2013

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2013 46th Hawaii International Conference on System Sciences
http://hdl.handle.net/10945/41122

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A Conceptual Model for Network Decision Support Systems

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Abstract

We introduce the concept of a network DSS (NWDSS) consisting of fluid, heterogeneous nodes of human and machine agents, connected by wireless technology, which may enter and leave the network at unpredictable times, yet must also cooperate in decision-making activities. We describe distinguishing properties of the NWDSS and propose a 3-tier conceptual model comprised of digital infrastructure, transactive memory systems and emergent collaborative decision-making. We suggest a decision loop of Sense-Analyze-Adapt-Memory leveraging TMS as a starting point for addressing the agile collaborative requirements of emergent decision-making. Several examples of innovative NWDSS services are presented from Naval Postgraduate School field experiments.

1. Introduction

The confluence of maturing wireless network technology, smart handheld devices, and unmanned sensors has transformed the information ecosystem landscape every bit as much as the Internet did two decades ago. The network has clearly become the dominant paradigm in all information systems domains and the unparalleled degree of connectionism which it enables has radically altered how individuals, businesses, governments, and societies operate and communicate. With the proliferation of unmanned systems (USs) gaining public visibility for peacetime as well as military applications, the influence and capabilities of networks will be extended even further, although perhaps not always in ways that seem desirable.

We have found that smart mobile systems, in conjunction with other sensors, particularly unmanned vehicles, which are deployed in support of organizational decision-making objectives lead to a new, highly dynamic and complex form of DSS which we term *network-DSS* or *NWDSS* [17]. An NWDSS is characterized by heterogeneous nodes of human and machine agents, connected by wireless technology, which may enter and leave the network at unpredictable times, yet must also cooperate in decision-making activities. The NWDSS comprises a hybrid of technological, social, and information networks which de facto, decentralize decision-making, pushing it to the "edge" of the organization [1] and, in the process, strongly emphasizing collaborative decision-making and knowledge flow.

Our objectives in this presentation are to introduce the NWDSS as a new type of IS by enumerating the essential properties of an NWDSS and to present a conceptual model for framing this new class of information system. The conceptual model is large in scope embracing a triad of *digital infrastructure* as the context for analyzing the technological network dimension, *transactive memory systems* for capturing the organizational knowledge of the social network dimension, and *emergent decision-making* as the process for agile collaboration within the social and technological integration. Examples from the Naval Postgraduate School's Tactical Network Testbed and Maritime Interdiction Operations (TNT/MIO) projects will be highlighted to illustrate the model.

2. NWDSS: Next Step in DSS Evolution

The trajectory of DSS over the past three decades has delivered us into a radically different era from when the DSS movement began as Table 1 shows at a high level. Systems consisting of one or more networks of wireless mobile "smart phones" constitute a dramatic departure from our conventional view of information systems, especially when we consider the challenges of designing, developing and controlling such systems. The presence of non-human agents in a network, e.g., unmanned vehicles adds an extra dimension of complexity with regard to collaborative activities. Add to this volatile mix the requirement for agile, near real time decision-making and it becomes clear that the old concepts and principles for thinking about decision support no longer abide.

We need a new framework for our discipline that addresses the highly dynamic and complex phenomena that earmark contemporary connectionist decision-making environments. We propose a new

1530-1605 2012

DOI 10.1109/HICSS.2013.32

category of DSS, network DSS (NWDSS), based upon the network-centric digital infrastructure which is rapidly emerging from developments in the areas of sensor technology, social media, mobile networks, "smart" phones, collaborative decision making, knowledge management, and computational modeling and experimentation.

a. Properties of NWDSS

The following discussion pinpoints properties of NWDSS which we claim distinguish it from the more traditional forms of DSS.

- *Fluid networks with heterogeneous nodes.* This is perhaps the defining aspect of NWDSS, namely in the most general case a mobile network with the objective of decision-making and consisting of highly heterogeneous nodes entering and leaving the network in unanticipated fashion. Nodes in an NWDSS may be humans, sensors, and/or software agents. Human nodes may represent individuals as well as different organizations such as military units, law enforcement agencies, firefighters, first responders, non-governmental organizations (NGOs), and various local, state and federal governmental agencies. The human nodes typically include the decision-makers in the network although intelligence in the network in the form of software agents may subsume lower level decisions such as network monitoring and management.

Networks and sub-networks may emerge or dissipate in ad hoc fashion as various nodes join or leave the community so that the structures of the technological, social and information networks are dynamic and unpredictable in the most general case. Instances of a node leaving the network may be a person who turns off his cell phone, a sensor which has become disabled or gone into silent mode, or a node which falls outside the range of the mobile network either because the node or the network moved. The semantics of missing nodes and associated node continuity and network stability is a challenging research objective of NWDSS.

- *Sensor-rich.* NWDSS in the most general context may contain non-human and human agents acting as sensors. The proliferation and miniaturization of non-human sensors is a major driver in the emergence of NWDSS, particularly in the arena of emergency response, homeland defense and military tactical operations. For example, unmanned vehicles (air, ground and sea) play a pivotal role in search and rescue, border patrol, and threat detection operations. As sensors become smaller and smaller, their scale covers several orders of magnitude from satellites to the level of nano-sensors embedded in human agents. The rapid evolution of smart mobile technology accelerates the sensor-based nature of NWDSS since mobile users themselves can act as sensors with the means to transmit and receive rich information in many different modes in very near real time.
- *Simultaneous man-machine, machine-machine and man-man interactions.* The presence of unmanned system-based sensors in the network extends significantly the requirements of collaborative activity beyond just human to human interaction. Traditional DSS focused primarily upon human-computer interactions (HCI) whereas NWDSS environments may include an array of sensors in addition to computers which complicate the man-machine interfaces. Man-to-sensor communication is critical, for example, when there are unmanned vehicles which must be guided to useful locations. Sensor-to-man communication is necessary when an autonomous sensor detects an event of interest. Sensor-to-sensor communication may be required to coordinate an unmanned aerial vehicle, for example, with a ground based camera as in border patrol applications. Human-to-human interaction can occur at many levels, for example two individuals communicating by mobile phones, teams negotiating or sharing knowledge across the network, or soldiers in the field relaying information back to the base. All interactions are critical in generating and sustaining *situational awareness* of the environment in which the NWDSS is operating.
- *Open, emergent, generative, self-organizing system.* NWDSS environments are open in that anyone from the set of eligible players can participate, or not, as s/he chooses. Examples of open systems include open source projects such as the Linux operating system and Wikipedia, open science collaborations such as the Polymath Project and the Galaxy Zoo [20], the Arab Spring twitter network, virtual worlds such as Second Life, and crowd sourcing [13]. These systems emerge as people learn about their existence and decide to participate, and these systems are also self-organizing as more and more people join and a need arises to organize the growing amount of knowledge that is being contributed.

Emergent systems are also generative in that system behavior and complexity in this context are seen to be generated from a simple set of rules applied to a universe of agents. Networks themselves are generative in nature, demonstrating clear patterns of power law driven, "bursty" behavior [4], underpinning our understanding of complexity [3]. The NWDSS, being network-centric in nature, embody all of the characteristics described herein. Not all of the above are "pure" NWDSS examples since all except the Arab Spring twitter case do not necessarily depend upon mobile networks and not all of them have decision-making as a central objective.

For example, the open source and open science efforts seem to be more about problem-solving rather than decision-making. However, the Civil-Military information sharing model for emerging network-centric Command and Control (C2) [8] represents an interesting example in which crowd sourced information, disseminated through a filtering network, produces a new risk management model.

- *Knowledge mesh and emergent knowledge processes.* NWDSS environments involve many different players and agents who form a virtual team for the purpose of achieving a set of objectives (e.g., containing a fire, monitoring and interdicting narcotics traffic, search and rescue). The knowledge contained within this cross-organizational coalition network is a critical parameter in the efficacy and effectiveness of the decision-making required to achieve the group objectives. In knowledge management terms, each network can be thought of as a *knowledge mesh,* embodying in principle the collective knowledge base of each node, coupled with *emergent knowledge processes (EKP)* which continually act upon the knowledge mesh by enhancing or otherwise modifying knowledge flow between the knowledge bases.

EKP systems are characterized by a changeable cast of users whose work profiles cannot be identified a priori, emergent work processes that result in fuzzy initial requirements that only become crisp through a succession of functional prototypes and a strong emphasis on knowledge flow across an organization [19]. One of the key knowledge flow processes in NWDSS is that of *expert reach back*, wherein decision-makers may need access to a specific knowledge base (whether human or artificial) as part of their decision-making process. For example, in a maritime interdiction operation, a ship boarding team may require, in real time, confirmation from a nuclear expert (human node in the network) about whether a discovered device onboard (perhaps a centrifuge) is intended for use in a weapon. In a similar vein, biometric data gathered in the same operation may be matched against existing databases (artificial agents in the network) to identify individuals who are potential threats. We suggest that this aspect of expert reach back argues for a transactive memory system approach to organizational knowledge which we discuss in more detail as part of our conceptual model.

- *Agile, collaborative decision-making "at the edge".* NWDSS environments such as emergency response and tactical battlefield operations embody a pronounced shift towards unstructured decision-making situations. These tend to be chaotic, unscripted, and fraught with high risk and severe time pressures in which decision-making must frequently be done with highly imperfect information and without a clear delineation of the available alternatives, the possible outcomes, or the probabilities attached to each. Furthermore, the norm typically involves many decision-makers from disparate organizational agencies who must collaborate and coordinate on series of interrelated decisions. Another important ramification of operating in such environments is that organizations become more flattened and decision-making gets pushed to the "edge", i.e. to the agents closest to the actions. These stringent NWDSS requirements demand agile collaborative decision-making models [2] which we address in our conceptual model.

- *Computational modeling and experimentation.* The study of emergent and generative systems of which NWDSS is an example leverages computational modeling and experimentation in the form of agent-based modeling and simulation (ABMS) combined with social network analysis as primary vehicles of analysis [10, 27].

- *DSS-based service ecosystem.* Figure 1 shows a schematic of man-machine interactions based upon an NWDSS-service cloud as the intermediary between the human/social and machine/technological sub-networks. The notion of DSS-based services is an essential part of the network infrastructure, particularly when taking into the account the social media dimension as well as the pronounced move towards cloud computing which dominates so much of the mobile services narrative in contemporary IT. Embedding decision support services within the network at both the technical and social levels is a critical design issue.

We claim the properties enumerated above comprise, a representative, if not exhaustive, depiction of NWDSS environments. We present an example of a tactical NWDSS to illustrate these concepts more fully.

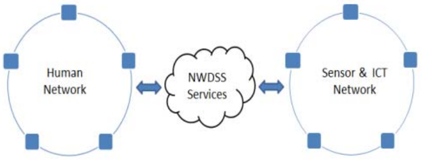

Figure 1. Man-Machine Interaction in Service-based NWDSS

b. NWDSS Example: Maritime Interdiction Operation (MIO)

Our recognition of network-driven decision support environments has grown from the extensive field experiments in mobile networks conducted by the Naval Postgraduate School over the past decade as part of the Tactical Network Test bed (TNT) [6] and associated Maritime Interdiction Operations (MIO) experiments. These experiments began primarily as discovery and constraints analysis field experimentation trials, designed to test and evaluate mobile networks but have steadily expanded to include a widely diverse set of users, sensors and decision technologies deployed to support tactical decision-making in operations such as search and rescue, target identification, and maritime interdiction. As an exemplar of NWDSS, Figure 2 shows a wireless network for MIO inspecting ships entering a pre-defined zone for possible terrorist materials.

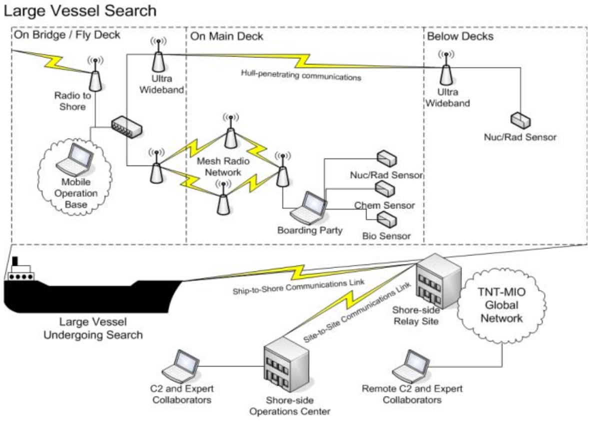

Figure 2. MIO wireless network for large cargo vessel search.

Based upon the MIO experimentation background, the distinguishing NWDSS properties could be illustrated as follows:

- *Fluid, heterogeneous nodes and sensor-rich*. The network consists of several sensor nodes for radiation, chemical and biological detection, as well as human nodes representing the boarding party, the shore-side operations center, and various expert collaborators (e.g., biometrics and nuclear identification) distributed across the country or world. (Note that the boarding party acts as a sensor as well in this scenario.) Some experiments have employed unmanned sea vehicles (USV) with sensors to alert the boarding parties of "ships of interest" and thus refine their search space. As the boarding party navigates within or beyond the zone, they may fall outside the network range and thus leave the network temporarily. Similarly, any of the collaborators may not be "on-line" or available at any particular moment in time, thus the network is fluid.
- *Simultaneous man-machine, machine-machine and man-man interactions*. Man-machine interactions occur in guiding the path of the USV and interpreting the various sensor readings. Machine-machine interactions occur between the network and the USV and the network and the nuc/rad/bio/chem detectors. Man-man interactions occur in many instances, for example, between the boarding party and the operations center, and the boarding party and the expert collaborators.
- *Open, emergent, generative, self-organizing system.* The mobile network is an adaptive network. New players can enter the system as needed, for example, a biometrics node could be added dynamically to help identify personnel aboard a "ship of interest".
- *Knowledge mesh and emergent knowledge processes.* The MIO tacit-to-explicit knowledge flow model highlights the unique team learning process, which takes place between boarding officers, remote experts, and watch officers at the supporting command centers, based on network-enabled association of individual knowledge flows. For example, expert reach back is required when a boarding party discovers a possible nuclear/biological/chemical device on board a ship and relays photographs to the appropriate expert collaborators. The members of MIO edge-type short life time (1-2 days) virtual organization of committees and teams learn from each other using instantaneous conferencing, messaging, and shared visual association of individual knowledge models.
- *Agile, collaborative decision-making "at the edge".* The boarding party is the "edge" in this example which works with other nodes in the network to determine through collaborative decision-making whether to release or commandeer the ship. Collaboration is supported via the Groove™ system which is preconfigured prior to each experiment.
- *Computational modeling and experimentation.* There has not yet been sufficient time or funding available for building simulation models of exercises, however an agent-based simulation game could serve as a planning tool for the next exercise, and data gathered from each exercise could in turn be used to refine the simulation. Incorporating stakeholders and decision-makers into a participatory game-playing modeling process could significantly increase knowledge flow and organizational learning.

3. Conceptual Model for NWDSS

Decision support can be thought of in high level terms as the intersection of organizations and information technology for purposes of decision-making. From the network-centric purview, both the organizational and technological dimensions rely upon networks: primarily social networks in the former and communications networks in the latter. We expand upon this simple model to propose a conceptual framework for NWDSS as shown in

Figure 3. We employ three major overarching conceptual components in this model to capture the complexity and dynamics of NWDSS environments: digital infrastructure, transactive memory, and emergent collaborative decision-making.

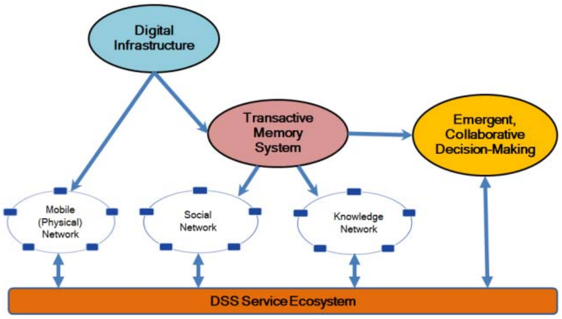

Figure 3. Conceptual Framework for Network DSS

a. Digital infrastructure

During the 1990's, the IS community began to shift its focus from systems to infrastructures and from organizations to networks. Motivation for this transition came from the confluence of several trends: the acceptance of emergent systems and networks as the basis of complexity, the increasing socio-technical nature of information technology, the success of open system experiments such as Wikipedia and Linux, and dissatisfaction with traditional system design methodologies in accommodating generative and emergent systems. The Internet linked the world, making people network-centric and network-aware in the process, and shifting the locus of information systems from organizations to societies, from local to global, and from applications to networked ecosystems. NWDSS are decision-oriented products of these transformations and so we choose to embed the technological dimension of NWDSS in the paradigm of *digital infrastructure*:

> "*digital infrastructures* can be defined as shared, unbounded, heterogeneous, open, and evolving sociotechnical systems comprising an installed base of diverse information technology capabilities and their user, operations, and design communities." [11].

These definitions and characterizations of digital infrastructure align well with the elements of NWDSS we enumerated in Section 2a. NWDSS are highly heterogeneous shared environments that combine social and technological networks as we have described. The emergent knowledge processes which characterize NWDSS prevent the a priori specification of requirements, functions, and applications satisfying those requirements. Rather these evolve as the system emerges. NWDSS are open and unbounded in this sense as well which we see in the use of wireless mobile networks and smart phones in social media settings.

Although *digital infrastructure* is a term which has been frequently used for a couple of decades, Tilson et al [26] argue that it constitutes a fruitful area of research which has largely been ignored by the IS research community. They present a research agenda predicated upon the duality of control and change within digital infrastructures, a topic of high importance in NWDSS as well. In keeping with our contention that NWDSS constitutes a new form of DSS, we have adopted digital infrastructure as a conceptual superset which parallels this evolution:

> " digital infrastructures herald a new stage in the evolution of IT, reflecting the fact that IT has become deeply socially embedded, is coordinated through diverse sociotechnical worlds and numerous standards, and is most visible during breakdowns." [25].

b. Transactive memory systems

Whereas we use digital infrastructure to capture primarily the technological aspects of NWDSS, we now turn our attention to the social network segment which we envision as being effectively a knowledge infrastructure within the digital infrastructure. There are two dimensions of knowledge in NWDSS: the social or organizational memory as exemplified in expert reach back, and the technological ICT-based knowledge bases such as the biometric databases in the MIO network. We propose the *transactive memory system (TMS)* as a unifying mechanism for characterizing network knowledge. TMS is defined as "a system through which groups collectively encode, store, and retrieve knowledge" [28].

TMS as a basis for network knowledge is, of course, not a new idea, having been introduced explicitly in this form by [29] who specified a structural component of TMS reflecting how individual memories link to a collective network, as well as three elemental processes associated with TMS: directory updating, information allocation, and retrieval coordination. These correspond informally to knowing who knows what in a group, assigning memory items to specific group members and accessing, or retrieving, knowledge by leveraging who knows what.

NWDSS environments involve many different players and agents who form a virtual team for the purpose of achieving a set of objectives (e.g., containing a fire, monitoring and interdicting narcotics traffic, search and rescue). The knowledge contained within this network is a critical parameter in the efficacy and effectiveness of the decision-making required to achieve the group objectives. How this knowledge is distributed in the network is critical for there will be nodes containing explicit knowledge as well as implicit (tacit) knowledge. Further we have found in our research that knowledge links may be either strong or weak in the social network sense and that this distribution profoundly affects the efficacy of the overall organizational memory.

Transactive memory systems provide a well-established paradigm with nearly three decades of research for thinking about how organizational knowledge is distributed and shared across the network, particularly for the case of ad hoc organizations which underlie so many NWDSS environments. Ren and Argote [23] identify four main research challenges in their comprehensive survey of TMS:

1. Consistency in measuring TMS
2. TMS as a multidimensional construct
3. Organizational-level TMS
4. Computational in conjunction with field experimentation to develop and test theories

The last two issues are particularly germane to our work with TNT/MIO. TMS research has typically focused more on teams rather than organizations; the ad hoc cross-organizational nature of the TNT/MIO NWDSS provides a fertile test bed for extending the organizational dimension of this research. The complementarity of field and computational experimentation in the form of participatory modeling is a prime property of NWDSS research. The TNT/MIO has already provided a rich harvest of field experimentation which needs to be augmented by simulation modeling.

TMS in concert with digital infrastructure offers a rich conceptual framework which integrates the social and technological dimensions of NWDSS. What remains to be discussed is the decision-making processes which must be supported by this confluence of social and technical domains.

c. Emergent, collaborative decision-making

The decision-making models typically referenced in the DSS literature are too limited to apply in full to NWDSS environments. Many of the earlier models such as Simon's Intelligence/Design/Choice [24] and Boyd's OODA (Observe / Orient / Decide / Act) loop [22] are focused upon individual decision-making whereas contemporary networked environments are much more likely to be group- or team-centric where there are typically multiple decision-makers requiring significant collaboration, often in near real time circumstances. .

We argue that such models must be based upon a paradigm of emergent decision-making in keeping with the emergent nature of network-based complexity. Collaboration in the context of emergent decision-making is qualitatively different, however, from that which is typically discussed in the DSS literature. DSS-based collaboration research emanated initially from work in group support systems (GSS) which relied strongly upon skilled facilitators to attain effective decision-making outcomes [21]. As thinking evolved beyond the GSS paradigm to more asynchronous modes of collaboration, research in collaborative environments nevertheless adhered to traditional IS design principles with emphases on identifying *a priori* objects and processes (e.g., goals, tasks, roles, products, activities, procedures, etc.) as overarching requirements for collaborative design science.

"A priori" does not work, however, in the emergent climate of NWDSS. Collaboration in firefighting or humanitarian relief assistance is inherently different than collaboration on a software project, for example. In the latter, there is ample time for planning and identifying tasks, roles, activities, deadlines and the like which can be configured into a structured collaboration environment, whereas in emergency response situations, there may be little or no time for pre-planning and the deliberate configuration of resources. NWDSS do not always have a centralized node, or operations center, particularly when emergent networks are involved. Decision-making in NWDSS is therefore pushed out to the "edge" of an organization, i.e. away from centralized command and control and towards the individuals "in the field". This places a much heavier reliance upon *agile* collaborative decision-making which can be thought of as collaborative, or emergent, decision-making under tight time constraints and imperfect information. In other words, collaboration in NWDSS environments is much more likely to be ad hoc than scripted, bottom up rather than top down, and "plan resistant" rather than "plan friendly". A further complicating factor in NWDSS involving unmanned vehicles is that collaboration must now consider man-machine as well as man-man interactions as part of the overall decision-making process.

To address decision-making in such a turbulent networked environment, we suggest a basic decision loop of Sense-Analyze-Adapt-Memory (Figure 4) relevant to tactical networking settings but which we believe is sufficiently generalizable to be applicable to other networked infrastructures. In this model, decision-makers and stakeholders in the Sense phase continuously receive data and information from sensors and humans in the network which is “stored” in Network Memory as part of the Transactive Memory infrastructure. This information is analyzed and integrated during the Analyze phase as part of the sensemaking process into a persistent situational awareness scenario. Sensemaking in this concept transcends Weick’s concept [30] in that it must deal more with ad hoc organizations overlaid upon existing organizations, coalitions, and non-aligned individuals. The Adapt phase is the decision-making part of the process wherein decision-makers decide how to react (if at all) to the situational awareness profile by devising one or more courses of action to be pursued. The timing of this decision loop may be seconds or minutes as in a combat engagement, or days, weeks, or months in a less time-sensitive environments such as a software design project.

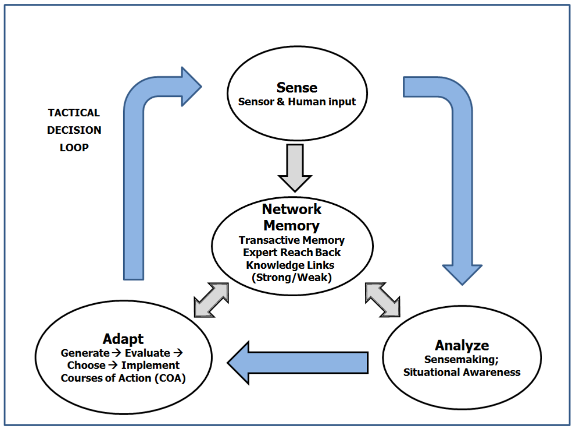

Figure 4. Sense-Analyze-Adapt-Memory decision-making loop

Decision-Making Environment	Associated Activities
Simple	Sense-Categorize-Respond
Complicated	Sense-Analyze-Respond
Complex	Probe-Sense-Respond
Chaotic	Act-Sense-Respond

Table 1. Cynefin Framework of Decision Environments and Associated Actions

The Sense-Adapt-Analyze part of the loop is an adaptation of the Cynefin framework (Table 1) which prescribes different sequences of actions contingent upon the type of decision environment [18]. Although Figure 4 would seem to correspond most closely to Cynefin’s “Complicated” scenario, our notion of “Sense” subsumes “Probe” since sensors such as unmanned vehicles, for example, do exactly that, and our “Adapt” stage is a counterpart of the Cynefin “Respond” activity. Thus, the “Complex” analogy is more appropriate. The key difference in our framework, however, is the Memory component which uses transactive memory structures and processes to addresses the knowledge and social network aspects of the decision-making environment. The Sense-Analyze-Adapt-Memory is likely not only taking place at many different locations and levels within the network, but may also be incorporating other models in the process. Using the battlefield example, soldiers on the ground searching for IEDs operate in a very time-constrained version of the loop wherein experienced soldiers may rely upon something similar to Klein’s case-based decision model [16] as their version of the Adapt process. Decisions at the command and control node(s) may be different, however. Time constraints may not be quite as pressing as on the ground, but the situational awareness will likely be broader and more complex, perhaps requiring coordination of several simultaneous operations. Thus, it would appear that hybrid models of individual and group processes are likely to be present in agile, collaborative decision-making depending upon the location of the decision-maker in the network (edge or center) and the roles they play in the decision process.

The Sense-Analyze-Adapt-Memory loop suggests to us that decision-making in NWDSS is a continuous spiral of emergence and convergence where the Sense-Memory stages represent the emergence of data, information, knowledge and ideas, and Analyze-Adapt represent the convergence of this knowledge into a plan of action. This is reminiscent of the Explicit-Implicit Interaction theory [12] which characterizes creative problem solving in complex and ambiguous situations as an alternating current of implicit and explicit processing that ultimately converges to a “solution”, or decision. Consider as an example the GSS model of brainstorming, ranking, and voting where brainstorming is the emergent process of identifying ideas and options, and ranking the options is the convergent process resulting in an eventual decision. Emergent processes in networks result in the self-organizing, convergent creation of hubs whether in identifying leaders as knowledge organizers and experts in open source and open science projects or recognizing control nodes where enough knowledge has coalesced to accelerate decision-making (e.g., expert reach back).

Research on emergent decision-making is in a nascent stage and presents exciting opportunities. We are optimistic that embedding this research within the context of digital infrastructure and transactive memory systems will prove useful in framing and illuminating the dynamics of agile collaboration.

d. DSS-service ecosystem

One of the defining characteristics of digital infrastructure is the emphasis upon services which are generative in nature responding to emergent requirements. Services in the infrastructure world replace applications in the system world. In NWDSS, services are required at each of the generic network levels in addition to the critical decision-making level. Figure 5 enumerates a partial list of NWDSS services grouped by the infrastructure, transactive memory and emergent decision-making categories. We will focus on just two aspects of this service ecosystem which have been, or are being implemented, in the MIO/TNT NWDSS, namely adaptive network management in the physical network domain and collaboration services in the TMS and DSS services arena.

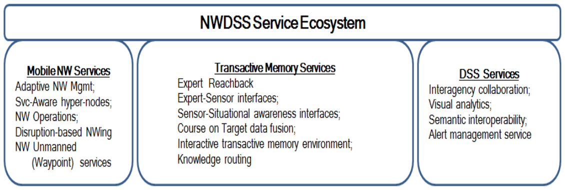

Figure 5. Representative Sample of NWDSS Services

i. *Adaptive network management.* Many NWDSS environments rely upon existing network infrastructure such as the Internet or mobile phone networks which more or less render the physical network transparent. In the case of ad hoc networks such as those required in emergency response or tactical military operations, however, the physical network requires substantial network management support. In mobile "on the move" environments, the physical network operations services must be able to adapt to a variety of fluid situations including nodes changing their physical locations, nodes transmitting in intermittent discrete bursts and rapid allocation of resources "on the fly".

ii. *Self-aware hyper-nodes.* Management of emerging tactical networks under these conditions can hardly be kept centralized. One of our major experimental findings [5] is that autonomous and human nodes of a tactical network must be well aware of each other's information processing states and services. One approach we are currently experimenting with is the introduction of *self-aware hyper-nodes* into the network. This novel self-organizing data network operation architecture has the potential to maintain application service continuity across the nodes that generate and receive data over disjoint moments of time in different locations that are not initially connected. Such an architecture would be based on 8th layer enabled hyper-nodes [7], which contain minimal elements of the network operation center functionality and are capable of negotiating video, text, and sensor data services with their neighbors.

iii. *Disruption-tolerant networking* Nodes may be intermittent in an NWDSS with communications unfolding through highly discrete moments of time. For example, a sensor node may turn itself off to avoid detection by an adversary and choose to transmit intermittently in burst mode only when there is an event of interest to report A new approach called *disruption-tolerant networking (DTN)* for self-organizing tactical networking with sensors, unmanned systems, and operators on-the-move, would obviate the need for maintaining continuous wireless time and space communication. The DTN approach would require delivering a significant amount of time-sensitive tactical situational awareness information through largely disjoint moments of time, by means of human or machine nodes rapidly changing their 3D location across significant distances. This would additionally take full benefit of integrating social networking into the cooperative process of sensor networking in the battlefield, thus enhancing the wireless service delivery network via new unconventional interfaces between mobile operators and networking devices.

iv. *Managing Sensor-Expert services.* With networks containing manned and unmanned vehicles, a formidable challenge arises with respect to the rapid allocation of network resources on-the-move. Specifically, a tactical level commander who wishes to launch an UAV needs to address in a matter of several minutes multiple tradeoffs between soft and hard constraints on the UAV selection, manned aircraft weapons, dismounted unit response, and networking capabilities. Executing such services on-the-move requires new robust multiple criteria computational models to be executed by a geographically distributed cloud of ad hoc mobile tactical handheld devices.

v. *Collaborative services: Transactive memory collaboration engineering.* Currently under development for the MIO/TNT exercise is an Integrated Detection Transactive Memory environment capable of leveraging remote experts' cognitive abilities in order to detect inconsistencies in multiple threat adjudication, rather than relying solely upon computational data filtering tools. This system is based upon the Electronic Virtual Transactive Memory (EVTM) which in turn evolved from an earlier EWall prototype developed for the Office of Naval Research [15]. and is being adapted by the

NPS team for tactical ground and maritime interdiction services. Features include

- a Workspace View which can self-synchronize with dynamic information sources and display interactive content, for example, a geographic map that provides real time updates about the current location of field operatives.
- a News View which displays data streams from different sources in a subject-time matrix. Objects can be copied from the News View to the Workspace View. Superimposed on the News View are feeds coming from cargo search active detection sensor, biometrics identification, and command center alerts.

In respect to the research design for testing the NWDSS elements, the MIO experiments, described in section 2.b, represent a good foundation. The other representative NWDSS testing scenarios could include decision support for manned-unmanned teaming in countering IED threats [6], monitoring flash crowds in urban environments, and casualty and logistics support in disaster relief operations. In such operational scenarios, an ability to track threat transfer collectively, the feasibility of rapidly identifying a threat's nature by means of real-time team working with the remote experts, as well as capability to maintain knowledge flow enabling ubiquitous situational awareness, by collectively deploying human and unmanned nodes, constitute critical research design tasks for testing the NWDSS capabilities (Table 2).

Experimental tasks: design variables and constraints	Properties of NWDSS
Tasks: -Tagging and Tracking, geo spatial monitoring of threat transfer, common operational picture tracking *Variables and constraints: delays, order of appearance)* -Collaboration between surveillance units and operations centers *Variables and constraints: dialog properties, type of data exchanged, frequency of messaging*	Fluid, heterogeneous nodes Sensor-rich environment Agile, collaborative decision-making "at the edge".
Tasks: Detection and Identification, network-controlled choke point and stand-off detection at high-speed pursuit *Variables and constraints: distances, spectra computing time, adaptive distance control, pattern matching*	*Simultaneous man-machine, and man-man interactions* *Open, self-organizing system*
Tasks: Expert reachback and cooperative mission control: Cooperative mission control between regional-global experts and sensor operators *Variables and constraints: multimedia data flows, computational delays, collective pattern recognition and graph analysis)*	*Semantic interoperability for situational awareness* *Computational modeling* *Knowledge mesh and knowledge processes.*

Table 2. Examples of research design for testing the NWDSS

4. Summary and Conclusions

We have introduced the concept of a network DSS consisting of fluid, heterogeneous nodes of human and machine agents, connected by wireless technology, which may enter and leave the network at unpredictable times, yet must also cooperate in decision-making activities. We have proposed a tripartite conceptual model of NWDSS invoking digital infrastructure to characterize the physical network dimension, transactive memory systems for the social and knowledge network components, and emergent decision-making processes for the collaborative dimension. Table 3 summarizes the properties differentiating NWDSS from traditional DSS, while identifying the elements of our conceptual model which apply in each case. We believe this supports our argument that NWDSS constitutes a new type of DSS based upon emergent principles rather than traditional information systems analysis and design.

NWDSS Property	Contrast with Traditional DSS	Conceptual Model Dimension
Fluid, heterogeneous nodes	Players fixed and homogeneous; often only single decision-maker involved	Digital infrastructure
Sensor-rich	Primarily human-centric; no smart mobile systems	Digital infrastructure
Man-machine, machine-machine, man-man comms	Primarily man-computer interface; limited network focus	Digital infrastructure
Open, generative, emergent, self-organizing system	Closed, hierarchical, systems analysis-driven; not network-centric	Digital infrastructure
Knowledge mesh and emergent knowledge processes	Brittle expert systems; crisp a priori requirements; individual vs. collective cognitive support	Transactive memory systems
Agile collaborative decision-making "at the edge"	Centralized decision-making; predefined "point" decisions; Collaborative decision-making works from pre-defined scripts rather than ad hoc	Emergent decision-making

Computational modeling and experimentation	Emphasis on structure vs. process models; limited field testing of DSS artifacts in supporting decision-making and learning	Emergent decision-making
DSS Service-based ecosystem	Stand-alone, application-specific systems with limited network capability	Digital infrastructure, TMS, Emergent decision-making

Table 3. Distinguishing Characteristics of NWDSS vs. Traditional DSS

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