can indicate level of dominance. The users can initiate (the task to be performed) – delegate (specific tasks to the system) - consider the result from the IF system in their decision making processes. Also, the interaction could be classified as authorities (users have authority over the IF system)- interactive (the task is divided) – submissive (the user is submissive and obeys the system). Furthermore, the interaction could be classified as task–user- monitor oriented, for example, is the role of the user to monitor the system or to use the system for accomplishing specific activities? The lack of response for this model in the IF community might be due to it being an informative model for understanding the different way users can interact with IF systems, however, it cannot be used as an instrument for evaluating or assessing the benefit of IF systems or as a tool to develop new IF systems.

Endsley’s situation awareness model (previously presented) has some off-springs which are specifically adapted to (and by) the IF community, that is, the Situation Awareness Framework (Salerno, Hinman, & Boulware, 2004; Salerno, Hinman, Boulware, & Bello, 2003) and the Dynamic Model of Situated Cognition (Miller & Shattuck, 2006). Firstly, the Situation Awareness Framework (Salerno, Hinman, & Boulware, 2004; Salerno, Hinman, Boulware, & Bello, 2003) is an attempt to combine the JDL model and Endsley’s SA model, and focuses on how to acquire situation awareness. An important aspect of this framework is that they note that “depending on prior knowledge and past experience of the situation both the bottom-up (as presented
by the JDL Model) and the top-down approach (as described by Endsley) are necessary”. Similarly, the *Dynamic Model of Situated Cognition* (DMSC) (Miller & Shattuck, 2006) originated from the discrepancy which existed between different researchers (mainly between operation research analysts and human factors’ engineers) regarding the concept of situation awareness. The model was created to “…illustrate the role played by humans and technology, demonstrating that appropriate consideration of both humans and technology is necessary to understand the process by which an event unfolds” (Miller & Shattuck, 2006, p. 2). Both of these models, which capture the process of situation assessment/awareness, indicate the current recognition that we need to be able to capture technology and human cognitive processes equally, that is, the independency between human decision making and IF (cf. Figure 9). However, in IF, human decision making is not well explored, hence, the following section examines research from cognitive science.

2.2 **Insights from Cognitive Science**

Areas of cognitive science, such as human decision making, which have previously not received sufficient attention in IF, are covered in this section. Furthermore, new concepts for IF, such as distributed cognition, are presented. In order to have a thorough understanding of users’ cognitive processes, such as the decision making process can be seen as the first step towards bridging the gap between human decision making and IF. Actually, it has been argued that a thorough understanding of the users’ decision making processes is needed in order to create an effective system which truly support its users (Zacharay & Ryder, 1997).
2.2.1 Human Decision Making

The interdependencies between human decision making processes and IF provides an interesting trade-off, that is, “[t]he fact that an increase in the number of sensors and the complexity of the network unifying them has engendered an increase in the amount of available data does not necessary mean that officers using that data will make better decisions” (Bolia et al., p. 191). In other words, there is an interesting trade-off between the number of sensors (information pieces) and the quality of the decision where an increase in sensors does not automatically result in a better decision (cf. Section 2.1). Hence, there is a need to better understand how humans really make decisions.

How we actually make decisions is a research question with a long tradition in various disciplines ranging from economics and psychology to human-computer interaction. The result is not a single, cohesive ‘decision making’ research community, but distributed over several disciplines. Consequently, many different types of theoretical frameworks have been developed over the years. Following Lipshitz, Klein, and Orasanu (2001), traditionally, there are two main themes within decision making: (1) theories which explain how we should make effective decisions (e.g., classical decision making, cf. Beach & Lipshitz (1993)), typically explored in economic and finance domains, and (2) theories which explain how we actually make decisions in the real world (i.e., naturalistic decision making (Zsambok et al., 1997)). In the following sections, both views are represented in order to provide an understanding of human decision making.

Classical Decision Making

Classical decision making (CDM) could be classified as a normative kind of decision making, that is, there is a belief that humans can make a rational and objective choice amongst alternatives, and choose the optimal one (Alenljung, 2008). This has also been referred to as traditional decision making, that is, “[t]he term ‘traditional’ is used to designate a large and heterogeneous body of descriptive and prescriptive research that uses normative models (e.g., subjective expected utility, Bayesian theory) as points of reference. This category greatly simplifies some significant differences in perspectives and approaches. ‘Classical decision theory’ is sometimes used to reference the same set of ideas and bodies of work” (Patel et al., 2002, p. 52). Following Patel et al., (2002), this has also been referred to as “rational decision making”. Theories such as Subjective Expected Utility theory (SEU), Multi-Attribute Utility (MAU), and Bayes’ theorem characterise the essence of early CDM theories (Edwards & Fasolo, 2001).

More specifically, SEU is a model of rational behaviour, which believes that a “decision should be reached by summing over the set of alternatives the utility of each alternative weighted by the subjective probability of its occurrence” (Crozier &
Ranyard, 1997, p. 5). This theory was later criticised by Simon who argued that people can make successful decisions by identifying the most satisfactory decision according to their goal, that is, bounded rationality (Crozier & Ranyard, 1997).

In bounded rationality, an assumption exists that rationality is dependent on the decision maker’s information processing capabilities. In other words, the decision maker has a limited capability to evaluate each alternative and reach the most optimal choice, per se, therefore, it is enough for the decision maker to reach the most satisfactory decision. To continue, Bayes’ theorem focuses on how to calculate probability with the emphasis on updating or revising probabilities in light of new evidence (Edwards & Fasolo, 2001). MAU is similar to SEU, but it acknowledges and emphasises on the values of different attributes attached to a specific option. The values can give an aggregated utility, which makes it possible to choose the most optimal decision.

Further, it should be noted that the focus is on how individuals make decisions (in isolation, as opposed to groups/teams), and the studies on which the theory is based (i.e., CDM) are often performed in laboratory settings (capturing activities such as tossing a coin etc.). Interestingly, there is an implicit assumption that this kind of gambling can be an all purpose analogy for making decisions in general (Beach & Lipshitz, 1993). Also, often traditional CDM models such as SEU often assume that the decision making process is a “mechanical procedure” (Crozier & Ranyard, 1997, p. 11), and consequently, they assume that the decision making process (the rules for the combination of probabilities and values) is independent of the context at hand. This highlights some of the limitations with CDM theories. Moreover, Beach and Lipshitz (1993) stress the fact that even when experts are trained to use classical decision theory in making decisions, they rarely follow those principles; instead, they follow their intuition. In addition, while CDM forces people to assign numerical values on each option and choose the one with the highest number, it is acknowledged that human decision makers do not explicitly do that for most of their decisions (Edwards & Fasolo, 2001).

In this context, naturalistic decision making theories emerged which focus on how humans actually make real world decisions. This should be seen in contrast to CDM research which often focuses on the decision event, that is, the act of choosing among a fixed set of alternatives based on fixed (stable) goals, purposes, and values (Orasanu & Connolly, 1993). Indeed, to bridge the gap between human decision making and IF, one needs to understand how we actually make decisions in order to be able to develop an IF system which can support the human decision making process. Hence, special attention is given to naturalistic decision making in the following section.
Naturalistic Decision Making

Naturalistic decision making (NDM) was initiated at the end of the 1980s and aims for the purpose of understanding how human experts make decisions in complex, real time, dynamic environments. In contrast to CDM, people in their authentic environments under realistic conditions are studied. Consequently, the decision making process being examined is significantly different because when the decision maker is under stress, time pressure, has access to other individuals, it goes beyond the knowledge structures, process and skills which are needed to make the decision (Zsambok et al., 1997). The focus is on expert decision making in complex situations. As the definition states:

“the study of NDM asks how experienced people, working as individual, or groups in dynamic, uncertain, and often fast-paced environments, identify and assess their situation, make decisions and take actions, whose consequences are meaningful to them and to the larger organization in which they operate” (Zsambok, 1997, p. 5).

NDM literature acknowledges a set of issues which characterise the decision situation (Orasanu & Connolly (1993) cited in Zsambok (1997)) as follows:

1. ill-structured problems (not artificial, well-structured problems)
2. uncertain, dynamic environments (not static, simulated situations)
3. shifting, ill-defined, or competing goals (not clear and stable goals)
4. action/feedback loops (not one-shot decisions)
5. time stress (as opposed to ample time for tasks)
6. high stakes (not situations devoid of true consequences for the decision maker)
7. multiple players (as opposed to individual decision making)
8. organisational goals and norms (as opposed to decision making in a vacuum)

These characteristics have also been visualised by Alenljung (2008), (cf. Figure 10). As illustrated, the characteristics of NDM correspond well to the characteristics of the environments typically utilising IF, that is, environments dealing with large amounts of information, which can be complex, inconsistent, imperfect and uncertain, that must be used under time pressure and a high level of stress (cf. Section 2.1).
More specifically, the essence of NDM can be viewed in terms of the research participants (experienced decision makers, not naive subjects), the purpose of the research (discovering how people actually make decisions in context rich environments), and the locus of interest within the decision episode (focus is not only on the option selection process, but also the process of situation awareness) (Zsambok, 1997). Looking at the decision making process in particular, one could say that NDM sees the decision making process as a temporally evolving event, in which different cognitive strategies are used, rather than a static one. Furthermore, action and perception are also crucial aspects of cognition, and human limitations are important factors in the decision making process.

As previously described, NDM outlines a difficult decision situation. The question at hand is how humans can make decisions under these conditions? Over the years, a number of different, general decision making models have been developed in the NDM community to characterise how individuals make decisions (Lipshitz, 1993). Following Lipshitz (1993), descriptions are given of nine of the most commonly used models within NDM which could be employed within IF to alternate the current focus and move away from the frequently used OODA-loop. Firstly, there are some models which focus on the actual decision making process. These are:

**Situation Assessment Model** (Nobel, 1993): Nobel developed a model which emphasised the importance of making a *situation assessment* in order to be able to make a correct decision. The process of making a decision is suggested to be as follows: First, concrete information about the situation is combined with background (context) information and general knowledge retrieved from memory to provide an understanding of the situation so that a tentative interpretation (“representation”) of the situation can be created. This representation includes specific expectations and is tested, retained, refined, or rejected over time, as new information is gathered. This model can be viewed at the recognition stage in the RPD model (Klein, 1997).
Recognition Primed Decision Making (RPD) Model (Klein, 1997): this is one of the most established models in NDM. It emphasises the importance of domain knowledge and previous experience in making decisions. The model is characterised by dealing with decisions made under high stress and time pressure. The concept of the model is that when experts encounter a new situation which demands a decision, they use their previous experience in order to solve the current situation. In other words, rather than choosing among alternatives, decision makers assess the situation and select the most appropriate decision. This process is divided into three main parts: situation recognition (the situation is classified as either typical or new and the decision maker identifies (recognise) distinguishing cues which are crucial for the situation), serial option evaluation (different alternatives are evaluated sequentially, with the most typical action first, i.e., an action queue, until a satisfactory alternative is reached), and mental simulation (to reach a conclusion whether an alternative is satisfactory or not, the decision maker acts it out in the mind using the imagination, i.e., a mental simulation).

Explanation-based Decision Making (Pennington & Hastie, 1993): this model is based on how jurors reach their decisions, however, it is said to be generally applicable to decision situations. The model emphasises the attempt to explain and understand relationships in the current situation. It consists of three phases: processing the evidence (to deal with contradictory information, it is organised in the form of a coherent story of what apparently has happened, i.e., an episode schema), defining verdict alternatives (the jury defines different verdicts and the accompanying attributes which need to be fulfilled in order to reach that verdict), and determining the verdict (the one that agrees with the previously created story board. In summary, the story based decision making process is argued to be applied in situations where there is a need to process large amounts of incomplete, piecemeal information presented sequentially in a jumbled temporal sequence. Here, people “construct a casual explanation based partly on the evidence and partly on inference and general knowledge” (Lipshitz, 1993, p. 112).

Dominance Search Model (Montgomery, 1993): the idea behind this model is that people, when making a choice among options, search for a dominant alternative. An alternative is dominant if it at least equals its alternatives and exceeds in at least one aspect, that is, one wants to find a good argument for making a specific decision (Lipshitz, 1993). This decision making process is performed in four steps: pre-editing, finding a promising alternative, dominance testing, and dominance structuring.

Image Theory (Beach & Mitchell, 1998): this theory consists of different concepts: images (a representation, cognitive structure, which organises values and knowledge to enable guidance of decisions), adoption decisions (decision makers do a “compatibility test” in order to choose a decision, i.e., a decision is adopted only if it does not violate any “image”), progress decisions (these are used to support the adoption of decisions by considering future states), and frames (a subset of the decision
makers principles, goals and plans). A distinguishing factor of this theory is the emphasis on the decision makers’ principles, values and ideals (frames) as a guide for making decisions.

Table 2. Assessment of NDM process models.

<table>
<thead>
<tr>
<th>DM process models</th>
<th>Time frame</th>
<th>DM trigger (user reacting to)</th>
<th>Type of data/problem</th>
<th>Decision taken</th>
</tr>
</thead>
<tbody>
<tr>
<td>Situation assessment model (Nobel, 1993)</td>
<td>Short</td>
<td>Situation at hand due to own experience</td>
<td>Situation assessment</td>
<td>Most compatible</td>
</tr>
<tr>
<td>RPD decision making (Klein, 1997)</td>
<td>Short</td>
<td>Situation at hand due to own experience</td>
<td>Ill-defined problems</td>
<td>Most satisfactory</td>
</tr>
<tr>
<td>Explanation based decision making (Pennington &amp; Hastie, 1993)</td>
<td>Long</td>
<td>Created (internal) representations</td>
<td>Implication rich, conditionally dependent information</td>
<td>Most reasonable</td>
</tr>
<tr>
<td>Dominance search model (Montgomery, 1993)</td>
<td>Long</td>
<td>Previously defined criterion</td>
<td>Many different alternatives</td>
<td>Most dominant</td>
</tr>
<tr>
<td>Image theory (Beach &amp; Mitchell, 1998)</td>
<td>Short</td>
<td>Situation at hand due to own principles, values, ideals</td>
<td>Situation assessment</td>
<td>Most compatible</td>
</tr>
</tbody>
</table>

All of the above mentioned models focus on the actual process of decision making, thus extending beyond the activity of choosing among alternatives (cf. CDM). By looking at the different models in detail, common themes emerge, which could be claimed to be central parts of human decision making (cf. Table 2). For instance, it can be seen that the decision is often subjective and dependent on the situation at hand, and the most optimal decision is not necessarily chosen. Also, the decision emerges as a reaction to the situation at hand, because it exists in the environment or as a result of the creation of a representation (e.g., story generation or criteria definition). Notably, IF is typically utilised in situations in such a way that all the models could be applied (cf. Section 2.1). Hence, it can be argued that there is a need to combine aspects from all the models in order to understand the complex situation in which the decision maker is situated. However, it might be difficult to create a decision making model which applies to all IF situations due to their diversity.

Furthermore, models which can be categorised as typological are models as follows (Lipshitz, 1993):

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4 The terms short and long are used in this context to emphasise that some models capture a decision making process which could take slightly longer time in a comparison.
Cognitive Control (Rasmussen, 1993): this model focuses on how people interact with complex automated systems. It distinguishes between skill-based behaviour (with expert sensory-motor performance such as cycling where there is no conscious attention needed to perform the task at hand, the behaviour is controlled by a dynamic mental model), rule-based behaviour (rules and knowledge which can be stated explicit, control the behaviour, i.e., a task which requires conscious attention), and knowledge-based behaviour (required in a new situation where a deeper understanding is needed in order to perform the task). The added value of this model is the distinction between habitual or automatic behaviour compared to performing a task which requires a more conscious behaviour (Lipshitz, 1993).

Cognitive and Task Continuum Theory (Hammond, 1993): the decision making process can be classified according to a scale, from intuitive to analytical. A decision is more intuitive depending on factors such as failure (when in doubt, guess). Likewise, the task can be judged on a similar scale. These two scales are also intertwined, “changes in the characteristics of tasks lead to predictable changes in the nature of cognitive processes” (Lipshitz, 1993, p. 126).

Decision Cycles (Connolly (1988) cited in Lipshitz (1993)): decision making in real settings is dynamic, therefore, it is not correct to study them as isolated instances of choosing among alternatives. Hence, the model developed by Connolly emphasises the cyclical interplay between situation assessment, evaluation of alternatives, and action. The model also consists of three domains and two levels, that is, the domain of the actual world, the decision maker’s cognitive map of this world and his/her values, as well as, the perceptual cycle and decisional cycle.

Argument-driven Action (Lipshitz, 1993): the basic idea behind this model is to select an action based on a specific argument (i.e., option ‘A’ is selected because of argument ‘B’). In the decision making process there are three generic modes of making decision: consequential choice, matching, and reassessment, and they differ in terms of five basic attributes, i.e., framing, uncertainty, logic, handicaps, and therapies.

All the models mentioned above categorise decision making/decision makers from some perspective. They could all be used within IF, however, among the models mentioned, Recognition Primed Model, Image Theory, and Rasmussen’s model of Cognitive Control are the most commonly used ones in NDM settings (Lipshitz, 1993).

It should be noted that using NDM is not straightforward. There are some criticisms of NDM, which is exemplified by Yates (2001). According to Yates (2001), it is a descriptive theory which does not provide a standard for evaluating the quality of decisions, it is hard to draw generalisations from the studies within NDM (often the situation is studied only once), it does not have many models on how to develop training and decision support, and finally, the results of the studies are often of higher level issues which can be hard to implement in decision support systems. The following section will further explain how to support decision making in more detail.
Supporting Decision Making
According to Shim et al. (2002) decision support systems (DSS) evolved during the 1970s and, in general, refer to computer systems which are intended to support complex decision making and problem solving such as the decision processes explained in previous sections. Traditionally, DSSs are based on rational (classical) decision making theories. As Sage (1991, p. 1) argues: “[e]mphasis in the use of a DSS is on provision of support of decision makers in terms of increasing the effectiveness of the decision–making effort. As we will see, this involves the formulation of alternatives, the analysis of their interpretation, and selection of appropriate options for implementation”. Over the years, different classes of DSS have emerged. Power (2002) provides a categorisation of different DSS as follows:

- **Data-driven DSS**, e.g., a system which provides access to large amounts of structured data often stored in databases to support analysis, i.e., enabling display and manipulation of data sets.
- **Model-driven DSS**, e.g., a system which is based on different representational and optimisation models to support decision making, i.e., enabling what-if analyses.
- **Knowledge-driven DSS**, e.g., a system which consists of knowledge, understanding of problems and problem solving skills within a specific domain, i.e., enabling suggestions and recommendations for actions (also called expert systems).
- **Document-driven DSS**, e.g., a system which gathers, retrieves, classifies and manages unstructured documents, i.e., enabling structuring of documents.
- **Communication-driven and Group DSS**, e.g., a system which supports collaboration, communication and coordination between multiple decision makers (also referred to CSCW technologies), i.e., enabling facilitation of solution to problems.
- **Interorganisational/intraorganisational DSS**, e.g., a system which supports organisations’ facilitation of information distribution, i.e., enabling service for users.
- **Function-specific or general purpose DSS**, e.g., a system developed to support a specific task or function, i.e., enabling automated support for routine tasks or facilitating general decision tasks.
- **Web-based DSS**, e.g., a system based on web technology, i.e., enabling delivery of decision support information or decision support tool.

A DSS may have elements from different categories, although, according to Power (2002) it is possible to extract one category as the ‘drive’ and focus of a particular DSS. In general, “[a] DSS is a computer-based information system that supports either a single decision-maker or a group of decision-makers when dealing with unstructured or
semi-structured problems in order to make more effective decisions. The DSS supports one or more decision activities carried out in a decision process” (Alenljung, 2008, pp. 79-80). Further, one could argue that, independent of the category, DSSs usually have a narrow, focused, and specific purpose rather than a general one. Power and Sharda (2005) also made the distinction between automated decision systems (e.g., systems which automate routine decisions in well-structured situations) as in contrast to decision support systems (e.g., auxiliary and ancillary systems which assist decision makers).

More specifically, Holsapple and Whinston (1996) argue that a DSS should fulfil one or more of the below listed characteristics to be named a DSS.

a) Contain knowledge describing aspects of the decision-makers environment, that indicates how to accomplish a range of tasks, and that indicates valid conclusions in different circumstances.
b) An ability to acquire and maintain descriptive knowledge as well as other kinds of knowledge
c) An ability to present knowledge on an ad hoc basis in various customised ways as well as in standardized reports
d) An ability to select any desired subset of stored knowledge for either presentation or deriving new knowledge in the course of problem recognition and/or problem solving.
e) Interact directly with a decision-maker or a participant in a decision in such a way that the user has a flexible choice and sequence of knowledge management activities.
f) Coordinate/facilitate interactions among multiple decision makers

A similar list of characteristics and capabilities of DSSs is provided by Turban et al. (2005). It should be noted that there is no general consensus of the components of a DSS; consequently, there is no agreement of standard characteristics and capabilities of a DSS (Turban et al., 2005). However, there exist similarities between the existing lists, validating their existence. In summary, one could argue that a decision support system should, in line with previous lists, provide up-to-date and timely information that is complete and accurate, in an appropriate formation which is easily understood and can be easily manipulated by a user (Turban et al., 2005).

There are different ways of developing DSSs. For instance, Zacharay and Ryder (1997) present an interesting framework describing how to develop and construct and ensure the effectiveness of DSSs. In essence, the framework identifies a set of design principles and a methodology (design process). In short, the design principles are as follows (Zacharay & Ryder, 1997):

a) A DSS should be tailored to a specific position or region of the expertise continuum (there is a difference between novice and expert decision making)
b) A DSS design must involve analysis of the cognitive processes and problem representation of the users as well as analysis of the external domain and physical systems involved
c) A DSS could either provide training to perform more effective decisions or a support for making decisions. The training component within DSS should be developed from the same cognitive modelling and analysis used for decision support design. DSS research is not straightforward, more recent studies focusing on DSS in medical settings suggest that there is a need to change the focus of decision making support. Patel et al. (2002) suggest a new framework which aims to, “(1) develop a more adequate descriptive account of the decision-making process, (2) to explain the adaptive as well as the suboptimal characteristics of decision makers, and (3) to recognize that decision makers are not solitary thinkers, but live in a social world with artefacts and populated by other agents who jointly determine the decision processes and outcomes” (p. 60). Hence, there is a need to expand the scope of the research which the decision support is built upon (Patel et al., 2002). In other words, there is a need to change perspective from the ‘classical view’ (i.e., CDM) which, traditionally, decision support systems are built upon, to an approach which combines problem solving and decision making, and acknowledges the role of conceptual knowledge and the naturalistic and dynamic nature of the decision environment.

Having theoretical insights regarding human decision making and how to support it, on the one hand, and IF, on the other, is not enough to bridge the gap between human decision making and IF. Knowledge about how humans use the surrounding environment and interact with it is also needed (i.e., how humans interact with other humans, information technology, and IF systems, etc.); such theories are presented in the following section.

2.2.2 Distributed Cognition

Within cognitive science, different theories exist which can be used to understand how human cognitive processes are organised, and how humans interact with their surrounding environment, for example, Activity Theory (Kaptelinin & Nardi, 2006), Distributed Cognition (Hutchins, 1995a; 1995b), and Situated Cognition (Suchman, 1987; Clancey, 1997; Clark, 1997). In this context, the Distributed Cognition (DC) framework, which has become a well established perspective in cognitive science, is presented in more detail, due to its applicability to the IF domain. For instance, DC has a process view which can be used to explain different phenomena in IF at different abstraction levels (cf. following sections). As such, it does not focus on the actual activities which are being performed (as within the Activity Theory perspective), rather, it focuses on the content of what is processed. In addition, DC has a theoretical language which can be used to explain both processes within artefacts (technology) and humans5, as in contrast to Situated Cognition. Furthermore, it has been proposed as a

5 DC uses the same theoretical language is used for capturing processes in individuals and artifacts (both are being treated as entities), but that does not imply that artifacts are considered as (biologically) cognitive (Halverson, 2002).
framework for advancing research within the HCI domain (Hollan, Hutchins, & Kirsh, 2000). The different aspects of DC are explained in the following sections.

**Extending the Boundary of the Individual**

DC shifts the emphasis from the traditional, rather narrow focus on the single individual’s internal cognitive processes (i.e., symbol manipulation inside the mind), to consider processes that take place within the larger unit of socio-technical systems. Such systems include people and the artefacts (e.g., information systems) they use, as well as the interactions that take place in the system (Hutchins, 1995a) (cf. Figure 11). Shifting the focus from the inside to a system level allows the observation of cognitive processes outside the individual mind rather than within the minds of single individuals. Consider the cognitive process of solving a mathematical equation. For example, the calculation can be carried out mentally in your head by activating different mental processes, or it can be performed by using pen and paper, or a calculator. In DC, when such artefacts are used, they are considered part of the cognitive process of problem solving. Moreover, the process itself is distributed across the system of the individuals and the artefacts in use, rather than being confined inside the individual’s head (as in the traditional view).

**Cognitive Processes as Distributed Processes**

Cognitive processes are considered to be distributed across the larger unit of a cognitive system, in which at least three different kinds of distribution can be observed (Hollan et al., 2000). The processes are distributed: across individuals in a group or organisation, between human-internal (e.g., memory, attention) and -external structures (e.g., computer systems, material and/or social environment), and they are distributed over time (cf. Figure 11).

![Figure 11. A comparison between traditional cognitive science perspective (a) and distributed cognition perspective (b) on human cognition.](image-url)
The cognitive process is delimited by the functional relationships among the people and the artefacts that are part of the process. This allows for capturing cognitive properties of the interaction which cannot be traced to a single individual or artefact within the socio-technical system, that is, properties of the collective behaviour (Halverson, 2002).

**Information Propagation and Transformation of Representational States**

DC focuses on the way information is propagated, transformed, and represented within the socio-technical system (Hutchins, 1995a). As information is propagated through humans and the artefacts with which they interact, representations and their states are transformed (cf. Figure 11). Representational state refers to how knowledge and information is represented in different states, as it is propagated and transformed in the conduct of an activity. For instance, the state of information displayed by a computer system transforms in response to a user’s key command. In other words, “a representational state is a particular configuration of an information-bearing structure, such as a monitor display, a verbal utterance, or a printed label, that plays some functional role within a process” (Hazlehurst, Gorman, & McMullen, 2008, p. 228). Thereby DC focuses on how artefacts are used and modified to support the cognitive process, that is, not only on what an object represents but also on how the properties of the object are exploited (Holland et al., 2000).

**Distributed Cognition as a Theoretical Framework**

DC is not a method, per se, instead, it is a theoretical framework that seeks to understand and explain the organisation of human cognitive processes by studying the tools humans interact with. In this context, the DC framework is particularly well suited for the analysis of the utilisation of complex systems. This is seen in the numerous studies conducted in settings such as: aircraft cockpit (Hutchins, 1995b), air traffic control rooms (Fields, Wright, Marti, & Palmonari, 1998; Marti, 2000), vessel board (Hutchins, 1995a), cardiac surgery (Hazlehurst, McMullen, & Gorman, 2007), emergency dispatch room (Blandford & Furniss, 2006), and co-ordination of collaborative activities (Perry, 1998).

In general terms, the focus is on the distributed collaboration between humans and artefacts involved in a joint task. For instance, Hutchins’ (1995b) study of an aircraft cockpit focused on the distribution of processes between internal structures (e.g., the pilot’s memory) and external artefacts (the equipment used by the pilots), and showed how human memory processes extend beyond the boundary of the individual to include external products as part of the process. The purpose of a study by Hazlehurst et al. (2007) was to understand the achievement of situation awareness in cardiac surgery, among a group of individuals. This study focused on the activity they performed, the tasks they accomplished, and the coordination devices used as they interacted in this structured environment. In addition to providing a theoretical understanding of cognitive processes, DC can also be used for designing and
supporting interactions between people and technologies. In a study by Marti (2000), DC was used to inform the re-design of an air traffic control system, and resulted in a system which provided better support for the operators’ activities. In summary, the use of DC, as an approach to analyse interactions between people and technologies, has resulted in a better understanding of tasks and procedures of individuals, as well as the way information is distributed within socio-technical systems. It has also led to a deeper understanding of the role(s) of artefacts in accomplishing tasks.

In addition, the DC framework has been used to inform other disciplines such as HCI (Hollan et al., 2000; Rogers, 2004). The HCI domain has developed from concentrating on the interactions between a user and a single computer to involving multiple people working on networked computers as well as ubiquitous computing. As the domain has developed, the human information processing paradigm, which HCI was originally founded on, does not accommodate all the aspects of this new environment. Hollan et al., (2000) propose that a DC perspective is necessary to allow for a better understanding of the emergent properties of interaction. Furthermore, using a DC perspective would lead to the following theoretical foundation for HCI (Hollan et al., 2000, p. 181):

- “people establish and coordinate different types of structure in their environment”
- it takes effort to maintain coordination
- people off-load cognitive effort to the environment whenever practical
- there are improved dynamics of cognitive load-balancing available in social organisation"

A DC perspective would influence all parts of the HCI development process such as studying the phenomenon, recording the data, encoding the findings, analysing the result, and designing/redesigning applications (Halverson, 1994). More specifically, a DC perspective would involve a commitment towards performing ethnographic studies and controlled experiments in which the objects of study are the work materials and workplaces at use (Hollan et al., 2000). Hence, it involves a commitment towards studying interaction in its context, that is, viewing the study object as embedded in an environmental and social structure.

Furthermore, (Hollan et al., 2000) point out examples where DC can provide a new perspective for HCI. For instance, it could enrich the possibilities of ‘direct manipulation’. This concept developed during the 1980s, and means that users should be able to directly manipulate objects and see the effect of their action (manipulation). The intention was to be able to use knowledge of the physical world in order to interact with the virtual world. For example, moving a document in a windows environment, with a mouse, could be performed in a similar way as a person moving a physical document between a desk and a folder. Direct manipulation has been developed from a traditional information processing paradigm which focuses on “symbols as tokens that refer to something other than themselves, but pays little
attention to the strategies people may develop to exploit the physical properties of the representing tokens themselves” (Hollan et al., 2000, p. 185). A DC perspective, on the other hand, would not focus on how well the action mimics a physical action in the real world, instead, it would focus on the properties and possibilities of the token as well as the representation (Hollan et al., 2000). Referring to the example of moving a document in a windows environment, DC would focus on the representation itself (e.g., can the icon representing the document be reduced, be enlarged, etc.), how it is used and manipulated to coordinate the activity. This would also promote history-enriched digital objects as well as argue for spatial rather than temporal organisation.

Indeed, the following section explains in more detail how one can bridge the gap between human decision making and IF by exploring knowledge from cognitive science as presented herein (i.e., human decision making and DC).

2.3 Intermission: Bridging the Gap between Human Decision Making and IF

Despite the fact that it has been argued that the effectiveness of the overall IF process is affected by the utilisation of HCI (Hall & Llinas, 2001), there are limited studies of the human factor in the IF community. Further, those that do exist provide encouraging research, for example, Bisantz et al. (1999), Blasch and Plano (2003; 2002), and Hall et al., (2007). For example, it has been shown that users can be an active part of these IF processes and even play a prominent role in the fusion process (Blasch & Plano, 2002; Chan et al., 2005). Aspects which have been highlighted thus far are different cognitive process limitations (Blasch & Plano, 2002), trust issues (Bisantz et al., 1999), and HCI issues (Blasch, 2006a; Hall & McMullen, 2004; Hall et al., 2000). However, most often, human factor research in IF inevitably ends up in some sort of independent, prototype specific user study (e.g., Brenton, Paradis and Roy (2002), Irvine (2003)). An exception is a recent study by Hall et al. (2007) which theoretically compared and contrasted the IF process (JDL model) and general decision making processes. Despite these recent studies, no clear overall picture of user interaction, or generally agreed upon consensus of the users’ role in IF (or what implications an IF systems has on its users) has yet emerged from the IF community. Hence, more research is needed.

IF is said to support human decision making, e.g., “data fusion processes are generally employed to support human decision making” (Steinberg et al. 1999, p. 432); “the purpose of information fusion is to produce information from different sources in order to support the decision-making process” … “The purpose of a fusion system should be tailored towards supporting a decision-maker” (Bossé et al., 2006, p. 1); “Ultimately, information resulting from the data fusion process is presented to the human decision-maker through a computer interface” (Bisantz et al., 1999, p. 1). Consequently, it is natural to consider insights regarding human decision making to inform IF research.
According to Patel et al. (2002), NDM has been studied in a vast array of domains ranging from firefighting to air traffic control, healthcare domains such as anaesthesiology, intensive care medicine, as well as nuclear power plant management, just to mention a few. Recently, the power of NDM has been recognised and it is suggested that NDM should also be used in the knowledge management domain (Meso, Troutt, & Rudnicka, 2002). Similarly, insights from NDM may be introduced to an IF context in order to bridge the gap between human decision making and IF.

In fact, NDM shares much of the same characteristics as those presented in the IF domain, i.e., the situation is dynamic, uncertain, and involves organisational goals and norms; there are different individuals, with different authorities, who need to be supported. Therefore, it could be argued that knowledge from NDM can be used to understand the human decision making processes in IF. Indeed, Brenton et al. (2002) argue that NDM, and in particular, the RPD model (Klein, 1997) and the SA model (Endsley, 2000) need to be accommodated for in command and control systems (which could be considered as large scale IF systems utilising IF techniques).

In addition, knowledge of NDM can provide new insights of the models used within IF, since they typically include ideas or are based upon theories of CDM. For instance, the decision making process is often viewed in a sequential order, where one optimal/objective decision could be reached (cf. Table 1). Beach and Lipshitz (1993) argue that “classical theory does not address the question of making correct decisions, it merely addresses the question of making decisions correctly- that is not the same thing” (p. 28). Also, as Rouse and Valusek argue, “[t]he resulting support do not, by definition, prescribe how tasks are to be performed. Instead, the emphasis is providing the information decision makers want, in the ways that they want it” (Rouse & Valusek, 1993, p. 272). In other words, we need to go beyond the CDM theories if we are to develop effective IF systems and be able to exploit the human user’s capabilities.

Actually, to gain insights in the areas of human decision making, on the one hand, and IF, on the other, can be seen as the first step towards bridging the gap between human decision making and IF. That is, traditionally, IF has a technical focus where decision makers are seen as passive receivers of information. With greater insights of human decision making processes, one could shift the focus from what is technologically feasible with IF technology to design IF technology which accommodates the human decision making processes. As Blasch (2006b) argues: “designing complex and often-distributed decision support systems ... requires an understanding of both the fusion process and the DM [decision making] processes” (p. 3). However, to have knowledge of the two areas is not enough. Also, there is a need to identify a way to bridge human decision making and IF so they can inform each other. Actually, it has been argued that “[w]hat ever the definition used, data and information fusion is not something that happens in a vacuum, and it should not be decoupled for the decision-making process” (Bossé, Roy & Wark, 2007, p. 8). In this thesis, DC (described in the previous section) is suggested as such a tool for bridging that gap.
between what one technically can build with IF technology and the human decision making processes to be supported. In detail, a DC perspective will provide the means to describe the interaction between human decision making processes and IF technology (cf. Paper IV), thereby enabling the two areas to inform each other.

The following section explains in more detail the suggested path to be able to bridge the gap between human decision making and IF.
3. Research Approach

Current IF research is mainly technology oriented and focused on the defence domain. Consequently, there is not only a lack of a user perspective in most IF research, but also a lack of generic user models which exceed military applications. With a few exceptions (Blasch & Plano, 2003; Blasch & Plano, 2002), currently existing studies often portray the user as a passive receiver of information. Indeed, that research does not explicitly consider users’ decision making processes to a great extent, nor the actual influence it has on the interaction with IF systems (Hall et al., 2007). The presented research aims to analyse IF, on the one hand, and on the other, human decision making, in order to be able to bridge the gap. Due to the nature of the research problem, the following research process has been chosen:

- **Identify** existing models and concepts of IF and human decision making (cf. Section 2)
- **Investigate** the possible interdependencies between IF systems/processes and human decision making processes (cf. Section 4)
- **Develop** new or adapt old models/theories (cf. Section 5)

A qualitative approach has been chosen as the research seeks to provide insights and understanding regarding the gap between IF and human decision making. The underlying research strategy is an inductive strategy with a holistic perspective (Patton, 2002). An inductive analysis aims at exploration, discovery, and inductive logic (Patton, 2002). Inductive analyses contrast typical experimental designs which require specification of main variables and research hypotheses before data collection begins. This means that the researcher needs prior knowledge about which variables are important and what kind of relationships exist. Inductive analyses, on the other hand, allow the discovery of multiple interrelationships among emergent factors in data without prior assumptions (Patton, 2002). Furthermore, “focus is on full understanding of individual cases before those unique cases are combined or aggregated thematically” (Patton, 2002, p. 57). A holistic perspective “assumes that the whole is understood as a complex system that is greater than the sum of its parts. The analyst searches for the totality or unifying nature of particular settings- the gestalt” (Patton, 2002, p. 59).

More specifically, a theoretical grounding, in terms of literature studies in information fusion and decision support/cognitive science, will explore the interaction between IF and human decision makers. In addition, theories and insights from cognitive science which could inform IF are identified. Empirical investigations use the literature studies as a starting point from which to conduct interviews and field studies of users of various existing IF systems, in order to understand the different
requirements IF systems may have. Moreover, the result is analysed in the light of the previously identified theoretical findings (cf. Figure 12). In this way, the empirical investigations can be used to *verify and exemplify the existence of the theoretical argumentations*.

In particular, Paper I is the theoretical grounding of the empirical research in Paper IV, while Paper II is the theoretical grounding of the empirical research in Paper V and VI. In addition, Paper III actually exemplifies the iterative approach by combining theoretical and empirical work. The two paths result in the building blocks which can characterise the interaction between human users and the IF system, that is, the interdependency between human decision making and IF (cf. Figure 12).

![Schematic overview of the appended papers indicating the underlying research approach.](image)

**Figure 12.** Schematic overview of the appended papers indicating the underlying research approach. (Abbreviations IF: Information Fusion; DC: Distributed Cognition; DSS: Decision Support System; HCI: Human Computer Interaction).

**Trustworthiness of Qualitative Research**

The presented research should be judged on its own theoretical basis, as argued by Lincoln and Guba (1985). Lincoln and Guba (1985) presented a set of principles specifically adapted to qualitative research for ensuring the trustworthiness of the research as follows:

- **Credibility** (i.e., internal validity) - Qualitative researchers should seek to establish the credibility of their findings, that is, the findings should make sense for the ones being observed/interviewed or within the context of the research being conducted. For example, in Paper VI, the findings were presented to the
participants to ensure their correctness (i.e., the technique of “member checks” (Lincoln & Guba, 1985)).

- **Transferability** (i.e., external validity) - Instead of aiming for random sampling and probabilistic reasoning, the research should be described in such a way that it can be transferred to other settings, thus, promoting generalisation. It is the researchers’ “responsibility to provide the data base that makes transferability judgement possible on the part of potential appliers” (Lincoln & Guba, 1985, p. 316). In other words, researchers should provide a detailed description to allow others to judge the applicability of the findings in other settings. See, for example Papers IV-VI for detailed descriptions of the studies performed.

- ** Dependability** (i.e., reliability) – Since it is difficult to replicate a qualitative inquiry, the aim should be to provide a trail (documentation of data, methods and decisions about the research) which can be used to judge the quality of the research. In this way, consistent findings could be produced, whether research was carried out as described, and factors that may have affected the results of the previous study were taken into account. See for example Paper IV-VI for detailed descriptions of the performed studies.

- **Confirmability** (i.e., objectivity) - Qualitative research should also be judged according to the degree of its confirmation by the data. In this instance, objectivity is moved from the researcher to the quality of the data, that is, the evidence of the findings should be seen in the data. Again, the importance of documenting the research process is emphasised so that a link between the data and the findings can be established.
4. Summary of Papers

The motivation for the first two papers (cf. Paper I-II) was the theoretical exploration of how IF is utilised to support human decision making and the possibility of using DC to situate the user in the context of IF systems. Paper III explores the known factors that affect users’ employment of IF systems. The motivation for the following three papers (Papers IV-VI) was to empirically investigate how users actively interact with and use IF systems in their decision making activities. The included publications are based on research carried out by the author of this thesis who also has made the main contributions to the included papers⁶. The specific studies on which the papers report are explained in the following sections.

4.1 Theoretical Grounding

The background section of this thesis has mainly focused on IF and human decision making. This section proceeds a step further and presents papers which summarise the results from the theoretical investigations regarding the possibilities of having a distributed cognition, decision support and human computer interaction (HCI) perspective of IF. It is argued that one can bridge the gap between human decision making and IF by using these perspectives.

4.1.1 Paper I: A Distributed Cognition Perspective on IF

This paper titled “Rethinking Level 5: Distributed cognition and Information fusion” reports on a theoretical study which proposes that a DC perspective of IF would provide a more comprehensive view of the IF process. Previously, the theoretical framework of DC (Hutchins, 1995a) has not only been used to understand the interaction between users and the surrounding environment such as other people, artefacts and technology (see for example, Boland, Tenkasi, & Te'en, (1994), Hazlehurst et al. (2007), Hutchins (1995b)), but also to provide new perspectives on research disciplines such as HCI (Hollan et al., 2000).

Method. Current IF research (as exemplified by the JDL model) was theoretically analysed with a DC perspective.

Result. The paper proposed that the implication of DC would be a new perspective of what components are included in the IF process. In IF, DC would consider users and other technologies as parts of the IF process (cf. Figure 13). This is

⁶ Papers I and Paper II are written with the support of the author’s main supervisor, Tom Ziemke. Paper III is written with the support of a fellow PhD student, Maria Riveiro, and the main supervisor. Paper IV is written with the author’s co-supervisors, Joeri van Laere and Tarja Susi as well as main supervisor. Papers V and VI are written with the support of both main and co-supervisors as well as representatives from industrial partners.
in contrast to the common technological view of IF which mostly considers Levels 0-4 in the JDL model as part of the fusion process.

![Figure 13. A schematic view of an IF process (Nilsson & Ziemke, 2006).](image)

### 4.1.2 Paper II: A Decision Support Perspective on IF

This paper, titled “Information fusion: A Decision Support Perspective”, reports on a theoretical investigation which aims to characterise IF systems and their ability to support human decision making from a decision support perspective, thereby enhancing a user perspective in IF.

**Method.** A review of decision support literature in terms of decision support classifications (Holsapple & Whinston, 1996; Power, 2002) was compared to existing IF systems found in the Information fusion Journal and the Information fusion conference proceedings.

**Result.** The paper provides an overview of IF and identifies common components of IF systems (cf. Figure 14). In addition, the result of this study is a proposal to classify IF systems as decision support systems and, thereby, to more strongly emphasise the goal of IF systems and further strengthen the decision makers’ role in IF research. Due to the fact that IF systems did not conform according to the existing DSS’ classifications, a new class is proposed as follows:

- **“Fusion driven DSS,” i.e., systems which are based on fused information from different sources such as sensors, databases and models, providing both automatic and semi-automatic fusion processes, i.e., enabling complex decision making from large amount of information (which may be conflicting/contradicting or uncertain) without information loss (e.g., information is not just filtered, but, for instance, aggregated) with respect for the user** (Nilsson & Ziemke, 2007, p. 5).
In addition, the following characteristics of IF decision support were identified:

“a) IFS contains knowledge of the environment due to data from different sensors, and could sometimes predict future states
b) IFS has the ability to acquire and store knowledge (information) from different sensors
c) IFS could present knowledge and information in various ways
d) IFS has the ability to fuse information, and present it to the user for further considerations
e) Users of IFS could interact with the system influencing both the process and the result
f) IFS could coordinate/facilitate interactions among multiple decision makers”. (Nilsson & Ziemke, 2007, pp. 4-5).

The category put forward extends previous decision support classifications and differs, for example, in terms of the role of the decision maker and the semi-automated nature of the support. Most computer based systems are either user driven, for example, a word processor, or data driven, for example, systems that react to incoming data, whereas fusion systems involve both modes simultaneously (Hall & McMullen, 2004). Another characteristic is that these tools often support a specific activity connected to human decision making processes, such as situation awareness, as compared to more rational based decision support.

4.1.3 Paper III: A Human-Computer Interaction Perspective on IF

This paper, titled “Investigating human-computer interaction issues in information-fusion-based decision support”, reports on a literature study of different human-computer interaction factors affecting users’ interaction with IF system. It proposes the embedding of the decision maker in the context of the IF systems, and identifies different design guidelines which could be used to inform the development of future IF systems. Finally, the paper provides a small evaluation to show the applicability of the identified guidelines.

Method. A literature review of IF research presented in handbooks, conference proceedings or the information fusion journal was carried out from an HCI perspective. Main categories were identified which could later be used to classify the
identified HCI factors in IF research. In addition, the empirical investigation indicated the applicability of the identified guidelines.

**Results.** The review identified users as embedded in the context of the IF system. A circular relationship is proposed among factors influencing user interaction to emphasise the context in which the interaction exists. This model is influenced by (Cummings & Tsonis, 2005; Paradis et al., 1999). As Figure 15 illustrates, the external environment affects the user in terms of the users’ cognitive abilities and the activities which can be performed. The users’ cognitive abilities limit the possible user activities which can be performed. The user utilises the interface in order to perform various activities. Consequently, the interface needs to access functionalities of the IF system. It must also be remembered that IF systems capture different aspects of the environment, and so on. Reviewing IF research, each identified HCI factor was categorised according to Figure 15, which is illustrated in Figure 16.

**Figure 15.** An illustration of users as embedded in the context of IF systems (Nilsson, Riveiro & Ziemke, 2008).

<table>
<thead>
<tr>
<th>CATEGORY</th>
<th>FACTOR</th>
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<tbody>
<tr>
<td><strong>External Environment</strong></td>
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<tr>
<td>Affects</td>
<td>Organisational demands</td>
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<td></td>
<td>Multiple decision makers</td>
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<td></td>
<td>Risk</td>
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<td></td>
<td>Temporal Aspects</td>
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<td></td>
<td>Dynamism</td>
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<td></td>
<td>Environmental Factors</td>
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<td><strong>Users’ cognitive abilities</strong></td>
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<tr>
<td>Determine</td>
<td>Cognitive issues</td>
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<tr>
<td></td>
<td>Situation awareness</td>
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<td></td>
<td>Trust</td>
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<td><strong>User activities</strong></td>
<td></td>
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<tr>
<td>Access</td>
<td>Decision making</td>
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<td></td>
<td>User Tasks</td>
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<td><strong>Interface</strong></td>
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<td>Utilises</td>
<td>Input/output devises</td>
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<td></td>
<td>Visualisation</td>
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<td><strong>IF system</strong></td>
<td></td>
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<tr>
<td>Captures</td>
<td>Multiple sources</td>
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<tr>
<td></td>
<td>Information flow</td>
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<td></td>
<td>Uncertainty</td>
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<td></td>
<td>Automation</td>
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</table>

**Figure 16.** Schematic view of the identified factors affecting user interaction in and IF context (Nilsson, Riveiro & Ziemke, 2008).
4.2 Empirical Investigations

This section presents the results from empirical investigations carried out by the author of the thesis (in cooperation with industrial partners, to some extent). In general, IF is empirically investigated as a decision support in contrast to IF as an isolated component which could contribute to a decision support (system). The empirical studies illustrate issues grounded in the previous theoretical investigations.

4.2.1 Paper IV: The User as an Active Component in the IF process

This paper, titled “On the Active Role of the User in Information Fusion: A distributed cognition perspective”, reports on a field study conducted in a maritime surveillance control room utilising IF based decision support to identify vessels, in order to support situation awareness.

**Method.** On four occasions (including a pilot test), at evenly distributed times around the clock to allow for different conditions, participatory observations (Waddington, 2004) of five experts were conducted for a total of 16 hours. The role of the researcher was “participant-as-observer”, which refers to a researcher “who forms relationships and participates in activities but makes no secret of an intention to observed events” (Waddington, 2004, p. 154). The collected data was analysed from a DC perspective, that is, it was analysed for patterns describing how information is propagated between systems and operators in the IF processes.

**Result.** The observations identified the IF process as consisting of both operators (interacting with technology) as well as technology (providing automatic processes) (cf. Figure 17). More specifically, the patterns found in the observations outline interactions by distinguishing the cognitive processes contributing to the IF process and by providing examples of transformations performed either by humans or technology. Also, the study distinguishes between different types of input sources. The main contribution of the study is that it identifies the user as an important and active link within the process, which enables different parts of the system to connect/be fused. The study also indicates how this type of support contributes to the users’ decision making process. In addition, this study empirically exemplifies the usage of DC as a tool for capturing the interaction between IF and decision making.

![Figure 17. An information fusion process as it includes both technology mediated transformations as well as human mediated transformations. Each box refers to a representational state.](image)

The fusion process as denoted by the JDL model.
4.2.2 Paper V: Evaluating an IF Based Decision Support Tool (Impact)

This paper, titled “A user study of the impact matrix, a fusion based decision support for enhanced situation awareness”, reports on an explorative evaluation of a military application which utilises IF to combine incoming intelligence reports in order to make predictions of future events, and thereby support human decision making.

**Method.** The empirical study was explorative in its nature and consisted of a presentation of the tool followed by open-ended interviews with decision makers. Each interview took about 45 minutes and followed an interview guide focusing on three key issues (human decision making, trust, and HCI) grounded in IF based decision support research. The study was structured as a concept test in which the application was presented to four decision makers (i.e., military officers), in order to inform future development of the tool as well as future evaluations.

**Results.** In addition to improvements in the application (cf. Figure 18), the results highlighted a number of different aspects of IF and decision support which were the users’ main concern. For example, there were issues regarding which activities in the decision making process could be supported, and, in this context, situation awareness was identified as a key factor on which the decision was based. There were also interesting issues regarding tradeoffs when using the probabilities for making decisions, that is, what degree of probability of an event (i.e., 70%) prompts decisions?

![Figure 18. Current interface of the tool as of December 2007. (a) Matrix indicating probabilities of event (b) list of incoming reports (c) map displaying geographical location of incoming reports (d) additional information (traceability) concerning the chosen event in “a” (e) information included in the indicated report in “b” (Nilsson, van Laere, Ziemke, Berggren & Kylesten, 2008).](image-url)
Indeed, the study indicated that the users graded the situation map displaying the incoming intelligent reports as more valuable than the prediction provided by the tool. Further studies are needed to examine this in more detail. In addition, the HCI of the application, in terms of the kind of information and how it was presented, strongly affected the users’ decision making process and cognitive processes. For instance, the tractability of the predictions in the HCI was very important for the credibility and utilisation of the tool (i.e., trust). Also which information regarding the situation/decision that the users recalled was correlated to the design of the HCI.

4.2.3 Paper VI: Informing an IF Based Decision Support Tool (situation)

This paper, titled “Extracting rules from expert operators to support situation awareness in maritime surveillance”, reports on a user study which aimed to conceptualise user knowledge in terms of rules which could be used to inform an expert system for supporting maritime situation awareness.

Method. Participatory observations (Waddington, 2004) were chosen as the method for extracting knowledge from the operators as they interacted with an overview display (cf. Figure 19).

![Figure 19. An overview display of current situation (Nilsson, Laere, Ziemke & Edlund, 2008).](image)

Participatory observation is a method in which the observer is included in the work environment while the operators are being observed. The method allows the observer to ask questions and be instructed by the users as they perform their work. Hence, participatory observations allow users to explain their actions while they are being performed (i.e., focus is not only on what they know, but on how they actually use that knowledge, which could be difficult to verbalise).
Results. The study identified factors which affected the users’ interaction and interpretation of the information presented in the overview display of the current situation. For instance, it was not only their previous experience, but also, for example, formal documents or the context of the situation which helped the users in interpret the overview display. Furthermore, specific rules were identified, which could potentially later be implemented in the expert system prototype. An example of such a rule is: “if vessel enters area X and has a name Y then the operator wants to be notified”. In most cases these rules were derived from organisational, group thinking, or individual experience.
5. Conclusions

The presented papers can be considered individually, however, taken together, the studies carried out (cf. Paper I-VI) identify a close relationship between IF systems and their ability to support human decision making, that is, an interdependency between human decision making and IF exists. The following section elaborates on this relationship and presents the combined implications from the findings presented in the included papers.

5.1 A Decision Maker’s Perspective on IF: Towards a Framework for the IF Community

The results thus far identify the building blocks of a future framework characterising users’ interaction as they are embedded in IF systems/processes (cf. Figure 20). The initial framework promotes a user (decision maker) centred perspective of IF and is presented as an instrument for understanding the various ways users can influence IF. The underlying idea is to provide different examples of what the interdependency between IF systems and human decision making may look like. As Figure 20 illustrates, the way humans influence IF can be captured in, for example, the definitions and the models used within IF.

![Figure 20. Graphical illustration of identified building blocks for a future framework characterising the interaction between users and IF systems.](image)

In this context, “[a] good framework is one that sounds reasonably plausible relative to available scientific data that turns out to be largely correct. It is unlikely to be correct in all the details. A framework often contains unstated (and often unrecognized) assumptions, but this in unavoidable. An example from molecular biology might be helpful. The double-Helical structure of DNA immediately suggested in a novel way, the general nature of gene composition, gene replications, and gene action. This framework turned out to be broadly correct, but it did not foresee, for example, either introns or RNA editing … The broad framework worked as a guide but, careful
experimentation was needed for the true detail to be discovered.” (Crick & Koch, 2003, p. 119, emphasis added). Hence, the aim of the initial framework is to identify different components which can be the underlying structure of the future framework. These building blocks can then be verified by further studies. Therefore, in its initial stage the framework is a descriptive framework, however, in the future, it could be developed into an actionable framework. The different components of the initial framework are as follows.

**Definitions**

The first areas, in which a decision making perspective can be highlighted, are in the definitions used. The theoretically grounded classification of IF driven decision support (cf. Paper II), (which has not previously been acknowledged as a decision support class), can due to the empirical work (cf. Paper IV) now be alternated and described as follows:

systems which are based on fused information from external (e.g., sensors, databases, documents and other information technologies), and internal resources (different cognitive processes), to enable complex decision making from large amounts of information (which may be conflicting/contradicting or uncertain) without information loss (i.e., information is not just filtered), with respect to the decision. The information fusion process can be characterised as consisting of transformations of representational states which are mediated by technology and humans. Hence, accommodating both automatic and semi-automatic fusion processes.

This classification of IF systems acknowledges users and describes in what aspects they can come to be acknowledged in IF. For example, users’ cognitive abilities can be an information resource for the IF process. These systems are often used in situations where users need to carry out complex decision making from large amounts of information which may be, for example, uncertain and contradicting. In this context, complex decision making refers to decision situations which exceed the users’ cognitive abilities (cf. Paper III) and require support. Such situations can be when the decision maker needs to deal with multiple decision makers, poorly defined problems, multiple or unclear objectives, and so on (cf. characteristics of NDM). Examples of such situations can be found in the defence and maritime domains, cf. Papers V-IV. Characterising the fusion process as “consisting of different transformations of representational states...” enables the functions associated with users to be equally accommodated in the fusion process (cf. Paper IV). More specifically, the aspect of human mediated transformations of representational states refers to the fact that humans mediate the IF process by performing different transformations either actively

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7 “Information fusion is the study of efficient methods for automatically or semi-automatically transforming information from different sources and different points in time into a representation that provides effective support for human or automated decision making” (Boström et al., 2007, p. 5)
or automatically, hence, humans enable different resources to be connected/be fused (cf. Figure 21).

(a) Actively- additional information resources are used upon demand to complete the IF process, for example, when an optic camera is used to identify unknown objects presented on an overview display. In this case, the human functions as a mediator between the optic camera and the overview display, performing the transformation of representational states. Also, the user mediates the continuous refinement of the IF process, by, for example, aiding the target tracker when an object is lost (i.e., when a target tracker is found on land, the user moves the target tracker to the right position at sea).

(b) Automatically- some of the information resources are automatically introduced to the process via humans, for example, the user automatically perceives audio information given via the radio. This information could then be added to the overview display, thus, the human mediates a change in representational states. In addition, different technology mediated transformations of representational states can be identified. The aspect of technology mediated transformations not only refers to automatically introducing information resources to the IF process, thus allowing different technologies to be connected/be fused. For example, radar data is automatically transmitted to be displayed on the overview display, thus, changing representational states. But also this aspect refers to some transformations being a continuous refinement process of the information process, for example, the target tracker automatically tracks identified objects at sea, thus, a continuous change in representational states occurs.

Models

The models used can also highlight and demonstrate a decision maker’s perspective of IF. Firstly, the model can emphasise the fact that the users interact both with the output of the IF system and that of the IF process (cf. Figure 21 and 22). In Papers IV-VI, it is demonstrated that the user interacted with both the IF process and the interface of the IF system, to different degrees. The models also emphasise the fact that the users are decision makers. That users are decision makers puts extra demands on a system in which there is an interdependency between the decision maker and the IF system. Papers V-VI includes examples of this interdependency.
Figure 21. A schematic view of an information fusion process, adopted from Nilsson et al. (submitted),

Moreover, a model can illustrate the embedding of decision makers in the context of IF systems (cf. Paper III) as well as in the context of the IF processes (cf. Paper IV), cf. Figures 21 and 22. As Figure 23 illustrates, the interaction between the decision maker and the IF system can be divided into different dimensions which, hence, characterise the “decision situation”.

Figure 22. A schematic overview of IF system components, adapted from Nilsson and Ziemke (2007).
This model, which is presented in Paper III, can be further validated through the empirical studies (cf. Paper V-VI). For instance, it was noted that the users’ cognitive abilities determined what type of information was being used and how the layout of the interface seemed to affect the users’ decision making processes (cf. Paper V). In addition, the relationship between the different components (i.e., users’ cognitive abilities, user activities and interface) is illustrated in the empirical studies, cf. Papers V-VI.

**Theoretical Insights**

Some conclusions regarding theoretical insights of human decision making and IF can be made. Firstly, a number of different factors which characterise human decision making in the context of IF have been identified. The situation is characterised by, for example, organisational demands, multiple decision makers, risk, temporal aspects, cognitive issues, situation awareness, trust, decision making process, visualisation, multiple sources, and so on (cf. Paper III). Some of these issues, such as organisational, and interface factors, are also presented in (verified by) the empirical studies reported in Papers V-VI.

In addition, insights regarding the interdependencies between human decision making and IF can be gained. Using an IF system as decision support is not without complications. For instance, there is an important trade-off between supporting situation assessment and/or impact assessment from a decision maker’s point of view (cf. Paper V-VI). From a decision maker’s point of view is it difficult to separate situation and impact assessment in a similar vein as proposed by the technology oriented JDL model.

Indeed, some decision situations are more suitable for impact assessment than situation assessment (i.e., long term vs. short term decision frames) (cf. Paper V).
also affects how decision rules should be framed, that is, should decision rules alert when a situation has occurred or when the situation is about to occur, in order to best support the decision maker (cf. Paper VI). In addition, the output of the decision making process is often not a specific decision which could be supported by one IF system, as implied by the JDL model. Instead, the decision making process consists of several decision making activities and the outcome is the process itself, cf. Papers IV-VI. Also, to be noted, the decision makers reported on in Paper V-VI did not have a mental picture of a future state, instead, they seemed to compare their achievements to the requirements of the task at hand (this should be compared to the different NDM models in Section 2.2.1, summarised in Table 2). In addition, the interdependency between the decision maker and IF has implications for how to evaluate IF systems. In paper V it is noted that there might be a difference between evaluating the interface of the system and evaluating the usefulness of the system as a decision support.

The listed issues have implications for how the interaction between users and IF systems should be supported when developing decision support utilising IF. At a later stage, the theoretical insight could be developed into guidelines to inform IF driven decision support.

5.2 Contributions

At the present time, IF, HCI, DSS, and DC are separate communities which have developed independently; however, there is a need to merge the ideas from the different communities to further develop the IF community. By doing this, the following contributions in this licentiate thesis can be highlighted:

- Introducing and promoting cognitive science research (i.e., decision making) as natural part of IF research, i.e.,
  - Detailed characterisation of an IF process as it includes both humans and technology (cf. Papers I and IV)
  - A new decision support class highlighting IF as decision support, i.e., IF driven decision support (cf. Paper II)
  - A characterisation of the decision situation as embedded in an IF context (cf. Paper III)
  - Empirical investigations of IF systems as decision support (cf. Papers V and VI)

- An analysis of human decision making and IF systems/processes and their possible interdependencies, i.e.,
  - Identification of possible interdependencies between human impact and situation assessment vs. machine impact and situation assessment (cf. Paper V and VI)
- Identifications of possible interdependencies between human decision making and the interface of IF technology (cf. Paper III and Paper V)
- Identifications of possible interdependencies between users’ activities and IF processes (cf. Paper IV)

More specifically, the proposed framework consists of a broad structure that promotes a decision maker’s perspective of IF, and shows the possibility and value of having such a perspective. Currently, the existing frameworks do not have a holistic view of the different ways users contribute to IF, apart from the initial work of Blasch and level 5 in the JDL model (Blasch, 2006a; Blasch & Plano, 2003). The presented framework would extend that work by providing more details based on investigations grounded in IF research.

As such, the research mainly contributes to the IF domain, but also partly to other related research areas, such as human factors, automation and decision support. For instance, cognitive science terminology, such as human decision making and distributed cognition, has been introduced to the IF community through a number of different publications. For instance, the results presented in this thesis not only highlight the users’ role as an active part of the fusion process but also details the interaction between users and the IF system, in contrast to the more common technological view in IF, exemplified by the JDL model (Level 0-4). In this context, the research contributes in terms of portraying the IF process as information propagation and transformation of representational states. A definition of fusion driven decision support has been introduced which captures these aspects of the IF process. The presented research provides empirical examples of the utilisation of IF systems which could inform future IF systems. Moreover, factors affecting users’ interaction with IF systems have been identified which could inform the development of IF systems, hence highlighting the role of the user and HCI issues in IF research. This particularly extends the work of Blasch and Plano (2003) and their “user dominant/machine dominant model” by indicating the intersection (the cut) between user dominant vs. machine dominant IF systems. Furthermore, this allows for equal considerations of technological as well as human aspects of IF. According to Miller and Shattuck (2006), it is necessary to have a model which considers both the human and technology to be able to understand the process by which an event unfolds. Moreover, decision making is treated here as a resource based process which portrays the decision as a continuous process and not a product or final goal, pin-pointed to a specific time, which can be supported by the information process. Instead, the decision making process is intertwined with the IF process. This has interesting implications for developing decision support and contrasts with the common view in IF research which assumes that the output of an IF process is to support a specific individual decision, cf. the JDL model.
The presented research also partly contributes to, for example, human factors research in the automation domain, due to the focus on the propagation of information as it is exchanged in a semi-automated process. In automation research the general approach is to focus on function allocation between a human user and the technology (Moray, 2001). In the research presented here the focus is not on functions distributed between operators and artefacts (technology), rather, the focus is on what information is transformed, which is typically not considered when discussing levels of automation (cf. Moray, 2001).

In addition, this licentiate thesis extends current decision support research, since it proposes a new class of decision support. This new class exemplifies supports which are semi-automated. Typical decision supports developed in the decision support community are not semi-automated decision supports to the same extent as IF systems.
6. Future Research

The research presented is part of the fulfilment of a PhD (cf. Figure 24). Thus far, the identification of models in IF (JDL, OODA, etc.) as well as cognitive science (DC, etc.) has aided the investigation of the interdependency between the decision making processes of humans and IF systems. The initial results have proposed the development of new and the adaptation of old models to highlight the interaction (interdependency) between users and IF systems. The findings are summarised into different buildings blocks which can be used as a starting point for the development of a future framework (cf. Figure 24). The aim of the future framework is to enable it to function as a tool for informing the development of IF systems (i.e., being an actionable framework). Future work will follow the same research approach as specified in Section 3, with a specific focus on the development phase. Having identified the areas of human decision making and IF is seen as the first step towards bridging the gap between human decision making and IF. Future work will require a move towards research of supporting decision making with complex systems, that is, the intersection between human decision making and technology (e.g., Brezillon & Pomerol, 1997; Neumann & Eymann, 2008). Hence, the following research question can be identified: How can cooperation (e.g., when and what to automate) between human decision making and IF technology be characterised to inform future development of IF systems/processes? The following section presents potential future work in some more detail.

![Figure 24](image_url). Schematic overview of research process indicating the progress between licentiate thesis and PhD thesis.
7.1 Informing IF Driven DSS

Future research will be directed towards verifying the results so far and continue to
develop the result into a format which can be used to inform future development of IF
systems (cf. Figure 25). As Figure 25 illustrates, one could use the building blocks to
identify guidelines and requirements which could then be used to develop the
framework. The building blocks will be extended to become more detailed due to a
specific focus directed towards one of the identified building block, that is, definition of
the IF process. This focus involves, for instance, case studies of “human” fusion in a
manufacturing scenario, as well as an investigation of user interaction in a semi-
automated process (an airport scenario). This would enable further explorations
concerning the concept of ‘transformations of representational states’ (i.e., the
existence of different types of transformations, such as visual, auditory, physical,
technical, etc.). Also, a more specific investigation of the framework’s possibilities to
inform IF systems is requested, as well as a theoretical discussion of the framework’s
implications for current IF research.

The overall aim of the developed framework will be to answer questions such as
when, and what to automate in the fusion process, how to enhance interaction, what in
the decision making situation needs to be accounted for in IF from a decision maker’s
point of view, thus, being an actionable framework. In addition, the research expects
to contribute not only to the IF community (e.g., publications at IF conferences and in
IF journals) but also but also to the decision making/decision support community (e.g.,
publications at the Human Factor and Ergonomics Annual Meeting and/or in decision
making journals).

Figure 25. Graphic presentation of the progression towards future framework.
References


# Abbreviations

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<tr>
<th>Abbreviation</th>
<th>Definition</th>
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<tr>
<td>CDM</td>
<td>Classical Decision Making</td>
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<td>CSCW</td>
<td>Computer Supported Collaborative Work</td>
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<td>DC</td>
<td>Distributed Cognition</td>
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<td>D-OODA</td>
<td>Dynamic OODA loop</td>
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<td>DM</td>
<td>Decision Making</td>
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<td>DMSC</td>
<td>Dynamic Model of Situated Cognition</td>
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<td>DSS</td>
<td>Decision Support System</td>
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<td>HCI</td>
<td>Human Computer Interaction</td>
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<td>IF</td>
<td>Information Fusion</td>
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<td>IFS</td>
<td>Information Fusion System</td>
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<td>MAU</td>
<td>Multi-Attribute Utility</td>
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<td>NCW</td>
<td>Network Centric Warfare</td>
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<td>NDM</td>
<td>Naturalistic Decision Making</td>
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<td>ODM</td>
<td>Organisational Decision Making</td>
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<tr>
<td>OODA</td>
<td>Orient-Observe-Decide-Act Loop</td>
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<tr>
<td>SA</td>
<td>Situation Awareness</td>
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<tr>
<td>SEU</td>
<td>Subjective Expected Utility theory</td>
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Paper I
Rethinking Level 5: Distributed Cognition and Information Fusion

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Abstract – The focus of most information fusion research, so far, has been on the technology, i.e. information processing in machines. However, the importance of also understanding human information processing, and the interaction between humans and machines, is gaining increasing recognition. This position paper argues that a distributed cognition perspective, which considers cognitive processes not as taking place solely inside people's heads, but as distributed over human thought processes and the material, social and organisational environment they are embedded in, may help to provide a deeper understanding of information fusion processes.

Keywords: Information Fusion, JDL Model, Distributed Cognition, Human-Computer Interaction, Context

1. Introduction

Information fusion is becoming increasingly important in the light of current developments of complex information technologies. Information fusion can be found in many different areas including, but not limited to, military applications, bioinformatics, manufacturing, agriculture, crisis management, etc. [1-4]. The most commonly used model to describe levels and elements of information fusion is currently the JDL model [1]. It explains, from a functional point of view, the hierarchical process of information fusion where typically input data from multiple sensors is transformed/condensed bottom-up to, for example, graphical displays of the most relevant information for human decision-makers. Most research in information fusion has its focus on the technical aspects such as probability and statistics, decision and estimation theory, pattern and image recognition, approximate reasoning techniques such as fuzzy logics, and other artificial intelligence tools [4], i.e. the techniques and methods used at levels 1-3 of the JDL model. Cognitive science, on the other hand, has so far had a relatively limited impact, partly in the form of ‘cognitive modelling’, i.e. the use of human-like or human-inspired techniques at levels 1-3 [5-7], and partly in the form of studies of human computer interaction (HCI), sometimes referred to as a “level 5” [1,8]. This position paper will focus on the latter.

Several researchers have acknowledged that there is a lack of research identifying the various HCI and cognitive issues [5, 8-10]. For instance, the need for adaptive interfaces to encourage human centred fusion has been recognised [8]. Also, social expectations have been identified as an area which needs to be investigated further [9]. In fact, it has been argued that the effectiveness of the overall information fusion process is affected by the utilisation of HCI [1]. In 2005, there was an editorial of the Information Fusion Journal dedicated to HCI issues [10].

Although there is, as briefly exemplified above, a growing understanding of the crucial role of the human user in information fusion, in our opinion, the perspective needs to be extended from thinking of information fusion as a process solely taking place in computer systems, to thinking of information fusion processes as processes including humans and their surroundings. That means, we need to widen the perspective of the fusion process from information fusion systems to information fusion processes (cf. Figure 1). An information fusion system often refers to the type of computer system characterised by the JDL model (levels 0-3), the process of transforming low-level sensory data to higher-level more abstract information. An information fusion process, on the other hand, also includes the context of the user(s), the material surroundings, the organisation they are part of, etc.
The need to pay more attention to the surrounding environment has also been pointed out by Brehmer [12] who argued that actions always have an effect on the environment which needs to be accounted for. In a similar vein, Blasch and Plano [30] emphasised the importance of context for user refinements to aid the fusion process, and Hall and McMullen [4] argued: “By rethinking the HCI for data fusion, we may be able to re-engage the human in the data fusion process and leverage our evolutionary heritage” (p. 336).

A related shift has occurred in cognitive science and artificial intelligence (AI) research in the last 15-20 years. While traditionally cognitive science and AI focused much on computational thought processes inside the heads of individuals, more recent work on distributed/situated/embodied cognition views cognition not as taking place solely inside people’s heads, but as distributed over human thought processes and the material, social and organisational environment they are embedded in. In this position paper we argue that taking a distributed cognition perspective in information fusion will be useful in achieving a deeper understanding of information fusion processes i.e. the embedding of information fusion systems in their cognitive and organisational context.

2 The JDL model

The commonly used JDL model is a functional model which describes the hierarchical process of information fusion from low-level sensory data to more abstract, higher-level information. There have been various extensions to the JDL model throughout the years [1]. The most commonly used model includes level 0 to level 4 [13]. However, there is a discussion whether or not level 4 should really be considered a ‘level’ in the JDL model [13, 1]. It has been argued that the so-called level 4 is actually a meta-process, i.e. a process which controls and optimizes the rest of the system and, thus, not a functional level itself (however, the details of this discussion are beyond the scope of this article). As briefly mentioned above, cognitive aspects have been incorporated to the JDL model both in levels 1-3 (e.g. cognitive modelling) and the higher levels (e.g. a suggested “level 5”), discussed in more detail below.

2.1 Level 5

A “level 5” was first suggested in 2000 by Hall, Hall and Tate [14] in order to explicitly account for functions associated with HCI. They argued that we need to remove the “HCI bottleneck” [14], which refers to the fact that broadband sensor data is fused through a narrow channel, i.e. the computer screen which the user interacts with, to be analysed by a broadband human being. It can be argued that the HCI interface becomes a bottleneck which prohibits humans from using their extensive pattern recognition and analytical skills to infer the information presented. Level 5 typically includes both cognitive and HCI issues, but is commonly referred to as “Level 5: cognitive refinements” [8, 14]. The level includes specific technical aspects which can be used for achieving cognitive refinements and recommended research areas, such as:

- time compression/expansion: human senses are especially optimised towards change detection; development of time compression and time expansion replay techniques could assist the understanding of an evolving tactical situation
- negative reasoning enhancement: humans have a tendency to ignore negative information and only seek information that confirms a hypothesis; techniques which exploit the idea of “absence of evidence” and “counter-evidence” should be developed
- pattern morphing methods: methods should be developed to translate patterns of data into forms that are more optimised for the users’ interpretations
- uncertainty representation: visual, auditory and haptic techniques should be developed in order to improve the detection of uncertainty

Blasch and Plano [11] suggested re-labelling “level 5: cognitive refinements” as “level 5: user refinements” and introduced the JDL-User model. The goal of the modified level is to extend the human capabilities. Their definition of level 5 is as follows [11]: “adaptive determination of who requires information and who has access to information (e.g. information operations) and adaptive data retrieved and displayed to support cognitive decision making and actions (e.g. altering the sensor display)” (p. 273). The aim with the level 5 is to support: cognitive workload, trust, attention, and situation awareness (see also [29] for a more detailed discussion of user refinements). However, the above definition has more recently
been suggested to include the ending: “... support cognitive decision making and actions (e.g. altering the sensor display) given social and political contexts” [30] (p.195). This definition acknowledges the importance of the social and political context for the usage of information fusion systems. However, it should also be noted that incorporation of a level 5 into the JDL model has not yet achieved common usage or acceptance by the fusion community [13].

3. Alternative models

The JDL model is not the only model used to capture and characterize information fusion systems. There are models which have tried, to some degree, to incorporate the human decision maker. For instance, Kokar et al. [9] approached information fusion from a design process perspective. They proposed a new object oriented reference model for data fusion systems where the data fusion process is top-down (the system constraints are considered first). Within this model the human capabilities can be easily accommodated, since no distinction is drawn between human and computer objects until the model is viewed from the realization perspective.

Another model is the Omnibus process model [15] which aims to capture the information fusion process by using a general terminology. The model includes a process flow chart, a dual perspective prescription for using it and a structured repository of fusion knowledge. Moreover, feedback loops are explicitly acknowledged in the model.

There are also models which have focused on the human decision process. Most prominently, Boyd’s OODA (Observe-Orient-Decide-Act) loop [16] originated from the military domain. It was intended to capture the command and control process and is still today the most commonly referenced model. It consists of four activities, i.e. observe- observe the environment, orient- position yourself in the environment, decide- make a decision of what to do next, act- perform the decision. The aim of the model is to enable faster decisions by identifying both your own decision steps and your opponent’s. However, it has been argued that the model gives a static picture of decision making, and therefore the dynamic OODA (DOODA) loop has been developed as an attempt to include the dynamic nature of the command and control process [12].

The DOODA loop model [12] was suggested in a military setting in order to capture the actual decision process by combining ideas from the OODA loop and cybernetic models. The model is divided into different functions (information collection, command concept, sense-making, planning, decision/order, military activity, effect). Some characteristic functions are as follow:

- **Command concept** – an overall concept of how an operation is to be conducted. This is one of the most important concepts in the model.
- **Sensemaking** - here, “sensemaking” refers to an understanding of the current situation and what can be done, the result of this function is a collective activity of the commander and his staff aimed at an action. However, it was emphasised that “sensemaking” should not be confused with the concepts of situation awareness. Nosek [17] also used the concept of “sense making” when describing how knowledge emerges in teams which interact with complex system. For instance, according to this view, the team creates the future by interacting with objects and the surrounding environment.
- **Effect** - the decision has an explicit, notable effect in the surrounding environment.
- **Arrows** - arrows determine the flow and feedback loops between the different functions, although overlaps between the different functions are acknowledged.

The goal of the model is to identify functions for an effective command and control process. The model may appear complex, however, the nature of a decision is complex; hence, a complex model cannot be avoided according to Brehmer [12].

To summarize, the studies briefly discussed above indicate that humans should and can successfully be incorporated into the information fusion process. As discussed in the following section, we propose a distributed cognition perspective as a valuable complement to capture the actual information fusion process.

4. Distributed cognition

4.1 A cognitive science perspective

The traditional (mainstream) view in cognitive science focused on mental processes inside the heads of individuals. However, more recently distributed cognition [18] has become a well established perspective in cognitive science, focusing not only on a single individual’s internal processes, but also on the interactions with the surroundings such as other individuals (groups), artefacts and other types of (information) systems as part of cognitive processes. In other words, cognition, is not longer explained in terms of information processing at the level of the individual, instead, cognition is argued to be better explained as a distributed phenomena [19]. Hence, cognition can be considered as distributed in a threefold sense:
• distributed across individuals in a group or organisation
• distributed between human-internal (e.g. memory) and -external mechanisms (e.g. computer systems, material and/or social environment)
• distributed over time

A key aspect of distributed cognition [18] is that there are individuals with usually well defined roles and tasks who interact with each other and with computer systems, e.g. information fusion systems; everyone possess their own expert knowledge but something more, something new emerges in the interaction between them, e.g. an information fusion process. In other words, one might say that the sum of the parts is greater than the whole. Thus, in a distributed cognition perspective the approach is that the cognitive process is not only within the heads of individuals; rather, the cognitive process is created in the interaction with the computer system and other individuals.

As a researcher one would be interested in the interdependencies between the individuals and the information fusion systems i.e. “in distributed cognition, one expects to find a system that can dynamically configure itself to bring subsystems into coordination to accomplish various functions. A cognitive process is delimited by the functional relationships among the elements that participate in it, rather than by the spatial collocation of the element” [19] (p. 176).

Approaching problems with a distributed cognition perspective could give the researcher or system developer a new way to understand problems. Indeed, in distributed cognition, the analysis (typically using in-depth ethnographic studies) deals with representing raw data collected at different levels of abstraction and detail, with a focus on changes in representation states [31]. Here, representational states refer to how knowledge and information are transformed to conduct an activity/action, e.g. the information displayed by a computer system transforms its state in response to a user keying in a command. For example, consider data from an ethnographic study of the activity of flying to a higher altitude in a plane, the coordinated activity of an air traffic controller, a co-pilot, pilot and the plane itself (i.e. a computer system) [31]. In this example, the distributed cognition approach/analysis identified [31]:

• the distributed problem-solving that took place
• the role of verbal and non-verbal behaviours
• the various coordinating mechanisms that were used

To give another example, in distance education one could have one or more students which collaborate through, for example, the internet. Video conferences are a common tool to use for interacting between the teacher and the students. In this case, Schrire [20] identified, using a distributed cognition perspective, the usage of the conferences and the interactions between the individuals. In particular, the author explained the emerging higher-order thinking which were characteristic to the conferences studied (which would have been difficult to identify without a distributed cognition perspective).

Furthermore, distributed cognition has been used to identify breakdowns in design processes. Busby [21] studied errors in the design process of a chemical process plant and a power generating plant. The problem studied was of the type “a designer forgets to include a particular kind of feature to the design”. The author concluded that “communication problems” were the most common cause. A typical communication problem could be a failure in the verification of one person’s results by another. Using a distributed cognition perspective enabled Busby “to reveal this kind of nested structure, its dependences on the interference of the participants, and the root of these inferences in their historical experience of earlier episode of similar kinds” [21] (p. 253). One could argue that the model of the internal organisational structure could be hard to identify without a distributed cognition perspective.

Holland et al. recently [19] proposed that distributed cognition should be used as a new foundation for HCI since in today’s society, one does not only work in front of a single computer, in fact, one most often work with connected ubiquitous computers. Thus, distributed cognition can be used to understand the emerging dynamic interactions which take place in our networked world of information and computer mediated interactions, i.e. the characteristics of today’s society [19]. The following subsection discusses in further detail how distributed cognition can be relevant to information fusion.

4.2 Distributed cognition in information fusion

In much information fusion research there has been a more or less implicit assumption that it is always better to fuse since adding more information can only help and not hinder the user when making
interpretations [3]. However, as Dasarathy [4] points out, there are a number of studies which indicate that more information is not always better, i.e. depending on the presentation/usage of the information it may be more or less complicated to make a decision. For an information fusion system developer, this balance can be hard to recognize. Using a distributed cognition framework it might be possible to identify the interaction between the human and the information fusion system, as similar to [21, 31], and thereby, identify the breakdowns (and when to fuse). To our knowledge, in today’s research in information fusion, the power of distributed cognition is not elaborated, even though, the subject is touched upon, as Blansch and Plano [32] acknowledge “A user fuses data and information over time and places and acts through their world mental model- whether it be in the head or with graphical displays, tools, and techniques” (p. 195). There are many different domains within information fusion which can benefit from a distributed cognition perspective due to the distributed nature of many fusion systems. For example, the defence domain is, by far, the most developed area to exploit information fusion. The focus in the defence domain is predicted to be on creating the new “network-centric warfare”. It is acknowledged that the network-centric environment demands distributed decision making (e.g. the decision is distributed between different individuals and locations). The aim of network-centric warfare is to enhance military capacity through the power of information from the following assumptions [22]:

- Information is shared
- Situation awareness and commander’s intent is available to all levels
- Operations are effects based and synchronised
- Decision-making should be collaborative

An important focus in network-centric warfare is to create shared situation awareness, “shared awareness aspires to achieve a common state of understanding within a group through the exchange of data and information” [22] (p. 4). To be able to create shared situation awareness it is important that the commander’s intent is accessible and understandable, also, it is important to understand that shared situation awareness can only be developed over time. The concept of shared situation awareness might seem vague and as a researcher it can be difficult to identify the meaning of “shared situation awareness”. Using a distributed cognition one has the terminology needed to identify the interactions between the different individuals and the interactions connected to the information fusion system, hence, the actual information fusion process can be captured.

The dynamic and distributed nature of the military command and control process is another related example where distributed cognition could make contributions. For instance, Bisantz at al. [23] developed a framework for aided, adversarial decision making (AADM), i.e. the use of decision aids based on information fusion in a cooperative and distributed defence domain. The authors identify a number of issues which needs to be considered when designing decision aids in the area of AADM. Trust is identified as a major issue defining the usage of the decision aid. It is important to know how much the user relies on the system and when that trust decrease due to the possible information attacks and failure in the automation of the system. Another issue is the distributed nature of AADM. Multiple locations, individuals and groups of individual together with the adversary force needs to be considered. Therefore, issues related to situation awareness are important for the interpretation of a decision. The authors also identified a number of specific dimensions to AADM (locus of attack, malfunction level, causes of failure or corruptions, time patterns of failure, predictable or unpredictable degradation).

A distributed cognition perspective on AADM would provide a common ground for the different factors presented and identify overlaps between different sources of data. Also, with a distributed cognition perspective one would more easily detect disruptions in the decision aid made by an adversary force. Indeed, a characteristic of AADM is the presence of the adversarial force and the vulnerability it involves e.g. information attacks.

Also, a distributed cognition perspective can, more specifically, be used when performing threat assessment/situation assessment. “Often the key indicators of potential, imminent or current threat situations are in the relationships among people and equipment that are not in themselves distinguishable from common, not–threatening entities” [28] (p. 2). For instance, [28] developed a new approach for threat assessment i.e. characterising, predicting and recognising threat situations. The goal was to establish a systematic approach to automating some of the above mentioned functions. Here, distributed cognition can be used as a valuable complement and tool in guiding the researcher in when to automate which functions.

Moreover, [11] proposed the usage of humans as to best locate and ID targets in group tracking, however, having a distributed cognition perspective would provide further understanding of the interaction between the human and the information fusion system, and thus, help to optimise the utilisation of the human capabilities. Not to forget, the value of context in information
Distributed cognition is about creating something out of the information fusion system and its surroundings. Considered as active components and the cognitive process is created in the interaction with the information fusion system and its surroundings. Distributed cognition is about creating something more which cannot be achieved through the individual parts, i.e., distributed cognition considers individuals with different roles and tasks and the overlap between them, as a result, a new shared understanding and meaning emerge. Indeed, “…effectiveness and efficient interactions between the fusion system and the user; the sum (as defined in the metrics) should be greater than the separate parts” [32] (p. 466). Hence, the user is no longer only viewed as a mere observer of an information fusion system; rather, the humans are included in the information fusion process.

5. Discussion

As humans, we have extraordinary skills which help us interact with the surrounding environment. We are good at recognizing patterns, identifying geographic proximity, and looking for relationships between natural objects and man-made objects such as bridges, roads, and buildings [8]. However, in information fusion one has yet to learn how to exploit this knowledge when designing complex computer systems. Some suggestions for future work and the added value a distributed cognition perspective provides are elaborated in the following subsections.

5.1 Humans as an active component

Traditionally in information fusion, one has tried to exploit human capabilities in designing interfaces and architectures of systems. For instance, the JDL model level 5 identified areas which needed more focus (such as techniques to direct attention). However, the interaction with an information fusion system has not been considered in a wider perspective, i.e., the information fusion system typically has not been put into the context of an information fusion process (as illustrated in figure 1), an information fusion process may include one or more users, one (or more) information fusion systems, also, the users usually belong to some sort of organisation and environment. Hence, the information fusion system, as such, does not define the information fusion process.

To be able to capture the actual information fusion processes, one needs to consider a vast array of aspects and, most importantly, one should remember that humans have an active role. The fact that humans should have an active role has also been recognised by Blasch and Plano [11] who “see the human as an active component in the fusion process to optimize sensors to best locate and ID targets” (p. 270). However, most often, humans are viewed as mere receivers of an information fusion system’s output, i.e., the receiver of fused information.

Distributed cognition can give us an appropriate approach to study humans as an actual integral part of the information fusion process (see also figure 1). In distributed cognition humans are considered as active components and the cognitive process is created in the interaction with the information fusion system and its surroundings. Distributed cognition is about creating something

5.2 Tackling problems outside-in

With a distributed cognition perspective one would tackle problems/situations from the outside in, beginning with the social and material settings, that way, culture, organisation, context, and history can be introduced in the information fusion process. Specifically, a distributed cognition perspective would enable the organisational perspective to be incorporated into the information fusion process. The significance of the organisation should not be underestimated since norms and goals of an organisation can directly guide the user, the decision maker; consequently, the organisation affects the usage of information fusion systems. Moreover, it can be suggested that it is important to consider an organisational perspective rather than only a group/team perspective [25] since we, in information fusion, often deal with people who have the authorization and the responsibility to make a decision in a certain area. In fact, it has been acknowledged that the traditional model in the command and control process, the well known OODA loop, is relatively static and does not explicitly take the surrounding environment into account. To address some of those problems, the DOODA loop has been developed [12]. In fact there is a strong correspondence between the concepts of sensemaking [12, 17] in the DOODA loop and concepts of distributed cognition. In our opinion, there is a possibility to extend the
perspective on information fusion by introducing terminology and concepts from distributed cognition.

Furthermore, as previously mentioned, looking at problems from the outside in would enable history to be included to the information fusion process. This is, to some extent, already utilised in techniques such as “tracks/path” where, for instance, the history (past) is used to predict the future. Also, Blasch and Plano [30] point out “the user maintains a cognitive model of the things that are going on and updates the cognitive model based on the context. Context includes the task of interest, the priority information, and some history of what the user has experienced in the past” (p. 198). The significance of the past to the information fusion process should not be compromised and having a distributed cognition perspective could explicitly account for that. In fact, one could argue that information fusion is all about fusing the past, present and future.

One also needs to consider the specific user’s interaction with the information fusion system, e.g. human factors. For instance, Bisantz et al. [23] identified important factors which influence the usage of an information fusion system, and, thus, the information fusion process. For instance, situation awareness is a very important factor in order to achieve a common understanding between the different individuals.

One important aspect of situation awareness, which also plays an important role for distributed cognition, is to which extent a task can be automated in a computer system without reducing human situation awareness. In other words, when a system is automated it might perform operations which the user is unaware of, hence, the user’s situation awareness decreases. Nevertheless, automating the information fusion process is still foremost a research issue [26]. Many researchers have considered the technical aspects, however, the users of the system are the ones making the decisions, and therefore, they are an essential part when automating the information fusion process.

The balance between the organisation, the individuals and the automation of the information fusion system is crucial; as a consequence, one needs to consider many different aspects, including trust, in order to achieve an overall effective information fusion process. The distributed cognition framework could be used to facilitate this balance. We argue that there is a need to rethinking the concept of the JDL model level 5 and acknowledge the human and the surrounding environment as parts of the information fusion process. This is also in the line with Blasch and Plano [30] who argue that context determines user refinements, i.e. the users’ action/activity. Distributed cognition, in our opinion, can provide an additional value, by providing an approach to achieve this incorporation and capture information fusion processes.

5.3 A natural shift in information fusion

It can be argued that the proposed development of information fusion research (i.e. the usage of distributed cognition) follows recent developments in cognitive science. Traditionally, in cognitive science one has only been interested of the inside of individuals (e.g. memory), however, in recent years the interest has been broadened to also consider cognitive science as something which emerge in the interaction with other individuals or environment i.e. distributed cognition. Today, distributed cognition is a commonly used and accepted perspective within cognitive science. The shifts from individual interaction to more distributed/collaborative interactions are also notable when examining the recent development of decision support technology [27].

In information fusion, researchers have begun to recognise the distributed nature that, in fact, is present in a wide range of information fusion processes [13, 22-23]. For instance, researchers have acknowledged the need to address the distributed nature of information fusion by referring to the distributedness of architectural issues and algorithmically issues (referred as “Distributed Data Fusion”, DDF) [13]. This is an important starting point which establishes the recognised distributed nature of information fusion, however, we propose that information fusion needs to be further developed and also take the human aspect into account. Distributed cognition can, as is proposed to HCI [19], be a new foundation for information fusion. This would be a natural development because one needs to consider the environment in which an information system operates to capture the actual information fusion process and hence, enable the breaking of the previously mentioned “HCI bottleneck”.

6 Conclusions and future work

This paper has briefly reviewed some of cognitive science’s potential contributions to information fusion, in particular the JDL model, and suggested that adopting a distributed cognition perspective can be a valuable complement to existing approaches to understanding and modelling information fusion, in particular information fusion processes. There is much technological research on how to create effective information fusion systems, however, it is suggested that one also needs to consider distributed cognition to create an effective information fusion process. One can argue that there is a difference between thinking of the information fusion process as a process in the information fusion system versus the information
fusion process, as defined herein. One need go beyond the HCI and take the insights from cognitive science (e.g. distributed cognition) into account in order to capture the actual information fusion process.

However, there is still a question of integrating the different theories in cognitive science, including distributed cognition, into information fusion, in order to capture the actual information fusion process. In particular, distributed cognition can provide crucial elements of a theoretical framework and an analytical methodology which could be used to capture the nature of information fusion processes and their embedding in the support of organisational, individual and automatic decision processes. This would be difficult to achieve with the more traditional static approaches in cognitive science such as cognitive task analysis [33]. Above all, the advances in cognitive science have yet to be incorporated in the information fusion process and this provides a great challenge and will be further examined in future studies.

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Paper II
Information Fusion: a Decision Support Perspective

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Abstract- The focus of most information fusion research, so far, has been on the technology, i.e. information processing techniques and algorithms. Consequently, there is a lack of research concerning the actual usage of information fusion systems in terms of cognitive and organisational issues such as supporting both individual and group decision making. This paper provides a retrospective of information fusion research so far and a future vision of information fusion systems as actual decision support systems. A methodology for developing decision support systems is suggested which could not only ensure the effectiveness of information fusion systems as decision support systems but also provide a natural user perspective and top-down approach to information fusion in general.

Keywords: Information Fusion, Information Fusion System, Decision Support, DSS, Decision Making

1. Introduction

Information fusion (IF) has been suggested to be a necessity in many of today’s and future information systems i.e. “while information technology can transform a data poor situation into a data rich environment, the fact remains that data need to be fused and analyzed effectively and efficiently, in order to provide appropriate information for intelligent decision making” [1, p 104]. Due to the current development of complex information technologies (giving users access to large amounts of information) there is an increasing recognition of the power of ‘information fusion’. Following Dasarathy [2], Information fusion refers to: “... exploiting the synergy in the information acquired from multiple sources (sensor, databases, information gathered by humans etc.) such that the resulting decision or action is in some sense better … than would be possible if any of these sources were used individually without synergy exploitation” [2, p. 75]. Accordingly, the focus of information fusion is the utilisation of large amounts of information from different sources in such a way that a better decision could, in a sense, be performed (thus, made by users). The traditional focus within information fusion research has been on the actual process of combining large amounts of information in a more comprehensive and easily manageable form [3]. Most often, the user is implicitly taken into account as in the previous stated definition. In fact, current IF research acknowledges [e.g. 4, 5, 6] that information fusion could be used to support and enhance the user’s decision making process (i.e. be a decision support system), but there has been little recognition, within the IF community, of the possibility to actually view an information fusion system (IFS) as a decision support system (DSS).

With a few exceptions [e.g. 7, 8], in most information fusion research, the user of an IFS is still considered as the mere recipient or observer of fused data. As a consequence, not only the possible utilisation of user’s decision making process is ignored, but also the possibility for using IFS as DSS. However, one could argue that there is a need to consider IFS as actual DSS for users.

Today, there exists encouraging research which focuses on the user aspect of IFS and its possibility to function as a DSS. For instance, [4, p 1] argue that “[t]he purpose of a fusion system should be tailored towards supporting a decision-maker or a human”. Other researchers such as Bisantz, et al. [6] have performed promising research which recognises the possibility for fusion based DSS.

Indeed, there are possibilities for treating IFS as a DSS, and it may lead to interesting implications, such as overcoming the fact that “the fusion community has typically overlooked the role of the user by designing them out of the system” [9, p 3]. It could also ensure the effectiveness of IFS due to the acknowledgement of the goal of IFS, hence, a more top-down perspective is provided. However, much research remains to be performed and research which already exists needs to be extended to truly consider IFS as DSS.

The remainder of this paper will first present a general view of an IFS, following by a description of what constitutes a DSS. Finally, a discussion is
As noted in [3], the use of ‘fusion’ is not new. Humans and animals have used a combination of different senses since the dawn of time in order to survive. In recent years, the concept of ‘information fusion’ (IF) has become even more important due to the large amount of information humans need to access on a day-to-day basis. The power of IF has started to be recognised. Indeed, empirical studies have shown that performance of the overall system improved with the number of information sources [3]. Also, it has been argued that “[f]usion of relevant sensor data … has proven effective in reducing false alarm rates, increasing confidence levels in early fault detection, and reducing time to failure of degraded condition requiring maintenance action” [10, p 1]. Indeed, information fusion could even be seen as a requirement for an effective system, as [11, p 1] argues: “Without data fusion, the user is faced with dealing with data that is redundant, inconsistent and conflicting…”. In other words, systems become more effective due to the exploitation of information from different sources, hence, enabling the possibility for reducing uncertainty (comparison of information from different sources), increasing the accuracy (information from different sources complement each other) and increasing robustness (the possibility for redundant information) [4].

There have been different attempts to characterise IFS, e.g. [4, 12, 13], actually, as the literature is presented today, there is no general consensus regarding the components of IFS, consequently, there are slightly different opinions on what is required of a system to be classified as IFS. However, basically, the system needs to receive information from different sensors (i.e. information sources). Accordingly to [12], sensors could refer to active sensors (radar and sonar), passive sensors (IR, visible, acoustic, magnetic and seismic), human sources (intelligence gathering) or data archives (weather, financial data). In other words, the specified sensors could be classified as either past (e.g. data archives), present (e.g. active sensors) or future sources (e.g. simulations/models).

The information received from the different sensors needs to be combined in such a way that more or better information could be achieved than you originally started out with (thus, the very reason for using fusion). Therefore, within the IFS there is an information fusion process which actually fuses the information provided by the different sources, typically captured with the JDL model [3]. This process is often automated with the purpose to support the user i.e. “[a]utomated data fusion processes are generally employed to support human decision making by refining and reducing the quantity of information that system operators need to examine to achieve timely, robust, and relevant assessments and projections…” [5, p. 432].

Traditionally, the fusion process has been seen as the actual data fusion process (e.g. algorithms and other AI techniques), however, more recently, it has been acknowledged that the user could actually contribute to the information fusion process [e.g. 7, 14, 33]. Hence, typically an IFS involves different degrees of automation and user involvement. The mixture between automation and the user’s contributions to the success of the system is also referred to as mixed-initiative interaction [15], recently acknowledged in IF research, e.g. [29]. Also, [7] has touched upon this issue by exemplifying the interacting with an IFS as an interval with the extremities ‘user dominant’ (the user is in control of the fusion process, i.e. no automation) and ‘machine dominant’ (freedom for the sensor manager, i.e. fully automated fusion process). Not to forget, this system is usually also part of a larger organisation, interacting with other IFS and individuals [33]. For an extended discussion of the information fusion process cf. [33].

However, no generally agreed-upon list of IFS characteristics exists (beyond the JDL model), but basically, ‘IFS’ refer to computer systems which utilise information/data from different sources, as previously described, to support a decision maker, cf. Figure 1.

![Figure 1. A schematic view of the components of an IFS.](image-url)

### 3. Decision Support Systems

DSSs evolved during the 1970s and, in general, refer to computer systems which are intended to support complex decision making and problem solving. Traditionally, DSSs are mostly based on rational (classical) decision making theories. As [16, p. 1] argues: “Emphasis in the use of a DSS is on provision of support of decision makers in terms of increasing the effectiveness of the decision-making effort. As we will see, this involves the formulation of alternatives, the analysis of their
interpretation, and selection of appropriate options for implementation”. Over the years, different classes of DSS have emerged. [17] provides a categorisation of different DSS as follows:

- **Data-driven DSS**, e.g. systems which provide access to large amounts of structured data from databases to support manual analysis, i.e. enabling display and manipulation of queries to a database or data warehouse to specific questions
- **Model-driven DSS**, e.g. systems which are based on different representational and optimisation models to support decision making, i.e. enabling what-if analyses.
- **Knowledge-driven DSS**, e.g. systems which consist of knowledge, understanding of problems and problem solving skills within a specific domain, i.e. enabling suggestions and recommendations for actions (i.e. expert systems).
- **Document-driven DSS**, e.g. systems which gather, retrieve, classify and manage unstructured documents i.e. enabling structuring of documents.
- **Communication-driven and Group DSS**, e.g. systems which support collaboration, communication and coordination between multiple decision makers, i.e. enabling facilitation of solutions.
- **Interorganisational/intraorganisational DSS** e.g. systems which support organisations facilitation of information distribution, i.e. enabling service for users
- **Function-specific or general purpose DSS**, e.g. systems which are developed to support a specific task or function, i.e. enabling automated support for routine tasks or facilitating decision tasks
- **Web-based DSS**, e.g. systems which are based on web technology, i.e. enabling delivery of decision support information or decision sup lists port tool

A DSS may have elements from different categories, although, according to [17], it is possible to extract one category as the ‘drive’ and focus of a particular DSS.

In general, it could be argued that, independent of the category, a DSS has a narrow, focused, and specific purpose rather than a general one. [18] also made the distinction between *automated decision systems* (e.g. systems which automate routine decisions in well-structured situations) as in contrast to *decision support systems* (e.g. auxiliary and ancillary systems which assist decision makers). More specifically, [19] argues that a DSS should fulfil one or more of the below listed characteristics to be named a DSS.

- g) … *contain* knowledge describing aspects of the decision-maker’s environment, that indicates how to accomplish a range of tasks, and that indicates valid conclusions in different circumstances.
- h) … *has* the ability to acquire and maintain descriptive knowledge as well as other kinds of knowledge
- i) … *has* the ability to present knowledge on an ad hoc basis in various customised ways as well as in standardized reports
- j) … *has* the ability to select any desired subset of stored knowledge for either presentation or deriving new knowledge in the course of problem recognition and/or problem solving.
- k) … *can* interact directly with a decision-maker or a participant in a decision in such a way that the user has a flexible choice and sequence of knowledge management activities.
- l) … *can* coordinate/facilitate interactions among multiple decision makers

Similarly, a more recent and exhaustive list of characteristics and capabilities of DSS is provided by [20]. It should be noted that there is no general consensus of the components of a ‘DSS’, consequently, there is no general agreement regarding standard characteristics and capabilities of a DSS [20] (however, one could see similarities between the existing characteristics, which, in a sense, justifies the existing lists).

In summary, one could argue that DSS should, in line with previous lists, provide up-to-date and timely information that is complete and accurate, in an appropriate formation which is easily understood and can be manipulated by a user [20].

There are different ways to develop DSS. For instance, [21] presents an interesting framework describing how to develop, construct and ensure the effectiveness of a DSS. In essence, the framework identifies a set of design principles and a methodology (design process) [21]. In short, the design principles are as follow:

- d) DSS should be tailored to a specific position or region of the expertise continuum (there is a difference between novice and expert decision making)
- e) DSS design must involve analysis of the cognitive processes and problem representation of the users as well as analysis of the external domain and physical systems involved
- f) DSS could either provide training to perform more effective decisions or a
support for making decisions. The training component within DSS should be developed from the same cognitive modelling and analysis used for decision support design.

In order to include the above identified principles, following methodology, DSS design process steps is proposed [21]:

1) **Cognitive decomposition and modelling**, i.e. representation and decision strategy of the user are studied and mapped out. More specifically, a ‘Task Summary Description’ (TSD) is created to capture the user’s decision making process. To create TSD they propose tools such as behavioural/cognitive analysis protocol and COGNET.

2) **Functional requirements definition**, i.e. decision makers’ cognitive model is analysed in order to create requirements for the DSS.

3) **Functional design**, i.e. from the requirements specific functions for the DSS are outlined.

4) **Architecture specification**, i.e. the technology are assembled to create the DSS.

5) **Detailed design and implementation**, i.e. system components are specified, implemented and tested.

In this method, the usage of TSD is a distinguishing factor i.e. the TSD in the first step allow taking into account the surrounding context (environment) when designing the system. For further details, cf. [21] where they provide tools to conduct each phase of the above mentioned process.

Research concerning DSS is not straightforward. More recent studies focusing on DSS in medical settings [22] suggest that there is need for a change of focus and to expand the scope of the research which the decision support is built upon. In other words, change perspective from the ‘classical view’ which, traditionally, DSSs are built upon, to an approach which combines problem solving, decision making and acknowledge the role of conceptual knowledge and the naturalistic and dynamic nature of the decision environment [22]. In the end, this would lead to development of technology which truly and successfully mediates decision processes.

4. **DSS in Information Fusion**

Judging IFS in general, they are implicitly treated as providing decision support, i.e. it is often acknowledged that the system will, eventually, be used for aiding human decision making, in some sense, e.g. [2-7]. Consequently, many IFSs are effectively considered to function like DSSs. In fact, there are studies which have emphasised that IF technology could, in fact, be the base for DSS.

Amongst others, [23] presented a ‘smart decision support system’ based on fusion technology (e.g. utilizing case-based reasoning, fuzzy clustering, fuzzy decision trees, k-nearest neighbour algorithms, Bayesian belief networks) which supports the user by reducing the complexity of military planning tasks and de-cluttering and speeding up the decision making process. [24] developed an expert DSS based on fusion techniques (fuzzy logic and evolutionary algorithms) which aimed to determine new multi-agent techniques, rules, and strategies for which no human expertise exists. In other words, an expert system was developed to function without human intervention, making decisions in areas of uncertainty where no previous human knowledge exists. Also, [25] examines DSS in the command and control process (which could be built on information fusion technology). They proposed a ‘Command and Decision Support Interface’ (CODSI) integrated in the development of DSSs enabling reassurance of the success of, for instance, fusion based DSS. Especially, CODSI together with SEATS (a test bed) [25] is used to study and measure human situation awareness and decision making. Second, it is also used as a concept validation tool where technological concepts are validated from a human performance and operational perspectives. [26] developed web-based DSS utilising information fusion techniques (combining two forecast/predictions models) to help managers make better decisions on what movie characteristics to choose for a specific movie. Further, [6] have explored the issues of trust in data fusion based decision aid. In detail, [6] studied degraded and distorted icons’ ability to illustrate uncertainty to users, and how that affected users trust to the information.

Interestingly, in 2006 two articles [27, 28] published in the Decision Support Systems Journal presents DSS based on fusion techniques (compared to almost no articles, apart from the two mentioned since the journal’s start in 1985). [27] used a data fusion approach in an information retrieval DSS. [28] developed C.A.S.T. which assisted teams to make effectively critical decision under time pressure. The idea was to support the anticipation of information need of other team members, hence, the process could be made faster. Information fusion was particularly used to reduce the cognitive workload of users. Those are examples of the recent interest and recognition of fusion techniques outside the information fusion community.

To conclude, using information fusion based DSS has proven to be effective, however, the
information must be presented in such a way that it conveys important aspects of the information and that the system can be trusted by the user [6]. Indeed, [18] argues that the interface of the DSS can bias the users and cause inappropriate elicitation approaches. Thus, both the cognitive aspects (e.g. decision making theories) and HCI aspects (interface issues) are important for the success of a fusion based DSS.

5. Discussion

In the information fusion literature, the idea of supporting human decision makers appears many times, yet, research, most of the time, does not consider IFS in the light of actual decision support. In the following subsections, some of the added value a DSS perspective provides for IF research is elaborated upon and some suggestions for future work are provided.

5.1 Information fusion systems as DSS

Throughout the IF literature it is acknowledged that IFS are intended, most of the time, to be used by a human user, e.g. “data fusion processes are generally employed to support human decision making” [5, p 432]; “The purpose of a fusion system should be tailored towards supporting a decision-maker” [4, p.1]; “Ultimately, information resulting from the data fusion process is presented to the human decision-maker through a computer interface” [6, p 1]. Hence, IFS could, indeed, be treated as DSS. In fact, considering the list of DSS characteristics provided by [19], IFS, in general, could consist of all components, as follows (cf. Section, 3):

a) IFS contains knowledge of the environment due to data from different sensors, and could sometimes predict future states
b) IFS has the ability to acquire and store knowledge (information) from different sensors
c) IFS could present knowledge and information in various ways
d) IFS has the ability to fuse information, and present it to the user for further considerations
e) Users of IFS could interact with the system influencing both the process and the result
f) IFS could coordinate/facilitate interactions among multiple decision makers

Hence, IFS fulfils the requirements stated by [19] and, to some extent, the list provided by [20]. Similarly, another point of view: IF could be considered as requirement for effective DSS, i.e. “Without data fusion, the user is faced with dealing with data that is redundant, inconsistent and conflicting ...” [11, p. 1]. Hence, not only should an IFS be treated as a DSS but also information fusion should be a component in DSS to become effective.

5.2 Fusion based DSS: A new class of DSS

In addition to identify different characteristics of IFS, there is an additional aspect to categorise DSS. [18, p. 1045] argue: “[c]ategorizing decision support systems can assist researchers and managers in understanding how this general class of information systems impact decision behaviour and how one should design and construct such systems”. In fact, [17] has a useful categorisation of different types of DSS. At first, IFS might be considered as data-driven DSS because of the emphasis on analysis of large amount of structured data. However, today’s IFS are much more complex, and could be used for different purposes, resulting in the possibility to be categorised according to several of [17] identified categories.

First of all, they do not only fuse data from databases (e.g. data-driven DSS) but also from models and simulations (e.g. model-driven DSS). Further, they could be developed for different tasks (e.g. function specific or general purpose DSS).

Secondly, the traditional view of DSS (such as the previous mentioned categories, e.g. data-driven DSS) does not properly take into account the mixed-initiative interaction [15] often exploited in IFS [e.g. 29]. Similarly, [3] argues that IFS is particularly challenging because of the information flow. Ordinary computer systems could be classified as either user-driven applications or data-driven applications. IFS comprise both modes of interactions, simultaneously. On one hand, data is received from sensors and processed by automated fusion processes for presentation to the user. On the other hand, the user is in charge of the system and can initiate interaction to retrieve information, perform computations and control the system resources and also provide input to aid the system. As a consequence, the interaction is complex and both modes need to be supported. This is further reinforced when comparing DSS [19] and IFS characteristics, e.g. cf. previous mentioned characteristic “e”, i.e. IFS’ users could influence the result, and even, when needed, encouraged to aid IFS to come to a conclusion, as a contrast to traditional DSS.

Thirdly, due to the typical environment captured by IFSs, they are not typical ‘decision support systems’. DSS are often based on the classical decision making paradigm which views
humans as rational beings capable of making objective decisions between alternatives. IFS, on the other hand, often deals with dynamic environments characterised by real-time data, ill-structured problem, shifting goals, multiple users, i.e. the characteristics of ‘natural decision making’ (NDM) (i.e. the research discipline which studies real decision making in its natural settings cf. [34]).

Therefore, taken together, a new class of DSS is needed which emphasise the added value and characteristics of fusion, namely, “Fusion driven Decision Support Systems”. This class complements the previous mentioned list provided by [17]. More specifically, the class would include the following aspects:

- **Fusion driven DSS**, i.e. systems which are based on fused information from different sources such as sensors, databases and models, providing both automatic and semi-automatic fusion processes, i.e. enabling complex decision making from large amount of information (which may be conflicting/ contradicting or uncertain) without information loss (e.g. information is not just filtered, but, for instance, aggregated) with respect for the user

In other words, the system does not only combine different information sources for aiding the user but also provides automatic and semi-automatic fusion processes i.e. providing control to the user (for examples of possible control functions cf. [7]). This is in contrast to ordinary DSS which are, according to [18], often categorised as either, automated decision aid or decision support system, cf. Section 3. Further, in line with the arguments of [22], traditional DSS, as currently constituted, cannot adequately inform the information fusion based DSS.

### 5.3 Benefits, Challenges and Drawbacks

Approaching IFS as DSS may have different implications for the development and design of IFSs, especially if the IFS is developed in a similar vain as the methodology provided by [21], cf. Section 3. Moreover, using this method, could allow for capturing the information fusion process as part of the context as suggested in [33]. Some of implications are further elaborated upon in the following subsections.

#### 5.3.1 Benefits

When considering IFS as DSS there are a number of benefits.

First of all, information fusion as currently constituted is lacking a user perspective, treating the IFS as a DSS would naturally give this perspective. Today, often papers present the technological aspects of IFS; forgetting to explain how it is actually going to be used by users i.e. how the interaction with the system works and actually, in what sense, users are supported by the system. A user perspective has been seen as less interesting and merely as an interface and visualization issue. Nevertheless, the role of the user should not be underestimated. Indeed, there is a common consensus which implies the need for a more user centred approach [3]. For instance, there is a transition within the information fusion community to extend the concept of the information fusion process to include humans as well e.g. [11, 7, 14]. However, there is a lack of means (beyond ‘level 5’) to reach and create this ‘user perspective’. Having a DSS perspective would ease this development, the framework provided by [21] is a great starting point.

Second, enabling this user perspective and treating IFS as DSS may ensure the effectiveness of the system. Today, IFS become more and more advanced and in order to optimise the system it is not enough to use more advanced sensors. As [6] argues, the ultimate performance of a decision aid does not only depend on its quality, but also of the possible utilisation of the system. It becomes clear that there is a need to approach IF from another perspective, i.e. the Decision support perspective. In other words, we need to acknowledge the goal of the information fusion system, e.g. the purpose with an IFS, is according to [3, 4], to some extent, to support the user’s decision making process. Treating IFS as a DSS may have implications for the design of IFS, and further ensure the success of the IFS (cf. [21]).

Third, treating IFS as a DSS would provide a natural top-down perspective. Driven by the JDL model, research in IF has, up till now, been bottom-up. This has lead to numerous studies focusing on the lower level of the JDL model. In contrast, treating IFS as a DSS could give a top-down perspective (thus, in extension, providing a holistic view of the information fusion process), increasing the research performed at the higher levels of the JDL model, especially, those dealing with user issues. In other words, having a top-down perspective would give the focus of who should be supported by the system, what information we need in order to make the decision, i.e. the goal of the system is acknowledged. This would enable the needs and requirements of users to be considered before considering what data we could actually fuse and what relationships we could find in the data to support a decision. In other words: “[i]f the fusion approach was attacked top-down, then the community would start IF designs by asking the customer what they need” [9, p.2].

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5.3.2 Challenges

However, it is not straightforward to treat IFS as DSS. There are a number of challenges. The first and maybe the most challenging is that of building an effective DSS because one needs to have a thorough understanding of the decision making process. Indeed, “maximally effective decision aiding requires the problem representation in the decision aid to reflect the problem representation and cognitive processes of the decision maker using the aid” [21, p. 1244]. However, in IF research, there is a lack of research focusing on the user’s decision making process embedded in an information fusion setting. Also, there is limited research which examines if, for instance, the fact that information is fused, affects the user’s decision making. There have been attempts, e.g. [7], however, much remains to be done. Consequently, in order to treat the IFS as DSS there is a need for research that considers the user’s decision making process when interacting with IFS. An interesting suggestion is provided by the DSS community, i.e. [1]. In this framework, a ‘Task Summary Description’ (TSD) is created to capture the user’s decision making process. From the TSD, requirements for DSS could be identified. To create TSD they propose tools such as behavioural/cognitive analysis protocol and COGNET [21].

Second, as things stand today, it may be difficult to change the focus from the more technical oriented IF research. Hence, it may be difficult to ensure the success of treating the IFS as DSS. This is also acknowledged by [35] who highlight the problem between human factors specialists and system designers when designing data fusion based system for supporting dynamic decision making (interestingly, they also propose a solution).

Further, there are other areas which have introduced DSS with promising results. For instance, [30] drew the conclusion, amongst others, that despite the fact that the concept of organisational DSS has evolved over many years, no study has examined enterprise resources planning (ERP) systems functioning as a type of organisational DSS (even though ERP and related systems perform similar functions as organisational DSS). [30, 31] address this issue and describe the characteristics of ERP systems as DSS and the benefits. This possible mapping further establishes the possibility for treating IFS as DSS.

Third, so far, the two disciplines of IFS and DSS have developed independently and there is a need for informing and combining the research results from the two areas, i.e. fusing the existing research results. Today, the two areas are dealing with similar problems. For instance, the IF community could be informed on how to provide a user perspective when designing IFS. Similarly, the DSS community could benefit from IF community, for instance, [32] argues that an efficient information system which supports decision making needs to present information of the past, present and future (thus, integrating databases with simulations and models i.e. the aim with IF). Clearly, IF might be a successful technique to utilise.

5.3.3 Drawbacks

There might be limitations and possible drawbacks in considering IFS as a DSS. For instance, looking at information fusion systems, one could see that it does not confirm to the neat logical view of DSS, i.e. DSS does not accommodate for, e.g. the active user (i.e. mixed initiative interaction, where the system could be supported by its users), which typically distinguish IFS.

Moreover, [22] recognises that there is a general need to go beyond the traditional view of DSS, i.e. we need to look beyond classical decision making (CDM) theories which they are built upon. [22] acknowledges that we (1) instead of CDM need to focus on problem solving skills, (2) to capture the nature of decisions a ‘Naturalistic Decision Making’ approach is essential, and (3) the technology (i.e. decision support) need to be considered as mediators of performance. In other words, there is a need to change how DSS are approached in order to build successful technology which could mediate human decision making processes. Further, they argue that we need to have a deeper understanding of a) performance in actual settings, b) effects of technology propagating through the different layers of an organisation, and, c) the adaptability of health professionals to an increasingly technology mediated world. These would be issues transferred to IFS. Hence, there are known limitations within DSS which need to be considered before treating IFS as DSS. However, by originally starting out with a special class of fusion based DSS and by using the proposed method by [21], the above identified drawbacks may be limited. Although, to be noted, the limitations of the DSS paradigm as demonstrated by [22], has yet to be noticed by the mainstream DSS community.

6. Conclusions and future research

In future, it is clear that IFS will play an ever larger role in our world, working for, and in cooperation with users. To date, most research in information fusion has not explicitly focused on treating information fusion systems (IFS) as decision support systems (DSS), at least not in the traditional sense of decision support research (similarly, very limited research presented in the DSS community.
uses fusion technology). The information fusion field has benefited from substantial research efforts in the technological aspects of information fusion, however, much research remains to be performed, especially concerning user aspects, hence, understanding the user’s utilisation of IFS and capturing the user’s decision making process. This paper proposes that treating IFS as DSS is a first step towards ensuring the effectiveness of IFS. In addition to a user perspective, it could also provide a top-down perspective to IF and overall ensure the success of the IFS. However, more research is needed. Indeed, [21] argue that an understanding for user’s actual decision making process is needed before being able to build effective DSS, hence, research capturing user’s decision making process and user’s integration to IFS, is essential.

Future work will further investigate the relationship between users and their IFS (i.e. the users’ decision making process exploiting capabilities of IFS), as similar to the ideas presented in [33].

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References


Investigating human-computer interaction issues in information-fusion-based decision support

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ABSTRACT
Information fusion is a research area which focuses on how to combine information from many different sources to support decision making. Commonly used information fusion systems are often complex and used in military and crises management domains. The focus of information fusion research so far has been mainly on the technological aspects. There is still a lack of understanding relevant user aspects that affect the information fusion systems as a whole. This paper presents a framework of HCI issues which considers users as embedded in the context of information fusion systems. The framework aims at providing insights regarding factors that affect user interaction to inform the development of future information fusion systems. Design considerations are presented together with a heuristic evaluation of an information fusion prototype.

Keywords
Information Fusion, Human Computer Interaction (HCI), Interaction, Framework, Decision Support

1. INTRODUCTION
Information fusion (IF) research originated within the military domain and refers to the process of combining data or information from several sources to perform inferences which might not be possible using only one single source [23]. IF based systems are often used in military, crises management or homeland security applications accessing large amount of information to support decision making [40], cf. Figure. Examples are systems which enhance situation awareness by fusing large amount of information from different sources to provide a visualisation of, e.g., vehicle movements in a geographical area, to support decision making, under time pressure, cf. Figure 2. Users have been recognised, indirectly, as an important consideration for the success of such systems. For instance, it has been argued that the effectiveness of the overall information fusion process is affected by the utilisation of HCI [23]. Similarly, it has been recognised that “[t]he fact that an increase in the number of sensors and the complexity of the network uniting them has engendered an increase in the amount of available data does not necessary mean that officers using that data will make better decisions” [10, p. 191]. Despite these acknowledgements, there is only limited research (e.g. [6, 22]) which examines the relationship between the human decision maker and information fusion technology. Consequently, no clear overall view of HCI (human-computer-interaction) issues has yet emerged from the IF community. Actually, reviewing IF research it can be found that the attempt to address user aspects almost inevitably ends up in some kind of independent, interface specific, user study, c.f., [28, 13]. This is a problem not limited to information fusion, for instance, as [27, p. 7] argues: “the vast majority of research on human-computer interaction design has been devoted to characteristics of displays that impact human perception, such as symbol legibility or detectability, and on relatively simple cognitive functions such as memory tasks. Fewer efforts have been devoted to understanding the effects of the format and manner in which information is presented on more complex levels of human cognition such as decision making”. Hence, mapping the interaction between IF based decision support and human decision makers that use them is essential in order to understand how to optimise such systems. This paper presents a framework of HCI aspects and factors that affect them in order to characterise user-system interaction within an IF context. The framework further identifies guidelines to be used in information fusion to
inform future IF systems, thus, extending the current technology driven IF research and enhancing the usage of
HCI knowledge in a new domain. In addition, HCI issues are situated in a complex decision making context
which might give new insights and can be further developed by the HCI community. The following sections will
first explain the IF domain, then discuss HCI issues relevant for IF, and then provide a heuristic evaluation of an
information fusion prototype based on the identified insights.

2. INFORMATION FUSION SYSTEMS
Due to the current development of complex information technology and the large amount of data that they make
available to very many people, the concept of IF is becoming increasingly important. The main reason is the
possibility to integrate data from different sources and process huge amounts of data from a large number of
objects with different characteristics and behaviours. The functionality of IF systems can be visualised by the
commonly referred JDL model (cf. [23, 24]), here captured in Figure 4. As can be seen in Figure 4, information
is collected by different sensors/sources (e.g., radar, sensors, databases, optic camera). An IF system can be used
for many different purposes, for instance, it can include Level 1 functionality which involves locating and
tracking objects such as vessels at sea or in harbours. The system can include Level 2 functionality such as
automated inference to find relationships among the collected information such as clustering of vessels in a
specific group. Also, the system could include functionality such as predicting future states, i.e., Level 3. Level
4 functionality involves refining the fusion process. An IF system can involve one or several levels of the JDL
model.

Monitoring this kind of systems is a challenging activity for humans, not only due to the amount of
information, the high number of variables involved or the opacity and complexity of the data mining techniques
used in the detection process, but also other factors such as time pressure, high stress, inconsistencies and the
imperfect and uncertain nature of the information. Actually, it has been suggested that a level 5 should be added
to the JDL model [25, 9, 6] to account for user issues. As in its current state, level 5 is neither widely
acknowledged by the IF community, nor well explored, i.e., “the fusion community has typically overlooked the
role of the user by designing them out of the system” [6, p. 3]. However, there are recent work by Blasch [6] that
identifies specific HCI issues (although, not derived from IF research) and presents his view of level 5. In
addition, one could find limited HCI aspects in IF handbooks such as, e.g., [23, 24]. However, more empirical
research is needed which investigate in detail HCI issues relevant to the domain of IF. In the following sections
an attempt to begin to fill this gap is provided where the proposed framework differs from, e.g., [6] in the sense
that Blasch only consider the perceptual needs of the user, various interface issues, and the user’s decision
making process. Also, this framework can be seen as an extension of studies such as [28] and [34] which only
consider user limitation and interface issues. Following section will present the framework in more details.
3. HCI FOR INFORMATION FUSION

The theoretical framework presented here is based on a literature analyse of IF studies from a HCI perspective. The main sources used for identifying these issues have been the following:

- The proceedings of the International Information Fusion Conference (years: 2000-2007)
- Information Fusion Handbooks ([23, 24, 12]),
- The international Information Fusion Journal (year: 2000-2007)

The focus has been on empirical studies where no limitation towards specific information fusion systems has been made when creating the framework. Also, due to the limited HCI research in the IF field, we have not limited ourselves to any particular type of HCI related study. In the following sections, the proposed framework is presented.

3.1 Overview of User Interaction

In the proposed framework users are embedded in the context of IF systems, cf. Figure 3. A circular relationship is proposed among factors influencing user interaction to emphasise the context in which the interaction exists. As illustrated in Figure 3, the external environment affects the user in terms of users’ cognitive abilities and the activities which can be performed. Users’ cognitive abilities limit the possible user activities which can be performed. The user utilises the interface in order perform various activities, consequently, the interface needs to access functionalities of the IF system. Not to forget, IF systems capture different aspects of the environment, and so on. Figure 3 summaries the main categories of factors which can influence user interaction. The figure is inspired by [42] which stresses the relationship between the user, the task and the technology as well as by the complexity chain proposed by [17]. Reviewing IF research, emerging insights and factors were continuously classified according to the broad an inclusive categorisation displayed in Figure 3, hence, enabling an iterative development of the framework. Figure provides an overview of (A) a specification of categories and the relationship amongst factors affecting human interaction; (B) specific factor related to each category.

The following section will provide an integrated view of user issues for IF by elaborating briefly on the issues identified in Figure .

3.2 Outline of abstracted factors and suggested design considerations

External environment

IF systems do not exist on their own. Issues in the external environment which influence the interaction between the user and the IF system are not to be underestimated. Parts of the environment is captured by the IF system through different sensors, however, the environment contains many other types of factors which makes the situation and the interaction with IF systems complex in terms of user cognitive abilities and activities to be taken into account, cf. Figure .
Organisational demands

Most often IF systems are used within some sort of higher level organisational context. The organisational demands are an increasingly important issue within IF research. For example, this applies in particular to the development towards network centric warfare (NCW), where information fusion is considered as a key enabling technology [42]. That means, the development is towards creating distributed networks connecting different organisations. Especially, in these environments the existing organisations set the boundary for interaction. For instance, in the case of users who have different levels of authorisation and job descriptions, the interaction is complex because usually not everyone is allowed to access all information. Some researchers have tried to solve this problem by having multi-role decision support where users are assigned different “job roles” [46], which, potentially could have access to different information. Not to forget, interaction with a “stand alone” IF system is also affected by organisational issues such as goals, policies and procedures. This issue was exemplified in a previous study of our research group [41] where, in fact, situation awareness was directed and guided by organisational goals. In other words, there are a number of organisational constraints which need to be taken into account.

- Enable different levels of availability of information to facilitate groups within organisations
- Provide the option of protecting sensitive data
- Capture organisational information which guide interaction to inform users
- Encourage role based systems
- Fit the IF system to the systems currently in used within the organisation

Multiple decision makers

Within organisations, multiple decision makers need to coordinate as well as interact with IF systems. It can even be argued that IF depends on team communication and team-based decision making [8]. This has implications for the interaction because each user may have different needs for the interaction with the system, but at the same time they need to communicate regarding the output from the IF system. For instance, it has been suggested that “similar information, tailored to roles, should be provided to both crew members so that Pilot and
Commander can communicate effectively and take on an appropriate share of the workload” [50, p. 17-5], as they work cooperatively on the task at hand.

- Provide overlapping information to facilitate communication between team members
- Use the similar language to facilitate team communication
- Introduce regular and advanced functions to accommodate different user needs

**Risk**

As IF originated from the military domain, IF systems are often used in such context where the consequences for your action (interaction) are severe such as different weapon systems or a pilots cockpit [50, 3]. Different users have different attitudes towards risk i.e. some might be more willing to take a risk than others). This can have implications towards how probabilities, often common feature of IF systems, are acted upon. Here, sufficient amount of training has an influencing role.

- Introduce thresholds to facilitate similar user decisions
- Provide guidelines on how to act on probabilities provided

**Temporal aspects**

The situation in which IF systems are used is often characterised by critical time conditions [16] and real time data, i.e., “[t]he functional role of a data fusion system is to provide timely and accurate information to the user” [43]. This is an important factor when designing the interaction with an IF system. Furthermore, a user study of our research group [39] examined a IF system where it was indicated that under time pressure the users did not have time to double check the data provided by the system, hence, prediction of future states was not suitable (because the user wanted to double check the prediction in order to use them). In another study of ours [41] it was concluded that the time of day or year can have implications for the interaction. It was noticed that the overview display showing the fused result was interpreted differently at different times.

- Indicate clearly temporal aspects such as time, date, etc., on the display to aid users

**Dynamism**

Usually the environment in which the IF systems are situated is dynamic. First the physical or artificial environment the system aims to capture is dynamic and ever changing. The objects for which you try to obtain information may be moving about in the environment which makes the interaction complex. In addition, the decision situation users are embedded in keeps changing, i.e., premises change over time and unexpected things happen. The implications for user’s decision making are not well studied.

- Provide flexibility in the system for changing requirements and tasks

**Environmental factors**

Most often IF systems involve the use of some type of sensors (e.g., detection devices, radars or optical cameras) placed in the environment, which can be sensitive to environmental issues such as weather. This could have implication for the interaction with IF systems. For instance, in a study of ours [41] the environmental conditions such as weather determined how to interpret radar readings and the overview displays of a geographical area. For instance, if many objects were displayed on the overview display that could just be due to the current bad weather conditions. Hence, the weather conditions influenced users trust in the display (i.e., users’ cognitive ability is affected by the external environment).

- Indicate if sensors are affected by environmental factors

**Users’ cognitive abilities**

In addition to factors in the external environment, interaction between users and IF systems is affected by users’ cognitive abilities. Indeed, users’ cognitive abilities set the boundary for what activities can be perform by users, cf., Figure. This needs to be acknowledged to effectives the interaction between IF systems and users.
Cognitive issues

There are a number of different cognitive abilities which are highlighted for the interaction with IF systems. For instance, it is highlighted that users have individual differences [24] in how to retrieve and process information which may have implications for the success of IF systems. Some users might best be suited for/prefer aural information compared to text based information. Also there may be differences in how you assess your workload [32]. Attention is also an often highlighted issue which needs to be considered for the effectiveness of an IF system, where design considerations (color, sounds, lines, popup windows, etc.) can direct attention towards specific interesting feature of the fused data, c.f., [28, 9]. Also, cognitive workload [9, 30] is another factor affecting the interaction with IF systems. For instance, it is noted that mental transformations (draw conclusion from presented information) and performing correlations and fusion tasks increases users workload [30]. Hence, there is a suggestion to focus on a subset of information to reduce cognitive workload [45]. Memory limitations are another factor which affects the interaction with IF systems [24], for instance, our short term memory can only hold 7 plus/minus entities at a time. This can be the very reason why in the study by Giompapa et al. [21] there was a saturation in operators processing capability when the number of input tracks were greater or equal to six. Also, mental stress [3] is a factor which is often present when interacting with IF systems, in particular military tactical systems which are used under time pressure and in stressful environments. Under stress users often change their inference process [24]. Furthermore, it is highlighted that it is important that there is a fit between users’ mental model and IF systems in order to support situation awareness [6]. This is further stressed by [32] which argue that it is a requirement for effective IF. In summary, “[t]o support the user, data fusion architectures must be examined to prevent/mitigate information overload and to expedite processing of the vast amounts of data.”[1, p. 1]. In addition, users can reason about the situation, assess the likely routes of a target and bring in contextual information to reason over uncertainty [6].

- Allow interface personalisation
- Direct users’ attention towards specific areas
- Restrict distracting clutter not to overload users
- Focus on a subset of the information and thereby reduce cognitive workload
- Support users mental model of the system
- Limit the amount of data which needs to be processed at the same time (according to “7+- 2“)

Situation awareness

In IF systems situation awareness (SA) is often an important and distinguishing factor. SA is a cognitive process of humans to understand and comprehend the surrounding environment. This should be seen in contrast to level 3 (Situation assessment) in the JDL model, cf. [33]. SA can be considered in terms of individual, team, shared and distributed SA. However, within IF, so far, Endsley’s view [18] on individual SA is the most dominant theory. There are a number of design considerations which are considered to improve SA. One idea is to direct users’ attention towards objects in different regions of interest (i.e., immediate, intermediate, distance) and thereby enhance SA of nearby objects [9]. Furthermore, in an air pilot cockpit an attempt to enhance SA was made by displaying a third dimension of the environment [3]. In addition to displaying a map and a regular flight log area, a “side view” of the actual air space structure was given which included information such as ground elevation, specific obstacles, the planed flying altitude and position along the planed track. Similarly, [44] provided a detailed (local) picture of a geographical area as well as a zoomed out view (i.e., providing context to the detail picture). This was also highlighted in a study of ours [39] were users reported that they wanted to have an understanding of their own situation in relation to the larger situation in which they existed (i.e., they wanted to know what others in the organisation were doing). It might be worth noting that these findings go beyond the common view in IF which is portrayed by Endsley’s SA theory for individuals which focuses on the relation between the actual objects in the environment.

- Provide alternative views of the situation at hand
- Enable switching between detail (local) and global view
- Show your own situation in relation to others

Trust

Trust is an issue which has been highlighted a number of times as an important factor for the utilisation of IF systems [39, 5, 31, 19]. Partly this is due to the presence of uncertainty and automation in IF systems and partly to the fact that IF systems are used as decision support. There are different design considerations to be made. For instance, [5] investigated the possibility of visualise uncertainty with degraded and distorted images, an in
extension improve the possibility to influence trust. Furthermore, in a study of ours [39] the application was designed in such a way that the predictions were made transparent to the users in order to increase their understanding and, thereby, increase their trust in the predictions. In the study, this had a positive influence. Regarding using a tool for decision support, sufficient trust is needed, or else the tool is left unused. Usually trust builds up over time, this was recognised by, for example, [30] which used training as a way to increase trust.

- Present uncertainty in the information provided
- Provide transparency to provide enable understanding of recommendations and predictions
- Direct user training towards confidence building rather than training as such

**User activity**

Users use their cognitive abilities to perform activities when interacting with the interface of the IF system in order to access its functionality, cf. Figure. The activities users perform determine the character for the actual user interaction.

**User tasks**

The user can perform various tasks, and thereby interact with the interface in different ways. The system should be designed in such a way that it does not interfere with the users’ tasks [30], i.e. users should be able to concentrate on accomplishing their task, not on how to operate the IF system. Much IF research considers monitoring a central task to be performed by users. Accordingly, users have a passive role towards the system. In contrast, [9] acknowledges that users not only monitor IF systems, actually, they can be an active part and contribute to the IF process utilised in such a system, e.g., select incoming data (level 0), choose objects of interest (level 1), defining an area of coverage (level 2), determining the level of threats (level 3) and refining the location of the sensor placements (level 4). Indeed, [7] has characterised the role of the user as follows:

- **neglect**, user defines roles and tells IF systems to respond to certain situations, i.e., the IF system makes the decisions
- **consult**, user consults the IF system in her/his decisions
- **rely**, user relies on the system to provide the information needed for his/her decisions
- **interact**, the task is divided between the system and the user

According to [7], the role to aim for is **interact**. Thus, when designing IF systems one needs to include interaction possibilities for the users. For instance, “[i]t is necessary to implement control and review procedures that may be applied by humans to improve fusion result” [14, p. 1]. The argument is that, for instance, complete knowledge can not adequately be represented in computer models; certain knowledge is only permitted to humans.

- Provide interaction opportunities for users
- Filter information but keep it available for users for flexibility
- The IF system design should not infer with the users tasks

**Decision Making**

In the IF literature it is widely acknowledged that IF systems are intended, most of the times, to support human decision making [47, 11]. Hence, users are often dependent on the success of the system in order to carry out and fulfil specific decisions. This dependency is an important factor affecting how users interact with IF systems. Actually, in a previous study of ours [39] it was concluded that there was a relationship between the utilisation of the IF system and users’ decision making process. Fitting users’ decision making processes with IF systems are not that easy. As [8, p. 5] argues: “DM [decision making] duration will either run shorter than the inter-arrival time interval of data generated by sensors, leading to starvation of the DM process, or else DM will run longer than the interval of between new data arrivals”. Hence, there is a need for a fit between users decision making activities and what the IF system produces. This can be achieved in a number of different ways. For instance, all information is not relevant for each decision, sometime certain information can even be classified as noise [44]. A study indicated that displays supporting naturalistic decision making processes such as supporting feature matching strategies will probably be used more while story generation and explanation based reasoning activities are only useful in specific instances, (e.g., when dealing with conflicting or uncertain data or having inexperienced decision makers) [36]. Supports based on story generation assembles data in an explanatory structure for each conclusion [27] where each explanation indicates how that information supports the suggested conclusion. Feature matching on the other hand associates specific features with expected action [27].
it is recommended to explain the reason behind a specific recommendation/decision, i.e., to incorporate explanatory capability [30]. Furthermore, “[a] promising design approach is to organize archival sensor data into modules that support critical decision making tasks” [37] p 27, that way users have easy access to the underlying data provided by sensors as well as the fused data.

- Provide a fit between decision makers decision making process and the output of IF system
- Incorporate explanatory capabilities, feature matching strategies, story generation or exploration according to the decision at hand
- Enable filtering options to extract the relevant information according to the decision at hand without hindering access to the non-filtered (original) data
- Provide access to both the fused data as well as the original data
- Facilitate fast decisions by providing easy access to certain information with no requirement for interaction

**Interface:**

The interface provides users with access to the functionalities of IF systems, i.e., the interface can be seen as “the technology linking the human and the environment” [44, p. 363], cf. Figure . Through the interface the operator perceives data, process information and acquires knowledge. The interface could be designed in such a way that it makes the interaction more or less complex. More specifically, the interface needs to be designed in such a way that it correctly reflects the functionalities and at the same time not overloads the users’ abilities, cf. Figure .

**Input/Output devices**

The interface of an IF system can be designed in different ways but most often it involves visual displays with a limited use of aural information and haptic devices [24]. Actually, to use different modalities can enhance users’ abilities and help them process more information simultaneously (using different human senses/processes). This has been recognised by, for instance, [43] who proposed a multimodal interface design. In the design architecture the following aspects were utilised: audible warning system generator, haptic pointing devices, fused video displays, visual enhancement to radar display, eye tracking system, and auxiliary monitor/panels which touch screen to enhance user performance. Also, a study suggested that you should not only present data in terms of text, but when possible use images [30].

- Use multiple modalities to support simultaneous processing of information
- Present data in visual form when possible

**Visualisation**

An important aspect of the interface of an IF system is visualisation [49, 28]. Commonly, the visualisation system is the core of the interface between the operator and the IF system. The importance of effective human interaction in visualization has been addressed by many authors in the information visualization research community, e.g. [26] [29]. Interaction is an essential challenge in the future of visualization and information fusion research. Freeman and Cohen [20] evaluated the effects on tactical decision making of a prototype decision support system display developed by the Space and Naval Warfare Systems Center. The strategic use of graphics was intended to support rapid decision making based on pattern recognition (e.g. weapons range rings and task management graph bars). In the military domain, Barnes [4] states that the ultimate purpose of visualisation aids to increase the commander’s ability to understand the battle dynamics, consider options and predict outcomes. Therefore, the system should provide with a time frame picture, showing the past, present and future state reflecting the impacts of the actions. The visualization system should be designed with an understanding of how users perceive and process information, interact with the system and make decisions. Additionally, it should include the particularities of every task and reflect how users operate individually and in collaborative environments.

- Visualise uncertainty, information reliability and quality of information
- Display past, present and future (predicted) information
- Present different levels of abstraction or granularity (in time and space)
**Information fusion systems**

In essence, the basic idea with IF systems is to capture and fuse information from the environment to support decision making, cf. Figure. The specific functionalities of IF systems make them complex to interact with, because, in a way, IF systems comprise specific functionality which distinguish them from other decision support and information systems [40], as discussed below.

**Multiple information sources**

The fact that IF systems fuse information from many different sources and thereby provide access to a large amount of information makes interaction complex. Users have access to a large amount of diverse information which may be conflicting or even distributed; this should be indicated to the users. Also, in different situations it is preferred to access the actual data compared to the fused data [37].

- Indicate type of source when using multiple information sources to aid interpretations
- Provide access to original data as well as fused data

**Uncertainty**

Due to the fact that information is fused from many different sources, some argue that the very goal of IF system is to reduce uncertainty [11]. Hence, when you interact with IF systems you need to deal with uncertainty regarding both original sensor readings as well as when sources are fused. Bisantz et al. [5] concluded that you need to provide information in a format that conveys important aspects such as its uncertain nature in order to provide effective support for users. In their experiment, degraded and blended icons were used to portray uncertainty regarding the identity of a radar contact as hostile or friendly. The results of these studies show that people understand uncertainty conveyed in such a manner and that the use of degraded images may be a viable alternative for representing uncertainty.

- Convey uncertainty in the information provided to users

**Information flow**

The interaction with IF systems becomes complex due to the fact that not only they fuse information from different sources but also they have a complexity in the information flow. Ordinary computer systems can be classified as either user-driven applications or data-driven applications [24]. Most often, IF systems comprise both modes of operations, simultaneously [24]. This has been exploited by the development of mixed-initiative interaction [35]. This is a fairly new concept which emphasises a flexible interaction between the user and the system in order to optimize the outcome i.e. each agent does what he knows best. In other words, either the user or the system has the initiative, controlling the interaction, while the other assists and contributes to the process [2]. A crucial factor in a mixed-initiative system is that the different roles are not predetermined, the division of tasks between the system and the user emerges during the interaction, depending on the task in hand.

- Provide flexibility in such a way that both a top down and bottom up approach can be used, when required.

**Automation**

Automation is a central aspect of IF systems where usually at least parts of the fusion process are automated. Indeed, in much work there is an implicit aim to increase the level of automation in IF systems [23] while others argue that we should go towards assisted system rather than automated to compensate the limitation of, e.g., both an automated target recogniser and human users [30]. As [15] explain: humans are better at: perceiving patterns, improvising and using flexible procedures, recalling relevant facts at the appropriate time, reasoning inductively, exercising judgement. Computers, on the other hand, are better at: responding quickly to control tasks, repetitive and routine tasks, reasoning deductively, handling many complex tasks simultaneously. Especially in new network centric warfare systems, there is a need for processing large amounts of information, but the enormous amount of information provided from multiple sources will put unrealistic demands on the users. It has been argued that IF together with automation is said to be one possible solution [16].

- Automate tasks which computers do best
4. INFORMING IF SYSTEM DESIGN
The research presented here reflects the current defence focus in IF research. However, there are some generalisation possibilities towards IF systems in general due to their specific characteristics, i.e., multiple information sources, accessing large amount of information, under time pressure, etc. It should be noted though that some IF systems may be more complex than others; therefore, not all aspects previously discussed are necessarily relevant, to the same extent, in all IF systems. The described framework can be used in different ways to inform IF systems design and potentially speed up the development process. In particular, it can be used for gaining insight into user interaction as well as what aspects are important to consider when designing IF systems. What is emphasised is a wider perspective which takes into account the embedding of users and IF system in the environment. This has implications when choosing methods for capturing requirements for new IF systems as well as when evaluating IF systems. Furthermore, a number of different guidelines has been extracted which can guide and evaluate IF prototypes.

4.1 Evaluation of an IF Decision Support Tool
One way to apply the framework is to use if for heuristic evaluations of prototypes to inform future. As an example, we here describe a tested IF prototype and the results from the evaluation.

Evaluated tool
The “Impact Matrix” is an IF based decision support application which can be used by commanders when handling various incoming intelligence reports (cf. [48] for a detailed description). The tool fuses incoming text reports and predicts future events such as kidnappings or demonstrations. Users have access to the incoming reports as well as a map displaying the origin (location) of the incoming reports, cf. Figure. Also, the tool consists of an impact matrix which organises the events according to how likely they are to occur and according to what impact they have if they do occur. Furthermore, users can access information regarding the reason for the predictions made, i.e., the background information which led to the conclusion. In other words, users’ decision making processes could potentially improve by “keeping track of which available information could be linked to potential future events” [48, p. 7].

Heuristic evaluation
Heuristic evaluation [38] is an easy and fast method for evaluating an interface. This can be a good alternative when, as in this case, a military application is evaluated where actual users are not easily available and the prototype is still in its early development process.

Figure 5. Interface of the tool ‘Impact Matrix’ tool. (a) Matrix indicating probabilities of event (b) list of incoming reports (c) Map displaying geographical location of incoming reports (d) additional information (traceability) concerning the chosen event in “a” (e) information included in the indicated report in “b”.
Procedure

In the heuristic evaluation, each principle was judged regarding whether or not it was applicable to the prototype and how well the principle was fulfilled. Special evaluation sheets were used to aid the evaluation process, cf. Figure. The interface of the prototype (Figure 5) was evaluated as a single unit. After being instructed regarding the functionality of the tool and provided with the possibility to interact with the prototype for a total of approximately 30 minutes, each principle was judged as: “yes”, “no” or “cannot judge”, along with reasons and recommendations for improvements. The evaluation of the interface took about 2 hours.

Results

Going through the different guidelines, a number of different aspects were highlighted. A summary of those are provided here. Some issues are already well incorporated into the application while other areas are identified as areas for further considerations and improvements. First of all, the interface provides filtering options as well as users’ access to all original information. This way, users are presented with flexibility in their interaction. The format the incoming information is presented in is adapted to a general standard used by the organisation. By providing alternative views for representing the information (list of incoming reports, map with headlines etc) users’ SA can be enhanced. The source of information and a description of reasons for calculated probabilities increase the possibility for users to develop trust towards the system. In addition, in the evaluation some improvement points were identified which could potentially increase the success of the system. To aid user interaction more information on how to act on probabilities and what the probabilities mean could be included. Also, temporal aspects are today not well indicated. Neither are the state of the information sources (affected by weather?) nor information on whether or not they conflict presented to users. Furthermore, how to accommodate organisational factors and the possibility for multiple users are issues which need further consideration. Also, the way descriptions of prediction are presented (i.e., structure of the interface) needs further consideration. It may be useful to consider feature matching or story generation or other explanatory principles to facilitate users’ decision making process. Some of the guidelines were not applicable to the prototype or can not be verified by a heuristic evaluation. These were, for instance, regarding the flexibility of the system, whether or not users’ mental models are supported, if future training of users is directed towards confidence building, is there a fit with users decision making process and the IF system, and is there flexibility in the information flow.

Conclusions

The evaluation indicates both positive aspects as well as improvements points to be further considered in future developments of the prototype. It should be noted that all the guidelines may not be relevant to all applications. Also, the heuristic evaluation needs to be performed together with e.g., user tests or interviews of intended users, in order to be evaluated against all the identified guidelines. Moreover, most of the issues identified in here are also discussed in a previous user study of ours [39].
5. CONCLUSION AND FUTURE WORK

The proposed framework characterises user interaction as embedded in the context of information fusion systems. It highlights the issues affecting the interaction between users and IF systems and emphasises the importance of HCI for IF. The framework indicates relevant factors to be accounted for when designing information fusion systems. Consequently, using the framework as a starting point could help to ensure the success of the system, and also, potentially speed up the design process.

As a result of the framework, there are implications for, e.g. requirements engineering. Some methods such as cognitive task analysis, which focuses on the mental process of users, do not take into account factors related to the external environment such as organisational factors (it only focuses on the mental steps to complete a task). Hence, one should choose a method or a collection of methods which cover all the aspects in the framework.

Moreover, from the literature analysis it can be concluded that there is only limited empirical research examining the interaction between users and IF systems. This is also reflected in the identified framework for IF-HCI issues. Thus, as a theoretical framework, it constitutes a good starting point; however, further empirical studies are needed in order to verify the relationship between the identified issues, as well as their relevance for decision making processes and the development of future information fusion system.

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Paper IV
Information Fusion in Practice: A Distributed Cognition Perspective on the Active Role of Users

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Abstract
Traditionally, the focus of most information fusion research has been on technology, as illustrated by, for example, different versions of the JDL data fusion model. Consequently, the human user has mainly been conceived as a relatively passive recipient of fused information. However, the importance of understanding the active role of human information processing in information fusion is gaining increasing recognition, as also reflected in discussions of a “level 5” in the JDL model in recent research. This paper presents a case study of the interaction of human and machine information processing in a maritime surveillance control room. A detailed analysis of the activities and information flows involved in identifying and tracking moving vessels illustrates how machines and human operators collaboratively perform information fusion in a highly distributed fashion. This analysis highlights the need for an alternative or complimentary way of analysing information fusion systems/processes that more clearly illustrates the interaction between human and machine information processing. To that end we suggest that current models of information fusion can be extended with the theoretical framework of distributed cognition to answer that need.

Keywords: Information Fusion, Distributed Cognition, Maritime Surveillance, User Study
1. Introduction: A Passive or an Active User?

Information fusion, or data fusion, aims to process multiple sets of data, gathered from multiple sources, in order to build a holistic view of the environment [1]. This representation of the environment should enable increased situation awareness and, ultimately, improved decision making. Based on an extensive review of models for information fusion, Hall et al. [1] conclude that:

- “All of the data fusion models described\(^1\) recognize that decision making and situation awareness are components of a complete data fusion system. However, the ability of the data fusion models to effectively represent the issues of situation assessment and decision making fall outside the traditional scope of the field.” [1]

- “In these environments, information is gathered from sensors and electronic communications, fused into meta-data and presented to a decision maker in the form of human-computer visualization. This is the realm of the data fusion models\(^1\). However, the process of situation assessment does not end there. At this point in the environment, the human uses cognitive sense-making to develop a situation assessment. This information is used to fuel their decision making process, the result of which is an action that affects the environment. This is the realm of decision making models\(^2\). Separately, none of these models cover the entire scope required by a situation assessment domain” [1]

A first question arising from these observations is whether or not it is desirable for the information fusion field to extend its traditional scope and include situation awareness and decision making as objects of study. We agree with the observation of [1] that “decision making and situation awareness are components of a complete data fusion system” (p. 6). Without insight into the situation awareness that is created and how it impacts decision making, it is impossible to define boundaries of the data fusion system in the design phase, and to monitor and manage its performance under operation. In terms of the JDL model one lacks necessary input for sensor management in terms of, e.g., mission objectives and mission constraints. Similarly, Blasch [2] argues that “[t]he user defines a fusion system, for without a user, there is no need to provide fusion of multi-sensory data” (p. 3). Situation awareness and decision making may not be the key issues in information fusion, but the relations between these concepts and core fusion processes need to be clarified. Thereby, information fusion systems designers and managers will be enabled to monitor validity issues (e.g., are we collecting and fusing relevant data and information?). Furthermore, incorporating the relations with decision making and situation awareness in

\(^1\) Hall et al. [1] analysed the JDL model and its revisions, the TRIP waterfall model, the DFD model and the Omnibus model.
the models, answers the need to provide ‘whole system solutions’, where core fusion processes are embedded in and adapted to real-life situation awareness needs and decision making practices.

A deadlock in the ongoing discussion of how to link data fusion models and decision making models to inform one and another, is how the information fusion community has conceived the human user and the interaction between humans and machines in information fusion processes. Ever since Hall, Hall, and Tate [3] as well as Blasch and Plano [4] independently introduced human-computer interaction issues to be included in a so called level 5 extension of the JDL model, there has been an ongoing debate on whether or not, and how, user related issues need to be incorporated. Several authors have stressed that this debate has not reached a final conclusion, for example “as the dotted line around level 5 denotes, there is still some debate in the data fusion community around whether level 5 is relevant to the goal of developing a functional model of data fusion.” [1]; “Two diverging groups include one pressing for fusion automation (JDL revisions) and one advocating the role of the user (User-Fusion model)” [2]; “… at this point choosing not to incorporate the suggested ‘Level 5’ of Blasch and Plano as, to our understanding, incorporation of this Level has not yet achieved common usage” [5].

A recurring issue in this debate is whether the user is a passive receiver of a situation picture, automatically generated by fusion technology (fusion automation), or whether the user is an active participant in the fusion process who, in collaboration with the fusion technology, generates and assesses a situation picture (user-fusion). Consider the differences between the two examples below. They are drawn from the application area of target tracking and object identification in maritime surveillance, which will serve as an illustrative case in the empirical part of this article:

**FUSION-AUTOMATION: the user as passive receiver**

“The crew is bombarded with sensor and information from communication links that must be correlated, fused and interpreted in order to arrive at some understanding of the tactical situation. Automation of the data fusion process has emerged as a possible option to assist the operators in coping with the ever-increasing flow and complexity of information, in their task of compiling the tactical picture. A multi-source data fusion (MSDF) system processes the data reported by multiple sources to derive the best estimates of the kinematics properties for each perceived entity in the environment, and to infer the identity and key attributes of these entities.” [6]

**USER-FUSION: the user as active participant**

In target tracking in the maritime surveillance fused information from different radars is utilised in order to identify objects positions to be tracked. In the studied setting, not only did the users (the

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2 Hall et al. [1] analysed the RPD model, the OODA model and OODA model variations.
operators) have to identify the radar readings as an object which initiates the target tracker, but also to associate the target tracker with the correct object when the target tracker lost the object to be followed. This is only one example of the way users work in cooperation with the technology in order to achieve their goals (this study).

The first example illustrates the dominant traditional view in information fusion. The so-called MSDF system generates tracks and identities which are used as input for a human decision-making process. Human-computer interaction (HCI) issues are framed as a problem of interface between the technology and the receiving user, involving issues like information presentation (menus, displays), transaction management (how do user and technology interact) and cognitive aids (tools to correct for human cognitive biases), as discussed by Hall, Hall, and Tate [3]. Based on the second example, we propose that, in many cases, the information fusion process extends beyond the boundary of the actual technology itself (e.g., beyond mathematical computation of radar data to determine position) to include manual functions performed by humans. Then human-computer interaction also involves issues like mission management (what are the larger objectives and constraints of my decision situation?) and information management (what information is most relevant, on what issues do I need more or less detail?), besides the earlier mentioned HCI-interface issues, as posed by Blasch [2]. However, a general problem in existing models for fusion-automation as well as user-fusion is that they model the interaction between user and information fusion technology on a very abstract level. Therefore it is hard to judge the correctness of these models and to analyse to what extent they actually disagree or just name similar issues differently. Furthermore these models are, in some senses, too abstract to really inform design or operational management of information fusion systems.

The study described in this article contributes to these discussions by illustrating human-machine interaction (i.e., user fusion as denoted above) in the case of target tracking and vessel identification in maritime surveillance on an abstract as well as a very detailed level. The theoretical framework of Distributed Cognition [7] is used on an abstract level to describe how humans and technology collaborative perform fusion, and to describe in detail the propagation of information and its transformations through the system. It is highlighted that sometimes machine processes mediate a transformation and that sometimes humans mediate a transformation. Furthermore, issues of human-computer interaction, cognitive refinement, user refinement, information management, and mission management are all equally relevant. As such, the study shows how a distributed cognition perspective can extend current information fusion models and provide for a modelling approach that better connects traditional data fusion models and decision making models.
Section 2 provides a theoretical background by discussing in more detail how existing models of information fusion portray the role of the user. Section 3 introduces the theoretical framework of distributed cognition as a means to model human-computer interaction. Section 4 presents the research design and Section 5 describes the case study results. Finally, the findings and their implications for information fusion research and practice are discussed and summarised in Sections 6 and 7.

2. Background: The Role of the User in Information Fusion Models

The discussion of data or information fusion models presented here does not aim at giving an extensive overview all aspects of all existing models. In our analysis we focus on how models portray the interaction between human users and information fusion technology. Models ‘commonly used’ in the field of information fusion have been selected by looking at which models are discussed in handbooks [8-10] as well as in overview articles [1, 11]. As Hall et al. [1] state, “[t]he dominance of the JDL model and the OODA loop implies that for any new model to be valid, it must assert its value in comparison to these models” (p. 12). Hence, our discussion will primarily focus on these two models and their revisions and variations.

2.1 The JDL Model and its Revisions
The most well-known and referenced model to conceptualise fusion processes is the JDL data fusion model (cf., Figure 1), created in 1985 by the US Joint Directors of Laboratories, which describes how low-level sensor data is transformed to higher-level information, such as object and impact assessment, typically used to inform decision making [9, 10]. The general model has over the years been revised a number of times, e.g., [2-4, 12, 13] (for a more complete review of the JDL model and its history see [1, 5, 10]). Note that Figure 1 only shows the overview level. Sub processes and specific algorithms are discussed in more detail on two hierarchical levels below the top level. A complete view of the model may be found in [9].
As discussed in the introduction, there are currently diverging viewpoints on how the role of the user should be portrayed in the JDL model. In [3] and [1] the user is perceived as a passive consumer of fused information; “this basic approach is often used in developing data fusion systems: the sensors are viewed as the information source and the human is viewed as the information user or sink” [3]; “Models in the field of data fusion provide a theoretical and functional representation of the data fusion process: starting from the collection of data from a sensor to the presentation of meta-data to the user” [1]. Consequently ‘level 5’ is restricted to human-computer interface issues, interface utilities, dialog and transaction management, and cognitive aids. Interface utilities do not only include the traditional functions related to display and interaction of menus and command languages, but also approaches that aim at a natural language dialog interfaces (recognising touch, voice, or haptic devices). In addition, dialog and transaction management involves monitoring and logging interaction of users in order to adapt the interaction modes to individual user preferences. Finally, cognitive aids may include aids to correct for known cognitive biases, to focus attention, to support negative reasoning, or to use intelligent software agents as advisors. In contrast, Blasch and Plano [4] as well as Blasch [2] acknowledge that the user actively participates on different levels of the JDL model, as shown in Figures 2a and 2b. Blasch [2] argues “[t]he IF community has typically overlooked the role of the user by designing them out of the system” (p. 3).

Figure 26. The JDL model (adapted from Hall and McMullen [9]).

Figure 2a. DFIG 2004 model adopted from (Blasch, 2006).
Commenting Figure 2a, where a clear distinction is made between roles of machines and roles of humans in information fusion, Blasch [2] states that “[l]evel 2 (SA) includes tacit functions which are inferred from level 1 explicit representations of object assessment. Since the unobserved aspects of the SA problem cannot be processed by a computer, user knowledge and reasoning is necessary” (p. 1). Furthermore, Blasch [2] addresses the problem that an information fusion system cannot just operate automatically top-down from available data or the situation at hand, but needs some user guidance. “Different situations will drive different needs, however the situation is never known a priori … To combat the difficulty with embedding known/unknown a priori situational information, the user has a priori notions that supersede the current situation which can augment the un-modelled situation. In the end, IF system designs are based on a user, not a machine or the situation.” [2]. Explaining Figure 2b Blasch describes how users actively contribute to different levels of the JDL model: “On level 0 the user determines what and how much data value to collect, on level 1 the user determines the target priority and where to look, on level 2 the user understands scenario context and user role, on level 3 the user defines what is a threat and adversarial intent, on level 4 the user determines which sensors to deploy and activate and the user assesses the utility of information, and on level 5 the user designs user interface controls” [2]. Finally, Blasch argues that the user and the fusion system should complement each other. Human users will, for example, do better than a machine because they are “(1) able to reason about the situation, (2) assess what are the likely routes of a target, and (3) bring in contextual information to reason over the uncertainty, whereas as target numbers and speed increase, a user will get overloaded, and thus, routine calculations and data processing can be offloaded to a computer” [2].

### 2.2 The OODA Loop and its Variations

In the mid 1950s Boyd developed an intuitive, straightforward model of decision making that aimed to explain why and how American pilots could decide and act faster than their Korean counterparts in one-to-one air
combat. The OODA loop model was not originally intended to explain more complex decision situations [14, 15]. However, due to its intuitiveness and simplicity it can be interpreted to fit almost any context [1].

**Figure 3. The original OODA loop.**

Bryant [15] notes that the OODA loop helps to distinguish between information gathering (observe, orient) and analysis and implementation (decide and act). Furthermore, Breton and Rousseau [16] argue that the OODA loop highlights the importance of two critical factors in decision making, namely time constraints and information uncertainty. Despite these benefits several authors have strongly criticised the application of the OODA loop in complex decision situations and proposed adaptations to the OODA loop to enable wider application. For example, Bryant [15] argues that the original OODA loop does not indicate how and why the four steps should be performed. Furthermore, he criticizes it to be a reactive rather than proactive model because the it suggests that “observation is a process of unbiased reception of information, that ‘facts’ will manifest themselves in what one observes” [15]. In contrast he argues:

“To understand the world – far from a lack of bias – people require pre-existing concepts to guide their interpretation of what they perceive. Such pre-existing concepts not only distinguish the most plausible interpretation of an observation but also guide us as to what portion of all the available sensory data is relevant and will direct our attention to important objects and events in the environment. The OODA Loop, with its undefined Observe and Orient processes does not even hint at this necessary dependence of perception on pre-existing knowledge and concepts. This is the greatest failure of the OODA Loop as a model of human decision making, a failure that has led to a mistaken emphasis on information gathering as a ‘bottom-up’ process that creates understanding of the battle space solely from gathered data. This, in turn, has been partly responsible for the over-emphasis on technology as a solution to C2 problems. When decision making is viewed primarily as a problem of obtaining as much information as possible, it is easy to conceive of automation as a solution. It should become clear in subsequent sections, however, why simply expanding the capacity to collect more, and more precisely resolved, data does not itself aid human decision making.” [16].

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3 Complex with regard to, for example, multiple decision makers, poorly defined problems, multiple or unclear objectives, et cetera.
The resemblance in arguments between Bryant’s criticism of the OODA loop, and Blasch’s critique of the JDL model is obvious. Both stress that fusion technology cannot autonomously solve issues like data selection and interpretation but that active user involvement is necessary. As mentioned earlier, several variations of the original OODA loop have been proposed recently, that incorporate these critiques. First of all, Boyd himself has always been aware of the limitations of his original model, and presented a more elaborated version in 1996. That version, illustrated in Figure 4, highlights the complexity of the orient phase and introduces feedback loops between the four stages, which acknowledges that the information interpretation and decision making process may be less straightforward and more iterative than originally portrayed.

![Figure 4. Boyd’s extended version of the OODA loop (adapted from [14]).](image)

To stress that it is not just obvious what data and information to gather and fuse, Bryant [15] renamed the OODA loop and proposed the CECA model, involving the steps: Critique, Explore, Compare, Adapt. CECA acknowledges that a user (decision maker) is not a passive recipient of information, but has a plan or goal that guides his/her information gathering and information fusions processes. As such, information gathering is a combination of passively receiving sensor input and actively searching for needed information (cf. Figure 5).

A number of other revisions have been proposed that acknowledge an active user, but cannot be discussed in detail here, for example Smith [17] and Brehmer [14]. Furthermore, Rousseau and Breton [16, 18] and Grant [19] have presented revisions on the OODA loop on a more detailed level of granularity, but they argue for a more mechanical view of the fusion and decision making process. As such, they are actually closer to the classic view of the passive user.
A common challenge for all these OODA variations is finding the appropriate balance between usefulness versus validity of the model. While the original model was easy to understand, but received criticism on validity, the newer variations have been criticised for being too complex and therefore poorly informing design.

2.3 Other Data and Information Fusion Models
Besides the dominant discussion around JDL and OODA, some other models have appeared. Salerno et al. [20] propose a model that integrates the JDL model, and Endsley’s model of situation awareness. In Salerno et al.’s model (cf., Figure 6), the arrows clearly indicate how an active user influences both perception and comprehension. This is in correspondence with Endsley’s original model that indicates how doctrines, rules, individual experience, abilities, preconceptions, and objectives influence situation awareness and decision making.
Another elaboration of Endsley’s model of situation awareness is shown in Figure 7. At first sight, this model makes a sharp distinction between an independent technological process, and a human interpretation process, in correspondence with the passive user perspective. In the accompanying descriptions it is stressed that the model aims to visualise human-in-the-loop issues: “Hence, the model was created to illustrate the role played by humans and technology, demonstrating that appropriate consideration of both humans and technology is necessary to understand the process by which an event unfolds.” Issues like distortions in the technical and human lenses, as well as feedback loops from the human interpretation part to the technical part, are addressed. However, how intense the contributions from technology and humans actually are, and how intertwined the interactions are, is not clear. Therefore we can conclude that the interpretation of Endsley’s model is not straightforward here, and may serve both those who argue for a passive user and those who argue for an active user.
Finally, Niklasson et al. [22] propose a model that integrates parts of the JDL model, Endsley’s model of situation awareness, and the OODA loop. This model acknowledges more clearly that humans and machines (can) contribute to all stages of information fusion and decision making, indicating that the user is an active participant rather than a passive receiver.

In the description of the SAM² model is shown how humans and machines participate in the fusion process on equal grounds, how parts of the fusion process can be executed by machines (left side of the model) and parts of the process can be executed by humans (right side of the model). Which side one chooses for a certain subprocess depends on the prerequisites given and the outcomes needed, e.g. one aims at utilising the strengths of both humans and machines, and compensating for each other’s weaknesses.
2.4 Reflection: The Need for a More Detailed Model of Human-Computer Interactions

As Hall et al. [1] point out: “A common weak point across all of the models in both data fusion and decision-making is the implication of the human-computer interaction. Only extensions to the JDL model and working variations of the OODA loop have attempted to explore the use of modern interface development theories and models to aid human in the loop. Therefore, any new model that attempts to cover this complete scope needs to carefully examine the effect of the intersection between human cognition, interface technology, and the environment’s task” (p. 13).

The following conclusions can be drawn from the overview of current models in information fusion. Firstly, there are currently different views on whether the user of information fusion technology is a passive receiver of information or an active participant in the information gathering and fusion process. Secondly, the models that acknowledge an active role of the user describe this role on a very abstract level, giving few hints to inform fusion systems designers how to enable collaboration between technology and users.

Our empirical research presented in the second half of this article contributes to this ongoing discussion in two ways. Firstly, the case study provides a clear example of how users in maritime surveillance actively contribute to the fusion process. Secondly, it will be demonstrated that the theoretical framework of distributed cognition [7] enables to model human-computer interaction at a much more detailed level than the models presented in this theory section.

3. Distributed Cognition

Distributed Cognition (DC) [7], which has become a well established perspective in cognitive science, is a theoretical framework that seeks to understand the organisation of socio-technical systems. This perspective shifts focus from the traditional, rather narrow focus on the single individual’s internal cognitive processes (i.e., symbol manipulation inside the head), to consider cognitive processes as taking place within the larger unit of a socio-technical system. Such a system includes the people carrying out a task, and the artefacts they use (e.g., information systems) [7] (Figure 9). Shifting focus from the “inside” to a system level allows observation of cognitive processes outside the individual mind, instead of having to infer what is going on, on the inside. Also, it allows to capture cognitive properties of the interactions within the socio-technical system, i.e., properties of the collective behaviour [23], which cannot be traced to any single individual or artefact. For instance, consider the cognitive process of solving a problem such as a mathematical equation. The calculation can be performed by using pen and paper, or using a calculator. The artefacts in use can be considered part of the cognitive process of problem solving, and the process itself is distributed across the system – the person and the artefacts s/he uses
– rather than being confined inside the individual’s head. The cognitive process itself is delimited by the functional relationships between the people and artefacts that are part of the process. When analysing a socio-technical system, the functional relationships also set the boundaries for the unit of analysis.

Figure 9. A comparison highlighting the difference between (a) the traditional and (b) the distributed cognition view, with respect to the unit of analysis. In (a) the cognitive process is inside the individual while in (b) the cognitive process is distributed among individuals and the environment in which they interact.

Cognitive processes are considered to be distributed across the larger unit of a cognitive system, in which at least three different kinds of distribution can be observed [24]. The processes are distributed: across the members of a group, between human internal mechanism (e.g., memory, attention) and external structures (e.g., computer systems, material and/or social environment), and they are distributed over time. A key aspect of DC is a focus on the way information is propagated, represented, and transformed within the socio-technical system [7]. As information propagates through the system’s entities (humans and artefacts⁴), the representations and their states are transformed.

A “representational state” refers to how knowledge and information are represented in specific instances when propagated and transformed in the conduct of an activity. For instance, the state of information displayed by a computer system transforms in response to a user’s key command. In other words, “a representational state is a particular configuration of an information–bearing structure, such as a monitor display, a verbal utterance, or a

⁴ As both humans and artefacts are “entities”, it might imply they are equal, but artefacts are not considered (biologically) cognitive [23].
DC focuses on how artefacts are used and modified to support the cognitive process, i.e., not only on what an object represents but also on how the properties of the object are exploited [24].

DC has been used to capture the utilisation of technology to support various human cognitive processes [23, 26-30]. That DC is particularly well suited for the analysis of complex systems is seen in the great many studies conducted in settings such as: aircraft cockpits [30], air traffic control rooms [31, 32], vessel boards [7], cardiac surgery [26], emergency dispatch rooms [33], and co-ordination of collaborative activities [34]. In general terms, the focus is on the distributed collaboration between humans and artefacts, involved in a joint task. For instance, Hutchins’ [30] study of an aircraft cockpit focused on the distribution of processes between internal structures (e.g., the pilot’s memory) and external artefacts (the equipment used by the pilots), and showed how human memory processes extend beyond the boundary of the individual to include external products as part of the process. Another study, by Hazlehurst et al. [26], aimed to understand the achievement of situation awareness in cardiac surgery, among a group of individuals. The study focused on the activity they performed, the tasks they accomplished, and the coordination devices used as they interacted in this structured environment. In addition to providing a theoretical understanding of cognitive processes, DC has been used for the design and support of interactions between people and technologies. In a study by Marti [31], DC was used to inform the re-design of an air traffic control system, which resulted in a system that provided better support for the operators’ activities. DC has also been suggested as an approach to research in human-computer interaction [24, 35]. In summary, the use of DC has resulted in a deeper understanding of the organisation of socio-technical systems, and the way information processing is distributed within such systems. It has also lead to a deeper understanding of the role(s) of artefacts in human activities.

Similarly, a DC perspective can be used to understand how IF technology and humans interact, and thereby also advance the research area of IF. In particular, a DC perspective would alter the view on what is included in the information fusion process (cf. Figure 10). As we have argued in [36], in IF “the perspective needs to be extended from thinking of information fusion as a process solely taking place in computer systems, to thinking of information fusion processes as processes including humans and their surroundings. That means, we need to widen the perspective of the fusion process from information fusion systems to information fusion processes ... An information fusion system often refers to the type of computer system characterised by the JDL model (levels 0-3), the process of transforming low-level sensory data to higher-level more abstract information. An information fusion process, on the other hand, also includes the context of the user(s), the material
surroundings, the organisation they are part of, etc.” (p.1). This is in contrast to the common technological view of information fusion which most commonly considers Level 0-4 in the JDL model as part of the IF process. In the following sections, an empirical investigation is presented, which exemplifies and further details a possible DC perspective on IF processes as argued in [36].

Figure 10. A schematic view of the components of an IF process (an IF system interacting with its surroundings), adapted from [36].

4. Research Design

4.1 Research Philosophy and Strategy
The aim of our empirical work presented in the following sections is to exemplify how the theoretical framework of DC [7] can extend, or complement, current models of information fusion to more clearly capture the active role of the user in semi-automatic information fusion processes. As the issue of active user involvement in information fusion is a relatively new and unexplored research area, we argue that it is appropriate to follow an inductive research philosophy and inductive reasoning aimed at theory building [37].

4.2 Research Method and Techniques
A case study of user activities was performed to exemplify the theoretical arguments presented in [36] and the first half of this paper. Generally speaking, research in the form of case studies consists of “a detailed investigation, often with data collected over a period of time, of phenomena, within their context. The aim is to provide an analysis of the context and processes which illuminate the theoretical issues being studied” [38]. Further, “case studies need to focus on analytical generalisation … [i]n other words, the generalisation is about theoretical propositions not about population … [r]ather, the argument is about the existence of processes, which may influence behaviours and actions” [38]. The case study presented here is ethnographically inspired using a qualitative method called participatory observations [39]. This method allows researchers to observe the
participants while being embedded in their work environment. In other words, the method allows the observer to ask questions and to be instructed by the users as they perform their work, and thereby increase the researcher’s first hand understanding of the situation.

More specifically, participatory observations [39] of five expert operators, with an average of three years of experience, were conducted during four occasions (including a pilot test), distributed evenly around the clock to allow for different conditions, which made a total of 16 hours of observation. The same researcher (the first author) performed all the observations for consistency. The role of the researcher was “participant-as-observer” [39], which refers to a researcher “who forms relationships and participates in activities but makes no secret of an intention to observe events” [39]. As preparation, and for complementary information, the researcher got an introductory presentation of the work setting and was given the possibility to access documentation concerning current work procedures. Field notes (pen and paper) were used to capture work procedures and events during the observations. The field notes were summarised and then verified by two of the expert operators for correctness. The collected data was approached from the DC perspective, that is, it was analysed for patterns describing how information propagated between systems and operators in the information fusion processes (cf. Section 3).

4. 3 Case Site: Maritime Surveillance
Maritime surveillance was chosen as a case study to exemplify semi-automated information fusion processes. Most often maritime surveillance involves identifying and tracking objects at sea or in a harbour. The case study was performed in a surveillance control room responsible for the security of an area outside the south-western Swedish coastline. The main task of the operators located in the surveillance control room is to identify vessels, analyse the situation, and when required, inform the responsible defence agency to take action. During the observations, a total of about 70 vessels were identified and tracked by the team of operators. The overall setup available to human operators in performing these activities, i.e., identification and tracking of vessels, is conceptually illustrated in Figures 11 and 12.
Figure 11. Maritime surveillance domain components.

As illustrated in Figure 11, the environment in which the user operates consists of different kinds of vessels, such as ships, freighters, ferries and even some boats, i.e., both objects which are of interest to observe (vessels) and objects which can be classified as “noise” (non-interesting objects). In order to track and identify these objects, there is a number of surveillance resources to be used, such as radars, optic cameras, AIS (automatic identification system), and VHS radio. Fusion of radar data allows the ability to use radar data to automatically track specific identified objects. For user interaction with the system, a graphical user interface (GUI) is provided, which allows both interaction between the operators and the system, and the possibility of displaying the output of identification and tracking of vessels.

Figure 12. A schematic view of current work process.

Using the components displayed in Figure 11, the task of identifying and tracking an object can be broken down as follows (cf. Figure 12):

1. An object is either picked up by radar (displayed as plots) or by AIS information (displayed with an identification number) to be displayed on an overview display.
2. A process is started where the user manually distinguishes interesting vessels from environmentally caused radar readings (noise). The identified vessel is classified either as unknown or the object is associated with the correct AIS information. To his/her help the user uses additional equipment situated in the control room. The continuous tracking of identified vessels is performed by a fusion algorithm that combines information from different sensors.

3. Finally, a report of interesting objects is transmitted via different technological equipment to headquarter.

Typically, there are five operators working in the control room in order to perform the above identified task procedures: one operator responsible for incoming intelligence reports, two operators responsible for manual identification of vessels, and two operators keeping track of the overall situational picture of the current situation, who are also responsible for taking action when required. Thus, all operators work collaboratively in order to perform the task procedure. More detail is provided in the next section.

5. Analysis and Results

In this section the observational data is discussed from a DC perspective. More specifically, DC was used for the analysis and identification of patterns in the data with a focus on the functional relationships between humans and technology within the information fusion process, and in particular the transformations of information as it is propagated through the socio-technical system. More specifically, we adopted a structured strategy focusing on three key issues in DC [7, 24, 29, 30], to analyse the data provided by the observations:

- **Unit of analysis:** the unit of analysis in DC is the socio-technical system, i.e., the people who are members of a social group, and the artefacts used in carrying out a task. The focus lies on the functional relationship between the system’s entities (humans and artefacts), and the information flow between them. Central to the analysis is the propagation of information through the system and the transformation of representational states.

- **Entities:** The entities of the socio-technical system include humans and artefacts. The entities have a mediating functionality, and as information propagates between them, the representational state of the information is transformed. The focus then is on what is mediated rather than an entity in itself.

- **Distributed cognitive processes:** Cognitive processes are distributed across individuals and artefacts, between (human) internal structures and external structures, and they are distributed over time. When
analysing the data, the main concern is not any particular entity as such, but rather to seek out patterns of interactions between entities.

5.1 Developed Notation
To visualise the transformations and entities in the socio-technical system a specific notation has been developed to describe the transformations in the information fusion process\(^5\) (cf. Figure 13). The above identified concepts, together with the defined modelling language, were used as a guideline to find patterns in the collected data, and our findings are presented as they emerged from the data. In the following sections, a walkthrough of the process is provided, from which the analysis can be unpacked, followed by the specific transformations of the process in detail.

![Figure 13. Developed DC Notation](image)

5.2 A Semi-automated Information Fusion Process
The process of identification and tracking vessels, as described above, is a semi-automated process, performed by a team of five operators working collaboratively with technology (Figure 14). In this context, “semi-automated” refers to the fact that some of the functions associated with identification and tracking are allocated

\(^5\) DC lacks a well developed graphical representation for visualising its concepts. Attempts have been made though, for example in Halverson [23]. That, however, is situation specific and does not apply here.
to humans and some to technology. Hence, the information fusion process extends the boundary of the technology itself, to include users. More specifically, the process involves the following.

To begin the identification process, an object is picked up by the different radars (displayed as plots) and/or by AIS (displayed with an identification number) to be visualised on an overview display. Next, the process starts when operators (i.e., the line of operators) manually distinguish interesting vessels from environmentally caused radar readings (noise) on the overview display (a description of the main artefacts used is presented in Table 1). When an object is located it is automatically provided with information such as position, direction, course, callsign, time of initiation and updated at, in addition to AIS standard information. Also, an automatic fusion algorithm that continuously tracks objects is automatically initiated as an object is located.

![Diagram](image)


When an object is located and provided with automatically generated information, the first line of operators needs to add more information to further distinguish the vessels, such as type, class, name, nationality, type of identification source (quality of source) and identified on list. In order to add this information the operator uses additional equipment in the control room, for instance, an long distance camera, Internet, or the list of identified vessels provided by email (cf., Table 1).
### Table 3. Main artefacts used by operators in the maritime surveillance control room.

<table>
<thead>
<tr>
<th>Main information sources</th>
<th>Description of functionality</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Overview display</strong></td>
<td>Main tool which operators interact with to identify and locate vessels. The overview display provides three different modes, depending on the task operators need to perform; The operators can view the original radar data, operators can choose to only view located objects, or view the trajectories of located objects. Information regarding the located objects is continuously updated for identification.</td>
</tr>
<tr>
<td><strong>Optical camera</strong></td>
<td>To verify the identity of located objects, a long distance optical camera with day and night vision can be used for visual identification.</td>
</tr>
<tr>
<td><strong>Intranet/Internet/email</strong></td>
<td>Additional sources to identify and store information regarding vessels are available for the operators. An Intranet is provided with information about internal routines. The Internet is used as a search engine for additional information, such as weather or the name of a vessel. Each day emails arrive with information regarding the identity of vessels passing the lighthouse.</td>
</tr>
<tr>
<td><strong>Summary report</strong></td>
<td>A sheet of paper containing a summary of attributes identifying vessels is provided by the first line of operators to the second line of operators, to be submitted to various systems (e.g., message equipment and diary).</td>
</tr>
<tr>
<td><strong>Message equipments</strong></td>
<td>Technology enabling information from the summary report to be transmitted to, e.g., military head quarter.</td>
</tr>
<tr>
<td><strong>Diary</strong></td>
<td>The information regarding identified vessels from the summary report is stored in a special “diary”.</td>
</tr>
<tr>
<td><strong>UHV/VHS Radio</strong></td>
<td>The radio is used as a communication tool for communication between control room and different vessels. Also, the operators listen in on the communication between different vessels at sea (they may mention the name of vessels and this information can be used in the identification process).</td>
</tr>
<tr>
<td><strong>Database</strong></td>
<td>Database containing pictures of different types of vessels. For instance, this database is used to determine what operators see in the optic camera (i.e., a comparison can be made).</td>
</tr>
<tr>
<td><strong>Folder</strong></td>
<td>Collection and storage of incoming faxes and other documents such as permits.</td>
</tr>
</tbody>
</table>

Most often a collection of these sources need to be utilised to add the required information. Mostly the operators change the overview display to only display located targets where they can focus on one target at the time to collect the required information (cf. Table 1). Each identified object needs to be verified (because the AIS information may have been intentionally changed) and checked for permission to operate in Swedish waters. A target that seems suspicious (e.g., a foreign vessel with no right or permit to pass or operate in Swedish waters) is prioritised and receives special attention. When the target is fully identified and double-checked, the most important attributes are written down on a special summary report, which is passed on to the second line of operators to be transmitted to the responsible agency, e.g., the military marine headquarter (cf. Figure 15). Also, the second line of operators makes a special summary (PowerPoint presentation) of what has been going on during their shift, to be presented to the following shift.
Figure 15. An overview of the overall information fusion process. Arrows indicate the flow of information between different entities, during which the representational states of the information also are transformed.

For instance, consider a specific government owned vessel which enters the area of surveillance. The target is picked up on radar and AIS, and is located by the first line of operators. The automatic information provides the basic attributes for the target. The operator identifying this specific target has different options to verify the vessel. For instance, the operator can check the incoming list of identified vessels from the lighthouse or wait until the object passes the long distance optic camera. Thus, the operator sees the vessel and identifies it as a government owned vessel. The type of source for verifying the object is then added as an attribute to the object. Also, the list of permits needs to be checked to see if the vessel has the right to operate on Swedish water. It can now be determined that the vessel is performing research regarding fishing according to its permit. Information regarding the vessel is noted on the summary report and when it is filled with information it is handed over to the second line of operators to be transmitted to the marine military headquarter. It should be noted that the process is continuous and therefore lacks a clearly defined output. For instance, information on identified vessels captured in the summary report is also added to the communication unit, and to the diary, both of which function as output as they are accessible by the responsible organisation, which is at a higher level in the hierarchy of the
organisation (cf. Figure 15). In summary, the information fusion process becomes semi-automated in terms of involving both humans and technology to fuse the necessary information to identify and track vessels.

5.3 Distributed Cognitive Processes

The identified semi-automated information fusion process is complex and a number of different cognitive processes are intertwined with the above described overall process. Cognitive processes are here considered as part of the information fusion process and can be considered as internal information resources supporting the IF process (cf. Figure 16). In this context, without the operators and their cognitive processes the identification and tracking of objects would not be possible. The distributed and sometimes shared cognitive processes are visible in the information flow in this socio-technical system where processes are distributed across time and space and where many of the resulting representations facilitate different shared cognitive processes (cf. Table 2).

To begin with, the identification of a vessel, for instance, involves partly the automatic fusion of radar data and AIS information, and partly the cognitive process of recognising an object as a foreign vessel. To recognise an object as a vessel that needs to be tracked is one of the most important human cognitive processes that contribute to the IF process. The recognition of an object can be triggered by several things. For instance, external information sources, such as email, draw the operators’ attention towards a specific kind of vessel, or their own previous experience and knowledge (memory) make them notice and attend to a specific vessel. To recognise an object is a top-down process where different features of the object are matched by the operators, with information from external information sources or internal knowledge. The actual memory capability is distributed between humans and artefacts. More specifically, the folder provides an external resource that extends human memory, and transforms individual memory into external memory shared by all the operators. The folder is also an object of interest in the information fusion process, and as such it not only draws the individual user’s attention but also facilitates shared attention. In addition, situation awareness (general understanding of the current situation) may trigger the operators’ attention towards a specific vessel.

Reasoning about the provided information is also needed in order to determine whether or not the located object should be further processed. Here, the operators’ ability to reason means transforming the information provided on the overview display to internal structures of the operators, where the information can be related to past experiences. For instance, email, telephone, and optic camera provide additional information that provides the operator with the possibility to trust the identity of the object (i.e., the information on the overview display). The information is then added as a property to the identified objects.
The decision making activity involves the concern of whether or not the information should be added to the communication unit for further access, by other organisations. Moreover, a key part of the information fusion process is communication which is mediated by several artefacts. Some equipment specifically provides means for communication, such as the Intranet and VHS Radio. The equipment mediates communication and facilitates a common understanding of the current situation, that is, situation awareness.

Notably, while situation awareness is facilitated by the overview display, other artefacts are equally important, e.g., optical camera, Intranet, and VHS radio. Situation awareness, then, is a process distributed among the operators and the artefacts they interact with, and there is no one individual or artefact that holds a complete situational picture. This means, situation awareness is not centralised on one single display, or in any other entity, since no entity on its own can provide meaning to the current situation. Even though the overview display summarises the current situation, the way it is perceived within the context of its use, emerges from the interaction between several entities, which leads to some certain understanding of the current situation. This is exemplified by the fact that each 12h period is summarised in a PowerPoint presentation which to some degree allows knowledge and situation awareness to be shared between co-workers (but it is not made accessible to other responsible organisations). It should be noted that the PowerPoint presentation is not only a report on identified vessels (a “summary report” including objective attributes such as name, position etc., describing identified vessels), but is also intended to captures operators’ subjective impressions of the current situation.
Figure 16. Overview of what triggers cognitive processes to support the IF process. The arrows indicate what triggers each process. For simplicity, an abstraction level has been chosen where each white box refers to a specific cognitive process, although, in reality, according to DC, these processes are distributed among humans and artefacts (cf., Table 2).

5.4 Trajectories of Information Propagation

Re-examining the overall information fusion process (cf. Figure 16), it includes much information that is propagated through the system of humans and technology, and many transformations of representational states are identifiable in the different artefacts used (cf. Table 2). As information is propagated through the socio-technical system, trajectories of information propagation emerge. In other words, the trajectory describes the path of information exchange over time. The identified trajectories exemplify the cooperation between operators and technology and the semi-automated nature of the information fusion process. For instance, we see that multiple radar data from external resources outside the control room are automatically transformed into visual information in terms of radar plots on an overview display (cf., Figure 17). The radar plots on the overview display are then accessible to the first line of operators who need to interpret the radar plots and located vessels. When the object is located a target tracker is automatically turned on. In other words, the information automatically transforms into different representational states as it is propagated between artefacts, without human intervention.
As the operators pick up information from other sources (e.g., Table 2 no 14, 15, 16, 5, 6, 9), summarise it, and use it to identify objects on the overview display, the information is propagated through the socio-technical system, and its representational state is changed (cf. Figure 17). For instance, the radio constantly provides audio information to the operators in the control room, and as it is picked up by the operators, its representational state is transformed into internal representational states of the operators. That information is then added and used to identify vessels on the overview display, and again its representational state is transformed (cf. Figure 18).

Similar propagations of information are initiated when information from other sources, such as email and fax, are used to identify vessels. In addition, knowledge in an operator’s mind (e.g., internal memory structures) changes its representational state and becomes accessible to others, as the knowledge is entered into the database containing pictures of vessels (Table 2, no. 7). Another example is the storage of experiences and knowledge on
the Intranet; a change of representational state takes place as internal knowledge is written down and stored in an external format, and the knowledge also becomes shared knowledge (cf., Table 2, no 3). When incoming faxes and other documents are collected and stored in a folder for easy access, the combined pieces of information (the folder’s contents) form a new representational state, and as new documents are added its representational state transforms again (cf., Table 2, no 8). Similarly, as information is added to the located objects on the overview display, the representational state of the individual object is transformed as well as the representational state of the overview display (cf., Figure 19).

![Figure 19. Change of representational state within an artefact. Each time a fax is added, the folder changes its representational state. Similarly, each time new information is added to the overview display its representational state changes.](image)

In summary, the information fusion process consists of changes in representational states as information is propagated through the socio-technical system, including both operators and technology. The identified trajectories exist between artefacts, within artefacts, and between artefacts and humans.
**Table 2.** A summary of human-technology interactions, and representational transformations. Each number corresponds to the numbers in Figure 14.

<table>
<thead>
<tr>
<th>Mediating artefact</th>
<th>Unit of analysis (the functional relationships between entities and the transformation of representational states of information related to the information fusion process)</th>
<th>Distributed cognitive processes facilitated by the artefact as part of the IF process</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Overview display</td>
<td>Visualisation of current surveillance situation including objects of interest; radar data is automatically transmitted to be displayed on a map; additional information is also continuously added to the objects identified in the display changing the representational state</td>
<td>Situation awareness, communication</td>
</tr>
<tr>
<td>2. Optical camera equipment (day/night vision)</td>
<td>Visual contact for identification of vessels; the perceived image is associated (through internal structures) with vessels stored in, e.g., internal memory and in the external database accessible to others</td>
<td>Situation awareness, trust</td>
</tr>
<tr>
<td>3. Intranet</td>
<td>System for storage of knowledge and experience of incidents; internal structures of humans are transformed into an external representation accessible to others</td>
<td>Attention, knowledge, communication</td>
</tr>
<tr>
<td>4. Internet</td>
<td>Backup system for overview display as well as a source of information; information transforms uncertainty to clarity</td>
<td>Knowledge</td>
</tr>
<tr>
<td>5. Message equipment</td>
<td>Recording of attributes of interesting vessels; radar data displayed on the overview display is transformed into written messages</td>
<td>Communication, attention</td>
</tr>
<tr>
<td>6. VHS Radio</td>
<td>Communication tool for communication between control room and different vessels as well as communication between vessels; auditive information provide context to the overview display</td>
<td>Situation Awareness</td>
</tr>
<tr>
<td>7. Database with pictures of vessels</td>
<td>Database containing identified vessels; information stored in the database is transformed into external representations accessible to others</td>
<td>Knowledge</td>
</tr>
<tr>
<td>8. Folder</td>
<td>Collection and storage of incoming faxes and other documents; pieces of incoming information are transformed into a representational state of combined information, for easy access</td>
<td>Memory, attention, knowledge</td>
</tr>
<tr>
<td>9. Diary</td>
<td>Document containing the most important incidents (identified objects); information on the overview display is transformed into a representation independent of time, accessible to others</td>
<td>Memory</td>
</tr>
<tr>
<td>10. Equipment controlling the radio</td>
<td>Equipment controlling choice of VHS channel; the information picked up from the chosen channel transforms into internal knowledge, which then may be further propagated to another entity</td>
<td>Attention</td>
</tr>
<tr>
<td>11. Communication unit</td>
<td>Facilitation of communication among operators; the artefact mediates communication and as information propagates through the artefact, from one person to another, it may be transformed (due to disturbances etc.)</td>
<td>Communication, awareness, trust</td>
</tr>
<tr>
<td>12. Telephone</td>
<td>To gain information and feedback on actions; information is propagated through the phone, and it may transform representations, e.g. in case of disturbances on the line</td>
<td>Communication</td>
</tr>
<tr>
<td>13. Report</td>
<td>A summary of identified vessels facilitate communication among the team of operators; information is propagated to other communication equipment enabling shared access, i.e., information from the overview display is transformed to a representation which can be used when interacting with other systems</td>
<td>Attention, communication</td>
</tr>
<tr>
<td>14. Fax</td>
<td>Provides information to the system; a representational state of information accessible to the operators</td>
<td>Attention</td>
</tr>
<tr>
<td>15. Email</td>
<td>Information on weather reports and lists of identified objects is sent by email: knowledge is transformed/exchanged in the functional system and people outside the functional system, also the information can be used to identify objects and provide context to the overview display</td>
<td>Attention, communication</td>
</tr>
<tr>
<td>16. Additional equipment: TV</td>
<td>Possibility to display additional information about current situation; the equipment transforms information from the overview display into meaningful information</td>
<td>Situation awareness, communication</td>
</tr>
<tr>
<td>17. Additional equipment: Computer with internet</td>
<td>Independent computer equipment; knowledge is transformed/exchanged between individuals in the functional system and people outside the functional system</td>
<td>Situation awareness, communication</td>
</tr>
</tbody>
</table>
5.5 Human and Technology Mediated Transformations

A distinct pattern among the trajectories of information propagation is mediated transformations of representational states. Firstly, *human mediated transformations of representational states* occur when the transformation between two artefacts is facilitated by humans. That is, when additional information resources (email, optic camera, fax, database, Internet, airplane) are actively requested by the operator to complete the information fusion process, e.g., when an optic camera is used to identify unknown objects displayed on the overview display. Here, the human operator functions as a mediator between the optic camera and the overview display, linking the two artefacts, and thereby enabling transformations of representational states (cf., Figure 20). Also, the user mediates the continuous refinement of the information fusion process, such as aiding the target tracker when an object is lost (i.e., when a target tracker is located on land, the user moves the target tracker to the right position at sea). The human operator *actively* requests additional information sources and thereby initiates the mediation of information by enabling different resources to connect/be fused (cf., Figure 6). This exemplifies that the trajectories of information flow between humans and artefacts.

![Diagram](image_url)

**Figure 20.** Humans mediate information propagation between optic camera and overview display, enabling changes in representational states. The same process is initiated for email, fax, database etc.

In addition, some of the information resources are automatically introduced into the process via operators, without being requested, e.g., when audible information given via radio is automatically perceived and added to the overview display. Thus, the human operator *automatically* mediates a change in representational states. In other words, input to the information fusion process can either be actively requested by operators or be automatically mediated by the operators.

Secondly, *technology mediated transformations of representational states* occur when, for instance, information resources are automatically included in the information fusion process via technology without
human intervention, allowing different technologies to connect/be fused. For example, multiple radar data are automatically transmitted to be displayed on the overview display (cf., Figure 21), which then can be interpreted by operators. This can be referred to as automatic input. Also, some representational states are continuously refined in the information process, e.g., as the target tracker automatically tracks identified objects at sea, and thereby change the information on the overview display.

![Figure 21. Automatic technology mediated transformation of representational states.](image)

### 6. Discussion

Part of the aim of this paper has been to (a) argue, along with other IF researchers, that current IF theories and models, in particular the predominant JDL model, do not sufficiently take into account the active role of human users in IF processes, (b) demonstrate with an empirical real-world case study that even in seemingly relatively simple cases there can be complex interactions between human and technological information processing in IF processes, and (c) demonstrate the usefulness of a distributed cognition perspective and methodology in analyzing such processes.

It might very well be argued that the empirical example of IF processes in a maritime surveillance control room discussed here is too simplistic to be an appropriate representative of advanced IF processes in general, which in other cases could be much more complex, much less interactive, or even fully automated and not involving human operators at all. It should be noted, however, that the point of the particular example and case study chosen here is not its universality, but rather to illustrate (1) that in many real-world cases of information fusion many of the rather abstract IF models discussed in Section 2, such as the JDL model, have their limitations, and (2) that a DC-style analysis can help to overcome some of these limitations in concrete cases. We believe that in this sense the chosen example indeed is representative of many – although certainly not
all – real-world cases of information fusion where human operators interact with each other and various technological tools.

It could also very well be argued that the DC-style methodology presented and used here has its limitations as well, and might not be able to scale up to, or be useful for, the analysis of all cases of human-machine interactive information fusion. In fact, we would certainly agree to that. The point of the example presented here of course has not been to introduce a ready-made methodology and demonstrate its universal applicability, but rather to take first steps towards complementing current IF theories and models with a DC perspective and methodology. We envision that, like the models discussed in Section 2, the DC methodology over time needs to be further adapted to, and co-evolve with, existing IF theories, models and practices.

The following two subsections will elaborate in some more detail what we consider the main results of the study presented here.

6.1 Identification of an IF Process Which Extends the Boundary of Technology

In the presented case study it has been shown that transformations take place as information propagates between multiple artefacts and human operators. This shows that IF processes, in fact, commonly extend beyond the boundary of one particular (technological) system, or a single linear (automatic) transformation from multiple data sources, towards a human receiver (as portrayed by the JDL model), and instead actually are emergent from the interaction between human and technological entities.

The IF process discussed here is in fact highly distributed between both several human operators and various pieces of technology. Furthermore, the fact that the IF process utilised in the maritime surveillance control room is a complex socio-technical system involving humans and technology, both transforming and mediating information in the IF process, points to an equal importance of humans and technology (and to some degree their interchangeability, as also posited by the SAM² model discussed in Section 2.3). That the IF process extends the boundary of technology is reinforced by the fact that external resources continuously affect the outcome of the process. That means the IF process does not exist on its own.

Furthermore, human users have here been identified as active components in the IF process, i.e., the operators aid, or in fact partially implement, the fusion process by refining the output and collecting more information when required. As discussed earlier, the active role of the user commonly is not acknowledged in many of the models existing in IF research, such as, for example:

- The currently most accepted version of the JDL model (cf., figure 1) and,
• the most often cited original version of the OODA loop, where no feedback loops are included in the model (cf., figure 3).

There are of course models such as the CECA model and SAM² model in which the user is portrayed as an active component. However, these models (so far) remain fairly abstract and general, and therefore do not describe in detail how the user can play an active role, how that role can be identified and analysed in concrete cases, and what the overall implications are. The latter point is examined in some more detail in the in next subsection.

6.2 Characterisation of the Interaction between Human and Machine Information Processing

As discussed in the introductory section, it has been acknowledged by several IF authors that, for example, the JDL model does not sufficiently capture, let alone explain, human-computer interaction and cooperation. In the particular case study discussed here, the technology components investigated could be categorised as operating at first and foremost JDL Level 1 (i.e., identification and tracking). However, taking a distributed view on the IF process (i.e., including both humans and technology) naturally the outcome also can be classified as contributing to situation assessment and awareness, i.e., Level 2 in the JDL model. This illustrates that the (technological) system might have been developed to have level 1 functionality, but once human users (with their background knowledge, inference capacities, etc.) are involved as a component of the overall system, it provides, to some degree, level 2 functionality as well (although not an automated level 2 system in this case). This fact has also been highlighted by Blasch in [2], where level 1 referred to machines and level 2/3 referred to denoted humans (cf., Figure 2a). The JDL model as such does not take this into account and in that sense does not capture the full granularity of IF processes emerging from the user and the (technical) system. Neither are other systems which contribute to, for example, situation awareness (situation assessment) accounted for. Even with the various extensions of the JDL model discussed in Section 2, the model does not explicitly address or examine the interaction between users and IF technology. Hence, as argued by Hall et al. [1], and discussed at length in the introduction, there is a need to accommodate the interaction between human cognition, interface technology, and the environment.

This paper attempts to contribute to filling this gap by analysing human-technology interactions as propagations of information and transformations of representational states (cf., Figure 22) that are relatively medium-independent, i.e., independent of whether they are carried out by people or machines. Focusing on how
information transforms and is transformed as it propagates through the system, provides a means to characterise these interactions. As a result, deeper insights into the role of HCI in IF emerge.

For instance, viewing the human user as an active component in the IF process, different categories of input could be identified in the case study. It could be seen that users actively requested information from additional information sources when necessary, while other information sources where automatically perceived by the operators (e.g., audio information from the radio were automatically perceived by operators, without request, providing situation awareness, i.e., the radio provided a context for the information displayed on the overview display). The latter point typically is not acknowledged in IF research.

Figure 272. Abstracted information fusion process from the identified transformation of representational states in humans and technology (see Figure 13 for key to symbols).

Furthermore, the interaction between operators and IF technology should be viewed as a two-way interaction, i.e., the users support the IF process and similarly, the technological system supports the user. It could be argued that a traditional view of the human user is embedded in the visualisation of the JDL-user model as it does not consider in what ways the system can extend the users cognitive processes. Blasch [2], for instance, (cf., Figure 2b) specifically highlights different ways the user can contribute to the fusion process according to the different JDL levels (i.e., value, priority, context, intent, utility refinement). However, as illustrated in Figure 2b, the interaction is a one-way interaction. Furthermore, although the ways users affect fusion processes has been identified, the relationship between the technological system and the user is not defined as a two-way interaction. That means, the contribution of the system to the user’s reasoning and the contribution of the interaction with other systems are not taken into account. In contrast, our study has highlighted the fact that (and how) cognitive
processes are distributed between humans and technology, both contributing to the IF process. Situation awareness, for example, is a process (or an outcome) distributed among the group of operators and the artefacts they interact with, rather than the output of a specific artefact such as the overview display.

7. Summary and Conclusions

This paper has argued for the need for a new, distributed perspective on information fusion processes, that goes beyond existing IF theories and models, in particular the JDL model, and has presented an empirical maritime surveillance case study to support the general argument. The case study illustrates that there can be an added value in applying a DC perspective and methodology to the analysis of IF processes as it supports/provides an integrated view of both user and technology mediated activities in the fusion process. This study also further confirms the ideas put forward in a shorter previous paper [36], which discussed the theoretical underpinnings of the DC approach and its relevance to IF research. With the case study presented here, the validity of the proposed theoretical framework is further strengthened. The overall findings can be captured in the following tenets:

- Many real-world IF processes, such as the example analysed here, cannot be reduced to the processing of a specific technical system; rather, the fusion process in many cases emerges from the interaction between technology and its user(s), and extends beyond user(s), artefact(s), and time.

- IF processes, such as the case studied here, consist of propagations of information through a system of artefacts and operators where changes in representational states can be identified. Also, human and technology mediated transformations occur which can be automatically or actively initiated. Furthermore, in the example external and internal (cognitive processes) information sources have been identified.

- A DC view leads to equal consideration of manual (operator) as well as automated instances of fusion in the same overall IF process. For instance, it does not distinguish between representational states in technology or operators, and the user is treated as an active component parallel to other (technological) components.

- Characterising the IF process as transformations of representational state, the operator is naturally accommodated as an active part of the process.
Different types of input to the IF process have been identified and can be (roughly) categorised as actively requested or automatically perceived ones.

A number of cognitive processes, such as situation awareness, memory, attention, trust etc., have been identified as internal resources of the IF process and these processes are distributed among the operators and the artefacts they interact with.

To summarise in one paragraph, the aims of this paper have been (a) to argue, along with other IF researchers, that current IF theories and models do not sufficiently capture the active role of human users in IF processes, (b) to demonstrate with an empirical case study that even in seemingly relatively simple cases, there are typically complex interactions between human and technological information processing in fusion processes, and (c) to demonstrate the usefulness of a distributed cognition perspective and methodology in analyzing such processes.

The DC perspective and case study presented here naturally only constitute initial steps towards a more encompassing DC framework and methodology for IF research, but we are convinced that further theoretical and methodological developments along these lines will be fruitful in the analysis of interactive IF processes, for example, in the identification of process failures, in the design and development of new IF processes and systems, as well as in the re-design or automation of existing ones.

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References


Paper V
A user study of the Impact matrix, a fusion based decision support for enhanced situation awareness

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Abstract – Today’s asymmetric threats put new challenges on military decision making. As new technology develops we have new possibilities to support decision making in such environments. However, it is important that the tools developed take into account users’ (commanders’) decision needs. This paper presents some initial user studies of Swedish commanders testing a prototype application developed to answer these new challenges introduced by asymmetric threats. The application aids commanders by supporting situation awareness in terms of providing an overview of incoming intelligence reports and displaying probabilities of future events. The user study focuses on how the tool can support commanders’ daily decision making activities. The results indicate that the general concept could be useful for Swedish commanders and analysts, but some suggestions for improvements are made. The issues found in this study will inform the continuing evaluation of this tool.

Keywords: Information fusion, HCI, decision support, decision making, user study, situation awareness

1. Introduction

Effective decision making is especially important for the success of military operations. Compared to the classical doctrinal approach, decision making activities in today’s military missions is characterised by asymmetric threats and peace keeping operations. More specifically, according to [1, p. 1] “… [i]n today’s international peacekeeping and peace enforcing missions, the ‘adversary’ is normally a multifaceted loosely-coupled combination of well-armed soldiers, irregular forces, criminals, civilian groups and other entities, using various types of vehicles and low or high-level technical equipment. These actors interact with sometimes hidden and non-correlated agendas, and collaborate if they judge it to be supporting their specific goals”. Hence, decision making in military command and control environments is today in many cases characterised by limited time, uncertainty and the availability of a large amount of unstructured information [2], i.e., where enemies are less obvious. Interestingly, as technology becomes more advanced, we get new possibilities, such as information fusion, to support this kind of decision making environment [2] (indeed, information fusion systems can be considered as a specific type of decision support, cf. [3]).

Currently in information fusion research, the actual utilisation of such tools and how they fits users’ decision making processes is a overlooked issue which needs more attention. This has started to be recognised in information fusion research [4], and today there are a number of more human-factor oriented papers within IF research (cf., e.g., [5-11]). However, more HCI research focusing more specifically on human decision making in the context of information fusion is needed. Indeed, it has been acknowledged that the introduction of technology such as decision support systems could alter the way tasks and decisions are distributed among commanders (e.g., a common operational picture available at all levels of command may have implications for, e.g., authority, within the command chain) [12].

This paper presents a user study which examines how the previously developed Impact Matrix tool [1] is perceived and could be used to support its intended users. In particular, this tool utilises information fusion techniques to predict
adversary intent [1] by combining incoming intelligence reports. The tool provides filtering and sorting functionality in addition to a probability distribution of future events to be used by decision makers.

The paper begins by presenting the background to the study in terms of human decision making and the developed prototype tool. This is followed by presentation and discussion of some initial user studies.

2. Decision making and situation awareness

There are many different decision making models utilised in environments characterised by time critical decisions such as military decision making, cf. [15]. A common element among those mentioned in [15] (e.g., OODA-loop, Kill Chain model, Triage model, SHOR model, action based model, recognition primed model) is that situation awareness, one way or another, underlies most decision models and is typically considered as an important requirement for human decision making. In the models mentioned, situation awareness refers to the decision makers’ understanding of the current situation. The importance of situation awareness has also been recognised in the development of decision support systems, for example, according to [16, p. 7] “[t]he TRADMUS program has adopted the position that decision aiding systems should assist in the decision making process, and focus on aiding the situation assessment portion of the decision making task”.

Looking specifically at situation awareness research, Endsley [17] is one of founders of the concept. Endsley [17] developed a model where situation awareness was divided into three distinct levels, i.e., Level 1: perception of current elements in situation; Level 2: Comprehension of current situation; Level 3: Projection of future status. As the model is displayed, the three levels of situation awareness are considered a prerequisite for making a decision which can result in an action. Also, the creation of a mental representation of the situation is emphasised. Here, situation assessment is often referred to as the process of achieving situation awareness. Endsley [18] continued to identify different elements which need to be supported for achieving situation awareness (SA) in, for example the aviation domain, i.e., geographical SA, spatial/temporal SA, system SA, environmental SA and tactical SA. It can be argued that the aviation domain naturally shares many of the characteristics of military decision situations.

Interestingly, there are similarities between Endsley’s model (previously explained) and the JDL data fusion process model. In the JDL model level 2 is referred to as situation assessment (cf. SA Level 2) and level 3 is referred to as impact assessment (cf. SA Level 3). It has been argued that Endsley’s model display the human part while the JDL model is a functional model of the data fusion process [19].

An application which intends to support both situation assessment and impact assessment, and subsequently users’ situation awareness, is described in the following section.

3. The Impact Matrix application

The Impact Matrix prototype has been developed in the context of the new challenges posed by asymmetric threats and has previously been presented at Fusion 2007, cf. [1], however, a brief description of the original tool is presented below.

The “Impact Matrix” is an information fusion based decision support application to be used as a tool for today’s commanders when handling various incoming intelligence reports. The aim with the tool is to support the decision makers’ situation awareness and, thus, increase their possibilities for proactive decision making activities. More specifically, the tool consists of an impact matrix which informs users of possible future events. The impact matrix presents the user with the probability of an event and provides the background information which led to this conclusion. The matrix also organises the events according to how likely they are to occur and according to what impact they have if they do occur, cf. Figure 1.

Each future event carries information about what indicators and observations have probed the event, i.e., a description as to why the system has reached a particular conclusion is provided. In addition to the matrix, the user has, through the tool, access to the incoming reports and a map displaying the origin (location) of the incoming reports. In other words, users’ decision making processes could, potentially improve, by “keeping track of which available information could be linked to potential future events” [1, p. 7].
The information provided by the tool enables the user to enhance his/her situation awareness of the current situation as well as future events, and, hence, provide possibility for proactive decision making (i.e., a decision which may hinder a possible future event) instead of reactive decisions (i.e., a decision which is here a reaction of the current situation). For a more detailed description of the technology behind the tool, cf. [1].

An initial informal interview was carried out during the spring of 2007 where the tool was presented for potential decision makers, and it was indicated that the application could be useful to support decision making and situation awareness [1]. In particular, it was highlighted that the tool could be used for training and debriefing. For instance, it would be useful to have the possibility to replay the events and discuss alternative decisions and actions [1]. The interview indicated the potential for the tool, but more studies are needed, which is the motivation behind the studies presented in the following sections.

4. User studies

The studies presented in this paper are part of the ongoing development process of the Impact Matrix application developed by the Swedish defence agency. This is an iterative evaluation process which will continuously inform the ongoing development of the prototype, hence, the explorative nature of the studies. Also, the studies are qualitative in terms of the data collected. In particular, the studies presented in this paper are part of the second round of evaluations performed during the autumn of 2007. The aim of the second round of studies was twofold: (A) to get user feedback on the tool as a concept, which complements the first round of evaluation, and (B) to identify issues which can inform future evaluations. In other words, the main concern has been to answer the following question:

- Is the ‘Impact matrix’ a useful tool when making decisions in today’s military operations, e.g., like Kosovo Force (KFOR) operations performed in Kosovo?

Hence, the presented studies are explorative, focusing on providing insight in how such a tool can be utilised. As a consequence, the impact matrix is not evaluated here in terms of the procedure of adding reports or creating the rules which probe decision makers. Instead, what is evaluated is the utilisation of the information provided via the interface of the impact matrix in terms of its possibilities of supporting different decision making process activities.

Test were performed on two occasions have been performed; these are explained in further details in the following sections.

4.1 User study 1

In the first user study, three of the authors (MN, PB, BK) were involved in the practicalities of conducting the study. The aim with this study was to explore the possible utilisation of the prototype by the intended decision makers (i.e., commanders) and the set-up of the study was similar to a usability test set-up.

**Location.** The study was performed at the Swedish Life Guard training unit and its international training department.

**Participants.** Two Swedish commanders participated in the evaluation. They had a background in national military operations and were in training for participating in international peace-keeping operations in Kosovo during autumn 2007.

**Scenario.** A scenario similar to the ones which the KFOR needs to deal with on a daily basis in Kosovo was implemented in the tool to simulate part of the decision making environment.

**Procedure.** The test started with a training session for the participants to get familiar with the application. The participants were given a short introduction and were asked to individually explore the system. After the training session the users was given a task of cooperatively planning the transportation of VIP persons between the airport and the military base. At the same time, they were asked to keep track of what was happening in the tool. The participants worked together. The side task was to simulate a more natural situation. The participants were observed during the completion of the task. After completion of the task, the participants were interviewed. The interview
questions followed an interview guide of open-ended questions (cf., Appendix). Although, the guide was not strictly followed, it allowed for improvised questions depending on the participants’ answers. In previous research regarding IF based decision support, three key aspects emerged, i.e., decision making [16, 20], HCI issues [13] and trust [10], as important for the development of such systems. Hence, the interview guide was divided into three main categories i.e., decision making, trust and HCI issues. For examples of the specific question asked, cf., appendix 1. The study took approximately 1.5 hour to complete. The interviews was transcribed and, when needed, translated into English for the purpose of this paper.

4.2 User study 2

Two of the authors (MN, BK) were involved in the practicalities of conducting this study. The aim with this evaluation was to complement the previous study in terms of more specifically capturing the interaction with the interface of the prototype (due to lack of it in the first study); hence, a change in set-up (procedure) was performed. In this test occasion, no side task was given, cf. User study 1, Procedure.

Location. The evaluation was performed at the Swedish Life Guard training unit and its international training department (the same as for study 1).

Participants. Two Swedish commanders participated in the evaluation. They had a background of participating in international operations in Kosovo during autumn 2007 (they participated in the evaluation the day after arrival to Sweden). Hence, they have a different background compared to the participants in User study 1.

Scenario. A scenario similar to the ones which the European battle group needs to deal with on a daily basis in Kosovo was implemented in the tool to simulate the decision making environment.

Procedure. The participants were given a presentation of the tool and had the possibility to test the tool for approximately 10 minutes. This was followed by a structured interview which lasted for approximately 45 minutes. The participants were interviewed together in order to allow them the possibility to trigger each other. The interview was recorded and during the interview the participants had access to the tool. The interview was characterised by semi-structured interview questions which aimed for capturing the usefulness of the tool. The questions followed an interview guide (see appendix) but allowed for improvised follow-up questions. The same interview guide was used as in study 1. Also, the interviews was transcribed and, when needed, translated into English for the purpose of this paper.

5. Results

The result is based on the transcriptions of the interviews performed during the two test occasions (i.e., study 1 & 2). These transcriptions has been individually analysed by the authors of this paper. We present the combined results from the transcriptions of both user studies (i.e., 4 participants), if not otherwise noted.

Better situation assessment

Today, there are only limited possibilities of getting an overview of the current (as well as future) situation. All interviewed decision makers liked the idea of getting information in terms of situation understanding (map with reports of current events) and impact assessment (probabilities of future events) because it would enable them proactive decision making. In their own words, they characterise their decision making process as guided by the “here and now” (i.e., reactive decision making), even though they would like to be more efficient and focus on proactive actions. In general, there is a strong belief that the system prototyped here could be very helpful in supporting decision making in operations common for the Nordic Battle group, one of the European Union Battle groups. The prototyped application is believed to be able to process more information and archive it in a more searchable way; hence, making it more accessible for the decision makers. Also, interviewees especially like that reports were linked to a specific location on the map. A searchable archive of events and traceability of reports are seen as the most valuable aspects of the system.

“Quick and dirty” impact assessment

The impact matrix receives mixed reviews by the interviewed decision makers. On the one hand, decision makers believe in the general idea, e.g., “the system can give you a first fast interpretation of the current situation by the probability measures of events, next one can check whether one agrees with the systems by checking the underlying reports”. On the other hand, decision makers consider the information on the maps as much more valuable compared to the information provided by the impact matrix, i.e., “30% of the screen is used for useless information. It is better to have a large map and to let the probabilities only pop-up in case of a major change. The probabilities will most likely be stable and not change every 2 minutes”. Furthermore, the calculation procedure is questioned; for instance: is there sufficient historical data to discern between accidental relations and causal relations? What is the logic or belief system behind these calculations? What if it was just a random event, how can that be accounted for?
Decision tradeoffs
Two of the interviewed decision makers raised concerns regarding the probability distribution provided by the tool. When should the decision maker make the call, i.e., what does it really mean to have 80% risk for kidnapping? Does that indicate that the decision makers using the tool should already have made a decision e.g., making phone calls alerting the relevant authorities. As one of the decision makers puts it, “80% risk for an event, to me that indicates that I should have been on the phone making phone calls a long time ago, 80% chance for an event is not something you would like to have to deal with”. In their current work environment, typically, a specific time or event is used as a turning point for making a specific decision (i.e., the situation can escalate until this event occur, then I have to make a decision). In the tool the decision makers’ raised concerns regarding how they should know the “exact number” functioning as a turning point for decision; i.e., there are interesting tradeoffs to be made.

Supporting situation awareness
The decision makers explained that for a commander it is important to have situation awareness of a specific geographical area (i.e., local situation awareness) as well as an understanding of what the other commanders are dealing with (i.e., global situation awareness). It was suggested that the situation map should provide information regarding a specific area while the impact matrix could provide information regarding a larger area which includes, for instance, the overall mission including other commanders’ (which may be from other countries) activities.

End users are intelligence officers rather than commanders
Although the application has been envisioned as giving real-time support to decision makers working in the field, 3 of 4 interviewees state that the application better fits the work of intelligence officers as a tool to pre-process information for decision makers such as commanders. For a commander in the field the application is too disorderly and contains too much invalidated or irrelevant reports. Therefore intelligence officers are seen as the natural users of the developed tool. “They [intelligence officers] need to present the conclusions for me so I can make better decisions”. Or elsewhere: “only an experienced decision maker could have direct use for this system, for inexperienced ones it distracts too much from their main task, leading other people”. And “it is not our job to filter information and judge intelligence reports”. However, it should be noted that the tool was judged to be useful for the interviewees (i.e., commanders) in debriefing and training (non–real-time situations).

Long-term rather than short-term decision frames
In line with the previous observation that intelligence officers rather than decision makers are the most likely and most natural end users of the system, the interviewees argue for a long-term decision making horizon (a week, a month) rather than immediate decisions based on real-time information. For example: “under time pressure there is no time to analyse multiple inquiry reports of intelligence officers”, and “when one has chosen ones strategy, there is no time to consider new information; one does not change an order lightly”. In addition, decision makers believed that they needed sufficient time to interact and control the output of the system, i.e., “time is needed to validate incoming reports as well as control the relations the system is drawing, therefore it should not be used for immediate decisions, but on the contrary the system can outperform humans on the long term, when it can signal for relations with incidents a long time ago”.

Role based customisations
Depending on role or personal preferences or the assignment one currently performs, decision makers argue that one can have very different needs. Therefore, they would like to have more possibilities to filter and select information in different ways, such as time frame (e.g. week, month), geographical area (e.g. a specific area of town), and type of events (e.g. accidents, findings of weapons) and so on. This would provide flexibility in the tool to be adapted to different decision situations.

Achieving trust
Decision makers reported that whether or not one relies on the application depends on whether one trusts the reasoning behind it (probabilities and relations between events), and whether it has performed well previously. Here, the traceability of the reasoning was considered very important. For instance, during the first study it was noticed that decision makers when a rise in probabilities occurred, they inspected the information regarding the reasoning behind the probabilities, also, they located the involving intelligence reports in order to make their own judgement where or not a sound interpretation was given by the tool, i.e., indicating the importance of traceability of predictions. Also decision makers reported that there was a potential to trust the system too much, i.e., you as a decision maker need to trust the system either way because there are no time to control the output of the system.
Recalling headlines rather than content
The interviewees in study 1 were specifically asked to recall the situation as it was presented by the tool. When answering that particular question, they only recall the headlines of the incoming intelligent reports, not the actual content of the reports; also, they mentioned all incoming reports, not just those interesting to their particular decision situation.

Maintaining control
Some of the decision makers reflected upon the intelligence reports used by the system. If you as an informer see something and decide to make a report on the event, you do not have control of how the system will portray the report. That is, dependent on the keywords you use in the intelligence report for describing, e.g., protest rally, it can be associated to different events in the tool which you do not have control over. One decision maker gave the example of a demonstration. A friendly protest rally may be misinterpreted as a critical event in combination with other events. The question raised was what if the protest rally was just a random event, how can that be accounted for? Furthermore, it should be ensured at some point that false information is deleted and “that the system is foolproof: a poorly formulated report should not create a massive alarm of many resources”.

Importance of experience from field work
Even though all the interviewees were positive towards the tool, there was one interesting issue which separates the two test occasions (study 1 & 2) apart. The first study involved commanders prior to deployment in an international mission. Those decision makers focused much on the possibilities of the tool provided. The commanders in the second study who had just returned from an international mission focused much on how the tool actual would work in the field in Kosovo. For instance, in the second study specific concerns regarding how to act upon the provided predictions were made (i.e., how high need the probability be for me to take action). These issues were not raised by the decision makers in study 1.

Selection of suggested improvements
A number of different improvements aspects were suggested by the interviewed decision makers. First of all, seeing the potential of the tool regarding incoming information, they wonder to what extent reports and other information sources in different formats can be incorporated automatically and translated into probabilities. This can be everything from paper written reports, faxes, and other computer applications, but also weather predictions, newspaper stories, UAV pictures. Historical data (written reports) can be extremely important to build up a knowledge base for a certain area. Currently much communication relies on spoken radio conversations, which is problematic to automatically convert into format that can be used for automated processing in a technical system. Several point out the importance of using a standardised report model to reach some level of standardisation. That can be problematic for (highly valued) reports from civil organisations. Also, the interviewees wonder whether the knowledge base that contains relations between current reports and future events is context dependent. Can the Kosovo dataset be used in Afghanistan? Can the French database of Kosovo be used by the Swedes that come after them? Finally, one can wonder to what extent so called “soft information” from “informal contacts” can be used in this system. One takes into account such information, but it can normally not be shared officially.

Second, more filtering options for the incoming intelligence reports were requested by the decision makers. For instance, one should be able to access reports within different time frames (e.g. utilisation of a timeline which could show all event for the last hour), different geographical areas (e.g. show event connected to a specific square) and on different topics (e.g., show all traffic accidents). Also the possibility for personalisation was raised.

Third, interviewees especially like that reports were linked to a specific location on the map, but they would like to integrate it with the possibility to show where different troops are currently located. Also, it was suggested that the situation map includes information relevant to a specific area while the impact matrix could provide information about a larger geographical area (thus, supporting local and global situation awareness).

Fourth, it was noted that the information in the matrix seemed constant (i.e., does not change rapidly), therefore, they argued for the use of pop-up box/menu that more clearly indicate changes in the status of a predicted event.

Fifth, the decision makers were confused by the timeline of the system. For instance, the intelligence reports which were listed, did the time indicate when the report was added to the system or when the actual event took place which generated the report? Also, the timeline of what intelligence reports the tool consisted of is not clearly indicated, i.e., one decision makers provided a scenario, “if I report one thing in 2003 and then 2009, will it be saved?” It was suggested that this would to be more clearly indicated in future designs.

6. Discussion
Generally speaking, one could argue that the answer to the original question “Is ‘Impact matrix’ a useful tool when making decisions in today’s military operations, e.g., like KFOR operations in Kosovo?” is that the interviewed decision makers saw the tool as useful and they could provide
specific examples on how to use the tool. For instance, it was emphasised that the tool may be best suited for decision environments with long term time frames. Looking at the result in details, some interesting tradeoffs are revealed which need to be reflected upon.

**The effect of interface on decision making**
The result of the studies indicates that the actual design of the graphical user interface seems to affect the cognitive processes/decision making processes of the decision makers. For instance, participants only recall the headlines when asked to recall the current situation. The headlines of the intelligence reports are displayed on the list of incoming reports as well as on the map cf. Figure 1. The user is provided with two representations of the same information, hence, probing the recall of the items. It may also be the case that they hadn’t paid attention to the content of the reports, or that the titles summarised what was important to them as decision makers. Also, when asked to describe the current situation provided by the tool no selection or filtering of information relevant to their decision was made. The interface of a decision support can guide the users’ attention towards a situation and thereby affect the users’ decision making process. Interfaces which has been developed with the decision making process in mind has been proven to be effective [21].

**Supporting situation assessment versus impact assessment**
In summary, it was identified that the tool can be used to two different ways utilising different aspects of the evaluated tool, i.e., as a tool to analyse incoming reports (filtering, organising, predict future events etc.) or as a tool to provide situation assessment over a specific geographical area. There is an interesting trade-off between the usefulness of the situation map versus the probability distribution of future event, cf., Figure 1. The results indicate that the impact matrix (i.e., probability distribution) is actually judged to be one of the least interesting features of the prototype, indicating that the situation map was more appreciated than the actual predictions provided by the tool. This indicates the importance of situation assessment rather than impact assessment for decision making. The reason for this may be due to a number of different factors. For instance, compared to the decision making situation the interviewees experience today, the situation map would make such a difference for the decision maker that they are exited to have access to the intelligence report and situation map. This is in line with their current work preference which sets the frame for their decision making process, i.e., a new tool which promotes impact assessment may have difficulties introducing another way of performing activities, i.e., today their work is characterised by reactive decision making (which is supported by situation assessment) not proactive actions (which is supported by impact assessment). It may also be the case that the decision makers first want to have a situation assessment before being able to dealing with impact assessment (cf. the different levels of SA [17]).

In general, looking at decision making models, situation assessment is one of the earlier step in the decision making process [15], hence, situation assessment is the primary focus for decision makers. This has also been recognised by Hutchins et al. [16]. When they developed a new decision support to be used in a military setting the focus was on situation assessment in order to support decision making.

Also, the difference of appreciation between situation assessment and impact assessment might be due to the set-up of the studies. The interviewed decision makers were commanders working in the field and an intelligence officer who has a more of long-term time horizon might find the impact assessment more valuable. Moreover, not enough explanation for how the probabilities were calculated may have been given. As a consequence, the result might be due to trust issues which need to be resolved, (cf. [10]). The prototype’s calculation of the probabilities was judged as hard to interpret by the interviewed decision makers. The situation map was not pre-processed and the decision makers had to make their own interpretation. The decision makers therefore had a tendency to trust the situation map more compared to the provided probabilities.

To conclude, one could argue that, in these studies, supporting the early decision making process (i.e., situation assessment) was considered as more important than supporting dealing with future events (i.e., impact assessment). This could be compared to a study [22] which compared the effectiveness of two decision support systems aviation implementations used in decision making activities under high time pressure and uncertainty. The study compared status displayed (cf. situation assessment) and command display (cf. impact assessment) and the result was that in the case of inaccurate information, the status display performed better, i.e., more robustly and less affected by automation biases.

As one can see here, there is an interesting trade-off between situation assessment and impact assessment and more research is needed. This is in line with [19, p. 513]: “Situation Awareness is focused on the tactical picture and is reactive, instead of strategic and pre-emptive”.

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**Paper V**
7. Conclusion and Future work

The prototype discussed here has been presented at a previous fusion conference, cf., [1]; however, this paper reports on the recent user studies regarding the ongoing development of the Impact matrix. Although the results in this study are based on limited data (i.e., four in-depth interviews), the research presented is a qualitative study that identifies interesting issues which need to be addressed in future versions of the Impact Matrix tool. Since these studies were performed the Impact Matrix tool, now called “Impaktorium”, has been updated and changed, both technically and due to the suggestions made by the respondents from the study.

Also, the results provide information which can inform future evaluations. Future work will involve more advanced user studies which, for instance, further examine the trade-off between supporting situation assessment versus impact assessment or the tradeoffs regarding the probability distributions, i.e., what trigger the decision maker to make a decision and take action.

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Appendix

These are the interview guides that were used in the presented user studies. For convenience, the questions have been translated into English.

Examples of open-ended questions regarding “HCI issues” (cf. [13]):
- What do you think of the information presented by the tool?
- Do you have any suggestion of improvements for the interface of the tool?

References


Paper VI
Extracting rules from expert operators to support situation awareness in maritime surveillance

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Abstract – In maritime surveillance, supporting operators’ situation awareness is a very important issue for enabling the possibility to detect anomalous behaviour. We present a user study which conceptualises knowledge to be implemented in a rule-based application aiming at supporting situation awareness. Participatory observations were used as a method for extracting operators’ knowledge. The result of the user study is in the form of a number of identified rules emerging from organisational factors, group thinking and individual experience. A description of the rule-based prototype is presented along with the result from the user study. This is also discussed together with the applicability of rule based systems and how to support situation awareness.

Keywords: information fusion, situation awareness, maritime surveillance, knowledge elicitation, expert systems

1. Introduction

A typical maritime surveillance task performed along the Swedish coast line is to track and identify objects at sea. To aid this task, video cameras, radars, and AIS (automatic identification system) track data can be used. Often, this information is fused and summarised into an overview display (i.e., situational picture) which operators use to obtain situation awareness, cf. Figure 1. To be continuously aware of what is going on and able to notice suspicious behaviour in such displays is difficult for operators mainly due to three aspects. First, operators have limited cognitive abilities which make it difficult to be attentive to an overview display that only shows small changes in each time step [1]. Second, the interpretation of the overview display is typically very individual, i.e., people have different knowledge and experience which makes them notice different issues in the display, and hence they are able to maintain SA differently [2]. Third, today, when interpreting the display, suspicious behaviours are less obvious compared to during the cold war when the activities outside the Swedish coast were characterised by known surveillance ships from mainly Russia, Germany and the UK.

Figure 1. An overview display providing users with information about current vessels near the southern Swedish coast line

Today, the enemy is characterised by other activities such as smuggling which may be difficult to notice. Fortunately, as technology advances, we have new possibilities to support operators’ interpretations of these types of displays used in maritime surveillance activities. For instance, there are different kinds of technologies (e.g., [3-5]) which from data (e.g. sensor data) automatically find anomalies. This helps users to detect unusual activities in maritime surveillance scenarios. In general, this kind of technique could be referred to as “bottom-up” approaches, i.e., from the available data one automatically identifies anomalies. In contrast, a more top-down approach can be used where, for instance, existing knowledge about suspicious behaviour is used to identify unusual activities. These systems most often utilise rules extracted from experts, cf., e.g. [6].

This paper presents a case study which identifies and extracts knowledge of expert operators to inform the ongoing development of a rule-based application [7] aiming at supporting situation awareness. The method for capturing knowledge from experts that we apply here is
participatory observations [8]. In the following sections, a brief description of the current version of the developed prototype is presented. Next, the results of the user study intended to inform the ongoing development of the tool are presented and discussed.

2. Background

2.1 Using expert systems as support

Expert systems originated in the mid 1960s [9] and have since then been used in many different domains such as finance, data processing, marketing, human resources, manufacturing [10]. Such systems typically use symbolic knowledge representation and logical reasoning techniques (e.g. case-based reasoning, fuzzy logic, etc.), sometimes, in combination with non-symbolic techniques (e.g., neural networks).

One particular category of expert systems is rule-based expert systems. These are systems which “contain information from human experts, and represent that information in the form of rules, such as IF-THEN” [9, p. 94]. Rule based expert systems were popular during the 80s and have lately gained increasing recognition. For instance, [9] reports on a wide range of applications developed during the twenty-first century such as Tutoring systems, Geosciences, Biochemical nanotechnology, agriculture planning, Apiculture, probabilistic fault diagnostic, indicating the applicability of rule based systems today.

A common problem for all expert systems is, according to [11], the ‘knowledge acquisition bottleneck’. This refers to the difficulties computer specialists often encounter when extracting knowledge from domain experts to be transferred into expert system applications. It is estimated that only approximately two to five units of knowledge can be extracted during one day [11]. There are a number of different methods developed for this purpose, i.e., capturing users knowledge and experience to develop expert systems, cf. [10, 11]. Amongst others, case analysis, critical incident analysis, commentaries, conceptual graphs and models, brainstorming, prototyping, performance reviews, are all examples of methods used for such occasions. Although interview transcripts are, by far, the most common source to inform such systems, it is well known that how you think you go about to do a task may not be how you actually do it, cf. [10,11]. Another possible technique is the capturing of knowledge as a side effect when automating a work process. In other words, in order to extract knowledge users answer questions as they interact with the system.

2.2 Supporting situation awareness

Expert systems can be used to support situation awareness, e.g., [12]. Looking specifically at situation awareness (SA) research, Endsley [1] who is one of the founders of the concept, developed a model where SA was divided into three distinct levels, i.e., Level 1: perception of current elements in situation; Level 2: Comprehension of current situation; Level 3: Projection of future status. As the model is outlined, the three levels of situation awareness are a prerequisite for making a decision which can result in an action. Also, it could be argued that the focus is much on what cues to provide in order to achieve an accurate mental model. Furthermore, according to the model, it is important to not just have a comprehension of the current situation but also of future events. Endsley [13] identifies different elements which need to be supported for achieving situation awareness in the aviation domain, i.e., geographical SA, spatial/temporal SA, system SA, environmental SA, and tactical SA. On the other hand, SA has been considered as the interaction among different entities [14]. In paper [14], a distributed cognition perspective is used for understanding the creation and distributedness of situation awareness, i.e., how multiple operators and the tools/artefacts they use collectively maintain SA [14]. The implication is that there is not as strong a focus on mental models inside a person’s head compared to Endsley’s model of SA.

3. Implementation: a rule based expert system prototype

A prototype of a rule based expert system application has been developed and published in 2006, see [7] for an extended description of the tool. As the authors point out [7]: “The basic idea behind the prototype is that in order to achieve greater situation awareness it is necessary to identify relations between individual entities and their immediate surroundings, neighbouring entities and important landmarks” (this is also in line with Endsley’s model of SA). Hence, a rule based situation assessment system that utilises both COTS and in-house software was developed. The basic idea is that long-term intentions and situations can be identified by patterns of more rudimentary behaviour, in essence situations formed by combinations of different basic relationships.

“It is built upon an agent framework that speeds up development times, since it takes care of many of the infrastructural issues of such a communication intense application as this is, and a rule based reasoner that can reason about situations that develop over time. The situation assessment system is developed to be simple, but structurally close to an operational system, with connections to
outside data sources and graphical editors and data displays" [7].

For providing an easy way for operators to add rules a rule editor has been created, cf. figure 2. As can be seen in Figure 2, the focus is on time based reasoning. To illustrate the potential of the tool, a smuggling scenario was implemented, cf. Figure 2 and 3. The scenario (i.e., the suspicious behaviour to be identified), displayed in Figure 2,

“... can be described as: two vessels, having departed from ports in different countries, meet up and stay together for some time, and then they split up and return to the ports from which they departed” [7]. This rule is implemented in the system, and if the rule finds a relationship, an alarm is triggered, hence, enhancing situation awareness and enables operators to take action.

![Figure 2. Rule editor displaying the rule of smuggling. At the top, components which the rule can be built from are displayed: approaching, leaves, belong to, travel with, in area, on list. To the left, users can choose to what degree they want to be notified by highlights or an explicit alarm. To the right, a graphical interface is provided where the user can create rules through “drag and drop”.](image-url)
3.1 Initial concept evaluation

An informal evaluation of the prototype was performed spring of 2007 by two of the authors (MN and JE). The aim with the concept test was to get initial user feedback of the tool and evaluate the usefulness of the tool for maritime surveillance.

Location. The test was conducted at a Swedish marine surveillance control centre in Malmö.

Participants. Two former operators participated in the test. They had both long experience of working in the control room. One of them has been responsible for introducing new technology in the surveillance control room; hence, there is a strong technological interest. Former operators were used due to their availability.

Scenario. A smuggling scenario involving two vessels departing from two different harbours was presented to illustrate the potential of the tool. The scenario took a couple of minutes to run.

Procedure. The evaluation was performed as a concept test where the tool was presented to the participating operators. After the presentation the operators were asked to brainstorm around the prototype. Their opinions were noted with pen and paper. The evaluation lasted for about 30 minutes.

Results. The evaluation indicated that the tool could be useful in the surveillance control room supporting operators’ daily work. One of the major benefits put forward was that the tool provides the opportunity to track evolving events. Typically, today, operators work in shifts which make it difficult to notice incidents evolving over longer periods of time. For instance, it is difficult to notice if one vessel is located for five days in the same spot (because the operators responsible for the area are constantly changing). Furthermore, the evaluation identified some suggestions for improvements. For instance, it was suggested that it would be beneficial to explain why a rule was added in order to limit the risk for deleting a rule just because the operator does not understand why the rule exists. It was also suggested that rules in the system should be able to be personalised. The operators argued that some people may want to have many alerts and others may want fewer alerts. Moreover, the evaluation indicated that the rules need to be adapted towards the activities of the operators. The presented rule of smuggling is very sophisticated; however, it does not reflect the daily work of the operators. Thus, for the operators to see the full potential of the tool, more knowledge of the work domain is needed; consequently, there is a need for further user studies which could inform future development of the tool.

4. User study

In addition to the initial concept study, a user study has been performed as part of the ongoing development process of the rule based situation assessment tool for sea-surveillance, cf. [7]. In its current state, the tool is equipped with rules based on fictitious scenarios. The aim with this study has been to identify relevant rules for sea surveillance in South Sweden, which could, then, be implemented in the tool and further evaluations could be performed.

Method. Participatory observations [8] were chosen as a method to extract knowledge from the operators. Participatory observation is a method which observes users by including the observer in the work environment. The method allows the observer to ask questions and to be instructed by the users as they perform their work. Hence, participatory observations allow users to explain the action while they are performed (i.e., focus is not only on what they know, but how they actually use that knowledge which they might not necessary be able to verbalise themselves).

Location. The observations were conducted at a Swedish marine surveillance control room in Malmö (the same centre as the initial concept test).

Participants. Seven operators with an average of three years experience participated in the user study (these were not the same people as the ones participating in the initial concept test).

Procedure. The observations were conducted during four occasions (including pilot test) distributed evenly round the clock to allow for different conditions, for a total of 16 hours. About 70 vessels were identified and tracked during the observations by the team of operators. During the observations, when needed, operators were asked to explain the reason for making a specific action. Field notes (pen and paper) were used to capture work procedures and events which could later be formalised into rules. A summary of the rules has
been verified by two of the operators for validity. The underlying focus of the observations was on the following question:

- How do operators in a maritime surveillance control room classify/interpret suspicious behaviour when interacting with the overview display (cf. Figure 1), i.e., when and what triggers users to make a decision and/or to take action?

**Case site: maritime surveillance**

The presented case study was performed in a marine surveillance control room responsible for the security of an area outside the Swedish coastline. The main task of operators located in the surveillance control room is to identify vessels and continuously analyse the situation being aware of the current state at sea, thus, involving identification of possible suspicious behaviour.

In general, there are five users working in the control room, i.e., one operator responsible for incoming intelligence reports, two operators responsible for manually identifying vessels, and two operators keeping track of the overall situational picture of the current situation. The participatory observations focused on the two operators in charge of keeping track of the current situation. To help they had an overview display which showed the output of the identification and tracking process of vessels, cf. Figure 1. They also had access to a number of additional technologies (e.g., radio, ships, airplanes, optic camera etc.) which, when needed, could provide additional information.

**5. Results**

The participatory observations resulted in a collection of field notes on how the team of operators interacted in the control room in order to be aware of what was going on at sea. The result revealed a number of different interesting factors concerning situation awareness.

At the beginning of a shift, the operators need to quickly get an understanding of the current situation. This is today supported by, for example, a formal debriefing by the previous work team, a specific daily report, and informal chat with colleagues. To be noted, more information than strictly the overview display is requested for getting awareness of the current situation, i.e., the cues provided by the overview display are not enough to get a accurate understanding of what is going on at the moment. That the overview display does not provide enough information is exemplified by the fact that different assessment of the information provided is made dependent on time (i.e., time of day/year). One of the operators explained that in July typically one sees a large number of boats/ships going from Germany towards Sweden cluttering the display. An automatic anomaly detector which identifies anomalies from data may trigger an alarm; however, the reason for the large amount of activities is that it is the start of the main holiday season in Germany. The limitations of the overview display are also reflected in debriefing where not only a snapshot of the overview display is provided but also actual photos of the vessels in the area. Operators reported that photos not only made their work more fun but they felt that they get a better feeling of what kind of vessels were in the area.

Furthermore, it was observed that each work team has to start their work from scratch, i.e., the knowledge of the current situation are just summaries in the form of a PowerPoint presentation. This presentation included the position and identity of vessels, not the achieved situation assessment. Also, this may lead to a lack of episodic reasoning (you do not transfer episodic reasoning between work teams).

The work is today divided between the different operators to be able to maintain situation awareness, i.e., the two operators responsible for identifying vessels alert the ones responsible for the overall situation if they see any suspicious behaviour. The operators had different ways for assessing the overview display (cf. Figure 1), i.e., to determine suspicious behaviour. A summary of factors affecting this assessment of suspicious detection (thus SA) is as follows:

- **Experience.** Dependent on experience one can see different information in the overview display, especially, a difference has been noted between the ones with less than a year experience compared to those that have been there longer. With experience, one is more likely to know what temporal and spatial patterns to look for.

- **Context.** The context of an event can classify it as a suspicious behaviour. It was emphasised that you need to be flexible in your interpretations of the overview display, one interesting pattern may not be interesting the other day.

- **Incoming reports.** Intelligence reports or other information from, for example, the coast guard or higher up in the hierarchy can provide information of interesting objects. The operators can be told to look for a specific pattern in the overview display.

- **Permits.** There are official documents describing what vessels have the right to be on Swedish water.
Furthermore, it was noted that differences exist between operators in what they identify as suspicious in the overview display. At one point, two of the operators were asked to make an individual assessment of the situation from the information provide by the overview display. The operators’ assessments overlapped; however, there were individual differences between them in terms of what conclusion they drew from the overview display. Moreover, it was noticed that the operators had different working procedures, hence, there is a demand for personalisation of rules. Also, there was a difference in how aware the operators were of their knowledge and how well they could articulate it. In other words, some could express a specific reason for making an action or taking a decision, others could not express why they took a specific action (they just reacted to the information on the display). It also was noted in the observations that the users had difficulties to maintain situation awareness of the overview display as it presents a quite constant state. Often the two operators responsible of the overall situational picture were occupied with side tasks, and only, now and then, looked at the overview display.

**Identified rules**
The participatory observations resulted in a collection of field notes regarding causes of actions which could then be identified and formulated as different rules. It was noted when and why users decided to act upon the information provided by the overview display. Some of the identified activities were performed routinely, i.e. one could have standard rules implemented in the system. Others were instances of special occasions which would require the possibility to adopt and add new rules. Furthermore, the rules presented here have been confirmed by two of the operators for validity. The following are examples of situations which the users would like to be notified of are as follows.

The first thing operators looked for when a new vessel entered the overview display was if they were government-owned. Hence, the first rule is:

1. if a vessel is government owned then the operator needs to be notified

At one occasion, the operators got a notification regarding a Swedish military training operation which would be in operation for a couple of days. The notification said that a safety zone had been created where people were asked to not enter. The information was provided by a text file transmitted by fax. Therefore, every vessel which entered Swedish waters was relevant and needed to be identified. This situation would appear a number of times each day. Hence, the operator used the following rule:

2. if a vessel enters area X and has a name Y then the operator wants to be notified

At one point, a discussion among the team of operators was raised whether or not the speed of a vessel was interesting. The conclusion was that a vessel which had a high speed was interesting because most commonly people are aware of and obey the existing speed limit. Hence, the operator implicitly used the following rule:

3. if vessels have a speed above X then the operator wants to be notified

In their daily work, operators routinely were provided with lists of suspicious vessels which need to be tracked. These lists were provided by email or fax. Hence, the operator used the following rule:

4. if a vessel has name X then the operator needs to be notified

On one occasion, an additional operator dropped by (this week he had other duties). When interpreting the overview display he asked about the name of a specific vessel. When told about it, he said that it should be checked out because “I think that vessel was there at that position last week also”. Also, it had been argued that a vessel making a sudden turn is interesting. Hence, the operator is interested in the following:

5. if a vessel is laying still and/or make a sudden turn then it is an interesting vessel and the operator wants to be notified

6. if a vessel is still during a longer period of time then the operator wants to be notified

One discussion among the team of operators was regarding what was hard to detect. One of the examples was to notice a change in speed. Hence, the following rule needs to be supported:

7. if a vessel abandons previous speed (i.e., high speed, low speed, high speed, etc.) then the operator needs to be notified

Quite often it was noticed by the operators that two vessels were going in parallel. This may have a natural explanation, e.g., two vessels changing crew, but it could also be a sign of an unwanted activity. Hence, the operators used the rules:

8. if two vessels going in parallel, in a certain range (x meters from each other) then further investigation was initiated

9. if two vessels are going towards each other, and upon encounter make a turn, then the operator wants to be notified
10. if one vessel encounters a smaller boat
then the operator wants to be notified

It was noticed that operators often focused their
attention towards specific areas of the overview
display. For instance, the sea has specific paths
where vessels usually travel (commonly referred to
as E4/E6). Typically, vessels which do not want to
be seen try to abandon the places where vessels
typically travel, i.e., they take routes which vessels
normally do not take. On the overview display this
behaviour is easy to identify, i.e. operators use the
following rule:

11. if vessels abandon a planned route or go
beyond the specific area commonly
referred to as E4/E6 then the operator
wants to be notified

6. Discussion

The study focused around the question “How do
operators in a maritime surveillance control room
identify suspicious behaviour when interacting with
the overview display (cf. Figure 1), i.e., when and
what triggers users to make a decision/action?”.
Looking at the identified rules, one can see that
they consist of different components. Most often
they consist of:

- relations (binary, unary)
- combination of future state and attributes
- combination of physical (border) and
  abstract (land) attributes
- describing situations evolving over time

In summary, the different rules emerge from both
organisational factors (e.g. operators have a task to
identify government owned vessels and are
provided with lists of interesting objects and
different permits), group thinking (operators
collectively have knowledge which is used to
identify suspicious behaviour) and their individual
experience (some of the rules are created from
operators experience).

In order to implement the rules, information from different sources is needed to
alert the operator. For instance, AIS attributes,
motion patterns of the vessels, local database of
names of interesting ships, and so on. AIS attributes
include time stamp, sensor ID, local track ID, ship
location and velocity estimates, ship shape (length,
width) estimates, ship type, ship name, navigation
status. Moreover, when the actual rule should create
an alarm need further evaluations. When creating
the rules the operators may create the rules so they
alert before the actual situation occurs or the rules
can alert when the actual situation has occurred.

Notably, some of the rules identified in
Section 4 cannot be implemented into the prototype
in its current version. Hence, the next step in the
development process is to identify what knowledge
is possible to implement and perform more
advanced user studies as well as develop the
prototype further.

7. Lessons learned: Implications for
practise and research

There are a number of different insights which we
as researchers and developers of situation
awareness applications can take with us from this
study.

The usefulness of rule based systems using fusion
techniques

The initial concept test identified the developed
prototype as a useful concept. The tool could be
used for managing problems operators commonly
encounter today. For instance, there is a problem of
identifying situations evolving over time due to the
changing of shifts. There are also problems of
maintaining awareness/attention towards an
overview display which does not significantly
change state often. A rule based prototype which
takes into account the operators’ knowledge could
ease those problems by being able to operate over
time and shifts alerting operators and directing
attention towards interesting situations such as
those exemplified by the previous identified rules.

In the participatory observation it was
noticed that an application such as the one
developed, would probably best work as a module
in cooperation with other systems. Even though the
system supports situation awareness, the users are
dependent on other factors which cannot be
transmitted by an overview display for achieving a
certain level of situation awareness. Also, having
the system as a module in cooperation with other
systems would overcome the problem typically
associated to expert systems (cf. Section 2). This is
in line with the system presented in [6]. However,
this study highlighted that it is important to have a
note where operators can explain why they have
included a certain rule. This would not only
improve the developed prototype but also the
application of [6].

Furthermore, studying the actual rules,
some of the rules need to be added “on the fly”, i.e.
a suspicious behaviour is identified and this
knowledge needs to be implemented into the
system (this rule may be valid during a limited time
period). Other rules are more stable and will always
exist in the system alerting operators. Also, some of
the rules do not need to have an explicit alarm
attached, instead, it is just needed to highlight the
output of the rule, e.g., nr 7 (colour mark vessels
which are going in parallel). In other words, the
alerts the rules create need to be flexible and

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adjustable. These issues are accounted for in the developed prototype by the rule editor which enables users’ flexibility and easy access to the rules.

Moreover, issues of when the rules should alert operators, i.e., the structure of the rule. For instance, one could create a rule which alerts the user of a situation, i.e., if vessel X is in area Y then alert the operator. Similarly, the rules could say: if vessel X is heading towards area Y, then it will put in at area Y. The first one could be interpreted as ‘situation assessment’ because it is an ongoing situation while the second rule could be interpreted as ‘impact assessment’ because it does not just alert the operator of an ongoing situation, it also makes a prediction of a future situation. This is a close trade-off between the different rules and they can be interpreted in different ways, further evaluations are needed.

It should also be noted that the rules identified mostly do not involve situations evolving over time and could be classified as “simplistic”. This might be due the lack of support for such reasoning in their current work procedures. Also, the users might only use the identified rules because it would make such a difference for their current work environment. In other words, it is hard to imagine more advanced scenarios because they are not aware of the technological solutions which exist today. Also, the operators were often reluctant to specify a specific number (e.g., speed), instead they reasoned in terms of range.

Moreover, the initial concept evaluation highlighted the importance of matching the developed prototype to its intended use, i.e., to see the full potential of a rule based system it needs to be tested with real users under realistic circumstances (i.e., the very reason for the presented user study).

Finally, the participatory observations highlighted the fact that operators often reasoned using many different information sources when assessing the situation. More specifically, they used the overview display in combination with other technologies and colleagues as well as the rules combined with different attributes. This implies the need for fusion techniques when developing rule based systems.

Acquisition bottle neck problem
There have been many different methods developed to capture knowledge from experts, cf. [11]. The represented user study exemplifies the applicability of participatory observations for studying expert knowledge connected to situation awareness. The question is if participatory observation is a good alternative for capturing knowledge from users. The experience from the study presented in this paper is that the method is well suited for this purpose because you as a researcher are allowed to interact with the users at the same time as they use their knowledge. To identify knowledge while acting often triggers operators to recall more compared to a normal interview session.

Supporting maritime situation awareness
The initial concept test of the prototype and participatory observations raised questions regarding how to support situation awareness. First of all, in the participatory observations it was noticed that situation awareness does not only involve knowledge about relations between individual entities and their immediate surroundings, neighbouring entities and important landmarks, but also, knowledge about time is an important factor for having an accurate understanding of the current situation. Time refers to, for example, what time of the day, year is it or how long time have the vessel been here. It can be argued that support of time is an important factor which needs to be accounted for. This is in contrast to situation awareness in the aviation domain [13] where, for example, spatial/temporal SA only refers to the planes’ own position and projected landing time. Knowledge about the time of day or year is not explicitly acknowledged as a factor affecting pilots’ situation awareness.

Furthermore, issues regarding when to alert the operator of an evolving situation emerged. In the initial concept test the question: should the rule initiate an alert when the event has happened or is about to happen were raised. Hence, there is an issue of whether or not supporting situation assessment (i.e., this situation has happened) or impact assessment (i.e., this situation is about to happen), here, more research is needed.

In a continuous activity such as surveillance, it is especially important to be able to notice suspicious behaviour. To be able to notice suspicious behaviour is depended on knowledge and experience of users. As such, it should be noted that there is a limitation of rule based (expert) systems. These systems seem to best work for known recurring events. Therefore, in order to support situation awareness, these systems should be utilised in combination with other technological solutions, cf. [6].

8. Summary and Future work
The evaluated prototype has been presented at a previous conference [7], however, this paper reports on the latest user studies. First, an initial concept evaluation identifying the usefulness of the prototype was conducted. The result indicated that the application could be used for transferring knowledge between the different teams of operators. Also suggestions for improvements such as including a place where the user could explain
why a rule exists were identified. A second user study was initiated to capture knowledge of users to be implemented in the prototype for future evaluations. The user study identified a set of rules to be implemented in the prototype as well as highlighted issues such as what to be supported. Moreover, the need for fusion techniques when developing rule based systems has been identified and the value of participatory observation as a methodology for capturing knowledge from experts was also demonstrated.

Future work will involve implementing the previous identified rules in the systems to allow for more advanced user studies concerning how to support situation awareness.

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