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The Situation Awareness Weighted Network (SAWN) Model

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We introduce a novel methodology to examine how a distributed organisation of military staff who feed a Common Operating Picture (COP) generates Situation Awareness (SA), a critical component for achieving agility. The model we propose combines two dominant scientific models of SA, by Endsley and by Stanton et al. respectively. The *Endsley* model posits that SA can ascend up three levels: Perception, Comprehension and Projection. The *Stanton* Distributed model proposes that SA exists across a social and semantic network of people and information objects in activities connected across a set of tasks.

The fusion of these we call the Situation Awareness Weighted Network (SAWN). The output of SAWN is a representation as a *weighted bipartite network* of the interaction between people ('human nodes') and information artefacts such as documents and system displays ('product nodes'); link weights represent the Endsley levels of SA that individuals acquire from or provide to information objects and other individuals. We will show how data can be collected through surveys or structured interviews against both 'steady-state' and crisis scenarios or exercises; in the latter case task models may be developed which provide the context for such data collection. A set of twelve survey/interview questions graduate the Endsley model into finer increments of SA. For each of these a respondent is asked about use and consumption of products, and interaction (including face-to-face, email, chat, phone, video conference) with another human node for the benefit of one or the other.

The resulting network representation reveals sources and sinks of SA, the means by which fusion increases levels of SA and how SA *flows* through a C2 organisation. Quantitatively, the network representation naturally leads to new metrics for SA flow such as nestedness and the weight gradient along paths in the graph. We illustrate the method with aggregated data.

1. Introduction

The C2 community understands well that agility – the property of being robust, resilient, flexible and adaptable [NATO 2006] – is critical in circumstances where organisations must quickly respond to rapidly developing situations with multiple elements whose connections are opaque. Situation Awareness (SA) – of individuals and the organisations in which they perform their roles – is, in turn, a key requirement for achieving that agility; there is little time for hierarchical handling, processing and authorised dissemination of information. Thus agents in the system must each be able to understand what is happening and make judgements as to what may happen next and enable others to do the same. For this reason, a model of SA that takes into account individual and distributed cognition is essential. This paper proposes such a model by unifying a number of existing approaches to SA. The model we arrive at is ideally suited to an organisational context of, for example, military staff who maintain a Common Operating Picture (COP) within the J2 (Intelligence) and J3 (Operations) functions in response to a rapidly unfolding crisis.

The context of this research is a recently completed study with an Australian Defence Force military headquarters organisation. We present in this paper an aggregation of the data set collected in the study such that the broad characteristics of the set are evident but individual staff, roles, units and their inputs/outputs are not identified. However, key to the context of our study are the following:

- Individuals or teams – entities we will say – have their attention drawn to some element either in their field of view or through some system display, and/or must develop an understanding of the current actions of those elements and/or what may happen into the future – we deliberately here draw on the language of one of the well-known models of SA, that of Mica Endsley [1985]. We say 'and/or' because these entities may not have access to sufficient information to enable them to understand the current actions or anticipate the future.
- These entities must then communicate that information, either as an information artefact (document, slide, update of a system display) or through personal interaction by some medium (face-to-face, phone, email, video, chat).
- Other entities, with access to other information or some of the aforementioned artefacts or interactions, may achieve the understanding or anticipation discussed above and in turn communicate that *value-added* information.
- Finally, some of the aforementioned entities or still others may formally be responsible for initiating actions based on the anticipated actions of the elements.

We see that these aspects are all present in a diversity of 'C2 Problems', from the threat of a military or terrorist adversary to the consequences of a natural disaster, and in a diversity of 'C2 Approaches', from hierarchy to complete network centricity. It is the coexistence of these that have warranted our fusion of the two dominant models of SA. One is the model that is well suited to the case of individual cognition and with some extension to 'team SA' [Endsley 1985, 1987, 1988]. The other is known as 'Distributed SA' [Walker et al. 2006, Salmon et al. 2010], which sees SA invested in a system of networked individuals (who may not belong to a team at all) and information artefacts. For reasons to become clear, we have named our approach the Situation Awareness Weighted Network (SAWN) model. We will define this model and provide a systematic data collection methodology, itself based on well-established methods in the scientific literature.

We emphasise that the intent of this paper is to explain the model and methodology and show how insights into the effectiveness of the generation of SA by a distributed system of people and tools can be gained in order to derive a 'future' C2 structure. The intent is not to make, here, statistically valid judgements of an existing system. Therefore, in this paper we will only sufficiently specify the data such that the representations we show are reproducible.

The study began with a comprehensive familiarisation with the setting through analysis of Standing Operating Procedures (SOPs), observations of headquarters activities across all time periods in the 24 hour cycle, including attendance at key daily briefs, and unstructured interviews with staff. At the same time we examined the literature on SA to determine whether existing models and measures could be applied and to provide data to address the study question. The overall study approach is depicted in Figure 1, to be explained further through the paper.
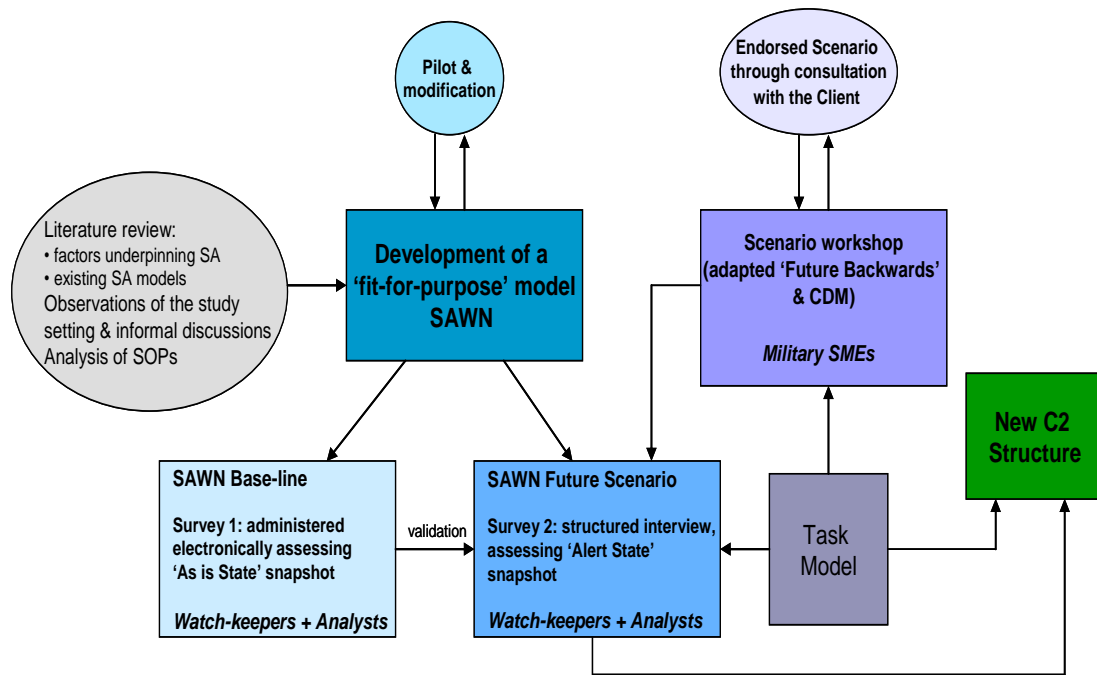


Figure 1 Overall study approach

In the next section we expand on the existing SA models drawn together into our proposal. We then elaborate on SAWN and the data collection methodology at the heart of Figure 1. A core part of this methodology requires an articulation of requirements for SA by planners and operators, which we describe. We then show the results of such a collection for a hypothetical context and discuss the broad applicability of the approach.

2. Existing Models of SA
SA has been subject to considerable research in the military and scientific communities over the last few decades. There are numerous SA models and measurements described in the academic literature dealing with individual, team, shared, and distributed situation awareness [Endsley 1985, Adams et al. 1995, Salas et al. 1995, Banburry et al. 2004, Houghton et al. 2008, Salmon et al. 2010, Walker et al. 2010, Hew 2011]. Most of the models discussed in the literature are in agreement that SA is a process by an individual human combining, integrating and interpreting information from the environment, system displays and other humans. The two models mentioned in the introduction are distinguished by being, contrastingly, an individual operator based model, that of Endsley [1985, 1987, 1988, 2000], and a distributed system model [Stanton et al. 2006, Salmon et al. 2009, 2010, Walker et al. 2010].

Endsley SA
Endsley [1985] defines SA as a level of awareness that an individual has of a given situation, an understanding of and knowledge of what is going on. Accordingly, SA is a product of situation assessment comprising three levels: the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future [Endsley 1985: p36]. These levels are depicted in Figure 2.

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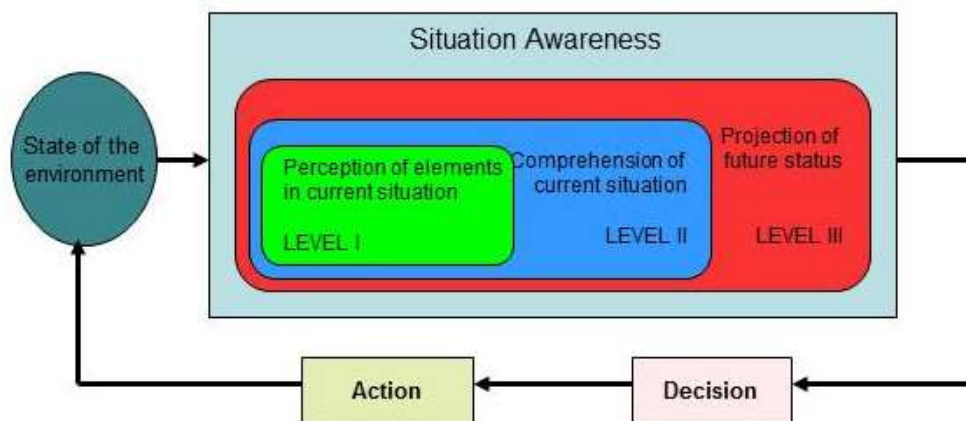
Figure 2 The Endsley model of SA

SA Level I is where data is merely perceived with no further processing. Level II involves interpretation of Level I data, enabling an individual to understand its relevance in relation to the task performed and goals to be attained. It is where an operator forms a holistic picture of the operational environment and comprehends the significance of objects and events in that environment [Endsley 1985]. Based on a combination of SA Levels I and II, together with experience and knowledge, operators may then forecast likely future states for the situation; this gives SA Level III. A key assumption in this three-level model is the pivotal role of mental models on the development and maintenance of SA. Mental models, resulting from training and experience, are used to facilitate the achievement of SA by identifying elements/events in the environments (Level I), then integrating them to gain understanding of their meaning (Level II), and finally for generating likely future states (Level III).

The measurement techniques associated with this model have been used and validated extensively, notably: the Situation Awareness Global Assessment Technique (SAGAT) where 'freeze-probe' techniques[1] are applied; the Situation Present Assessment Model (SPAM) where probes are administered in 'real–time'[2]; the Situation Awareness Rating Technique (SART) eliciting subjective assessments of SA and usually administered post trial; and observer rating where domain experts observe and rate participants performing a task under study.

The Endsley model has been widely accepted as a result of its positioning of SA between cognitive science and individual/personal experience.

Distributed SA
A difficulty with the Endsley individual operator model arises when it is applied to collaborative systems. Moreover, the measures associated with this model, apart from relying on subject matter experts and being rather intrusive, are most suitable for assessing SA in stable environments and where SA-related elements can be pre-defined, namely where 'ground truth' is known [Salmon et al. 2009, Saner et al. 2009]. However, when the tasks are

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[1] A task is randomly frozen and all displays/screens are blanked. A set of SA queries regarding the current situation at the time of the freeze is applied and participants are required to answer questions based on their knowledge and understanding of the situation at that point. Responses are compared to the state of the system at the point of freeze and the overall score is calculated at the end of trial.

[2] No freezing of task under analysis and SA related queries are administered on-line while an operator is performing a task. The queries are developed in advance by a subject matter expert.

dynamic, collaborative and changeable and the outcomes are not known, then a different non-linear approach is more suitable. The premise, then, of the Distributed Situation Awareness (DSA) model is that cognition is *distributed* and *emergent* in systems comprising interacting human and technological agents [Salmon et al. 2010]. DSA thus enables the assessment of SA in complex environments where situations change dynamically and where team members possess unique and compatible portions of awareness. At the systemic level, awareness is distributed across different human and technological agents involved in collaborative tasks. At the team level, members experience a situation differently depending on their knowledge, experience, training, task, role and goals. SA involves interactions between operators via a *social* network, between operators and the technology/artefacts through a *propositional* (or knowledge) network, and between tasks and the information they require to perform them connected in a *task* network. SA is associated with individual agents but may not reside within them as it is borne out of interactions between them [Salmon et al. 2010]. The advantage of the DSA model is that it accounts for different information elements for a given task in terms of their usage, sharing, and ownership. It allows representation of the changing nature of tasks and task phases in response to a dynamic operational environment.

In more detail, propositional networks are created by defining the concepts or information elements and their relationships, expressing what needs to be known for the performance of tasks [Anderson 1983, Crandall et al. 2006, Houghton et al. 2008, Salmon et al. 2010]. The information elements for a given task are discerned either by observation or via the Critical Decision Method (CDM) [Klein 1989, Hoffman et al. 1998]. Propositional networks thus build a team SA picture from all the pieces that individuals hold. Each element in a defined relationship should be built from a proposition that can be either true or false and for which it is critical that there is a name for the relationship.

Why unify the models?
Our initial observations in the study clearly recommended both models of SA. The distributed property of the headquarters staff, both as a team and with their interaction in a wider community and with the products they generate, was evident. So too was the effort of individual subjects in analysis of sensor data to understand and anticipate actions of platforms and people to build the COP; adding-value was something our operators consciously sought to do. That the Endsley and DSA models may be unified was first proposed by our colleague, Patrick Hew. While addressing the integration of human and machine elements in SA [Hew 2011], he proposed a model built on Time Coloured Petri Nets (capturing the distributed SA aspect) consisting of a hierarchy of agents identified by the terms Data, Track, Actions (capturing the three Endsley SA levels). Such an output is built based on a scientist's understanding of the application domain (for example, sensor-shooter systems and interactions in coordinated Fires) – much like Business Process Modelling (BPM). In this respect the approach diverges from the spirit of Social Network Analysis in which the network is directly built on raw interaction data. It therefore suffers from some of the subjectivity of BPM, where the scientist must interpret how the business is performed and generate a stylised model. For that same reason, developing models out of data is also manually intensive. This motivates our approach in SAWN to have 'social' and *'information artefact'* interactions captured in the same data collection instrument.

3. SAWN
Traditional Social Network Analysis captures the interaction patterns of individuals in some form of exchange, which may be purely social or business in nature. Individuals are nodes in a network and the interaction is a link between nodes. SAWN expands on this by including nodes representing information artefacts: documents, PowerPoint slides, signals and whole or parts of system displays used. Individuals thus transact information between themselves and/or information artefacts. These transactions are represented as links. This much combines the propositional, social and task network aspects of DSA. In distinction to DSA, SAWN sees *weights* applied to the links – as line thickness or, in our case, colours – where the *weights*

indicate the SA level, according to the Endsley model. Finally, we can distinguish separate networks for the pulling (or consumption) and pushing (production) of information. A simple example of SAWN is shown in Figure 3 where individuals A, B, C, D interact with each other and with information artefacts X, Y, Z, W. But through this transaction A has delivered low SA (thin line) to B, but B correlating this with information product Z has delivered higher SA to C who finally, through access to artefact W, provides the highest SA level to D.
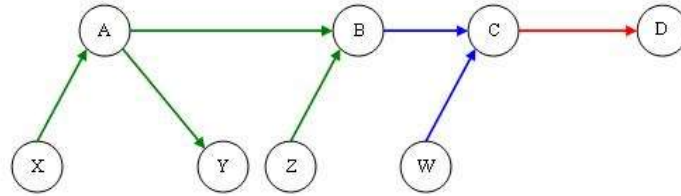
Figure 3 Representation of a Situation Awareness Weighted Network

4. C2 context

The military headquarters in our study works broadly in the lower operational to upper tactical spectrum of command, structured using the Common J Staff System (CJSS), interacting with other Joint Task Forces (JTFs), coalitions (US, UK, NZ, Canada) and other external organisations. At the core, watch staff contribute to the maintenance of, effectively, a COP which should be thought of here as a combination of numerous displays. This is the articulation of the accumulated SA delivered to the rest of the headquarters. These same staff, fulfilling either a J2 or J3 function, issue routine briefs, drawing from the COP. The J3 watch staff are also responsible for initial responses to events outside formal standing JTF Areas of Operation. Elsewhere in the J2, analysts provide support with deeper examination of events. We may identify a range, then, of 'organisation' and 'product' nodes for the prospective SA network, which we list in Table 1.

Table 1 Nodes in the bipartite network after aggregation of raw data; italics indicate organisational nodes that were sampled.

Organisations	Characterisation	Products	Characterisation
OCmnd	Commander, or function/section Heads	Pemail	Formal email that documents information (rather than ad hoc communication)
		Pweb	Documents acquired through intranet
		Pbrief	A fused brief from J3 and J2 staff (see below)
		PCOP	Parts of a COP maintained by J3 and J2 staff
OJ3W1	Senior Officers in J3 Watch	PJ3Brief	Routine Briefs from J3 Watch staff
OJ3W2	Junior Officers/NCOs in J3 Watch	PJ3Ord	Orders issued by J3 Watch staff
OJ3WS	Support officers in J3 Watch		
OJ3S	Support officers in J3	PRpt	Formal Reports by military staff
OJ2W1	Senior Officers in J2 Watch	PJ2WBrief	Routine Briefs by J2 Watch staff
OJ2W2	Junior Officers/NCOs in J2 Watch	Padhoc	Ad hoc document or PowerPoint slide to capture ongoing events
OJ2A	Analysts in J2 Staff	PJ2AnBrief	Analysis Brief by J2 staff
		PThrAss	Risk Assessments
OJ2S	Support officers/NCOs in J2 staff	Popen	Open source information – internet
OStrat	Strategic Level Staff external to the HQ	Penv	Reports on physical environmental conditions

OExt	Organisations external to Australia	PExt	Reports from organisations external to Australia
OInt	Other intelligence organisations	PInt	Reports from other intelligence organisations
OJTF	JTF HQs	PJTF	Brief or formal signal from JTF HQ
OSS1	Single Service (Army, Navy, Air Force)	Pdef	Signals from Single Service units
OWOG	Non-defence government departments	PWOG	Reports from non-defence government departments

5. Data Collection Methodology

In adapting propositional networks to SAWN, two points of caution were addressed. The first is that, when natural language is used to represent connections, words can often mean different things to different people so that terms in questions were carefully defined and trialled across subjects. The second issue is in the question of when one stops building the network, namely determining when it is complete. To that end a clear boundary was established to only include the differing SA perspectives of the J2 and J3 functions of the headquarters.

We thus designed a survey with questions designed to progress incrementally through Endsley's SA levels from perception through comprehension to projection, and to elicit the distributed nature of SA measured through use/produce and interactions. The survey then comprised a set of 24 questions related to products (P) and organisations (O). The 'Products' questions ascertain the role of products that an individual prepares for others and those that are relied on for that individual's SA. The 'Organisations' questions look at the relative importance of formal and informal interactions with groups and/or individuals in organisations external to the subject for their SA. The Survey design for 'steady-state' and 'Crisis Scenario' snapshots is depicted in Figure 4, which indicates the sets of words used in the questions ("draw attention", "identify", and "understand history", for example).
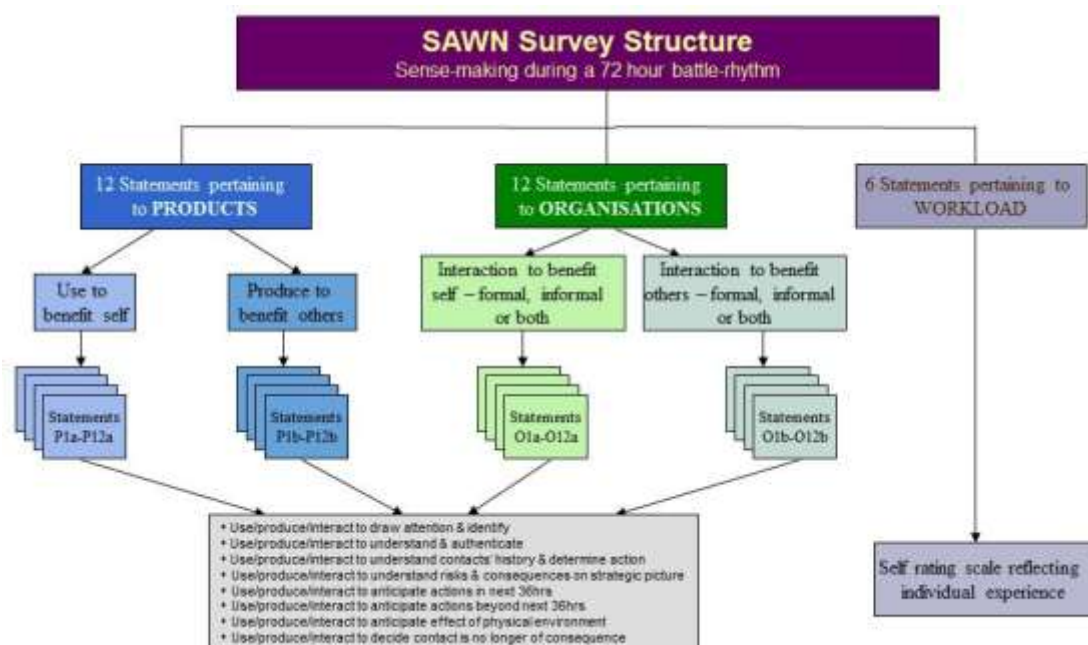

Figure 4 SAWN Survey design

For the 'steady-state' (or 'baseline') snapshot, the survey was administered electronically via Excel attachment to an email. Participants were asked to consider and briefly describe the most significant events of the past 36 hours from the time of answering the survey

but considering their anticipated activity for the next 36 hours. They were then asked to choose from a drop down list up to four products and organisations, respectively, in order of relevance to a given SA activity.

For the 'Crisis Scenario' snapshot, participants were individually interviewed. Following an immersion in a set of events and sequence of tasks requiring a COP, which themselves were derived in a separate scenario workshop (to be explained below), participants were asked to select products they would use/produce and to nominate organisations they would interact with to achieve their SA or support someone else's SA.

Based on evidence in the literature that SA is impacted on by aspects of cognitive workload [Endsley 2000, Saner et al. 2009, Gryszkiewicz & Chen 2012], we probed this issue in the survey. We adapted the National Aeronautics and Space Administration Task Load Index (NASA-TLX), a validated research instrument [Human Performance Research Group 1988]. The participants were asked to rate their perceived levels of workload in terms of mental and temporal demands, their familiarity with the task(s), level of frustration, fragmentation/effort required to perform them, and to rate their performance. The responses were recorded on a 7-point scale where 1 represented the lowest and 7 the highest workload level. We do not present results of these aspects in this paper.

In both survey and interview, minimal demographic data was collected, namely affiliation, rank, length of service and posting. The latter data provided indication of expertise/knowledge, important elements of individual SA. To the 'steady-state' survey, 38 responses were received, with 17 from J3, and 21 from J2. The 'Crisis Scenario' interview involved 27 participants with 15 and 12 from J3 and J2 respectively.

6. Developing a Scenario based Task Model
In order to analyse the generation of SA in a possible future crisis scenario we needed to understand what tasks, information and intelligence would be required. To this end we developed, in consultation with senior J2 and J3 staff, a scenario description covering a hypothetical event, a timeline, and a range of constraints and assumptions. The scenario description used the constraints to push the boundaries of the study participants such that the tasks and information needed through the scenario were non-routine. This description was distributed to military SMEs who were invited to a knowledge elicitation activity in a DSTO Operational Test & Evaluation facility [TTCP 2006]. Through this, the tasks, information and intelligence requirements through the period of the scenario were articulated. Participants were drawn from planning, operations, intelligence, and single-service units in the headquarters. A combination of two dialogue methods was used to elicit these requirements: Future/Backwards (FB) and the aforementioned CDM.

FB is a technique that facilitates planning in complex operational environments by widening the range of requirements and perspectives of a diverse group of players [Cognitive Edge 2012]. The FB process began with participants determining the desired end state to be achieved at the end of the 72 hours of the scenario development and then delineating critical decisions/actions needed (decisive points) to take place in order to achieve that end state and determining when they should occur. The FB technique resulted in obtaining discrete time frames punctuated by the decisive points which were used to determine tasks and COP requirements to carry them out. A modified CDM [Klein et al. 1989] was employed as the dialogue method to elicit these needs, principally because of its role in DSA's Event Analysis for Systemic Teamwork (EAST) methodology [Walker et al. 2006]. At its core, CDM is a retrospective interview that applies a set of cognitive probes to actual non-routine incidents requiring expert judgement or decision making [Klein et al. 1989]. It asks participants to recollect an incident, in a narrative or unstructured manner and then provides a set of probes/questions, to understand what specific decisions were made through the course of the

incident. Indeed, as noted in the literature, CDM was particularly useful because of the varied expertise of the participants of the workshop. Furthermore, CDM was appropriate because the scenario contained several non-routine incidents, for which each subject had separate real experience. These incidents were then conflated and timed to occur within a short period of time to require rapid decision-making. CDM was modified through the wording of probes to account for the hypothetical nature of the scenario as the specific sequence of events had never been encountered by the study participants.

As mentioned previously, FB was used to identify the decisive points of the narrative. From here, the workshop facilitator guided each of the participants to describe the events and tasks that would occur between each decisive point. Finally, specific probe questions were asked to gain the information and intelligence required to support each of the tasks/events. The combination of FB and CDM also allowed probing of participants in a way that was deliberately unfamiliar to them, thus requiring greater thought in developing their responses.

During the workshop we used the *SimVision* simulation software [Jin and Levitt 1996; Levitt 2004] to capture, in real-time, the participants' responses. 'Swim-lanes' for each of the participant units were placed within the display pane of the software. As participants described the tasks they would perform, icons representing tasks were placed in the nominated swim lane. Once all tasks for a given time period had been identified, participants then nominated the information and intelligence required for the COP for each task. These were in turn represented on the display using a specific icon. Tasks, Decisions and COP items were then linked in a notional workflow. The *SimVision* template is shown in Figure 5.
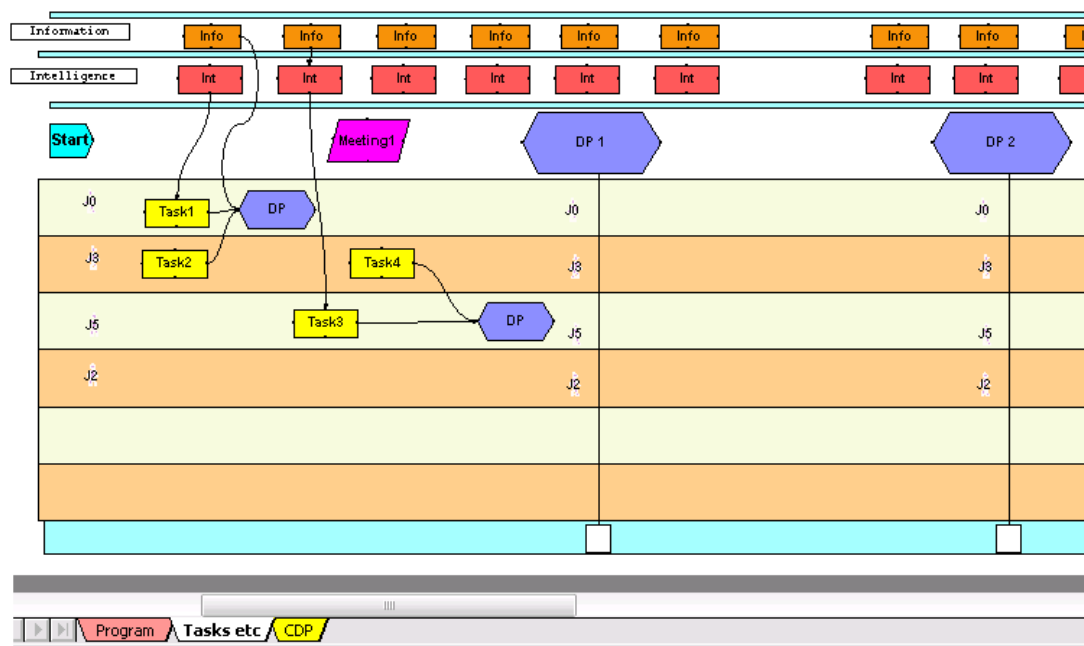
Figure 5 SimVision Task/Intelligence/Information Template

The output then was a list of tasks and associated COP requirements for the crisis event arranged around four Critical Decision Points (CDPs) with approximately 80 associated tasks, a tenth of which were on-going tasks throughout the period of the scenario.

During the workshop 34 COP requirements were identified to successfully respond to the scenario. The sources/producers of this information were then separated into Internal and External Providers. The results of this were then synthesised into a short document and a quad chart summarising the key events, tasks and COP needs through each of the four decision phases. This document was distributed to participants before the 'crisis scenario' interview.

During the interview, a summary of the scenario via the quad chart was presented to the participants prior to being asked about their interactions, use and generation of products.

7. Results

Link Weighting and Aggregation scheme

Each link between an individual and a product in response to a specific question was assigned a numerical weight, with values one and two for the first two questions at the lower Endsley level and then building up to higher values as explained in Table 2. The weighting scheme was chosen such that nomination of a given individual or product in answer to multiple questions at lower Endsley levels did not lead to the same or greater aggregate weight if that individual or product was nominated in answer to a single question at a higher Endsley level. Thus, even if a product was nominated in answer to all questions at Endsley Levels I and II (aggregate weight of 66.0), its weight would still be less than if it was nominated just once in answer to a question at Level III (minimum of 68.0). In this way it became clear where the predominant contribution in terms of Endsley levels lay for each individual or product. Next, the results for multiple individuals were aggregated into the one 'organisation' node, because of both people rotating into the same specific role in a shift roster (in the raw data) and the aggregation of roles into the generic nodes of Table 1. Here we average by summing the weights from those individuals being aggregated who have nominated a specific product or organisation and dividing by the number in that aggregated node that nominate the product/organisation. For example, if there are four people in a shift role but only three of them nominate a certain artefact then the sum of the weights of the links to that artefact is divided by three.

Colour scheme

As explained, data was captured with 12 questions refining the three Endsley levels into finer gradations. The resulting networks are quite complex if shown to that level of fidelity. Therefore, to provide a more readily understandable view we aggregate the data according to the nodes in Table 1 and combine the weights to the three Endsley levels.

Table 2 Colour scheme for nodes and links in SAWN diagrams

| Node	Node Colour	Link Endsley Level	Link Colour
Sampled organisations	**Purple**	I: Perception (Qs1–3) Weights: 1.0, 2.0, 3.0	**Green**
Non-sampled organisations	**Orange**	II: Comprehension (Qs 4–8) Weights: 8.0, 10.0, 12.0, 14.0, 16.0	**Blue**
Products	**Green**	III: Projection (Qs 9–12) Weights: 75.0, 82.0, 68.0, 82.0	**Red**

We also aggregated the numbers of links per SA level according to the scheme in Table 3.

Table 3 Distribution of weights according to bins

Level of Bin	Weight Range
1	0–2.66
2	2.66–5.33
3	5.33–8
4	8–16
5	16–24
6	24–32
7	32–40
8	40–48
9	48–56
10	56–64
11	64–162
12	162–260
13	260-358

We present the resulting SAWN diagrams (generated using NetMiner) shrunk in size but placed side by side to provide a comparison of their structure between 'pull' and 'push' and between steady-state conditions, Figure 6, and crisis conditions, Figure 7. In the Appendix these diagrams are expanded in size where they may be examined in greater detail. To allow the interactions between the sampled staff to be most visible we arrange those nodes on the outside, products interior to them and external nodes (counter-intuitively) at the centre of the network. Colours for nodes and links are as explained in Table 2.
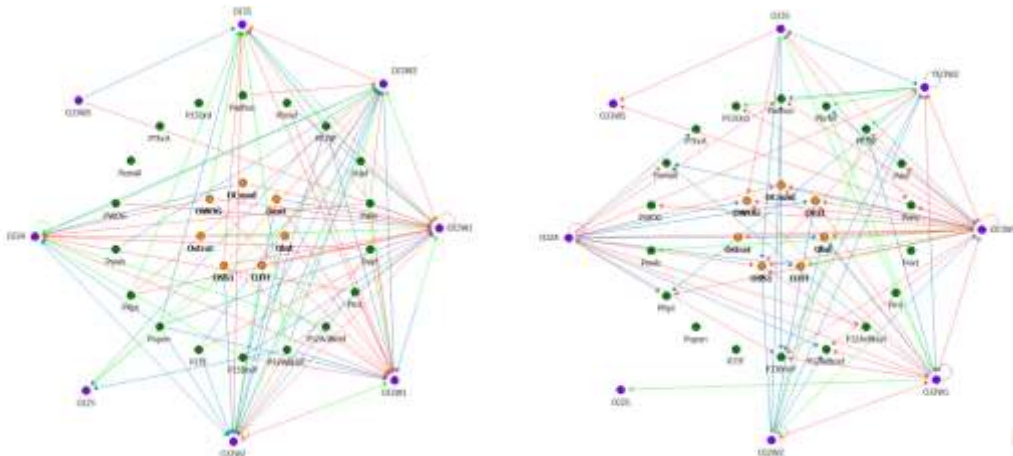
Figure 6 Situation Awareness Weighted Networks for Steady-State activity:
pull (left), push (right). External organisations (orange nodes) are arranged in the centre,
products (green nodes) in the next layer, and sampled organisations (purple nodes) in J2 and J3
in the outer ring. Green links are Perception, Blue links Comprehension and Red links are
Projection. For pull links the point of the arrow is on the node that draws the data in with the
link colour showing the SA attributed to the interaction by the pulling node; for push links the
point of the arrow is on the destination with the colour of the arrow showing the SA attributed to
the interaction by the source.
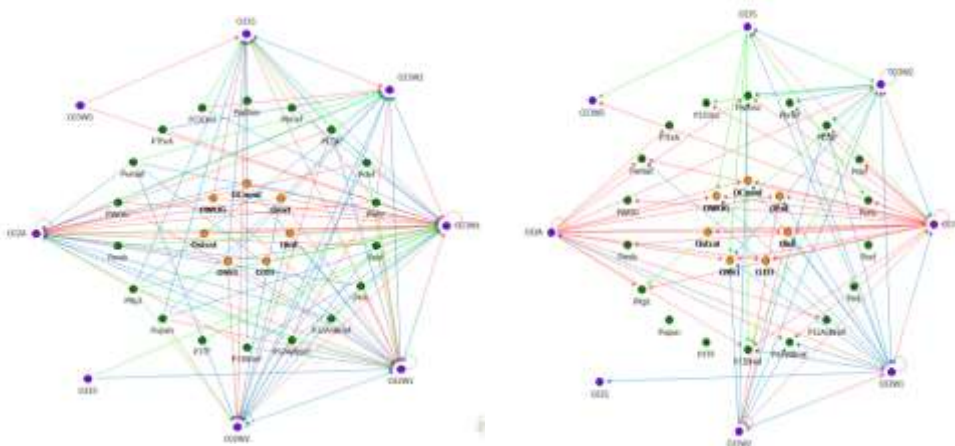
Figure 7 Situation Awareness Weighted Networks for Crisis activity:
pull (left), push (right). External organisations (orange nodes) are arranged in the centre,
products (green nodes) in the next layer, and sampled organisations (purple nodes) in J2 and J3
in the outer ring. Green links are Perception, Blue links Comprehension and Red links are
Projection. For pull links the point of the arrow is on the node that draws the data in with the
link colour showing the SA attributed to the interaction by the pulling node; for push links the
point of the arrow is on the destination with the colour of the arrow showing the SA attributed to
**the interaction by the source.**

We observe a number of features in these diagrams. First, for both steady-state and crisis, there are more links for pull than push: our subject organisations are genuinely *consolidating* information. Second, the pull data is, generally, at low levels of SA and push is at higher levels (there are more green links in the left hand networks and more red links for the right hand networks): thus the subjects, through the consolidation of information, are *value-adding SA*.

These features can be seen alternatively by counting the numbers of links per SA 'sub-level' according to the 13 point scheme in Table 3 and plotting a histogram, as shown in Figure 8. We see there that, for both steady-state and the crisis, the number of links at low levels of SA (green areas) is more for 'pull' than 'push' for levels 1–4, and more for 'push' than 'pull' for levels 12 and 13. Also, the larger number of SA sources for the crisis scenario is evident, particularly at the thresholds for Endsley Levels II and III; for example, at Level II more than 140 links to sources were identified in the data.

In fact there is a significant literature on this type of behaviour. In recent decades, scholars in interpersonal communication have shown interest in understanding information seeking behaviour during crisis or emergency situations. A prominent theory here is 'uncertainty reduction theory' which posits that people engage in intensified information seeking activity to alleviate uncertainty when they are under threat or facing a crisis, perceived or actual [Berger & Calabrese 1975, Afifi & Weiner 2002]. Overall, the research indicates that in conditions of high uncertainty and task complexity people seek more information from different sources for decision making than for routine tasks and they show preference for verbal as opposed to written media [de Alwis et al. 2006]. Our data is consistent with this research as during the scenario, the participants reported far greater need for products and interpersonal interactions.

We also observe in the networks that higher ranked staff (OJ3W1, OJ2W1) generate higher levels of SA than lower ranks, and in turn this high level is provided to commanding officers (OCmnd). This is consistent with the organisational design of these units, which work to a standard military hierarchy. However, we also observe team behaviour seen in the self-loops in both Figure 6 and Figure 7, where SA is passed between individuals in the same role through a shift handover or within teams.

The networks also expose differing, even conflicting, perspectives on the SA value that individuals or products provide. For example, in the steady-state pull data (Figure 6, left) we observe that the links between OJ2W1 and OJ2W2, and OJ2W1 and OJ3W1, each change colour. The colour attached to the arrowhead indicates the level of SA that the node at the point of the arrow (for 'pull' data) receives from the adjacent node. Thus OJ2W1 receives Perception from their subordinate OJ2W2 (the green arrowhead), and OJ2W2 receives Projection (red) from their superior officers OJ2W1, a reasonable state of affairs. Contrastingly, OJ3W1 receive Perception from OJ2W1 while the latter receives Comprehension from the former. However, looking at the out/push data for steady-state (Figure 6, right) we see clear red arrows between OJ2W1 to OJ3W1: both believe they have pushed Projection levels to the other. Observe in the crisis scenario (Figure 7, left) that this is quite different: OJ3W1 *expects* to receive Projection from OJ2W1, while the latter only expects Comprehension from the former. Thus the SAWN representations enable a focus on possibly conflicting perspectives with the scope for enhancing these relationships through exercises and experimentation.
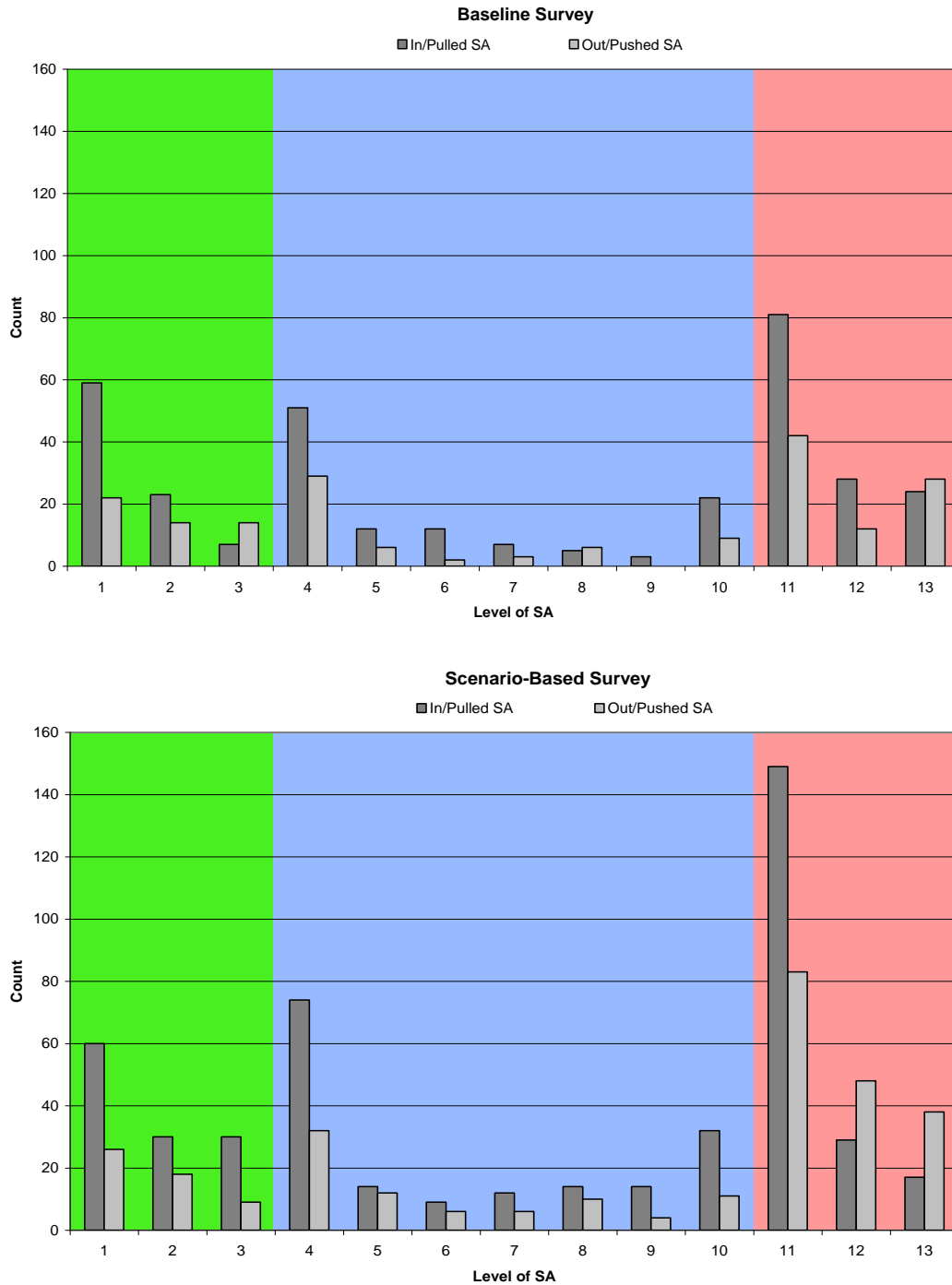
Figure 8 Histograms of numbers of links per SA level for steady state (top, 'baseline') and crisis conditions (bottom, 'scenario-based'). In (dark grey bars) and Out (light grey) links are distinguished. Also the backgrounds are coloured according to the three-level SA model: green=perception, blue=comprehension, red=projection.

Quantitative Analysis of SA flow. The application of weighted bipartite networks now permits the use of novel metrics to assess the flow of SA. We describe two of these here, the notions of *nestedness* and SA *gradients*, and give a numerical example of the latter.

Nestedness arises in environmental modelling to analyse the inter-dependence of species communities, for example plants and animals, in an ecosystem [Almeida-Neto et al. 2008],

and is the degree to which poorly interacting species couple with highly interacting species. Representing the bipartite network as a matrix of ones and zeroes, a nested species network would take the form shown in Figure 9, with many filled cells in the top left corner and many empty cells in the bottom right.
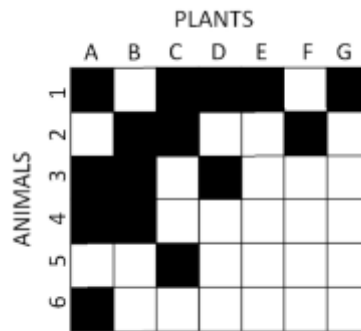
Figure 9 Example of a highly nested plant-animal species network: a black cell means there is an interaction between an animal and a plant.

Thus, in a nested network there will be found a core of high degree nodes interacting with each other but also with a set of low degree nodes (the latter therefore do not interact with each other). Mathematically this is formalised in the 'Nestedness metric based on Overlap and Decreasing Fill' (NDOF). This metric has recently been generalised to weighted networks [Almeida-Neto & Ulrich 2011], but still relies heavily on a strong contrast between degrees in the bipartite graph as a signal of nestedness.

In fact our SAWN data, if we focus on the pure bipartite aspects of organisation to product interactions, does not exhibit strong nestedness: though clearly team leaders such as OJ3W1 and OJ2W1 are more connected than others (reflecting the hierarchy) there are no subject 'organisational' nodes that lack connections to products. This potentially reflects a degree of self-synchronising behaviour within the set of J2 and J3 staff sampled; everyone plays a role in seeking, analysing and generating information. If we had extended the sample to higher ranks (those in the OCmnd node), things might look otherwise where many senior ranking officers may rely entirely on a verbal brief from their subordinates. Thus, we hypothesise that SA weighted networks with high nestedness will reflect strongly hierarchical behaviour.

The SA gradient measure builds on paths and reachability in SNA [Wassermann and Faust 1994]. First we can identify nodes pulling the lowest levels of SA and those pushing the highest levels of SA. We then identify paths between them, either solely through other organisational nodes or via product nodes. Insights may be gained by considering both shortest, average and longest path lengths. Then a gradient for the path may be defined:

$$\Delta S = \frac{1}{N_a} \sum_{a \sim path} \frac{\left(w_{ii_a}^{(push)} + w_{ii_a}^{(pull)} \right)}{2}.$$

Here we average over both pull and push weights for the N_a nodes a along the path.

Arguably, in a crisis the shortest paths are critical. So in our SAWN data, this quantity is straightforward at the level of fidelity of Figure 7. The OJ2W2 node pulls data at the lowest level of SA (Perception) in the crisis scenario, with a flow through the OJ2W1 node and then to the critical OJ3W1 node which pushes at the highest level, Projection. This results in this simple case in a gradient of

$$\Delta S = 1.75$$

In both cases here, because the number of our subjects in the study is relatively small (especially after aggregation) and their relationships are already close, the quantitative analysis of the network data is simple. But in larger, more distributed organisations where agility may be a greater challenge, such quantitative measures will be valuable.

8. Conclusions and Future Work

We have unified two leading models of Situation Awareness and integrated the resulting network view of distributed adding of value into a coherent data collection methodology. We used aggregated data collected in a study in the Australian Defence Force to populate the model. The resulting representations show behaviour consistent with the hierarchical C2 arrangements of our test subjects and the literature on how managers engage in increased information seeking in situations of high uncertainty, and reveals where team work is active. In this specific application, the method has identified the difference between how a COP is maintained under steady-state conditions and how personnel expect it should be maintained in a crisis. In particular, the nascent C2 relationship between OJ3W1 and OJ2W1 was recognised to be critical: each belong formally to different Branches but mutually depend on each other for sources and fusion of SA. On this point, the study recommended routine exercises across these organisations to enhance the existing informal relationship and facilitate an emergent process for the dissemination of SA across the two entities.

In more general terms, this method may confirm that existing arrangements are functioning, or reflect possible missing links or process steps; such 'gaps' can further be measured in terms of graph theoretic metrics, such as those discussed in this paper. SAWN diagrams can also expose both conflicting perceptions about the value of particular organisational roles or information artefacts, and flows and progressive value-add of Situation Awareness through organisations. Ultimately, comparing against normative models, the representations can identify whether the flows and build-up of SA enable agility.

A challenge for the future is to streamline the means of administering the underlying questionnaire of the methodology. In this application steady state data was acquired by an electronically administered MS Excel forms survey and crisis response data by interview (with an analyst populating the survey form). In the first case, respondents found the survey challenging because of subtle differences between questions reflecting incremental progression through Endsley's SA model. Also navigating long lists of products and organisations was found to be frustrating. This was despite breaking up the form into logically discrete parts, and a range of 'smarts' in the survey form designed to provide explanatory information. These challenges were overcome in the interview, with the analyst explaining any subtleties and guiding the eye of the interviewee across the lists (colour coded according to the nature and source of organisations and information artefacts). However, for more senior officers, whose roles require accessing multiple organisations and sources, this led to long interviews – up to 90 minutes in some cases. Though this is less than the two hours cited for CDM, it was still a challenge for staff dealing with ongoing real operations.

The model and methodology can be extended in a number of ways. To the extent that the Endsley levels may be seen as a decomposition of Boyd's 'Orient' stage of the OODA loop, the methodology may be applied across the entire spectrum of activities in Endsley's model (including Decision and Performance of Actions) to give a fully distributed network representation of her model. Such a representation would then be applicable across all aspects of a C2 organisation.

In the case discussed in this paper we applied the model to an in vivo organisation in real operational circumstances for steady state, and a hypothetical scenario for the heightened state. This means that in no case did the analysts involved in the study have access to 'ground truth' by which the Situation Awareness generated by the subjects could be 'validated'. This is not a flaw of the model as such but the nature of the application (itself a consequence of the problem we were invited to address). The same limitation applies to self-rating techniques such as SART. But SAWN, in integrating different perspectives on the same information product, allows for some degree of testing or triangulating the subjective judgements of operators. SAWN is also applicable to simulated environments such as human-in-the-loop

experiments or command post exercises. In that context, where analysts do have access to 'ground truth', a more thorough validation of the awareness reported by an operator can be achieved. Furthermore, in keeping with the DSA and WEST methodology, SAWN can be applied post-event as well as in steady-state and hypothetical scenario situations. SAWN can be applied to non-military environments, such as emergency management organisations, which frequently step between steady state and crisis events; this provides further contexts for method validation.

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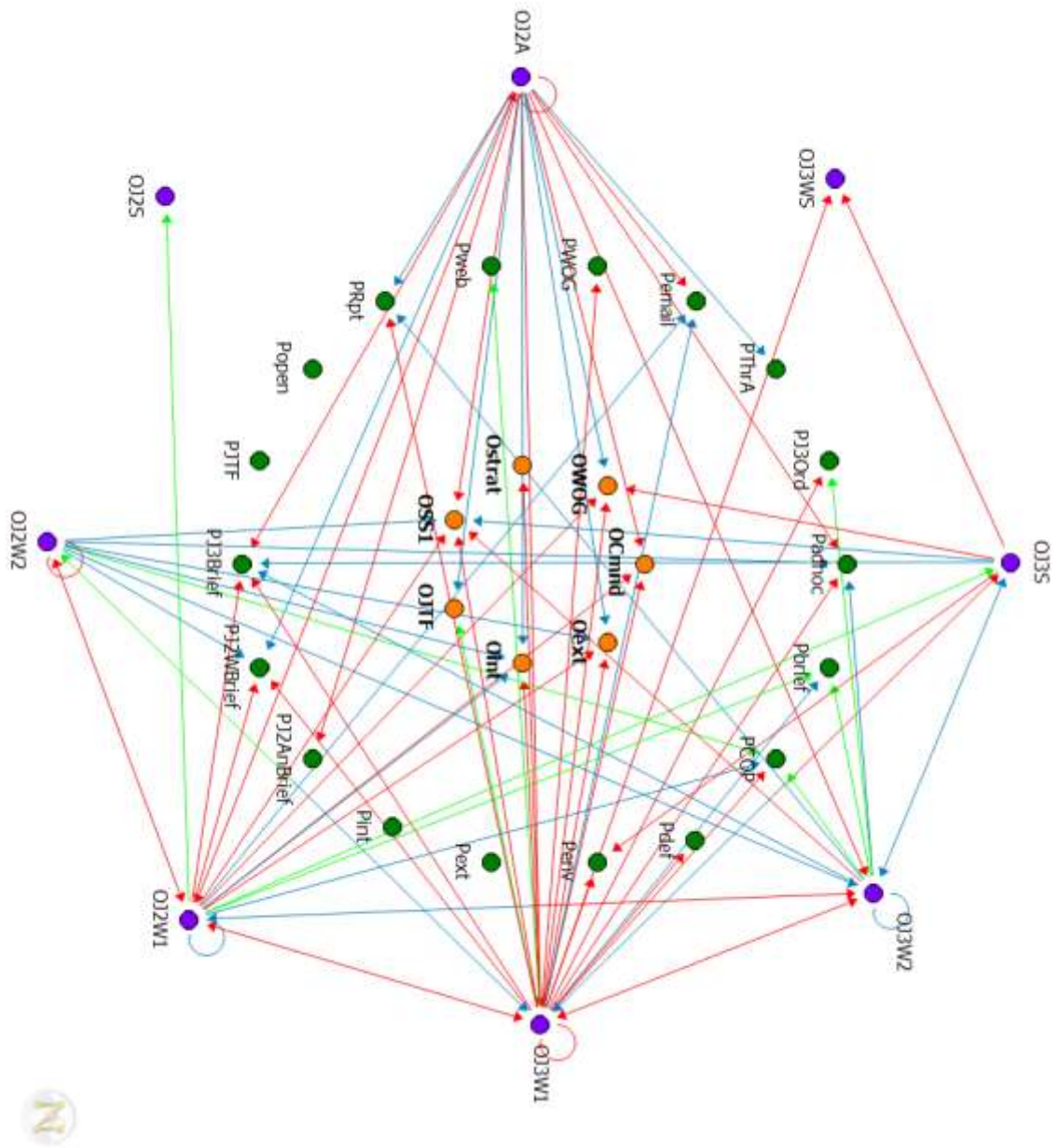Wasserman, S., Faust, K., *Social Network Analysis: Methods and Applications,* Cambridge University Press, U.K., 1994.

Appendix: Expanded SAWN diagrams
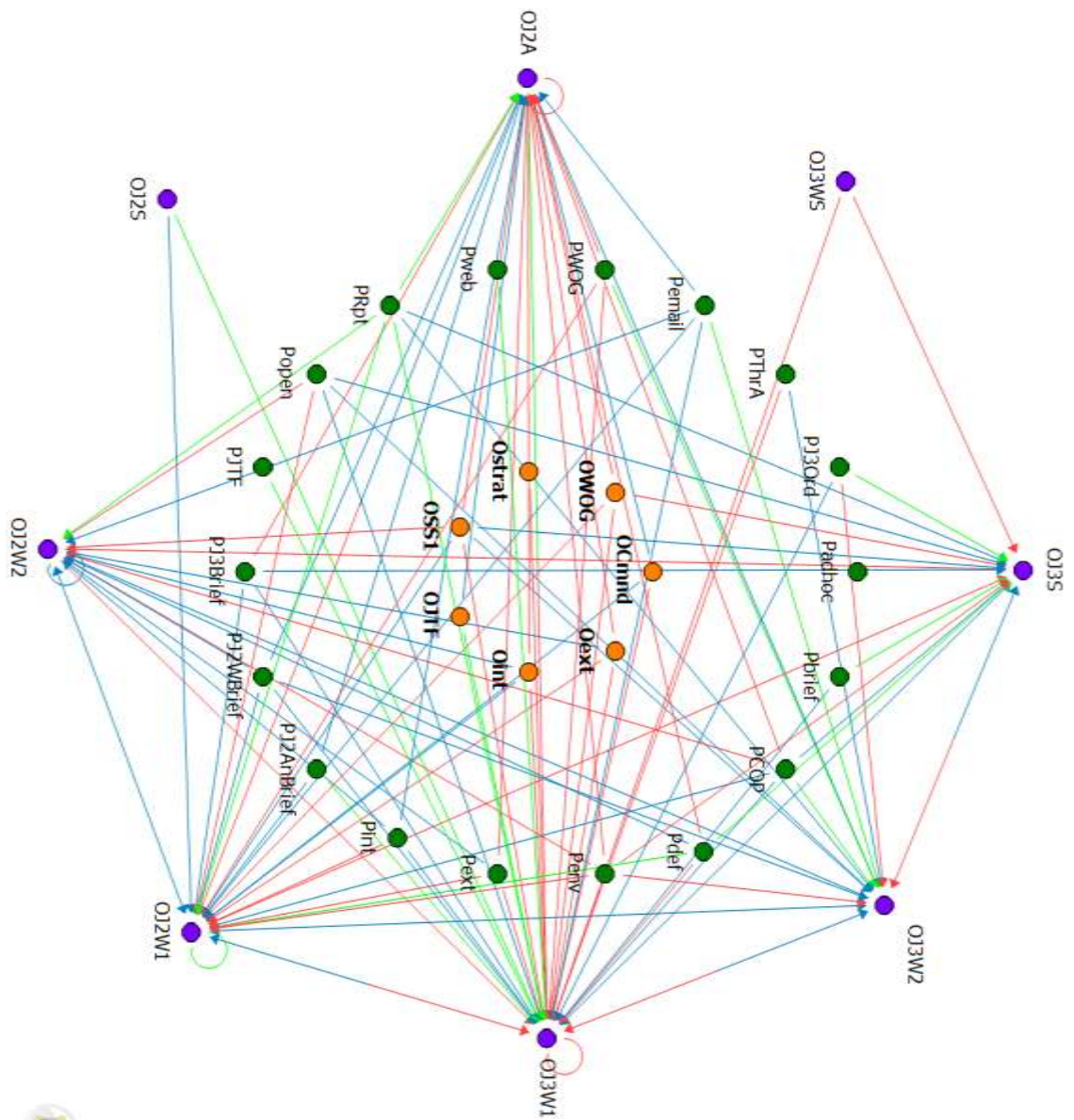

Figure 10 SAWN Steady-state pull

Figure 11 SAWN Steady-state push

Figure 12 SAWN Scenario pull

Figure 13 SAWN Scenario push