A Net-Enabled Approach to Modelling Joint Interagency Systems

The Arctic Search and Rescue Network

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Abstract

This report discusses a new network-based modelling framework that we have developed for representation and analysis of joint interagency systems. Agents in such systems differ by the roles they play in the system, by the environmental domains in which they operate, and also by other case-specific attributes. The agent heterogeneity gives rise to an Operational network, which represents a step-by-step execution of a response action to a particular incident. The network measures of the Operational network serve as performance indicators for the entire system. The utility of the presented modelling framework is illustrated using an example of the Canadian Arctic Search and Rescue system. Under our approach, the system is viewed and modelled as a set of inter-linked dynamical networks with embedded heterogeneous agents. Each agent is encoded as a multidimensional string of data, which represents agent attributes. The resulting dynamical network model, SARnet, provides visualization and computational capabilities for system analysis and exploration. The visualization capabilities of the model are used to examine the architectural make-up of the system and to explore its multidimensional agents. The computational capabilities are applied to analyze the Operational network of a real incident in the Arctic. The presented modelling framework is applicable to a variety of joint interagency systems. SARnet is a prototype dynamical network model that implements the presented modelling framework, creating a virtual laboratory in which different aspects of system performance can be efficiently evaluated.

Résumé

Le présent rapport porte sur un nouveau cadre de modélisation en réseau élaboré afin de modéliser et d'analyser les systèmes interagences. Les agents de ces systèmes diffèrent en fonction de leur rôle dans ces systèmes, des domaines environnementaux dans lesquels ils évoluent, et d'autres attributs selon le cas. De cette hétérogénéité des agents émerge un réseau opérationnel qui représente l'exécution étape par étape d'une réaction à un incident précis. Les mesures réseau du réseau opérationnel servent d'indicateurs de rendement pour le système complet. L'utilité de ce cadre de modélisation est illustrée avec l'exemple du système canadien de recherche et de sauvetage dans l'Arctique. Dans notre démarche, ce système est analysé et modélisé par un ensemble de réseaux dynamiques interreliés intégrant des agents hétérogènes. Chaque agent est représenté par un ensemble de données pluridimensionnel qui constituent ses attributs. Le modèle de réseau dynamique qui en résulte, nommé SARnet, rend possibles visualisations et calculs afin d'analyser et d'explorer le système. Les fonctions de visualisation de ce modèle servent à étudier l'architecture du système et à explorer ses agents pluridimensionnels. Les fonctions de calcul sont exploitées pour analyser le réseau opérationnel d'un incident réel s'étant déroulé dans l'Arctique. Le cadre de modélisation présenté est applicable à une vaste gamme de systèmes interagences. Le cadre de modélisation présenté a été mis en œuvre dans le prototype SARnet ; ce modèle réseau dynamique constitue un laboratoire virtuel dans lequel nous pouvons évaluer efficacement divers aspects des performances du système.

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Executive summary

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Background: Joint interagency systems comprise social and technological components from different environmental domains and involve coordination of effort across several government and non-government agencies. In general, such systems are designed to perform two main functions: detection of significant events and execution of appropriate responses. Agents or active players in such systems differ by the roles/specialization and by the environmental domains in which they operate, among other case-specific attributes. The Canadian Arctic Search and Rescue (SAR) capability is an example of such a system. The SAR system incorporates a large number of highly-specialized SAR assets/agents with a broad range of capabilities to support the main functions of the system: detection of a distress alert and execution of an efficient SAR response. Arctic SAR relies on coordination between several government departments (including the Department of National Defence, as the lead government department on SAR), volunteer organizations, the private sector, and, in some cases, international bodies. A rapid expansion of air and maritime transit through the Arctic region puts an emphasis on assessments of current and required Arctic SAR infrastructure. Network-based modelling and system-analysis techniques presented in this report will facilitate such assessments.

Methodology: In this report, we present a new modelling framework that makes use of modern network technologies for representation and analysis of joint interagency systems (such as the Canadian Arctic SAR system). Under our approach, the system is viewed and modelled as a set of inter-linked dynamical networks with embedded heterogeneous agents. Each network node denotes a system component and the links between two nodes denote some relationship between those components. The emphasis is given to the relationships (links) and to the dynamics of how these relationships change in the course of a response action.

To accommodate the agent heterogeneity in network models, we introduce five classes of agents depending on their role in the network: sensor, router, actor, database, and controller. Sensors gather and pass information through a designated router to a relevant controller. Controllers coordinate a response action and task other agents. Actors accomplish the bulk of tasks, associated with a response. Databases store information and make it available to other agents. We also introduce six environmental domains in which these agents operate: maritime, land, air, space, cyber, and cognitive. Each agent is encoded as a multidimensional string (data array) where each dimension represents a particular agent attribute or property. The agent heterogeneity gives rise to the Operational network, which provides a conceptual representation of a step-by-step execution of a response action. The Operational network is the most important network in the model, as its measures serve as performance indicators for the entire system. As long as the system can create an efficient operational network, it can be considered efficient. The concept of the Operational network provides a useful and powerful tool for system analysis.

Assortative mixing is another network-based system-analysis tool introduced here. Assortative mixing according to scalar or vector attributes provides a convenient way for visualizing multidimensional data in the form of assortative networks. Assortative networks are used in this study to visualize and then visually examine agent attributes. Assortative networks can also be used to store assorted information for similarity or range search in medium-to-high dimensional spaces.

Principal results: SARnet is a dynamical network model of the Canadian Arctic SAR system that implements the above methodology, providing a convenient for system analysis representation of essential system components and relationships between those components. Conceptually, the Arctic SAR system is represented in SARnet as a set of inter-linked networks. Mathematically, the network representation translates into computational procedures on multi-dimensional arrays of data, where each multi-dimensional data point corresponds to a system component.

The following system components are included in SARnet: SAR assets actively involved in SAR response; various organizations responsible for delivery of SAR services in the Arctic; skill sets, protocols, and procedures relevant to SAR; resources required to support SAR operations; and geographic locations relevant to Arctic SAR. The following networks are included in the model: the Interagency net, which represents inter-agency collaboration on SAR; the Organizational net, which links organizations with their respective SAR assets; the Knowledge net, which links SAR assets with their respective areas of expertise ('who knows what' relationship); the Resource net, which represents the 'who has access to what resource' relationship; and the Standby network, which represents the standby posture of the SAR system. The Standby net links agents based on working relationships, such as 'who works with whom', 'who communicates with whom', 'who reports to whom' (for actor agents), 'who tasks whom' (for controller agents), and 'who has info about whom' (for databases). Several location networks are also included. These are the airport network and the location network that links locations (by geographic name) with SAR assets and Arctic survival kits.

In the SARnet model, SAR assets (agents) are represented by 90-dimensional strings of data, where each of 90 dimensions represents a particular agent property or attribute. The first 15 dimensions are reserved for five agent classes, six environmental domains, and four SAR domains: Air SAR, Maritime SAR, Ground SAR, and Joint. The remainder specifies the number of agent classes with subclasses (in this version of SARnet, one); mobility factors (in this version, two: mobile or portable); availability factor; agents' skill sets (29 in this version); access to resources (12 types of resources are currently included), 26 affiliations; standby times (two: working hours and quiet hours); and latitude and longitude of the home unit location. The last four variables are continuous, whereas others are either binary or categorical.

For the purpose of model validation, we have developed the Operational network of a real incident, which occurred in the Arctic in December 2008. A comparison of the SARnet Standby net and the December 2008 Operational net shows that SARnet adequately captures all essential components and structural characteristics of the real system. Network analysis results identify the key system entities and structural features (such as the chain of command), contributing to the successful outcome of the December 2008 operation. Some system deficiencies and the ways of how these deficiencies could be overcome through automation of parts of the SAR Mission coordination process are also discussed.

Significance of results: SARnet is a prototype dynamical network model that provides a virtual laboratory in which various aspects of system performance can be efficiently evaluated. Such aspects as resilience to technical failure or attack and strategic readiness can be assessed through simulating generation of operational networks in 'what-if' scenarios. The visualization and computational capabilities of the SARnet model provide useful and powerful tools for operational-to-strategic level analysis of a variety of discrete distributed systems of interest to Defence and Security. The visualization capabilities of the model can be used for exploration of the architectural make-up and multidimensional components of joint interagency systems. The computational analysis capabilities can be utilized for evaluating system efficiency and providing science-based recommendations for improvements. It is our hope that the SARnet dynamical network model will find useful applications in Operational Research and Analysis.

Future work: The SARnet model of the Canadian Arctic SAR system allows for a straightforward application of the Generative Network Automata (GNA) – a novel network simulation technique developed by Dr Hiroki Sayama of State University of New York. The GNA-based tool is being incorporated into SARnet for automated generation of operational networks on the Standby network.

Sommaire

A Net-Enabled Approach to Modelling Joint Interagency Systems

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Contexte : Les systèmes interagences sont composés d'éléments sociaux et technologiques de divers domaines environnementaux, et nécessitent la coordination des efforts de nombreuses agences gouvernementales et non gouvernementales. Ces systèmes sont habituellement conçus pour mener à bien deux fonctions principales : détection d'événements importants et application des mesures appropriées. Les agents ou acteurs de ces systèmes diffèrent par plusieurs attributs, notamment leur rôle ou leur spécialité et le domaine environnemental dans lequel ils évoluent. Le système canadien de recherche et de sauvetage (SAR) dans l'Arctique constitue un exemple d'un tel système. Le système SAR intègre un grand nombre de biens et d'agents de SAR très spécialisés disposant d'une vaste gamme de compétences et de capacités à l'appui des principales fonctions du système, c'est-à-dire la détection d'un signal de détresse et l'exécution des mesures de SAR appropriées. Le système de SAR dans l'Arctique est fondé sur la coordination entre plusieurs ministères gouvernementaux (notamment, comme ministère responsable de la recherche et du sauvetage, le ministère de la Défense nationale), des organismes bénévoles, le secteur privé et dans certains cas des organismes internationaux. Or, l'expansion rapide des déplacements aériens et maritimes dans l'Arctique nous pousse à évaluer l'infrastructure actuelle et nécessaire du système de SAR dans cette région. Les techniques de modélisation et d'analyse systémique fondées sur les réseaux présentées dans le présent rapport faciliteront ces évaluations.

Méthodologie : Le présent rapport décrit un nouveau cadre de modélisation qui exploite les technologies de réseautique modernes afin de modéliser et d'analyser les systèmes interagences comme le système canadien de recherche et de sauvetage (SAR) dans l'Arctique. Dans notre démarche, ce système est analysé et modélisé par un ensemble de réseaux dynamiques interreliés intégrant des agents hétérogènes. Chaque nœud du réseau constitue un élément du système, et les liens entre chaque nœud représentent un lien quelconque entre ces éléments. Nous portons une attention particulière aux liens et comment ils se modifient au cours d'une mesure (réponse) de recherche et de sauvetage.

Nous avons créé cinq classes d'agents (capteur, routeur, acteur, base de données et contrôleur) afin de tenir compte de l'hétérogénéité des agents du modèle. Les capteurs recueillent les données et les transmettent à un contrôleur par un routeur préétabli. Les contrôleurs coordonnent une réponse et attribuent des tâches aux autres agents. Les acteurs exécutent la plupart des tâches associées à une réponse. Les bases de données emmagasinent les renseignements et les rendent accessibles à d'autres agents. Nous avons aussi créé six domaines environnementaux où évoluent ces agents : maritime, terrestre, aérien, spatial, cybernétique et cognitif. Chaque agent est modélisé sous forme de chaînes de caractères pluridimensionnelles, ou matrice de données, où chaque dimension représente un attribut ou une propriété précise de l'agent. De l'hétérogénéité des agents émerge le réseau opérationnel, c'est-à-dire la représentation conceptuelle de l'exécution par étapes d'une mesure de réponse. Le réseau opérationnel est le réseau le plus important du modèle, car ses diverses mesures

servent d'indicateurs de rendement pour le système complet. Un système pouvant créer un réseau opérationnel efficace est jugé être efficace. Cette notion de réseau opérationnel constitue un outil d'analyse du système puissant et utile.

Nous présentons aussi dans le présent rapport un autre outil d'analyse de système fondée sur les réseaux : la combinaison par appariement. Combiner les éléments par appariement, en fonction de facteurs scalaires ou vectoriels, est un moyen pratique de visualiser des données pluridimensionnelles sous forme de réseaux associatifs. Nous utilisons ici ces réseaux pour visualiser puis étudier visuellement les attributs des agents. On peut aussi utiliser les réseaux associatifs pour emmagasiner des renseignements connexes aux fins de recherche par ressemblance ou proximité dans les domaines de dimensions moyennes ou élevées.

Principaux résultats : SARnet est un modèle en réseau dynamique du système canadien de recherche et de sauvetage dans l'Arctique, qui met en place la méthodologie décrite ci-dessus ; il permet ainsi la représentation aux fins d'analyse systémique des éléments vitaux du système et leurs interrelations. Sur le plan conceptuel, SARnet modélise le système SAR dans l'Arctique comme un ensemble de réseaux interreliés. Sur le plan mathématique, la modélisation de ces réseaux consiste en des procédures informatiques appliquées à des matrices de données pluridimensionnelles dont chacune des unités de données correspond à un élément du système.

Voici les éléments intégrés à SARnet : biens SAR participant activement aux activités de SAR ; diverses organisations responsables à la prestation de services SAR dans l'Arctique ; compétences, protocoles et procédures pertinents aux activités de SAR ; ressources nécessaires au soutien des activités de SAR ; et les lieux géographiques pertinents aux activités de SAR dans l'Arctique. De même, voici les divers réseaux qui composent le modèle : le réseau interagences, qui représente la coopération entre les diverses agences dans les activités de SAR ; le réseau organisationnel, qui établit les liens entre les organisations et leurs biens de SAR ; le réseau de connaissances, qui relie les biens de SAR à leurs domaines de compétences respectifs (liens « qui connaît quoi») ; le réseau de ressources, qui représente les liens entre les agents et les ressources à leur disposition ; et le réseau de disponibilité, qui représente le régime d'attente du système de SAR. Le réseau de disponibilité relie les agents en fonction des liens de travail, comme « qui travaille avec qui », « qui communique avec qui », « qui rend compte à qui » (pour les acteurs), « qui attribue des tâches à qui » (pour les contrôleurs), et « qui détient des renseignements sur qui » (pour les bases de données). SARnet comprend aussi plusieurs réseaux de lieux : ce sont le réseau d'aéroports et le réseau de lieux qui relie les emplacements (par toponyme) aux biens de SAR et aux trousses de survie dans l'Arctique.

Les biens de SAR sont modélisés dans SARnet comme chaînes de données de 90 dimensions, où chacune des dimensions représente une propriété ou un attribut précis de l'agent. Les quinze premières dimensions sont réservées pour les cinq classes d'agents, les six domaines environnementaux, et les quatre domaines SAR : SAR aérien, SAR maritime, SAR terrestre, et SAR joint. Les autres dimensions précisent le nombre de classes et de sous-classes (dans la présente version de SARnet, une) ; les caractéristiques de mobilité (dans la présente version, deux : mobile ou portable) ; la disponibilité ; les compétences de l'agent (29 dans la présente version) ; l'accès aux ressources (la présente version comprend 12 types de ressource), 26 affiliations ; les périodes de disponibilité (deux : heures de travail et heures de repos) ; et latitude et longitude de l'unité ou du lieu d'appartenance. Les quatre dernières variables sont continues ; toutes les autres consistent en données binaires ou en catégories.

Pour valider ce modèle, nous avons recréé le modèle opérationnel d'un incident réel s'étant déroulé dans l'Arctique en décembre 2008. Une comparaison du réseau de disponibilité de SARnet et du réseau opérationnel de décembre 2008 a montré que SARnet modélise adéquatement tous les éléments et caractéristiques structurelles vitales du système réel. L'analyse du réseau a permis de cerner les éléments et caractéristiques structurelles vitaux du système, comme la chaîne de commandement, ayant contribué à la réussite de l'opération de décembre 2008. Notre rapport traite aussi de certaines lacunes du système et des moyens de les rectifier par l'automatisation de certains éléments du processus de coordination des missions de SAR.

Importance des résultats : SARnet met en œuvre un modèle réseau dynamique constitue un laboratoire virtuel dans lequel nous pouvons évaluer efficacement divers aspects des performances du système. Des scénarios prospectifs dans lesquels on simule la création de réseaux opérationnels permettent d'évaluer des aspects comme la résistance aux pennes techniques et l'état de préparation stratégique. Les capacités de visualisation et de calcul du modèle SARnet constituent des outils puissants et utiles d'analyse des paliers opérationnels à stratégique de divers systèmes distribués distincts d'intérêt pour la défense et la sécurité. Les capacités de visualisation peuvent servir à explorer l'architecture et les éléments pluridimensionnels des systèmes interagences, alors que les capacités de calcul peuvent servir à évaluer l'efficacité du système et formuler des recommandations pour l'améliorer fondées sur la recherche. Nous espérons que le modèle en réseau dynamique SARnet sera utile en recherche et analyse opérationnelle.

Travaux à venir : Le modèle SARnet du système canadien de SAR dans l'Arctique permet d'appliquer assez simplement le GNA (Generative Network Automata), une technique de simulation novatrice élaborée par Hiroki Sayama, de la State University of New York. Nous intégrons actuellement au SARnet un outil fondé sur le GNA qui permettra de générer des réseaux opérationnels dans le réseau de disponibilité.

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1 Introduction

This report presents a new modelling framework that makes use of modern network technologies for representation and analysis of joint interagency systems – a class of socio-technical systems of particular significance to Defence. Joint interagency systems comprise social and technological components from more than one environmental domain: e.g., air, maritime, and land; and involve coordination of effort across different organizations: e.g., the Department of National Defence (DND), Other Government Departments/Agencies (OGD/A), and the private sector. In this study, we are concerned with the systems that perform two main functions: detection of a significant event and execution of an appropriate response action.

The modelling framework is built upon the net-enabled approach proposed by Pestov in [1, 2]. Dynamical network models are used to visually represent a joint interagency system and to evaluate its performance through computation. In general, each network node denotes a system component and the links between two nodes denote some relationship between those components. Each network node is encoded as a multidimensional string (data array) that can dynamically change its state, depending on operational requirements. The emphasis is given to the relationships (links) and also to the dynamics of how these relationships change in response to state changes of system components (nodes) during an operation.

The utility of the modelling framework is illustrated on an example of the Search and Rescue (SAR) system for the Canadian Arctic. The following characteristics of the system have been taken into consideration when choosing an illustrative example for this study:

1. The Canadian Arctic SAR system is an inherently joint capability that involves a large number of inter-connected components from different environmental domains: SAR specialists, ground patrols, aircraft, ships, various information systems, and satellites.

2. Arctic SAR relies on coordination of effort between different government departments, volunteer organizations, the private sector, and, in some cases, international bodies.

3. There are strong inter-dependencies between structural and functional dynamics of the SAR system that result in the pattern of complex adaptive behaviour.

The importance of Arctic issues, in general, and Arctic SAR, in particular, has been stressed in a number of high-profile policy documents [3, 4, 5]. Growing concerns about the current state of Arctic capabilities have also been expressed by the Arctic research community. As pointed out in recent publications [6, 7, 8, 9], a rapid expansion of maritime transit through the Northwest Passage and the emergence of Arctic cruises, often with over 2500 people aboard, have placed increasing demands on the current SAR infrastructure. According to Leclerc [10], there were 11 cruise ships, 9 adventurers and 16 research vessels in the Canada's Arctic in 2008, as compared to just 10 vessels (including two cruise ships) in 2003. In addition to the more than five-fold expansion of Arctic cruises, there have been continuing increases in air traffic activities over the region. As Leclerc reports in [10], polar transit air traffic increased by 50 per cent from 2001 to 2005. The above trends make the assessment of current and required SAR capabilities important. The network-based modelling framework presented in this report will facilitate such assessments.

The evaluation of maritime SAR effectiveness conducted by the Canadian Coast Guard (CCG) [11] revealed lower than average levels of service for the Arctic: 69.23% for the waters of Northwest Territories; 86.67% for the James Bay area; 81.48% for the Eastern Arctic; and 93.10% for the Nunavut area. In [11], effectiveness of the SAR system was defined as the percentage of lives saved out of the total number of lives at risk for the region, averaged over a five-year period. The 2000-2004 historical data of SAR incidents was used in the study. The statistical analysis indicated that on average 96.2% of lives at risk were saved across Canada. Lower than average SAR effectiveness for the Arctic was attributed to harsh climatological and hydrological conditions. Although the CCG study was capable to pinpoint the problem areas, it came short of providing any science-based solutions or recommendations on how the situation could be improved.

As stressed in [6], the solutions to the unique challenges of the Arctic must take a system-of-systems approach. Networks implement systems approaches through providing a convenient way for system representation in high-level computer models. In [12, 13], a network is defined as a set of items, called nodes, with connections between them, called links. There is no limitation on how the items/nodes can be encoded: they can be one-dimensional data points, multidimensional data arrays, or even dynamical systems [14]. Links can be directed or undirected and can also carry additional information through encoded weight (strength) values. Furthermore, networks are dynamical constructs, as they can dynamically change their state or structure or both. The significance of dynamical network models for defence and security applications is discussed in [15, 16, 17].

Depending on the nature of dynamics, all network models are subdivided into three broad categories:

1. Networks with rich functional/state dynamics, but fixed structure. The nodes in these network models have functions assigned to them (e.g. Boolean functions in Random Boolean Networks [18]). The assignment of functions allows for changes of the network states over time. However, the number of nodes and connections between them remain fixed at all times.

2. Networks with varying topology, but no functions assigned to the nodes. These network models can modify their structure according to the rules of attachment, when new nodes and links are added to the network with some assigned probability. Well-studied examples of such network models include small-world and scale-free networks [13].

3. Networks with coupled structural and functional dynamics. In these network models, structural changes cause changes in network states and vice versa. Most real networks show coupling between functional and structural dynamics.

The latter network models deserve a detailed consideration. In [19], these network models are referred to as adaptive networks. Another commonly used term is complex dynamical network [20] or, simply, complex network [12]. A distinctive feature of these network models is the existence of a dynamical feedback loop between network topologies and functional states. Gross and Sayama [19] illustrate this feature on an example of the disease spread in human population. In their example, the dynamics of the prevalence of the disease depends on linkages between individuals. But the evolution of linkages also depends on the states of individual nodes, as individuals are allowed to cut links with infected neighbours.

1.1 Specifics of Socio-Technical Systems

Many socio-technical systems of interest to Defence and Security take the form of networks and show the network-like adaptive behaviour. The Canadian Arctic SAR system, which we consider in here, is an example of such system. Socio-technical networks comprise social and technological components: people, teams, organizations, devices, and equipment. As such, they inherit characteristics of two well-studied network classes: social and technological. However, there are significant distinctions.

Most social networks are assortative, whereas most technological networks are disassortative [12]. Assortative networks are networks that favour connections between nodes with similar properties. Disassortative networks are the opposite: components that have different specs or that perform distinctively different functions tend to connect in disassortative networks. In this regard, socio-technical networks are closer to technological rather than social networks. However, the structure of socio-technical networks is not predefined/fixed, as that of most technological networks. In socio-technical nets, components are often allowed (or are designed) to build new links and add new nodes to the network, in accordance to operational requirements. As a result, the structure of socio-technical networks changes dynamically. But again, the dynamics of structural change is not that of social networks [20]. As a consequence, caution should be taken when applying existing network analysis techniques to networks that include both social and technological components.

Network analysis involves application of network measures, both at the level of individual components and at the system level. Graph measures [21] and extended graph measures [20] (e.g. degree centrality, betweenness, and cognitive demand [22]) are the measures of performance of individual components. Other network measures (e.g. network density, diameter, fragmentation, and communication speed) are performance indicators for a system as a whole.

It should be kept in mind, though, that interpretation of the above measures has been derived from empirical data on social networks. As a result, direct application of these measures to socio-technical systems may not be appropriate. Pestov and Verga show in [17] that a use of degree centrality to measure the significance of individual components of a critical infrastructure system could, in fact, produce misleading results. As another example, let us consider a problem of network resilience to random or targeted node removal. In such studies, the integrity of the giant component is normally used as a measure of system resilience [12]. It is obvious that this approach and other performance evaluation approaches, which have been developed for very large networks with a distinctively different mechanism of structural dynamics, may not make sense for evaluating performance of socio-technical systems.

Carley [20] argues that socio-technical systems are better represented by sets of inter-linked networks between different types of node, e.g. agents, organizations, resources, knowledge, and (geographic) locations. The approach by Carley, called Dynamic Network Analysis (DNA), has become widely accepted for modelling social, organizational, and socio-technical systems. Pestov and Pilat [23] take the DNA approach further by proposing to model socio-technical systems as dynamical networks with embedded heterogeneous agents. In this report, we apply and further develop the approach proposed in [23].

1.2 Outline of the Report

In Section 2, we present an overview of the current state of the Canadian Arctic SAR system. In this context 'current' means as of January 2011, when most SAR data was collected. Then we proceed to Section 3, where we describe various phases of model development and methodologies used. Section 4 is devoted to SARnet - a dynamical network model of the Canadian Arctic SAR system. The purpose of SARnet is to demonstrate the utility of the modelling framework. We show how network technologies can be used to visualize and explore the Arctic SAR system. In Subs. 4.4.1, we use the case log of a real incident, which occurred in the Arctic in December 2008, for the purpose of model validation. We give our conclusions and point out to some potential avenues for future research in Section 5.

2 The Canadian Search and Rescue System

The Canadian Search and Rescue (SAR) System, collectively known as the National Search and Rescue Program (NSP) for the federal element of search and rescue [24], is a joint effort of various levels of government, the private sector, and volunteer organizations. It is administered by the National Search and Rescue Secretariat (NSS) [25]. The NSS is an autonomous arm's length organization within the Department of National Defence, accountable to the Minister of National Defence who is also the Lead Minister for search and rescue. While the NSS does not direct or manage the work of its partners, it brings them together to encourage collaboration and to ensure best use of their resources.

The Executive Director of the NSS chairs the federal Interdepartmental Committee on SAR (ICSAR). The government agencies involved in ICSAR are [25]:

- Canadian Forces (CF), Department of National Defence (DND);
- Canadian Coast Guard (CCG), Department of Fisheries and Oceans (DFO);
- Royal Canadian Mounted Police (RCMP), Public Safety Canada;
- Transport Canada;
- Meteorological Service of Canada, Environment Canada;
- Parks Canada, Heritage Canada.

Responsibility for the "overall effective operation of the federal coordinated maritime and aeronautical search and rescue system" in Canada is assigned to the Commander of Canada Command. Canada Command is the military organization responsible for all routine and contingency CF operations in Canada and North America [26].

Within the non-federal jurisdiction, the NSS works directly with provincial and territorial SAR authorities and police services. Several volunteer organizations provide secondary SAR duties. These include the Canadian Coast Guard Auxiliary (CCGA) [27] and the Civil Air Search and Rescue Association (CASARA) [28].

2.1 The Command and Control Structure

The land and sea area under Canadian jurisdiction is divided into three SAR Regions (SRRs), as illustrated in Figure 1. A designated Joint Rescue Coordination Centre (JRCC) oversees SAR operations in each region, respectively. These centres are JRCC Victoria in British Columbia, JRCC Trenton in Ontario, and JRCC Halifax in Nova Scotia. The SRRs are named after their respective JRCCs. In addition, there are two Marine Rescue Sub-Centres (MRSC) located in eastern Canada: MRSC Laurentian in Quebec City and MRSC Newfoundland in St. John's that coordinate local maritime SAR response.

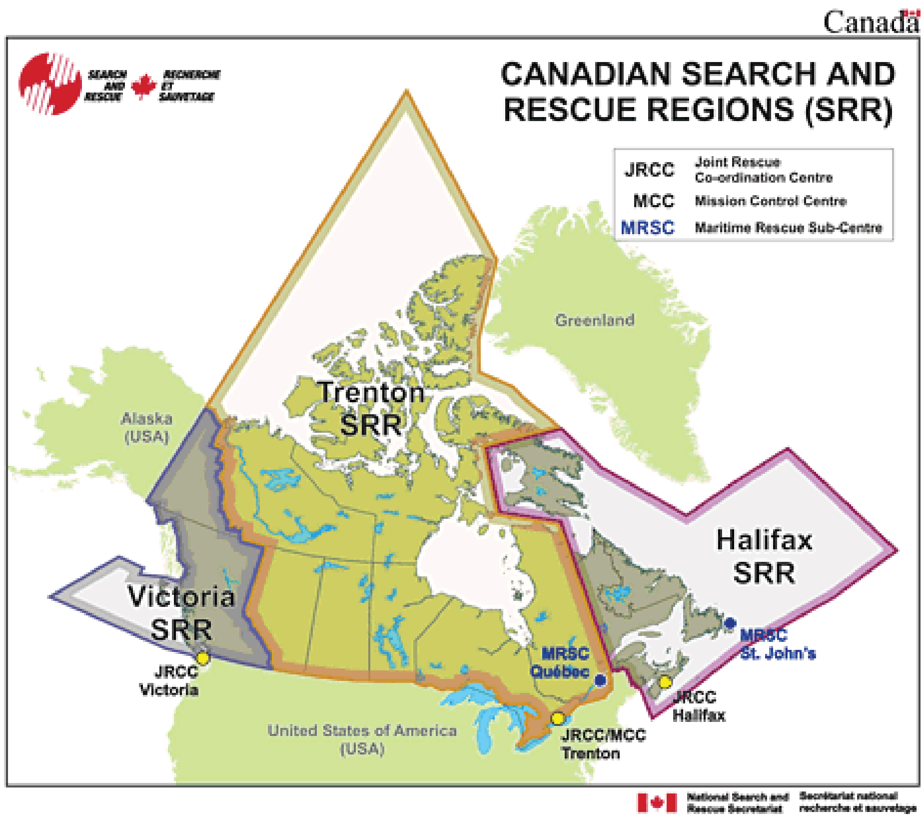

Figure 1: *Canadian Search and Rescue Regions (image from www.nss.gc.ca).*

Canada is viewed as a world leader in SAR response [29]. Efficiency of the Canadian SAR system stems from a short chain of command headed by Canada Command. Each SAR region is represented by a Search and Rescue Region (SRR) Commander. The Trenton SRR is headed by the Commander 1 Canadian Air Division (Comd 1 Cdn Air Div), also designated as the Combined Forces Air Component Commander (CFACC). The Victoria and Halifax SRRs are led by the Commanders of the Joint Task Force (Pacific) and the Joint Task Force (Atlantic), respectively. Each JRCC is commanded by an Officer in Charge (OIC) who directly reports to the region's Commander. The SRR Commanders can task CF air and naval resources within their regions, as well as Coast Guard resources. The Commander of Canada Command can task all needed CF resources from anywhere in Canada [26]. The Command and Control (C2) structure of Canadian SAR is described in detail in [29].

JRCC collects and distributes essential information concerning a SAR incident and coordinates SAR response. Responsibility for the operation of JRCCs is shared between the Canadian Air Force and CCG. The JRCC operations room is manned 24 hours a day, seven days a week by an Air Force officer (SAR pilot or navigator) and two CCG (deck) officers as SAR Mission Coordinators [30, 31]. JRCC Halifax also has a CCG Maritime SAR Support officer and a CF Assistant Air Coordinator [30, 31]. During periods of heavy activity, extra personnel may be called upon to support operations [30]. The MRSCs are manned solely by CCG officers and have no Air Force Component.

An array of communication networks is available to JRCCs and MRSCs [30]. All marine and aeronautical incidents or any other incidents, which may pose a threat to life or property are reported to a relevant JRCC or MRSC. The communication networks enable direct communication between the centre and SAR assets (personnel, vessels, and aircraft). To facilitate communication between the centre and a distress scene, an On Scene Coordinator (OSC) may be appointed and transferred to the first aircraft or ship that arrives on scene. All information produced or received during an incident is logged at the facility and will be used later to produce a post-operational report [30, 31].

The SAR Mission Coordinators (or SAR coordinators) perform duties of coordination of SAR response. Upon notification of an incident, one of SAR coordinators is appointed as a Search Master. The Search Master is responsible for all search and rescue efforts until the incident is closed [31]. In that capacity, s/he requires timely access to data to make informed decisions with regard to prosecuting the incident. A number of specialized SAR technologies, designed to increase the effectiveness of SAR response, support the work of the Search Master. These include the SAR Mission Management System (SMMS), International Satellite System For Search and Rescue (SARSAT), and Information System on Marine Navigation (INNAV) [31].

The SMMS provides the SAR coordinators with a set of software tools centered around the SARMaster application – a case management tool specifically developed for the Canadian SAR process [31]. SARMaster incorporates the spatial data capabilities of Geographic Information Systems (GIS) with the textual data capabilities of Relational Database Management technologies. The software also supports integrating real-time data feeds [32].

The SARSAT [33] is part of an International program, Cospas-Sarsat, hosted by three nations: Canada, USA, and Russia. The system is composed of:

- distress radiobeacons which transmit signals during distress situations;
- instruments on board satellites which detect the signals transmitted by distress radiobeacons;
- ground receiving stations, referred to as Local Users Terminals (LUTs), which receive and process the satellite downlink signal to generate distress alerts; and
- Mission Control Centres (MCCs) which receive alerts produced by LUTs and forward them to relevant JRCCs or MRSCs.

The SARSAT system includes two types of satellites: satellites in Low-altitude Earth Orbit (LEOs) and satellites in Geostationary Earth Orbit (GEOs). The LEOs provide coverage of the polar regions, which are beyond the coverage of geostationary satellites. JRCC Trenton houses the Canadian MCC.

INNAV [34] is a Canadian information system that collects, processes, and displays in real time marine traffic information. While other Marine Communications and Traffic Services focus on displaying radar, mapping and communications data, INNAV addresses all the functions required for waterway management. It uses a robust operating system with linked regional servers to ensure 24-7 service. Even if network links between operation centres fail, INNAV is designed to continue working with site resident data. Marine information is automatically re-synchronized when links are re-established.

In this study, we are concerned with the Arctic region, the main part of which falls under jurisdiction of JRCC Trenton located on the CF air base in Trenton, Ontario. The lower half of Baffin island and eastern part of the Labrador Peninsula fall under JRCC Halifax located in Halifax, Nova Scotia. JRCC Halifax also serves as a back-up facility for JRCC Trenton.

2.2 Maritime SAR

The Canadian Coast Guard – Central and Arctic Region (CCG C&A), is responsible for maritime SAR in the Arctic [35]. One of the primary areas of responsibility for the CCG C&A is the provision of maritime SAR resources in areas of federal responsibility. Other primary SAR services that the CCG C&A provide include the co-ordination, control and conduct of SAR operations, with the assistance of DND, and the detection of maritime incidents.

In addition, the CCG C&A oversees the activities of the Canadian Coast Guard Auxiliary – Central and Arctic Region, CCGA C&A, a volunteer organization. The CCGA C&A was incorporated in September 1978 under the sponsorship of the Federal Government, for the purpose of providing organized voluntary maritime SAR and the promotion of safety afloat in an Auxiliary support role to the Canadian Coast Guard [27].

Through Marine Communications and Traffic Services (MCTS) centres [36] located at Inuvik and Iqaluit, the CCG C&A provides marine safety communications for the Arctic region, including monitoring international marine radio distress frequencies to detect distress or other calls indicating a vessel or person in need of assistance. Furthermore, the MCTS centres provide broadcasting marine weather information and notices to shipping concerning hazards to navigation, and conduct screening of ships entering Arctic waters.

The following categories of vessels are used in maritime SAR incidents:

- Primary SAR Vessel: a specially designed, equipped and crewed vessel that has SAR as its main responsibility (stationed in areas that have a high risk of SAR incidents).
- Multi-tasked SAR Vessel: a CCG vessel that is tasked to deliver SAR and at least one other operational program.
- Secondary SAR Vessel: any government vessel.
- CCGA Vessel: a vessel operated by the CCGA.

- Vessel of Opportunity (VoO): any other vessel not mentioned above, close enough to provide assistance to a vessel in distress. (Under the Canada Shipping Act and international law, every vessel at sea is required to assist in a distress situation.)

The CCG does not have primary SAR vessels operating in the Arctic. However, there are CCG secondary SAR vessels operating out of Hay River, Northwest Territories: CCGS Dumit, CCGS Eckaloo, CCGS Nahidik, and CCGS Tembah [37]. (CCGS stands for CCG Ship.) There are also CCG icebreakers that operate in the Arctic: CCGS Louis S. St-Laurent, CCGS Terry Fox, CCGS Amundsen, CCGS Des Groseilliers, CCGS Henry Larsen, and CCGS Pierre Radisson [38]. Most of these larger vessels are equipped with one or more Eurocopter BO 105 rotary winged aircraft that can be used for secondary SAR. The CCG secondary SAR assets operating in the Arctic are listed in Table 1.

Table 1: *The CCG secondary SAR vessels.*

Vessel Name	Vessel Type	Home Port	Officers	Crew	Year Built
Dumit	Special Navaids	Hay River, NT	4	6	1979
Eckaloo	Special Navaids	Hay River, NT	4	6	1988
Nahidik	Special Navaids	Hay River, NT	6	6	1974
Tembah	Special Navaids	Hay River, NT	4	5	1963
Louis S. St-Laurent	Heavy Icebreaker	St. Johns, NL	13	33	1969
Terry Fox	Heavy Icebreaker	St. Johns, NL	10	14	1983
Amundsen	Medium Icebreaker	Québec, QC	12	26	1979
Des Groseilliers	Medium Icebreaker	Québec, QC	10	26	1982
Henry Larsen	Medium Icebreaker	St. Johns, NL	11	20	1987
Pierre Radisson	Medium Icebreaker	Québec, QC	12	26	1978

The CCG rescue specialists are the ship's crew members who have received training in Advanced First Aid (Level 2) and related medical training such as Standard First Aid/CPR certificate, treatment of severe hypothermia and near drowning. They perform ocean rescue, treat injuries, and provide disaster scene management which may includes fire fighting [30].

The CCGA C&A supports the CCG with volunteer members and assets in 11 Arctic communities [10]. There are currently at least 14 CCGA vessels registered in the Arctic region [31].

The overall lack of primary maritime SAR assets in the Arctic is of concern [11]. The fact that secondary SAR units are not always positioned to provide SAR services in areas of high risk is also of concern [11].

2.3 Air SAR

The primary Air SAR assets for the Trenton SRR are the 424 Squadron [39] out of Trenton, ON and the 435 Squadron [40] out of Winnipeg, MB. For the Halifax SRR, the CF primary SAR assets are the 413 Squadron [41] out of Greenwood, NS and the 103 Squadron [42] out of Gander, NL. The 440 Squadron [43] out of Yellowknife, YT can act as a secondary SAR asset in the Arctic region. Table 2 provides a summary of Air SAR assets.

Table 2: *CF Air SAR assets.*

Asset Name	Asset Type	SRR	Home Unit	Location
424 Squadron	primary	Trenton SRR	8 Wing	Trenton, ON
435 Squadron	primary	Trenton SRR	17 Wing	Winnipeg, MB
413 Squadron	primary	Halifax SRR	14 Wing	Greenwood, NS
103 Squadron	primary	Halifax SRR	9 Wing	Gander, NL
440 Squadron	secondary	Trenton SRR	17 Wing	Yellowknife, YT

In addition to the CF Air SAR components, CASARA [28] provides air-based SAR assets on a volunteer basis. Nine Arctic communities are actively involved in the organization [31]. The CASARA volunteers receive training as search pilots, spotters, navigators or administrators to supplement military SAR crews. Many of these volunteers own or rent aircraft and possess knowledge of their respective local areas. The organization maintains lists of personnel and phone numbers for accessing additional support, if needed. The CASARA volunteers can be tasked by a responsible JRCC to provide assistance in aircraft searches. The CF conduct regular training exercises with CASARA. Remuneration is provided to CASARA for usage or rental of aircraft [30].

The SAR technicians are the members of a CF group of elite, highly trained SAR specialists who provide on-scene medical aid and evacuation of casualties. They are military aircrew who deploy from rotary or fixed wing aircraft, usually in a team of two. The primary responsibilities of SAR technicians include: parachuting into distress scenes; providing on-site life-saving and -sustaining medical care; carrying out survival procedures under all climatic and terrain conditions; and extraction of casualties by air, land or sea (e.g. hoisting a casualty off a sailboat). They also act as spotters and direct the dropping of equipment and supplies by parachute or hoist. SAR techs receive medical training that corresponds to Advance Life Support paramedic [30].

Primary SAR aircraft maintain a 1/2 hour standby posture during the working hours (08:00-16:00 weekdays) and a two hours posture during quiet hours (16:00-08:00 and weekends) [30]. Crews assigned to standby duties must become airborne within the indicated standby times after they are tasked.

Table 3 lists CF primary aircraft types involved in SAR operations: rotary, fixed wing, and fixed wing STOL (STOL stands for Short Takeoff and Landing).

Table 3: *CF SAR aircraft.*

Aircraft	Type	Crew	SAR Techs	Squadrons
Griffon	rotary	3	2	424
Cormorant	rotary	3	2	424, 413, 103
Hercules	fixed wing	5	2	424, 413, 435
Twin Otter	fixed wing STOL	2	N/A	440

The Griffon helicopter (Figure 2) is equipped with a forward-looking infrared camera, which is able to seek out aircraft and personnel by the heat they give off. The latter feature makes this helicopter an ideal search aircraft. The crew consists of two pilots and one flight engineer, plus two SAR techs [30]. It is also used to provide aero-medical support and casualty evacuation.

Figure 2: *The Griffon helicopter shown with a group of scientists and Air Force personnel; the person in orange uniform is a SAR tech.*

Figure 3: *The Cormorant helicopter.*

Figure 4: *The Hercules aircraft; the inserts show SAR equipment and medical kits stored inside.*

Figure 5: *The CC-138 Twin Otter aircraft (image from www.airforce.forces.gc.ca).*

The Cormorant helicopter (Figure 3), a powerful three-engine aircraft, has long-range capabilities for extended searches and a large cargo area, which can carry up to 12 stretchers or a load of 5,000 kg. The crew of three consists of two pilots and one flight engineer, plus two SAR techs [30]. SAR technicians are often hoisted from the helicopter to pick up patients in remote areas or off ships.

The Hercules (Figure 4) is a long range, high speed Aircraft capable of delivering emergency equipment, supplies, and SAR technicians to the scene via air drops. The crew of five consists of two pilots, one flight engineer, one navigator and one loadmaster, plus two SAR techs [30]. (Photos in Figures 2 - 4 are courtesy of Lawrence M. Mac.)

The CC-138 Twin Otter (Figure 5) is a 19-passenger STOL utility aircraft. The crew commonly include two pilots, but may also include spotters when on a SAR mission. Since 1994, 'Twotters' support Canadian Rangers and Regular forces in the Arctic.

2.4 Ground SAR

Ground SAR in Canada is conducted under the legal authority of the individual provinces and territories. This authority is delegated for operational response to the police service of each jurisdiction. At the provincial level, the RCMP are the operational authority for ground SAR in the Arctic. Ground SAR cases, such as searches for the passengers and/or crew of a downed aircraft, as well as searches for missing hunters and hikers, are responsibilities of the RCMP under provincial contract policing.

The Canadian Rangers, a sub-component of Army Reserve, provide patrols and detachments for employment on national-security and public-safety missions in sparsely settled northern, coastal and isolated areas [44]. The 1^{st} Canadian Ranger Patrol Group (CRPG), with headquarters in Yellowknife NWT, has over 1500 Rangers in 56 patrols in communities across the North [45, 46]. Its activities encompass Nunavut, Yukon, Northwest Territories, and Northern British Columbia.

Many Canadian Rangers in the 1^{st} CRPG are Inuit and speak Inuktitut as their first language. Others speak Dene or other native languages. In terms of Canadian Ranger tasks, they conduct sovereignty patrols, provide guidance and local knowledge to Canadian Forces during land exercises, and participate in Search and Rescue operations, as their primary activities.

The CF Land Advanced Warfare Centre (CFLAWC) provides operational support to SAR teams and offers extensive courses on Arctic operations advising, parachute rigging, aerial delivery, and more. CFLAWC can deploy two six-member teams on four hours notice to provide additional support, when MAJAID (Major Air Disaster) is declared by a responsible JRCC.

2.5 The Major Air Disaster Emergency Response Plan

MAJAID (Major Air Disaster) is the CF emergency response plan to a major air incident in the remote regions of Canada, especially the high Arctic [47, 24]. A major air incident is defined as an incident that exceeds the local resources of a responsible JRCC. Similar response plans to a major marine incident have been developed for various SRRs by the CCG. These are referred to as the MAJMAR response plans [24].

The MAJAID plan incorporates all necessary and available military assets for the delivery of aid to a remote crash location. Links with other federal departments, the province or territory involved, and the affected airline are also incorporated in the plan [48]. The plan makes provisions for the establishment of a Forward Operating Base (FOB) near the crash site, which can be used to support the MAJAID response throughout the operation. A FOB may contain an airfield, hospital, or other facilities. The establishment of a FOB can substantially reduce reaction time and increase the chance of survival for the victims.

NAVCAN (Navigation Canada) will likely provide the first notification of a developing situation [47]. NAVCAN is the private sector civil air navigation services provider for air traffic control, flight information, weather briefings, aeronautical information services, airport advisory services and electronic aids to navigation [49]. As soon as the first notification is received, a responsible JRCC declares a MAJAID, depending on the magnitude of an incident. The MAJAID declaration initiates a rapid succession of events to deliver immediate, additional support to survivors. The MAJAID implementation base will have staff called in to coordinate the dispatch of the C-130 Hercules aircraft. According to the size of the crash, the aircraft will be loaded with equipment, including air-deliverable (parachute-droppable) MAJAID kits, and with a 12-man airborne support group from CFLAWC.

The MAJAID kits contain tents, medical supplies, a field hospital, rations, heaters, generators, blankets, environmental clothing, and an eight-wheeled all-terrain vehicle (called the ARGO), to help people survive in the extreme weather conditions. MAJAID kits are located at CFB Trenton and they could sustain up to 320 persons for 72 h [50]. There were four kits for up to 80 persons, originally. All 80-person kits have been replaced with 20-person survival kits to increase the likelihood of success of parachute drops [26]. There are also MAJAID 2-person medical kits located in CFB Trenton. MAJAID kits and the content are shown in Figure 6. Figure 7 shows an open 2-person first-aid kit. The content label is shown at the upper right corner. (Photos are courtesy of Lawrence M. Mac.)

Other available resources include Survival Kit Air Droppable or SKAD. The SKAD consists of two ten-person life rafts and two survival bundles. The kit is designed to meet the conditions of survival on water. The bundles contain food, fresh water, clothing and tools [30].

In addition to MAJAID and first-aid kits, there are Arctic survival caches that are strategically placed in seven Northern airfields and that can sustain up to 325 persons: six 50-person kits and one 25-person kit. The 50-person kits are located in Inuvik, Whitehorse, Yellowknife, Rankin Inlet, Resolute Bay, and Iqaluit, each; and the 25-person kit is located in Alert [6, 10].

There are currently 114 airports in the Canadian Arctic (north of the 60^{th} parallel) [51]. The size and type of the airport runway specify which planes are able to land at each airport. Some airports also carry specialized fuel used by specific aircraft. The locations of airports play an important role in SAR response. Due to large geographical distances and limited fuel carrying capacity, SAR rotary aircraft typically need to refuel several times en route to a distress site [52].

The great distances, harsh operating environment, and also the lack of infrastructure to support and sustain SAR response of any significant magnitude present a challenge for Arctic SAR [53, 6].

Figure 6: *MAJAID kits and the content, including the ARGO eight-wheeled all-terrain vehicle.*

Figure 7: *The MAJAID 2-person medical kit; the insert shows the content label.*

3 Model Development

In this section we describe the development of the dynamical network model of the Canadian Arctic SAR system, called SARnet, and the methodologies used in the process. The overall objective of this modelling exercise is to demonstrate the utility of dynamical network models for representation and analysis of joint interagency systems, such as the SAR system.

To achieve this objective, the model development process has been subdivided into the following three phases:

1. Data Acquisition
2. Model Construction
3. Incorporation of Computational Analysis Tools

In Subs. 3.1 and 3.2, we describe concepts and methodologies that we have developed and applied in the first two phases. Subs. 3.3 presents an overview of network-based computational tools that have been incorporated into the current version of the SARnet model. The Generative Network Automata (GNA) – a network simulation technique developed in [54] – is being incorporated into future versions of the model.

3.1 Data Acquisition

The data acquisition phase included gathering of information on Arctic SAR from available sources, such as government publications and reports, relevant websites, and subject-matter experts. Our visit to the JRCC Trenton and 424 Transport and Rescue Squadron in October 2009, which included meetings with the CCG officers on duty and members of the Royal Canadian Air Force, laid the groundwork for this effort.

Most data for this project was obtained from Canadian Government websites. Other accessed Internet sources included the websites of volunteer and private-sector organizations, involved in search and rescue. Table 4 lists major websites, accessed in this project for the purpose of data acquisition. Individual web pages that we accessed under these websites are listed in the References section.

The NSS website (www.nss.gc.ca) provides an overview of the NSP and lists all participating government departments together with links to relevant departmental web pages. Annual reports and policy documents are also available for download from the website. The information from the NSS website (including that from reports and other publications posted on the website) was used to gain understanding of the interagency structure of the NSP and relationships among participating agencies.

The CCG website (www.ccg-gcc.gc.ca) contains multiple web pages that cover various aspects of Maritime SAR, its structural characteristics, and functions and responsibilities of SAR service providers. The website provides links to CCG reports, including the CCG Search and Rescue Manual [30], which is used in Section 2, as the main source of information on Maritime SAR.

Table 4: *Internet information sources.*

Web Site	URL
National Search and Rescue Secretariat	www.nss.gc.ca
Canadian Coast Guard	www.ccg-gcc.gc.ca
Canadian Coast Guard Auxiliary Central & Arctic	www.ccga-gcac.ca/about/central_e.asp
Civil Air Search and Rescue Association	www.casara.ca
National Defence and the Canadian Forces	www.forces.gc.ca
Chief Review Services	www.crs-csex.forces.gc.ca
Canada's Air Force	www.airforce.forces.gc.ca
Canadian Army	www.army.forces.gc.ca
Canada Command	www.canadacom.forces.gc.ca
SAR Mission Management System	smms.forces.gc.ca
COSPAS-SARSAT	www.cospas-sarsat.org
Weather and Meteorology	www.ec.gc.ca/meteo-weather
NAVCAN	www.navcanada.ca
The Northern Research Forum	www.nrf.is
Wikipedia	en.wikipedia.org/wiki

The CF websites, especially the web pages of the Royal Canadian Air Force and Canadian Army, provide comprehensive information on Air and Ground SAR. The data gathered from the CF websites is summarized in Subs. 2.3 and 2.4.

The information from non-government sources was cross-referenced with data from government and other trusted sources (e.g. CASARA and CCGA) to eliminate potential inconsistencies. In total, more than 40 web pages relevant to Arctic SAR were accessed in this project for the purpose of data acquisition.

To ensure that information from the Internet sources was accurate and up to date, we sought advice of subject-matter experts. We would like to specifically mention the contribution of Mr David Lever of Canadian Coast Guard. Mr Lever has more than 40 years of experience as a CCG deck officer and SAR Mission Coordinator. He performed duties of a Search Master on many occasions, and served as a trainer and mentor for several generations of SAR Mission Coordinators. His insights into the inner workings of SAR Mission Coordination were invaluable for this project. The case log of a real SAR incident in the Arctic, which Mr Lever provided, was used for the purpose of model validation. Model validation results are presented in Subs. 4.4.1.

In our home organization, we consulted with Mr. Rick McCourt of the DRDC CORA Force Readiness and Air Systems Section on Air SAR issues, and with Dr Michel Ducharme of the DRDC Valcartier System of Systems Section on Arctic survival issues.

3.2 Model Construction

The Arctic SAR data that we gathered provided the foundation to construct the SARnet model. The net-enabled approach [1, 2] was the main modelling methodology used in the process.

Under the net-enabled approach, the Arctic SAR system is viewed and modelled as a set of interlinked networks with nodes and links representing system components and relationships among those components, respectively. There are several good reasons for using the network representation [15]:

1. *Visualization Capabilities:* Networks provide a convenient graphical representation of a system in the form of graphs [55]. With the graphical representation, various aspects of the system can be visualized, and then visually examined. In this way, network visualization capabilities offer a viable alternative to conventional table data. It should be kept in mind, though, that networks are more than graphs in the same way as vectors are more than directed line segments, which represent them. The network visualization capabilities can be used as follows:
   (a) To recreate a 'bird's eye view' of the entire system, which is easy to grasp and analyze;
   (b) To serve as a tool for multi-dimensional data visualization and exploration.
2. *Computational Analysis Capabilities:* As soon as a system is represented as a network (or a set of multiple networks), it becomes a mathematical object. Various mathematical operations and computational algorithms can be used on networks (e.g. matrix algebra, graph re-writing algorithms, evolutionary computation, network optimization, and agent-based simulation). The network computational capabilities can be used as follows:
   (a) To provide a tool for operational-to-strategic level of system analysis (e.g. for evaluating system performance in terms of strategic readiness, resilience to technical failure or attack, and responsiveness to changing external conditions);
   (b) To develop a tactical tool for automated generation of coordinated rapid response actions that involve diverse multiple players and assets.

Mathematically, the network representation translates into computational procedures on a set of multi-dimensional arrays of data, where each multi-dimensional data point corresponds to a system component. Thus, the SARnet model incorporates both conceptual and mathematical representations of the Arctic SAR system. The conceptual framework is accessible through network visualization tools under *ORA, the network visualization and analysis software (see [22]; also see [56]). The mathematical context is built into the model in the form of mathematical relationships, and can be utilized through the application of computational analysis tools.

Dynamic Network Analysis (DNA) [20] – the main conceptual framework we build upon – provides an efficient means for representing heterogeneity between system components through the introduction of different node classes (e.g. organizations, resources, knowledge, agents, and locations). However, it does not fully accommodate heterogeneity within the agent class, which is characteristic of joint interagency systems. Agents in such systems differ by the role they play in the network and by the environmental domain in which they operate. This heterogeneity is important, as it affects system dynamics.

3.2.1 Agent Representation

The idea of abstract agents comes from agent-based models or, for short, ABM, where a specified number of entities, equipped with particular properties and behaviours, are simulated [57]. Depending on a simulation environment, ABM can be divided into two vast categories: ABM on location and ABM on networks [58]. In network models, agents are network nodes that represent active players in the system. They process and exchange information, carry out knowledge-intensive tasks, form new connections, and add new nodes to their network. The network environment determines, restricts and enables the behaviour of agents and their interactions [58].

In SARnet, agent nodes represent SAR assets: CCG officers, teams of SAR techs, CRPG patrols, JRCCs, aircraft and ships with the crew, and various information systems. For a complete list of SARnet agents, see Tables A.1 – A.4 of Annex A. These are highly specialized entities, trained or designed to perform specified tasks, often in a specified environmental domain. Unlike social networks (which consist of people only), heterogeneous agents of the SAR system (or any joint system, for that matter) cannot easily re-train or replace other agents. The agent specialization results in a distinctive pattern of system dynamics [23]. To accommodate the agent heterogeneity in network models, we have extended the DNA framework in [23] through the introduction of five classes of agents: sensor, router, actor, database, and controller; and six environmental domains of operation: maritime, land, air, space, cyber, and cognitive.

Sensor agents represent system entities that detect a significant event, gather information about that event, and then pass gathered information to a designated router. Router agents distribute and direct the flow of information within the system, and also enable communication between different agents. The Search and Rescue Satellite Tracking (SARSAT) system, which provides distress alert and location information on SAR incidents to SAR authorities, is an example of a sensor agent. SARSAT passes information through a Local Users Terminal (LUT), which is a router agent, to the Canadian Mission Control Centre (MCC). The MCC, which is also a router, receives alerts and forwards them to relevant JRCCs or MRSCs. The environmental domain of SARSAT is space. Some types of sensors can operate in air, maritime, or land domains. Routers typically operate in the cyber domain.

Actor agents represent system entities that are directly involved in the conduct of SAR response. They accomplish the bulk of tasks and duties, associated with SAR response, possess knowledge, and access resources. They can exchange information with other agents, request access to resources, establish new links with neighbouring agents, and create shortcuts to distant agents. In SARnet, actors are the teams of SAR techs, aircraft, vessels, ground search teams, and volunteers. In general, most of these actors operate in a designated environmental domain: maritime, land, or air.

Databases store information and make it available to other agents. Some of these facilities are Read-Only (RO) (e.g. the CASARA telephone directory), whereas others are Read-Write (RW) databases. Information System on Marine Navigation (INNAV) and SAR Mission Management System (SMMS) are examples of RW database agents. Both systems are dynamic information sources that are able to acquire and process new information and exchange that information through knowledge. The environmental domain of database agents is cyber.

Controllers coordinate a response action and task other agents. These agents have the power to modify the system through adding new nodes and links to the network. They have knowledge of significant segments of their network and available assets. JRCC Trenton and the Search Master (the CCG officer who oversees a SAR response) are examples of controller agents in SARnet. The environmental domain of the SARnet controller agents is cognitive. Note that some systems may include non-human controllers operating in the cyber domain.

For sake of clarity, we assume that an agent cannot hold more than one role simultaneously. However, they could change their role during various phases of a response action. For example, an actor could assume the functions of a controller, if required. Similarly, a router may become an actor in an operation. For example, the RCMP agent, which is deemed to be a router, could assume an actor role in conducting ground search.

The agent classes described above differ with respect to how they access, process and exchange information, and also with respect to what degree of knowledge about the system they have. For instance, a sensor agent may only have information about its next neighbour – a router, whereas a controller may have knowledge about a significant segment of the network, including agent specs.

The environmental domain is an important agent property/attribute, especially when joint systems are concerned. In the defence context, jointness means interoperability across different environmental domains. Therefore, to adequately represent a joint capability the network model must include components from more than one environmental domain. It should be noted that some agents cannot change the domain of their operation, whereas others can operate across several environmental domains. The latter is generally an exception. In SARnet, the SAR tech teams work from an aircraft (e.g. conduct search) and on the ground (e.g. provide First Aid at the distress site).

Table 5 summarizes the agent classification. The SARnet instances of agent classes are listed in Tables A.1 – A.4 of Annex A.

Table 5: *Summary of agent classes.*

Agent Class	Functions	Environmental Domains
Sensor	senses, detects, and passes gathered info	space, air, maritime, land
Router	distributes the flow of info and enables com links	cyber
Actor	executes a response action as tasked	air, maritime, land
Database	stores and provides access to info	cyber
Controller	coordinates a response and tasks agents	cognitive, cyber

In addition to the agent classes and environmental domains described above, we introduce four SAR operational domains: Maritime SAR (see Subs. 2.2 for the domain description), Air SAR (as described in Subs. 2.3), Ground SAR (see Subs. 2.4), and Joint (most joint components are described in Subs. 2.1). The latter classification is a useful addition, as the network that represents the entire SAR system can be partitioned based on the traditional subdivision of SAR service providers to help identify SAR assets suitable for specific tasks. Note that each SAR domain may include agents operating in different environmental domains. For example, the database agent INNAV belongs to Maritime SAR, as it provides marine traffic information, but operates in the cyber domain.

Mathematically, an agent is represented by a string of dimension N of the following form:

$$\sigma = [\sigma_1, \sigma_2, \dots, \sigma_N]. \tag{1}$$

In Eq. 1, σ_i is a binary variable that assumes values of $[0,1]$, or categorical variable that assumes values $[0,1,*]$ ($*$ stands for N/A), or continuous variable that assumes any real value.

Dimension N equals to the sum of the following parameters:

- number of agent classes (five in this case – see above);
- number of agent environmental domains (six in this version – see above);
- number of SAR operational domains (we distinguish between four SAR domains);
- number of agent classes with subclasses (one in this version);
- number of mobility factors (two in this case: mobile or portable);
- availability factor;
- number of knowledge nodes included in the model (29 in this version of SARnet);
- number of resource nodes (12 in this version of SARnet);
- number of organization nodes (26 in this version of SARnet);
- number of standby times (two in this case: working hours and quiet hours);
- latitude and longitude of the location of a home unit.

The last four variables in the above list – standby times and geographic coordinates – are continuous variables, whereas others are either binary or categorical variables. Standby times are specified times within which a SAR asset must be able to respond when called to duty. Different standby times are set for working and quiet hours. (Quiet hours cover hours outside a working period from 8:00-16:00 and weekends.) Geographic locations are locations of home units where SAR assets are normally located.

The unit values found in the first 15 positions of string σ indicate the agent class of a SAR asset, the environmental domain in which it operates, and the SAR operational domain to which the asset belongs, i.e.:

$$\exists i, j, k \begin{cases} \sigma_i = 1 & (i = 1, \ldots, 5) \\ \sigma_j = 1 & (j = 1, \ldots, 6) \\ \sigma_k = 1 & (k = 1, \ldots, 4) \end{cases} \quad (2)$$

There is only one agent class with subclasses in this version of SARnet – the database class. Therefore, the 16^{th} position in string σ is reserved to represent the subclasses of the database class. σ_{16} assumes values 0 or 1 when the SAR asset in question is a database RO or RW, respectively; and $*$ when it is not a database.

A SAR asset is deemed stationary, when both mobility factors are set to 0 (neither mobile nor portable). The availability factor is set to 1, when an asset is available for duty, and to 0 otherwise (e.g. for technical reasons).

Dimensions corresponding to knowledge and resource nodes indicate whether or not SAR assets have access to a particular knowledge or resource: $\sigma_i = 1$ means ‘Yes’; $\sigma_i = 0$ means ‘No’.

Dimensions corresponding to organization nodes indicate the membership of SAR assets in a particular organization: $\sigma_i = 1$ means ‘Yes’; $\sigma_i = 0$ means ‘No’.

Depending on the number of knowledge, resource and organization nodes included in the network model, dimension N could be relatively high and may include between 20 and several hundred dimensions. In this version of SARnet, $N = 90$. Note that dimension N could be increased to include more node attributes, if needed.

Table 6 summarizes the SARnet agent representation.

Table 6: *Multidimensional representation of SAR assets.*

Position in σ	**Designation**	**Variable Type**
1–5	agent class	binary
6–11	environmental domain	binary
12–15	SAR domain	binary
16	database subclass	categorical
17–18	mobility	binary
19	availability	binary
20–48	knowledge/expertise area	binary
49–60	resource	binary
61–86	organization	binary
87–88	standby time (working and quiet hrs)	continuous
89–90	latitude and longitude	continuous

The *ORA network visualization and analysis software [22] can be efficiently used to visualize and explore the above multidimensional data, as we show in Section 4.

3.2.2 The Concept of the Operational Network

In Subs. 1.1, we discussed some specifics concerning structural dynamics of socio-technical systems. As a consequence of these specifics, standard network-analysis techniques are not directly applicable to such systems. In particular, assessing network resilience to node removal in terms of the integrity of the giant component (as it is routinely done for large social or technological networks [12]) does not make sense, when considering socio-technical systems.

To overcome this deficiency of network analysis, we have developed a new concept of a network, which we call the Operational network. In what follows, we elaborate how the concept of the Operational network can be used to evaluate performance of joint interagency systems, a particular case of socio-technical systems, using an example of Arctic SAR.

The Canadian Arctic SAR system, which we described in Section 2, has been designed to provide a comprehensive range of SAR services. Conceptually, these services could be categorized as two main functions: (1) detection of an incident, and (2) execution of a SAR response. The second function involves collection of information concerning an incident, identification of the location of a vessel or aircraft in distress, delivery of aid, and extraction and evacuation of casualties.

The sequence of services, which will be provided after a distress alert is received, follows prescribed protocols and procedures (e.g. MAJAID and MAJMAR protocols). The SAR protocols serve as a blueprint for tasking SAR assets based on their specialization and availability. The nature (e.g. location of the crash site) and size of the incident also determine the choice of SAR assets being called upon.

As a result, a new network is dynamically created between SAR assets actively involved in a SAR response: new nodes join the network (e.g. a Vessel of Opportunity), and new links and shortcuts develop (e.g. between the Search Master and local CCGA unit).

To summarize, the Operational network is a step-by-step conceptual representation of the execution of a response action. The agent heterogeneity (see Subsubs. 3.2.1) is the main driving mechanism that governs the formation of the Operational network.

The Operational network is the most important network of SARnet, as its measures serve as performance indicators for the entire SAR system. As long as the system can create an efficient operational network, it can be considered efficient. Here, network efficiency is understood in terms of network measures, which we discuss in Subs. 3.3.4. Numerous examples of the application of network measures for evaluating operational efficiency of different systems are given in [12].

The following questions about system performance can be answered using the concept of the Operational network:

- *Resilience to technical failure or attack:* Will the system *degrade gracefully*[*] or will it fall apart after one or several nodes are removed?
- *Strategic readiness:* Can the system create the Operational network capable to handle an incident that is out of the ordinary, because of its size or severity?
- *Responsiveness to changing external conditions:* Can the system modify itself in response to changed external conditions, so that it is still able to create the efficient Operational network?

The above questions are important for system analysis. In the first case, the performance of the unperturbed operational net can serve as the baseline for evaluating the effects of random or targeted node removal. The second question can be answered through simulating a generation of the Operational network in 'what-if' scenarios (e.g. using the Generative Network Automata (GNA) [54]). The last question is a network optimization question. It can be answered through Evolutionary Computation (EC) (see Subs. 3.3 below) and simulation. The EC application for optimizing geographical networks has been explored by us in [59, 60, 23].

In Subs. 4.4.1, we use the case log of a real A1 incident[§], which occurred in the Arctic in December 2008, to develop and analyze a sample operational network.

[*]Degrade gracefully means that the system is still able to create the Operational network, albeit less efficient.
[§]The A1 class of incidents denotes air incidents with lives at risk.

3.3 Network-Based Tools

The SARnet model provides a virtual laboratory in which various aspects of system performance can be evaluated through accessing the visualization and computational capabilities of the model. Here, we describe the network-based tools that we have developed and applied in this project.

3.3.1 Assortative Networks

The notion of assortative mixing or homophily comes from social network science [21, 12]. It is a kind of selective linking, where nodes with similar properties or attributes (e.g. age or income) are linked in the network. In cases when an attribute of a node is expressed as a scalar or a vector, assortative mixing can be quantified by calculating a correlation coefficient for the attribute in question [12]. If network nodes represent multidimensional entities (similar to SARnet agents – see Subs. 3.2.1), then assortative mixing according to scalar or vector attributes can be used to visualize this multidimensional data in the form of *assortative* networks.

For example, each SARnet agent is represented by the multidimensional string σ with scalar variables σ_i $(i = 1,\ldots,N)$ (Eq. 1). Then various networks can be developed that link pairs of agents according to the value of one of these variables. Taking a step further, one can also perform assortative mixing according to a substring $\tau \subset \sigma$. A number of assortative networks between agent nodes could be obtained in this way.

Assortative networks can be visualized and used as an analysis tool for multidimensional data exploration. They can also be used to store assorted information in simulations or to perform range search[†] or similarity search[‡] in medium-to-high dimensional spaces. The utility of assortative networks is illustrated in Subs. 4.2.

3.3.2 Network Generation with a Distance Measure

In some cases, networks are not provided with input data, but need to be computed. Here, we show how it could be done using a distance measure. The proposed network-generation technique is applicable to any set of nodes equipped with a distance measure (e.g. the geographic distance between locations, the Hamming distance between binary strings, or the kinship measure between individuals.)

Let us consider a set of nodes S with a distance measure $d(u,v) \geq 0$. Set S represents some entities of the system in question, and distance $d(u,v)$ is any distance between a pair of nodes $(u,v) \in S$ defined on S. Then, the connectivity function δ on S is defined, as follows:

$$\delta(u,v,r) = \begin{cases} 1 & : \quad 0 \leq d(u,v) \leq r \\ 0 & : \quad d(u,v) > r \qquad (r \geq 0) \end{cases} \tag{3}$$

[†]Range search is one of the central problems in computational geometry which arises in database applications. A query range defines a region in a multi-dimensional space and searches for all data points in the region [61].

[‡]Similarity search is a particular case of the range search problem which aims to retrieve all points in the database most similar to the query point, according to a user-defined similarity measure [62].

In Eq. 3, r is the connectivity range. We say that two nodes (u,v) are connected, when $\delta(u,v,r) = 1$, and not connected, when $\delta(u,v,r) = 0$. Then each value of r generates a network on S.

In [23, 59, 60], the geographic distance and connectivity range corresponding to the fuel range of the CH-146 Griffon were used, as an example, to generate the airport network. (The Griffon helicopter is commonly used in SAR operations.)

The Hamming Distance and Weighted Hamming Distance

The Hamming distance and its variants is perhaps the most versatile distance measure for analysis of multidimensional data sets. The Hamming distance between two strings of equal length is the number of dimensions at which the corresponding variables are different. That is:

$$d(\sigma,\tau) = \sharp\{i\colon\, \sigma_i \neq \tau_i\}, \tag{4}$$

where σ and τ are strings of equal length.

If some of the variables are continuous, then the Hamming distance could be augmented through replacing the number of dimensions, which correspond to continuous variables, by the sum of absolute values of differences between these variables. That is:

$$d(\sigma,\tau) = \sharp\{i\colon\, \sigma_i \neq \tau_i\} + \sum\{|\sigma_k - \tau_k|\}, \tag{5}$$

where σ_i and τ_i are binary or categorical variables, and σ_k, τ_k are continuous variables.

In the case when some dimensions are more important than the others, the weighted Hamming distance can be used. The weighted Hamming distance is defined by:

$$d(\sigma,\tau) = \sum\{\omega_i\colon\, \sigma_i \neq \tau_i\}, \tag{6}$$

where ω_i is Hamming weight corresponding to dimension i.

3.3.3 Evolutionary Computation on Networks

Evolutionary Computation (EC) and its sub-class, Genetic Algorithms (GA), are powerful techniques that mimic natural evolutionary processes. EC combines iterative randomized search and optimization algorithms to solve combinatorial problems with large search spaces [63]. GA are a type of evolutionary algorithms that implement natural mechanisms inspired by biological evolution (namely: natural selection, inheritance, crossover, and mutation) to the population of the optimization problem (e.g. binary strings, trees, or networks) [64]. GA allow for automated optimization of networks by applying bio-inspired reproduction mechanisms to the population of “what-if” networks [64]. In the process of repeated application of the reproduction mechanisms, evolution of the population takes place. The standard GA use a single objective function that evaluates each individual to a numerical fitness value. For an optimization task with GA, the algorithm tries to minimize or maximize the fitness of the individuals in the population.

The utility of network optimization with GA is illustrated in [23, 59, 60]. The method is based on an evolutionary search of ‘what-if’ networks generated from a given seed network by node deletion and addition.

3.3.4 Network Measures

Networks come equipped with statistical measures that have been developed in Network Science for evaluating the performance of large social and technological networks [13]. These quantitative measures have been validated on numerous examples [13]. Such measures as density (also known as complexity), fragmentation, and communication speed are important performance indicators and can provide useful information about the modelled system. However, caution should be exercised, when applying these measures to medium-to-large socio-technical systems (Subs. 1.1).

Various graph measures [21] and extended graph measures [20] have been widely used in Social Sciences for analyzing social and organizational systems. Such measures as degree centrality, betweenness, and cognitive demand (see [22] for measure definitions) can be used to infer the significance of individual components for the network in question. It should be kept in mind that the interpretation of these measures have been derived from empirical material on social network, and hence could produce misleading results when applied to socio-technical systems [17].

4 The SARnet Model

In this section, we proceed with a step-by-step illustration of the construction of the SARnet dynamical network model of the Canadian Arctic SAR system from gathered Arctic SAR data. The Canadian Arctic SAR system is an example of a joint interagency system, as it involves components from different environmental domains and coordination of effort between DND and OGD/A (see Section 2 for the system description). The agents or active players of the SAR system are heterogeneous entities that differ by the roles they play in the network and by the environmental domains in which they operate. Therefore, dynamical network models with embedded heterogeneous agents proposed by us in [23] are appropriate for the SAR system.

In Subs. 4.1, we follow the DNA approach [20] in introducing different node classes to represent diverse components of the SAR system. In Subs. 4.2, we extend the DNA approach to accommodate the agent heterogeneity in the SARnet model.

4.1 Node Classes and Networks

Based on analysis of gathered Arctic SAR data, we use the following node classes to represent the SAR system components in the network model:

- *Agents:* SAR assets that play active roles in execution of a SAR response.
- *Organizations:* members of the NSP responsible for delivery of SAR services in the Arctic.
- *Knowledge:* areas of expertise, protocols, and procedures relevant to SAR.
- *Resources:* resources required to support SAR operations.
- *Locations:* geographic locations relevant to Arctic SAR.

Agent nodes represent SAR assets that are actively involved (albeit in different capacities) in a conduct of SAR operations. They access resources, possess knowledge, collect and exchange information with other agents, and do tasks. Some agents represent social components of the SAR system. Whereas other agents denote technological components or the mixture of both types in one entity. Examples of social components include CCG officers, teams of SAR techs, and Canadian Ranger patrol groups. SMMS and INNAV are technological components. Aircraft and ships with the crew are examples of mixed components. The complete listing of the SARnet agents is given in Tables A.1 – A.4 of Annex A.

Most agents represent SAR assets that are present in the real system at all times. For example, the agent JRCC Trenton denotes the actual rescue coordination centre of that name located in Trenton, Ontario. However, some agents are used as proxies for entities that are added or created on an ad hoc basis during a particular response action. A Vessel of Opportunity (VoO) and Forward Operating Base (FOB) are examples of such ‘ad hoc’ agents. The ad hoc agents are introduced in SARnet to reflect the dynamics of the SAR system.

For sake of simplicity, agents with identical attributes are grouped and then included in the model as meta-nodes [22]. Thus, the meta-node CCGS (CCG Ship) represents four CCG secondary SAR vessels, currently operating in the Arctic: CCGS Dumit, CCGS Eckaloo, CCGS Nahidik, and CCGS Tembah. Similarly, the meta-node agent, CCG icebreaker, denotes six CCG icebreakers: CCGS Louis S. St-Laurent, CCGS Terry Fox, CCGS Amundsen, CCGS Des Groseilliers, CCGS Henry Larsen, and CCGS Pierre Radisson. CCGAS is a meta-node agent that represents 14 CCGA vessels, operating in the Arctic waters. The SARnet meta-node agents are marked by $*$ in Table A.1 – A.4.

Organization nodes are abstractions of large groups of agents that denote membership or employment relationships in a conventional sense. They represent government departments, agencies, private-sector and volunteer organizations responsible for delivery of SAR services in the Arctic. The following government departments and agencies are included in SARnet as organization nodes: RCMP (Public Safety), Transport Canada, Parks Canada, Meteorological Service of Canada (Environment Canada), CCG (DFO), and CF/DND. The Department of National Defence and its subsidiaries are represented by the following organization nodes: CF/DND, NSS, Army, Army Reserve, Canada Command, CFLAWC, 1^{st} CRPG, Air Force, 424 Squadron, 435 Squadron, 413 Squadron, 103 Squadron, and 440 Squadron. The subsidiaries of the Department of Fisheries and Oceans are represented by CCG and CCG (C&A). Volunteer organizations are represented by the following nodes: CASARA, CCGA, and CCGA (C&A). Also included are NSS and ICSAR. There are two organization meta-nodes, Local Community and Private Sector, that represent Arctic communities and the private-sector group of SAR assets, respectively. The Cospas-Sarsat node represents the International program Cospas-Sarsat.

In total, 26 organization nodes are included in SARnet. This number can be expanded by including organizations at different levels of government. Likewise, the meta-nodes can be replaced by the sets of nodes that they represent (e.g. the Local Community meta-node can be replaced by the nodes representing each Arctic community of interest). (See Subs. 4.5 to find out how it could be done using *ORA.)

The knowledge node class represents expertise, protocols, procedures, and skill sets that are required for delivery of SAR services. The main purpose of knowledge nodes is to provide a match between the specialization of SAR assets and task requirements. This is a distinctive feature of the SAR system, where learning typically requires a large time scale. Thus, unlike social networks, knowledge diffusion does not play a significant role in SARnet.

The knowledge nodes, included in this version of SARnet, are: MAJAID and MAJMAR protocols, Primary Care Paramedic (PCP), Standard First Aid and CPR (SFA/CRP), casualty medical treatment, medical evacuation (medevac), medevac prep, Arctic survival, ocean rescue, ground search, search from aircraft, aid drop from aircraft, parachuting (at night, on ice, and on water), communication (by radio, flairs, smoke, ground signal, and hands signals), helicopter hoisting, SAR Mission coordination, asset tasking and coordination, on scene coordination, disaster scene management, Public Relations (PR) (including press release and information dissemination services), weather forecasting, marine communications and traffic services, marine data integration (radar, target tracking and communications), air traffic information services, distress alerts and location data provision, investigation of Emergency Locater Transmitter (ELT) cases, SAR assistance, search techniques, and knowledge of the local area.

In total, 29 knowledge nodes are included in this version of SARnet. This number can be expanded, if needed.

Resource nodes represent system components that organizations own and SAR assets use to accomplish their tasks. Some resources could be geo-referenced to a specified location (e.g. Arctic survival caches located in 7 Northern airfields – see Subs. 2.5), whereas others could be portable. Portable resources denote smaller resources that can be moved or carried by agents. These resources do not need to be geo-referenced since their location is identical to that of the agents carrying them. Portable resources typically denote SAR equipment such as First Aid kits.

The following resource nodes are included in SARnet: sixteen 20-person MAJAID kits, 2-person first-aid kits, six 50-person kits, a 25-person kit, Survival Kits Air Droppable (SKAD) which also includes two 10-person life crafts, Night Vision Goggles (NVGs), illumination flares, smoke markers, Self-Locating Datum Marker Buoy (SLDMB), pumps, radios, and Forward-Looking Infrared Radars (FLIR).

In total, 12 resource nodes are included in SARnet. This number can be increased to include more resources (Subs. 4.5)

Location nodes are used in SARnet to represent various geographic locations relevant to the provision of SAR services in the Arctic. We include the following geo-referenced locations in the model: CFB Trenton, 114 Arctic airports (north of the 60^{th} parallel), nine way-points on the cruise ship route in the Northwest Passage, and 15 Arctic communities: Inuvik, Norman Wells, Hay River, Yellowknife, Cambridge Bay, Rankin Inlet, Whitehorse, Teslin, Resolute Bay, Iqaluit, Alert, Fort Resolution, Fort Chipewyan, Aklavik, and Pangnirtung. An Arctic community is included in SARnet, if at least one of the following SAR system components is located in that community: (1) CASARA units; (2) CCGA units; and (3) Arctic survival kits (50 or 25-person). Note that all locations of CRPG patrols are not included in this version of SARnet.

Basic network data for constructing the SARnet model is shown in Table 7. In the table, columns and rows correspond to source and target nodes, respectively. Networks at the intersection of rows and columns link source and target nodes. Location vs. Location nets are not shown in the table, because of space constraints. The links in individual networks represent different types of relationships between components of the SAR system, as the table elaborates. If required, different weight values can be assigned to the links to reflect the strength of relationships. This feature is not used in the current version of SARnet.

Table 7: *SARnet basic network data.*

	Agents	**Organizations**	**Knowledge**	**Resources**
Agents / SAR Assets	Agent x Agent who works with whom	Agent x Organization who is a member of what	Knowledge net who knows what	Resource net who has access to what
Organizations	Organizational net who has what SAR asset	Interagency net who oversees/ collaborates with whom		Org. x Resource who owns what
Locations	Location x Agent who is located where			Location x Resource what is located where

The node classes, described above, and individual networks associated with these node classes are problem specific and can be easily expanded, if needs arise. For instance, a new node class, called 'Tasks' [22], can be added to represent various tasks associated with SAR response. This node class may include the following nodes: search for incident location, deliver aid, penetrate disaster scene, treat casualties, conduct evacuation, etc. Then the following networks can be developed in addition to the network listed in Table 7: the Assignment network (Agent x Task), which links agents to the tasks they are assigned to perform; and the Workflow network (Task x Task), which represents the sequence of tasks associated with SAR protocols (e.g. MAJAID). The procedure for addition of new node classes and networks to network models is described in Subs. 4.5. The task node class and associated networks are not included in the current version of SARnet.

The Interagency net that represents the organizational structure of the NSP is shown in Figure 8. The *ORA network visualization and analysis software [22] was used to visualize the Interagency net and all other networks presented here. In the figure, links represent relationships between organizations. The relationships could be hierarchical (e.g. DND vs. its subdivisions) or collaborative (e.g. collaboration through ICSAR). Hierarchical relationships are represented by unidirectional links, with arrows pointing from lead organizations (source nodes) to their subsidiaries (target nodes). In this context, subsidiaries also include organizations which lead organizations oversee. Collaborative relationships are shown as bidirectional links. The central SAR organization is represented by the NSS node. CASARA and CCGA (C&A) are two organization nodes that have collaborative links to local communities, represented as the Local Community meta-node. Cospas-Sarsat and Private Sector are two isolates in the Interagency net, but they are linked to their respective SAR assets in other networks of SARnet. The Interagency net is important for understanding interactions between various organizations within the SAR system.

The Organizational net, shown in Figure 9, is another important network for understanding the interagency aspect of the SAR system. It links organizations with their respective SAR assets. In

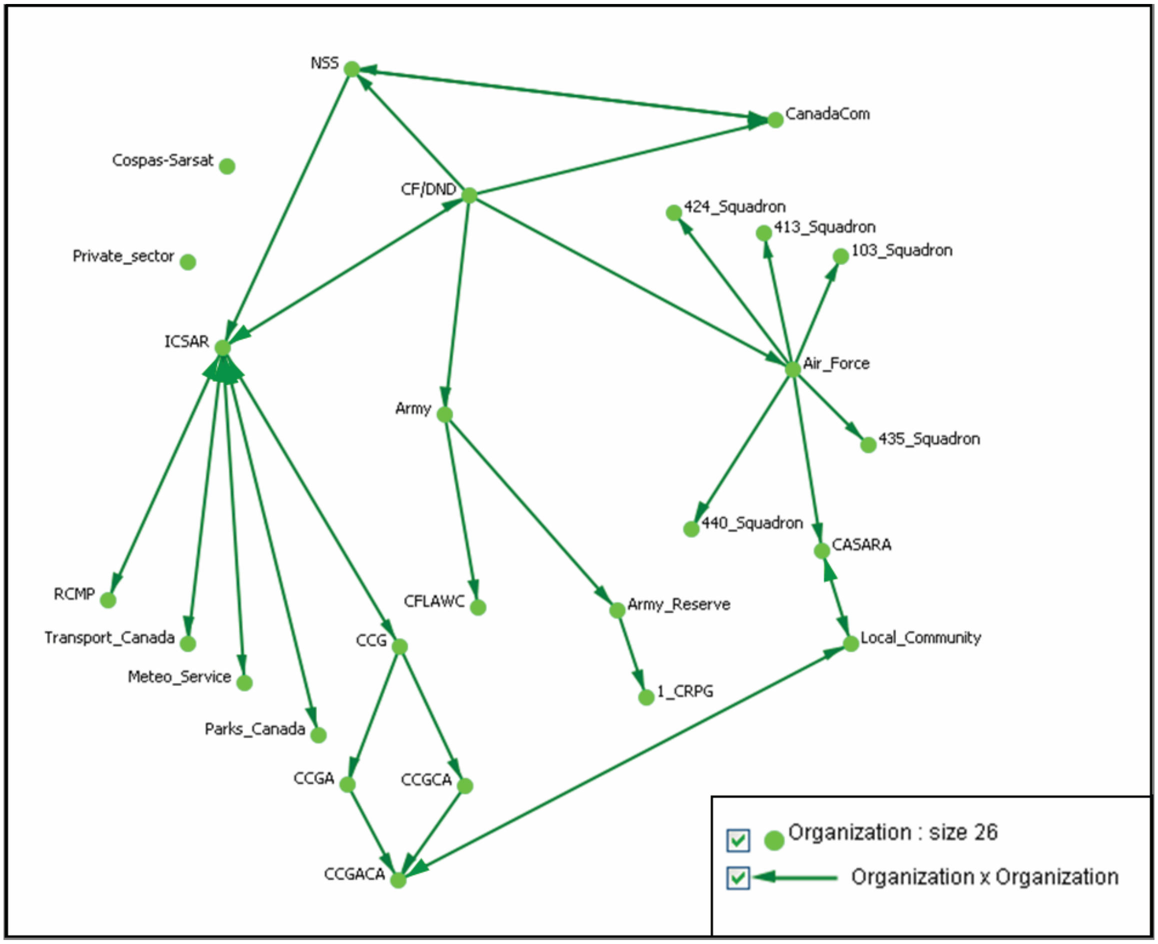

Figure 8: *The Interagency net (Organizations vs. Organizations) shows the interagency structure of the SAR system. Hierarchical and collaborative relationships shown as unidirectional and bidirectional links, respectively.*

the figure, organization and agent nodes are shown by green and red dots, respectively. Link colour matches the colour of the source nodes (in this case, organizations). Links are directed from the source to target node to indicate the ‘who has what SAR asset’ relationship.

The Knowledge net links SAR assets with their respective areas of expertise. It represents the ‘who knows what’ relationship in the SAR system. The Knowledge network is important for system analysis, as it displays the skill sets that are required for provision of SAR services. Thus, isolated knowledge nodes may identify capability gaps in terms of SAR expertise, and pendants (a knowledge node connected to a single SAR asset which is not a meta-node) may point out to potential system vulnerability. The Knowledge net of the SARnet model is shown in Figure 10. The ‘who knows what’ relationship is depicted by unidirectional links with agents and knowledge being source and target nodes, respectively. Again, arrows point to target nodes (in this case, knowledge).

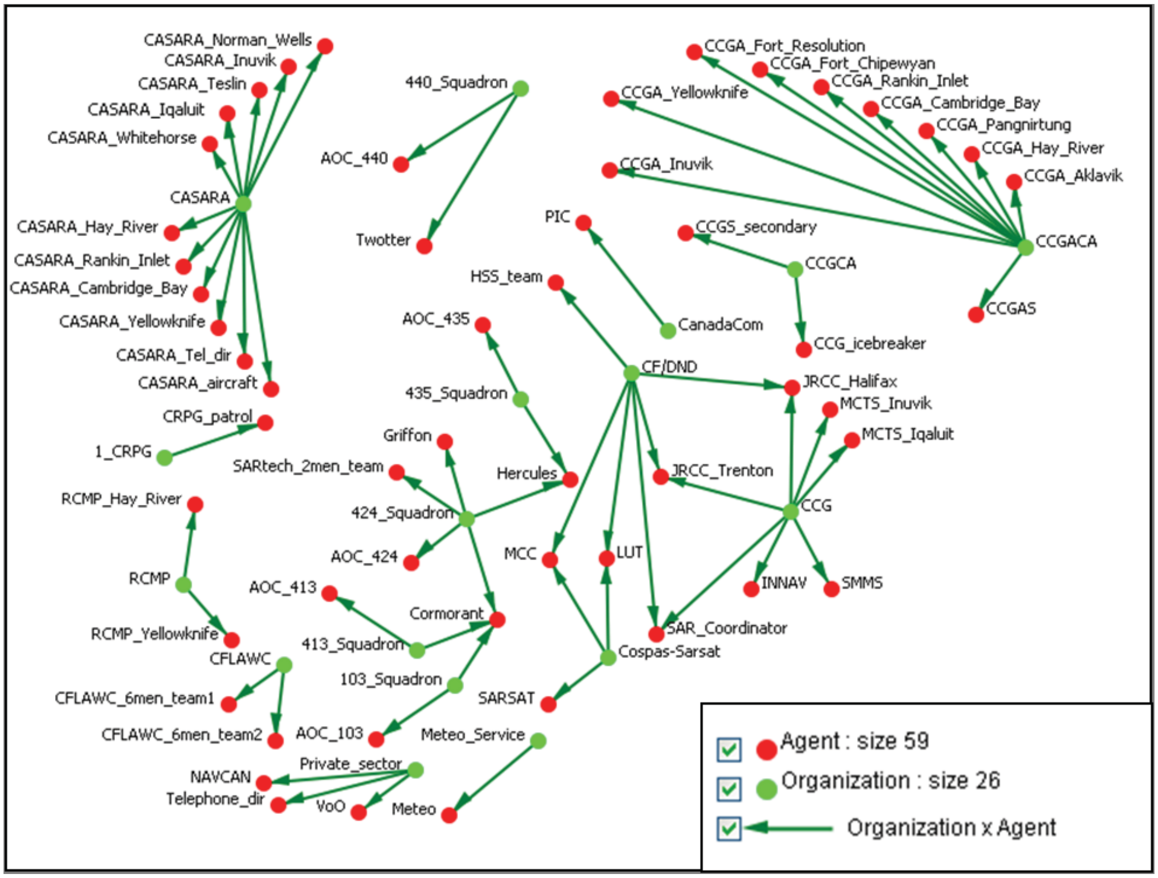

Figure 9: *The Organizational net (Organizations vs. SAR Assets) shows organizations and their respective SAR assets. Unidirectional links represent the 'who has what' relationship.*

The Resource net (SAR Assets vs. Resources) links agents with resources, representing the 'who has access to what' relationship between these node classes by unidirectional links from agents (source nodes) to resources (target nodes). The Resource net can be used in system analysis for identification of capability gaps in terms of material support. The Resource net of the SARnet model is shown in Figure 11. One can obtain a similar resource net that links organizations with their resources (Organizations vs. Resources), using the network multiplication technique under the ORA Matrix Algebra tool (see [22]; also see Annex B of [15]):

$$[\text{Organizations vs. Resources}] = [\text{Organizations vs. SAR Assets}] \times [\text{SAR Assets vs. Resources}],$$

where $\times$ denotes matrix multiplication of the corresponding matrices of the Organizational and Resource nets.

In Figure 10 and Figure 11, agents with similar attributes with respect to access to knowledge and resources are collated into meta-nodes. Thus, CASARA and CCGA units are represented by the CASARA regional and CCGA regional meta-nodes, respectively. Similarly, MCTSs, AOCs, and RCMP units are represented by the MCTS, AOC, and RCMP meta-nodes.

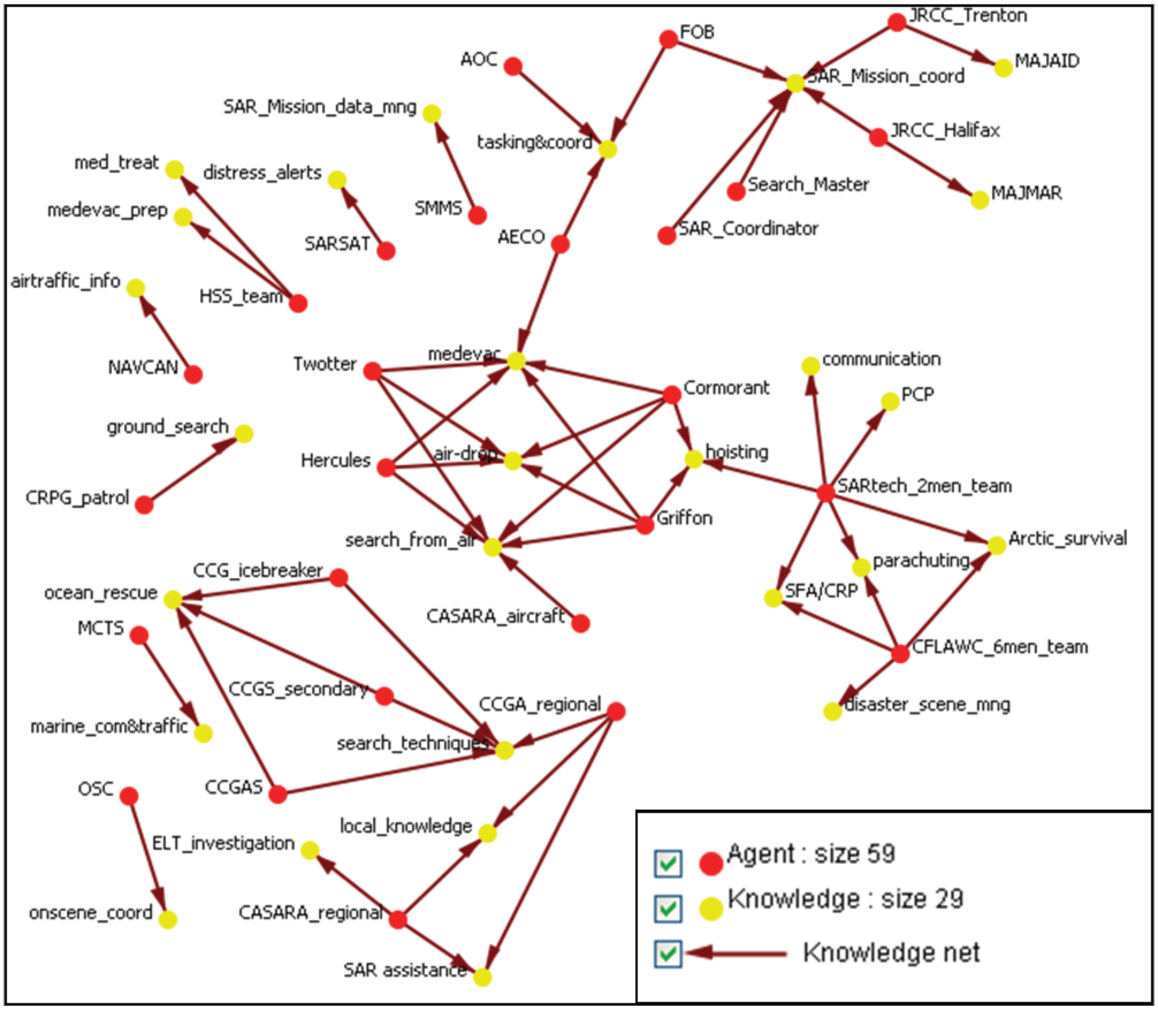

Figure 10: *The Knowledge net (SAR Assets vs. Knowledge) links agents with their respective areas of expertise. Unidirectional links represent the 'who knows what' relationship.*

Location nodes are used in SARnet to develop various location networks based on the 'who/what is located where' relationships (Location vs. Agent and Location vs. Resource nets in Table 7), as well as Location vs. Location nets (not shown in Table 7) based on a distance measure (see Subs. 3.3.2).

Figure 12 shows the location network that links locations (by geographic name) with SAR assets and Arctic survival kits. Brown and blue-green undirected links indicate locations of SAR assets and resources, respectively. Again, agents and resources with identical properties are collated into meta-nodes. As can be seen from the figure, there are no primary SAR assets in the North. Moreover, most of SAR assets designated to the Arctic are located outside of the region. Note that the 1st CRPG has patrols in more than 40 Northern communities; only 8 are shown in Figure 12. For a complete listing of the locations of CRPG patrols see [45, 46].

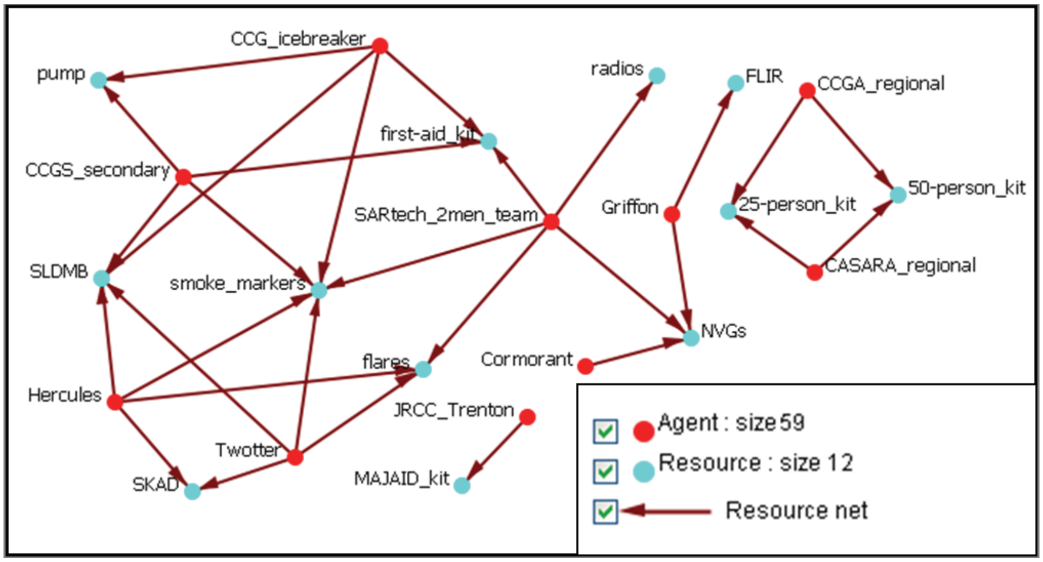

Figure 11: *The Resource net (SAR Assets vs. Resources) represents the 'who has access to what' relationship.*

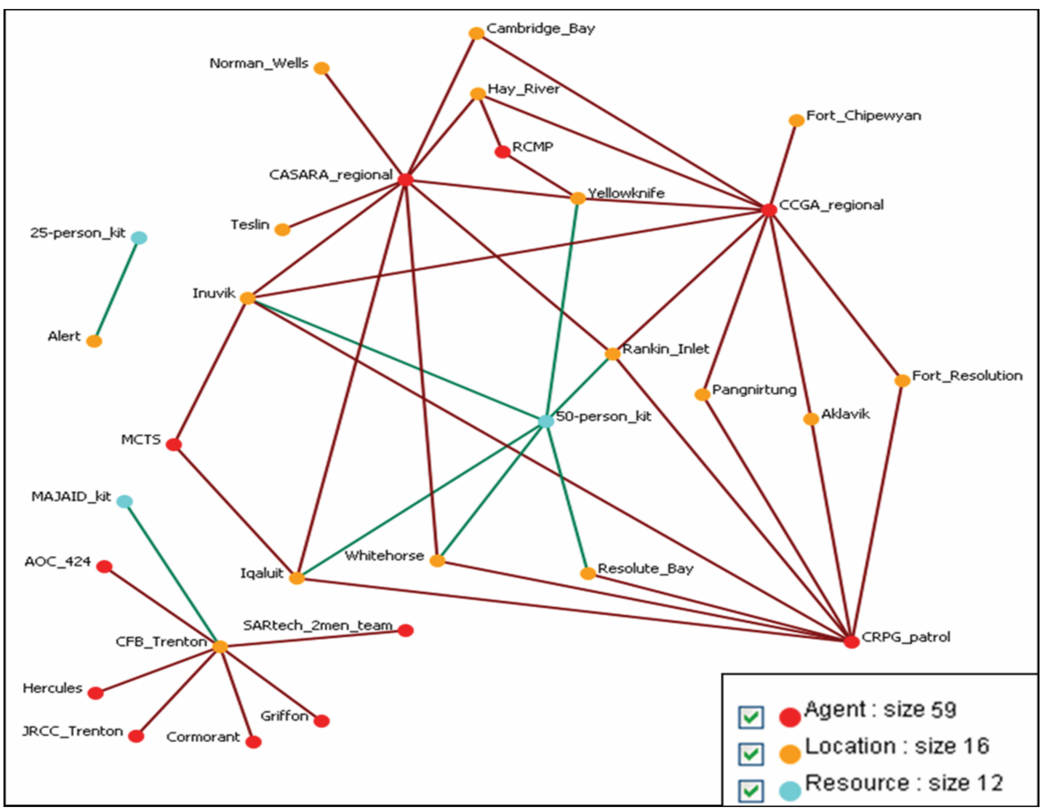

Figure 12: *The Location net (Locations vs. selected SAR Assets and Resources) represents the 'who/what is located where' relationship.*

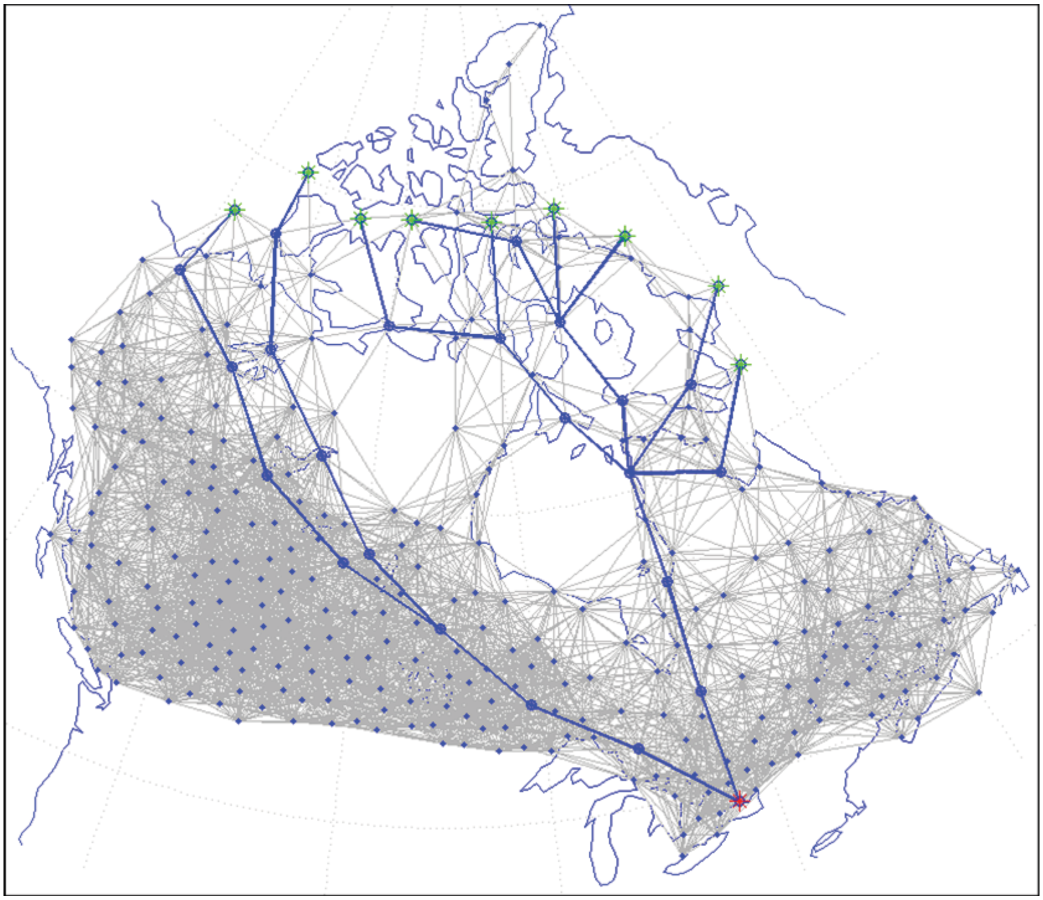

Figure 13: *The airport network and SAR response paths. The airport net consists of airport nodes (blue dots) and connection links (grey lines). Response paths (blue lines) are minimum hop shortest paths from CFB Trenton (red star) to sites along the Northwest Passage (green stars).*

Figure 13 shows the network of airports on the map of Canada together with possible SAR response paths to the sites on the cruise ships route in the Northwest Passage (airport location data from [51]). The airport locations are shown by blue dots and the links are depicted by grey lines. The red star corresponds to the location of CFB Trenton, and the green stars represent possible incident sites along the Northwest Passage. SAR response paths are represented as minimum hop shortest paths by blue lines.

Unlike other networks in the model, the airport network was not provided with input, but had to be computed (see [59] for details). In [59], the connectivity range of 5.8 arc degrees (approx. 354 nmi) was used, as an example, to illustrate the application of network generation techniques, described in Subs. 3.3.2. The distance of 5.8 arc corresponds to the fuel range of the rotary wing aircraft CH-146 Griffon. While C-130 Hercules aircraft have a large fuel range, their operation is constrained by specific landing and take-off requirements. Therefore, rotary wing aircraft such as the CH-146 Griffon are used to reach remote disaster sites, to rescue survivors, and to carry them back to the nearest airport or hospital. According to [59], five to eight hops of a Griffon helicopter are required to reach potential incident sites from CFB Trenton. A network hop represents a distance between two airport fuel stops. It should be noted that each fuel stop increases the probability of technical failure or delay (e.g. due to fuel shortage or specific refueling requirements of the aircraft).

Agent vs. agent networks are represented in this version of SARnet by two networks: Standby and Operational. The Standby and Operational nets are discussed in Subs. 4.3 and Subs. 4.4, respectively. In addition to networks described above, a number of assortative networks (Subs. 3.3.1) are included in SARnet. These are discussed below.

4.2 Exploring the Agent Heterogeneity with Assortative Networks

Agents in SARnet are represented by 90-dimensional strings of data σ (Eq. 1). Each of the 90 dimensions represents a particular agent property or attribute (Table 6). The first five binary variables in σ denote agent classes that we introduced in Subs. 3.2.1 based on agent specialization: sensor, router, actor, database, and controller. Next six variables represent the environmental domains in which agents operate: maritime, land, air, space, cyber, and cognitive. σ_{11} to σ_{16} represent SAR domains: Air SAR, Maritime SAR, Ground SAR, and Joint. Assortative networks provide a tool with which these multi-dimensional data sets can be efficiently explored. In what follows, we illustrate the utility of assortative networks for multi-dimensional data visualization.

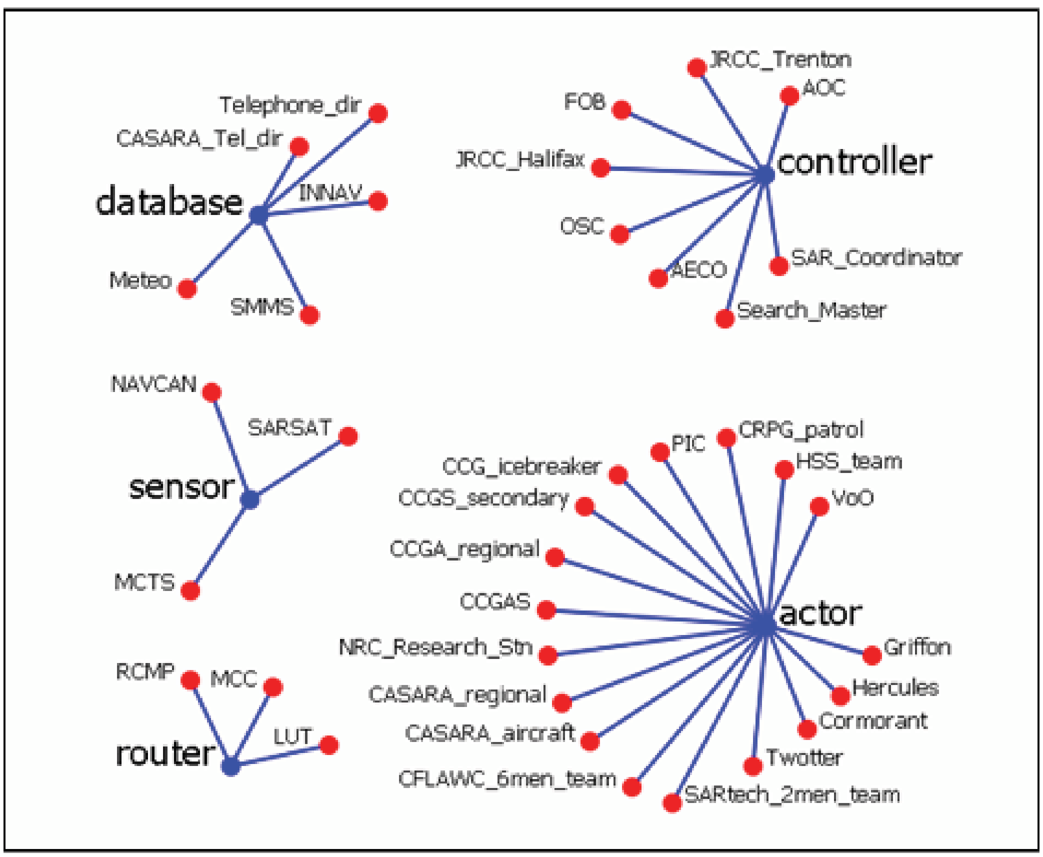

Figure 14: *SAR assets (red dots) grouped and visualized according to agent classes (blue dots).*

Assortative networks according to the first 15 dimensions of string σ are shown in Figures 14 – 16. In the figures, agents are shown in red. The agents attributes/dimensions are labeled and coloured according to the following colour scheme: ground/land domains are shown in green, air in blue, maritime in navy, space in black, cognitive in orange, and joint in magenta. Links connect agents to their corresponding attributes. Link colour matches the colour of the attribute. Figure 14 visualizes agent classes, as represented by substring $\tau = [\sigma_1, \ldots, \sigma_5]$. In Figure 15, SAR assets are grouped according to environmental domains of operation ($\tau = [\sigma_6, \ldots, \sigma_{11}]$). Figure 16 shows four groups of SAR assets according to the traditional subdivision of SAR services ($\tau = [\sigma_{12}, \ldots, \sigma_{15}]$). The *ORA software [22] was used to develop and visualize assortative networks.

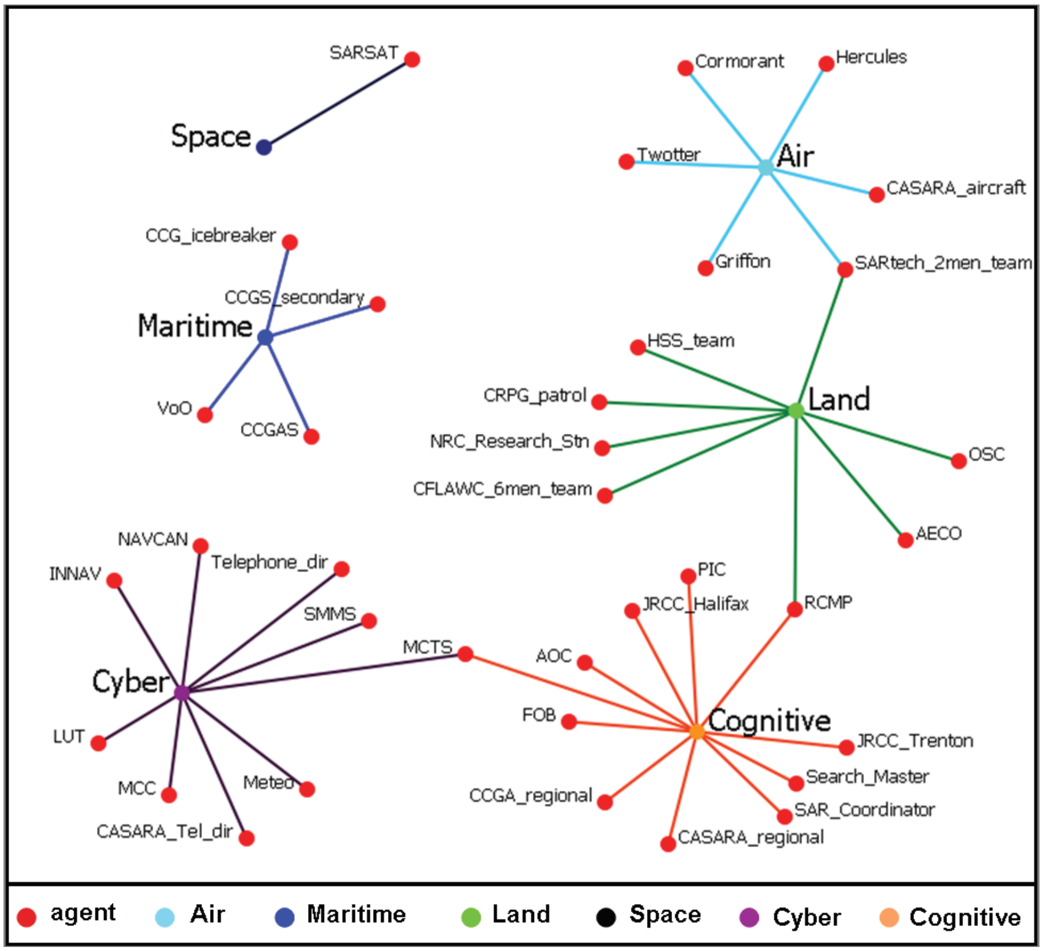

Figure 15: *SAR assets grouped and visualized according to environmental domains. Link colour matches the colour of the domain.*

Assortative networks, presented in Figures 14 - 16, provide useful information about SAR assets. The Knowledge and Resource nets, shown in Figures 10 - 11 respectively, can be used to group SAR assets according to their access to knowledge and resources. The corresponding assortative networks are the transpose of the Knowledge and Resource nets, respectively. Similarly, the Organizational network, shown in Figure 9, can be transposed to develop an assortative network according to the membership in organizations.

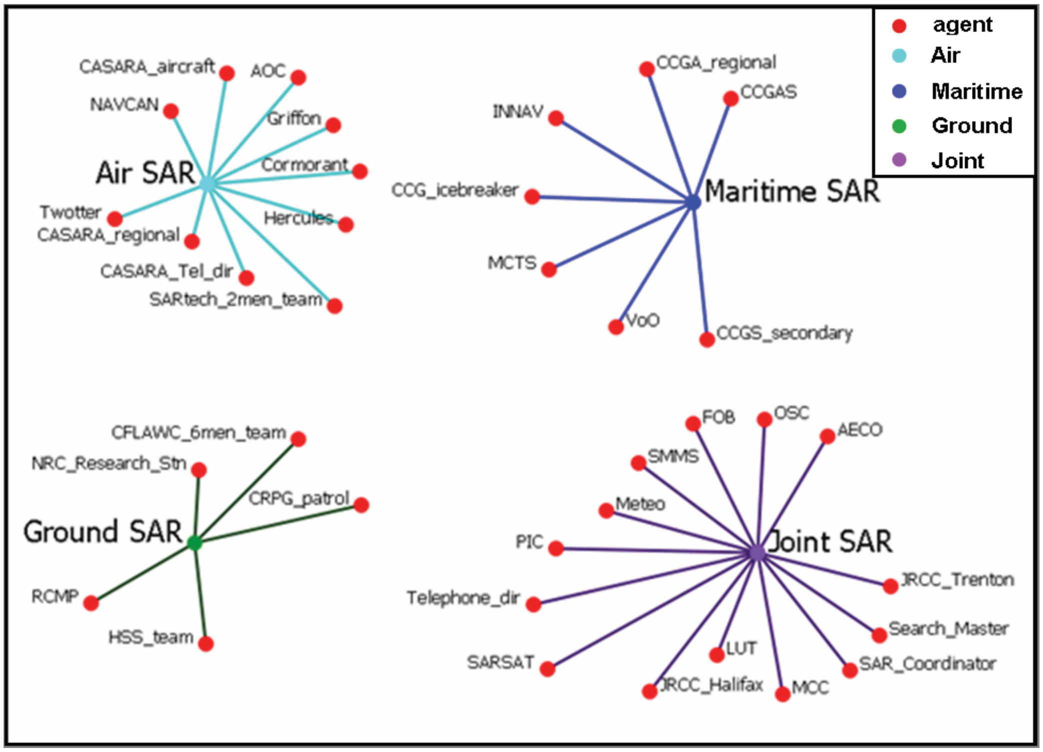

Figure 16: *SAR assets grouped and visualized according to SAR domains. Link colour matches the colour of the domain.*

In addition to the visualization capabilities described above, assortative networks can serve as supplementary constructs for quick automated search of available SAR assets through application of medium to high-dimensional range search [61] or similarity search [62]. Automating the search process will help to identify appropriate SAR assets to perform the task at hand in an efficient way and in accordance with SAR protocols and procedures. Automated search with assortative networks can be used in system analysis at the operational to strategic level of decision making, as well as a tactical tool in the conduct of SAR operations. This useful application of assortative networks will be explored in the future.

4.3 The Standby Network

The Standby network is a network between SAR assets that maintains the standby posture of the SAR system and performs everyday functions, such as maintenance and training. It links agents based on working relationships, such as ‘who works with whom’, ‘who communicates with whom’, ‘who reports to whom’ (for actor agents), ‘who tasks whom’ (for controller agents), and ‘who has info about whom’ (for databases).

The resulting network is shown in Figure 17. All agents are shown in red, with an exception of ad hoc agents, which are shown in blue. Some ad hoc agents are created in the course of an operation (e.g. FOB), while others temporary join the SAR system when called upon (e.g. VoO).

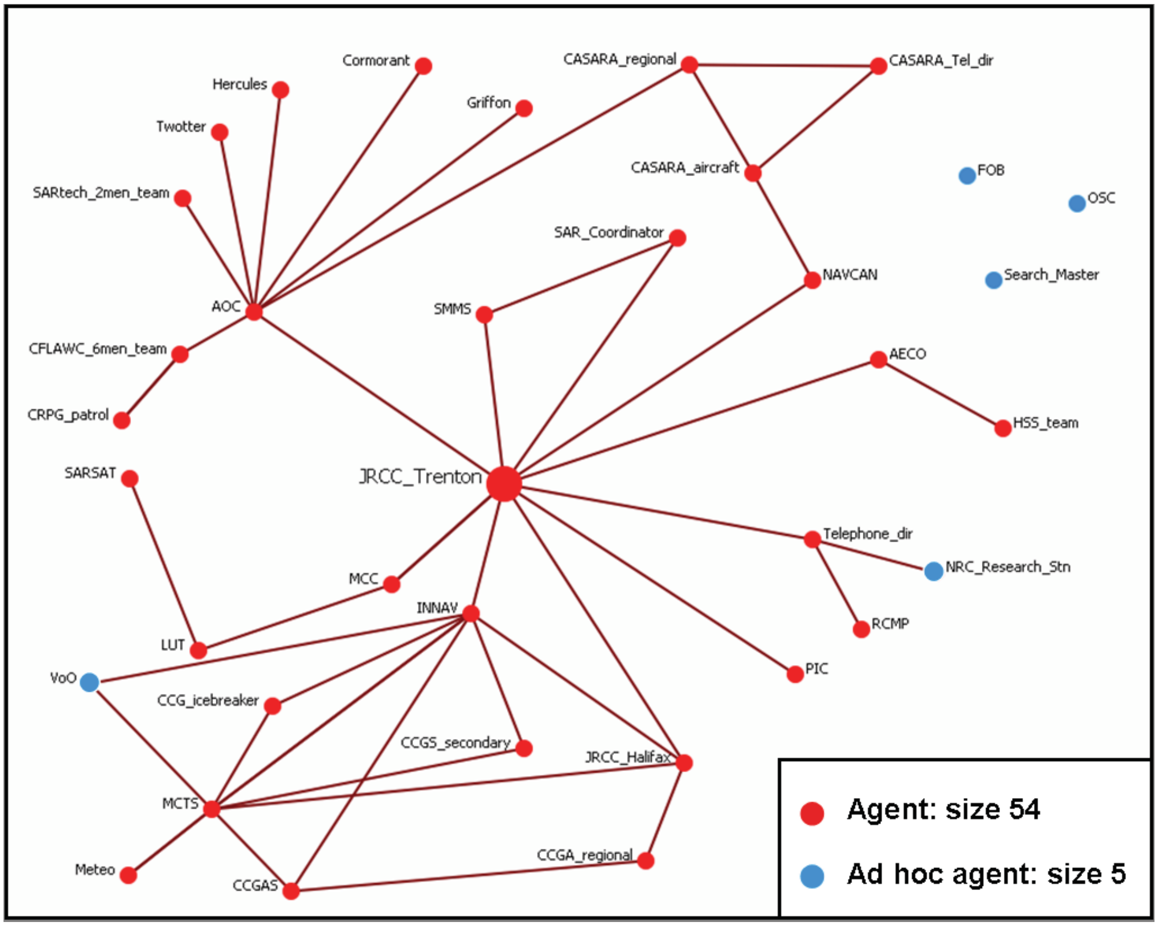

Figure 17: *The Standby network represents the standby posture of the SAR system.*

Again, agents with similar attributes are grouped into meta-nodes. The meta-nodes are used for representation purposes only, and can be expanded in simulations. The VoO ad hoc meta-node represents all commercial ships in the Arctic waters tracked by MCTSs and INNAV (as indicated by links in Figure 17). These ships are not part of the SAR system, but could be charted to provide SAR services, when needed.

Similar to other networks included in Table 7, the Standby net has been imported into *ORA as table data. Alternatively, one can obtained the Standby net by exploiting matrix algebra capabilities available within the *ORA Matrix Algebra tool [22], using the following matrix algebra operation:

$$[\text{Standby net}] = [\text{Organization x Agent}]^T * [\text{Organization x Agent}]\,,$$

where $[\text{Organization x Agent}]^T$ is the transpose of the Organizational network.

The above method could be the only viable option, when information about system functionality is limited or not available (e.g. in the case of adversarial or illicit systems).

4.4 The Operational Network

The Operational network represents the operational architecture of a response action to a particular SAR incident. It dynamically develops on the nodes of the Standby network (Figure 17) and links SAR assets, which are called upon to provide specified SAR services.

The following chain of events triggers the creation of the Operational network:

1. A sensor agent (e.g. SARSAT) detects an incident and sends distress alert and location information through appropriate routers, LUT and MCC, to the controller agent, JRCC Trenton which houses the Canadian MCC.

2. JRCC Trenton initiates a SAR response by appointing one of the controller agents representing SAR Mission Coordinators, as the Search Master. From now on, the Search Master is responsible for the SAR operation in question until closure of the case.

3. The Search Master takes necessary steps to prosecute the response, such as
   (a) verification of the Last Know Location (LKL) and other relevant information about aircraft/vessel in distress, including the number of People on Board (PoB);
   (b) consulting database agents about actor agents nearest to the LKL;
   (c) requesting assistance from other controller agents (e.g. AOCs);
   (d) tasking appropriate actor agents;
   (e) securing resources (e.g. fuel for aircraft, accommodation for the crew, hospital emergency room, survival equipment);
   (f) declaration of MAJAID or MAJMAR, if warranted;
   (g) establishment of FOB, if warranted;
   (h) deployment of OSC;
   (i) issuing notifications, updates, and briefings (e.g. to the Next of Kin (NoK), relevant authorities, and media);
   (j) coordination of rescue effort;
   (k) authorization and coordination of redeployment of SAR assets to home units.

As a result, a new network develops between agents of the Standby net: new links/shortcut appear between SAR assets actively involved in the response (e.g. between the Search Master and local CASARA unit) and new nodes join the network (e.g. VoO is charted to conduct the rescue). SAR protocols and procedures serve as blueprints for the network development. The dynamics of the Operational net differs from that of other networks, as its architecture evolves at the time scale of minutes or hours instead of months or even years, as in the case of other networks in the system.

The nature and size of the incident determine what SAR assets will be involved in the response action in question. Of particular significance are the type and location of the incident (i.e. marine or air); and the number of lives at risk. If this number exceeds six, then MAJMAR or MAJAID will be declared and corresponding protocols will be followed [24].

The main driver for the formation of the Operational net is the agent heterogeneity. Such attributes as agent class, environmental domain, and SAR domain (as visualized in Figures 14, 15 and 16, respectively) play an important role in selecting the most appropriate responders among SAR assets. The agents' skill sets and access to resources (as depicted in Figures 10 and 11, respectively) are taken into account, too. The LKL information also plays a role in what SAR assets will be deployed.

Conceptually, the process of the generation of the Operational network can be subdivided into the following steps:

1. Searching for the most appropriate SAR asset to perform the task at hand;
2. Issuing an order to deploy; and
3. Tasking and deployment of the identified asset.

In general, the above steps will need to be repeated, according to prescribed SAR protocols and procedures.

Computationally, these steps correspond to the following:

1. Medium to high-dimensional similarity search or range search;
2. Changing the node status to active; and
3. Generation of a new segment of the Operational net.

The above steps will need to be repeated iteratively.

Note that it is possible to represent SAR protocols as networks between nodes of a new class, called Tasks [20]. This feature is not included in the current version of SARnet, but will be incorporated into the next version (see Subs. 4.5 on how it could be done.)

As we point out in Subs. 3.2.2, the network measures of the Operational net serve as performance indicators for the entire system. Such measures as density (also known as complexity), fragmentation, and average communication speed provide useful information about the performance of the SAR system and can be efficiently used at the operational-to-strategic level of system analysis. The development of a decision-support tool for quick automated search of the most appropriate SAR assets is another potential application of the concept of the Operational network (Subs. 3.2.2). SAR mission coordination is a highly complicated manual process that is performed by the Search Master. Land-line, radio and electronic communication between the Search Master and multiple entities is the main means for identification and tasking of available SAR assets. Automated generation of parts of the Operational network will help to reduce response times, optimize use of SAR assets, and decrease cognitive loads on human coordinators.

In what follows, we present a sample Operational network that we developed based on the Search Master's log of the December 2008 A1 (air with lives at risk) incident in the Arctic. This is done with two purposes in mind: (1) SARnet validation; and (2) identification of possible ways of improvement in terms of SAR Mission efficiency through application of modern network technologies.

4.4.1 The December 2008 Incident in the Arctic

On 7 December 2008 a small two-engine Cessna plane with two PoB crash-landed in the Arctic (approximately 120 nmi from Iqaluit, Nunavut). The plane sank within minutes. The Swedish pilot and his Australian co-pilot (the only two people who were on board) managed to escape through the plane window on a slab of ice. Prior to the crash, the men sent three Mayday calls, which were intercepted by two other aircraft, a KLM commercial flight and a CF aircraft. The calls were then relayed to the Montreal Area Control Centre (Mtl ACC, as referred to in the case log). The Montreal ACC is one of seven ACCs, operated by NAVCAN; its area of responsibility includes the Arctic, among others. The Montreal ACC relayed the Mayday calls to JRCC Halifax, which is the JRCC responsible for that sector of the Arctic.

The Canadian SAR system mounted a response to the incident, which involved three SAR squadrons (103, 413 and 424), RCMP and CASARA regional units, local police, Swedish authorities (the plane belonged to a Swedish air company), CCG services, and private-sector air and marine assets. In less than 18 hours from the time of the first mayday call, the two survivors were rescued by the Fishing Vessel Atlantic Enterprise (with mild frostbites, otherwise in good condition). JRCC Halifax identified and tasked the vessel, and coordinated the search and rescue operation.

The Vessel Monitoring System (VMS) – the predecessor of INNAV – allowed for a quick identification of the VoO, nearest to the Last Known Location (LKL). The information about two fishing vessels in the vicinity of the LKL was obtained in the first five minutes after the initiation of the SAR response. In the next 15 minutes, one of the identified vessels – Atlantic Enterprise – was contacted by the JRCC, tasked, and began the sortie. During the first hour, the Search Master was able to obtain primary radar hit on the LKL from NORAD (15 nmi north of the original LKL), which played an important role in directing the search. Direct and Air-Ground-Air (AGA) communication links between the Search Master and deployed SAR assets helped to speed up the response. A use of NORAD (which is not part of the SAR system) and other ad hoc assets (e.g. Aircraft of Opportunity or for short ACoO) greatly facilitated the rescue effort.

The Search Master had the power and authority to access military, CCG, and private-sector SAR assets through communication links to relevant controller agents (such as AOCs), and then through creating direct links (shortcuts), in some cases via routers, to the deployed assets. In total, the Search Master's log of the incident referred to 79 different entities. With 53 of them (or 67% of the total number of agents involved), the Search Master had a direct communication link (shortest possible chain of command).

According to our analysis, the following factors contributed to the overall success of the operation:

- Efficient Vessel Monitoring System (VMS);
- Timely and accurate identification of the LKL;
- Efficient marine and AGA communication systems;
- Use of ad hoc assets (VoO, ACoO, databases and routers);
- Short chain of command.

The short chain of command of the Operational network, created by the Search Master in the course of this operation, was the main contributing factor to the successful outcome. However, the network architecture could be further optimized through automation of some parts of SAR Mission coordination. For example, the Search Master had to make several phone calls to different entities regarding the information on ice conditions at the LKL. This information could be made available to the Search Master through automatically accessing relevant database agents immediately after preliminary location information was transmitted to the JRCC. Also, the Operational network included several dead-end communication links to controller agents, who could not provide any SAR assets. These inefficient links could be eliminated and the entire network could be streamlined through the introduction of automated search capabilities into SAR Mission coordination.

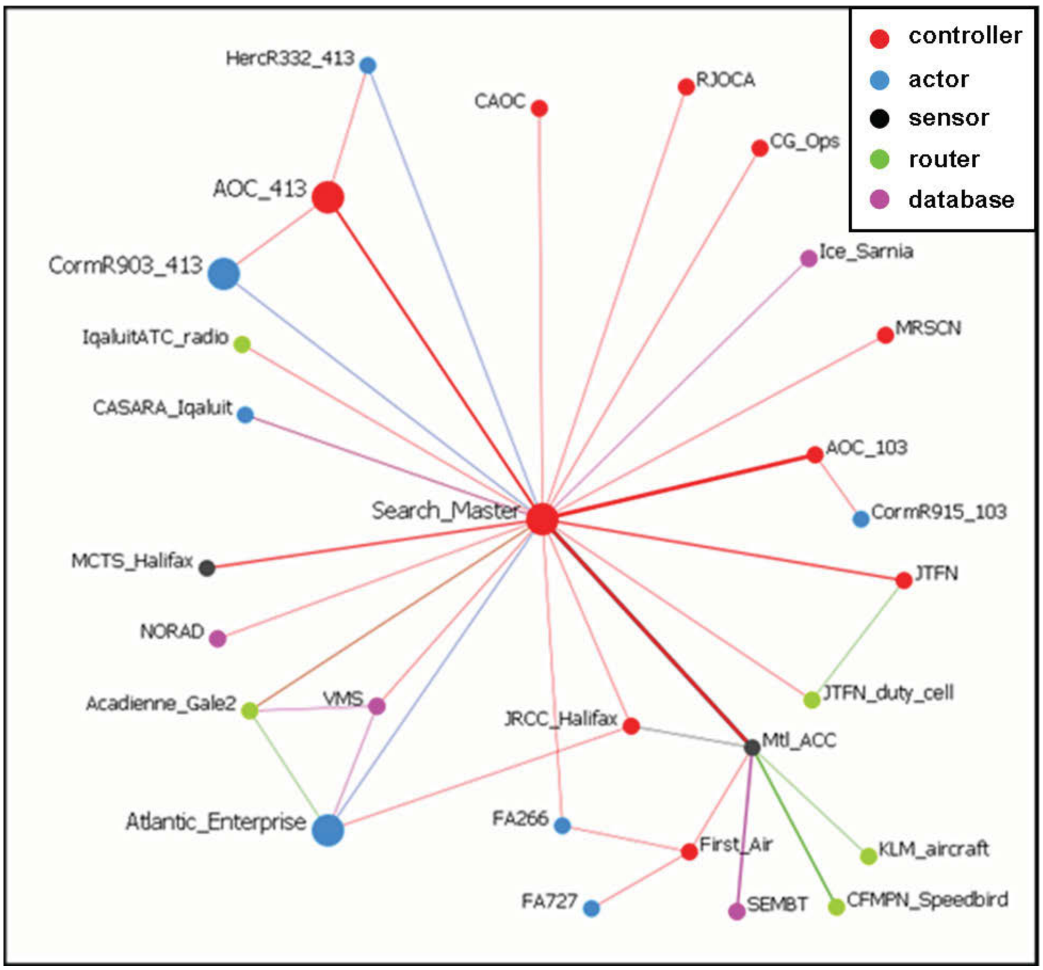

Figure 18: *The A1 Operational net 1 hour after the response initiation.*

Figure 18 and Figure 19 show the snapshots of the Operational network 1 and 3 hours after the response initiation, respectively. The final snapshot is shown in Figure 20. In the figures, controllers are shown by red, actors by blue, sensors by black, routers by green, and databases by magenta dots. The link width is proportional to the number of calls (including electronic and other types of communication) between corresponding agents.

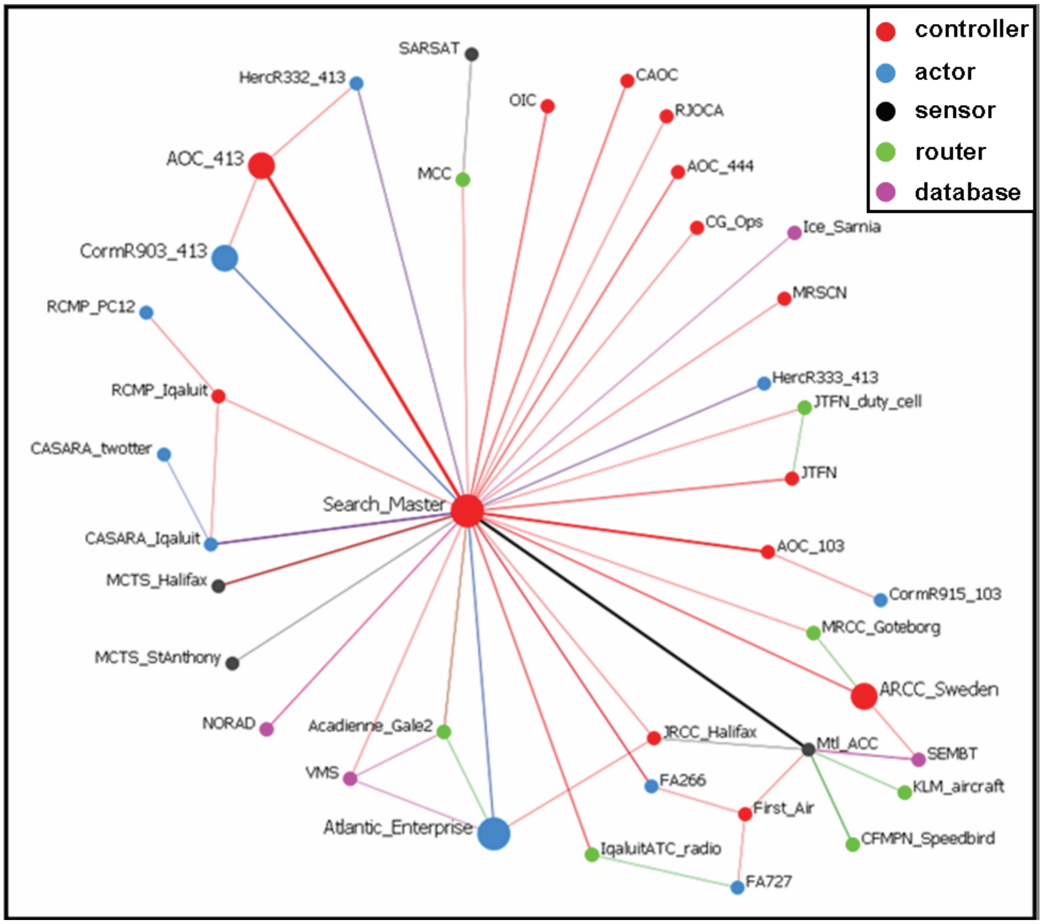

Figure 19: *The A1 Operational net 3 hours after the response initiation.*

A comparison of Figures 18 – 20 indicates that all major players were quickly identified and added to the network at early stages of its development. By the end of the first hour of the response, the network included 28 agents and 41 links, i.e. 30% of the final network (Figure 18). After the first three hours, 40 agents and 64 links, i.e. nearly 50% of the final net, were in place (Figure 19). By the time when the PoB were rescued (i.e. 18 hours after the response initiation), more than 80% of the Operational net had developed.[¶] Network dynamics is summarized in Table B.1 of Annex B.

The final A1 Operational network included the following CF assets: two Cormorant aircraft (CormR plus tail and squadron numbers in the figures), four Hercules aircraft (HercR plus tail and squadron numbers), and an Aurora aircraft. The Cormorant and Hercules aircraft carried SAR Techs and one Hercules carried an OSC. The Cormorant and Hercules aircraft were used to conduct search from the air. One of the Cormorants (CormR903 413) hoisted the PoB from the fishing vessel and transported them to the Iqaluit airport, where they were met by an ambulance. The Aurora aircraft was used to carry a replacement crew and to transport CF staff back to home units.

[¶]The remaining 20% consist of notification and briefing calls to Canadian and Swedish authorities and the media about successful rescue, plus calls regarding arrangements to return SAR assets to home units, made by the Search Master. Since these calls were made before the case was closed, they were also included in the Operational net.

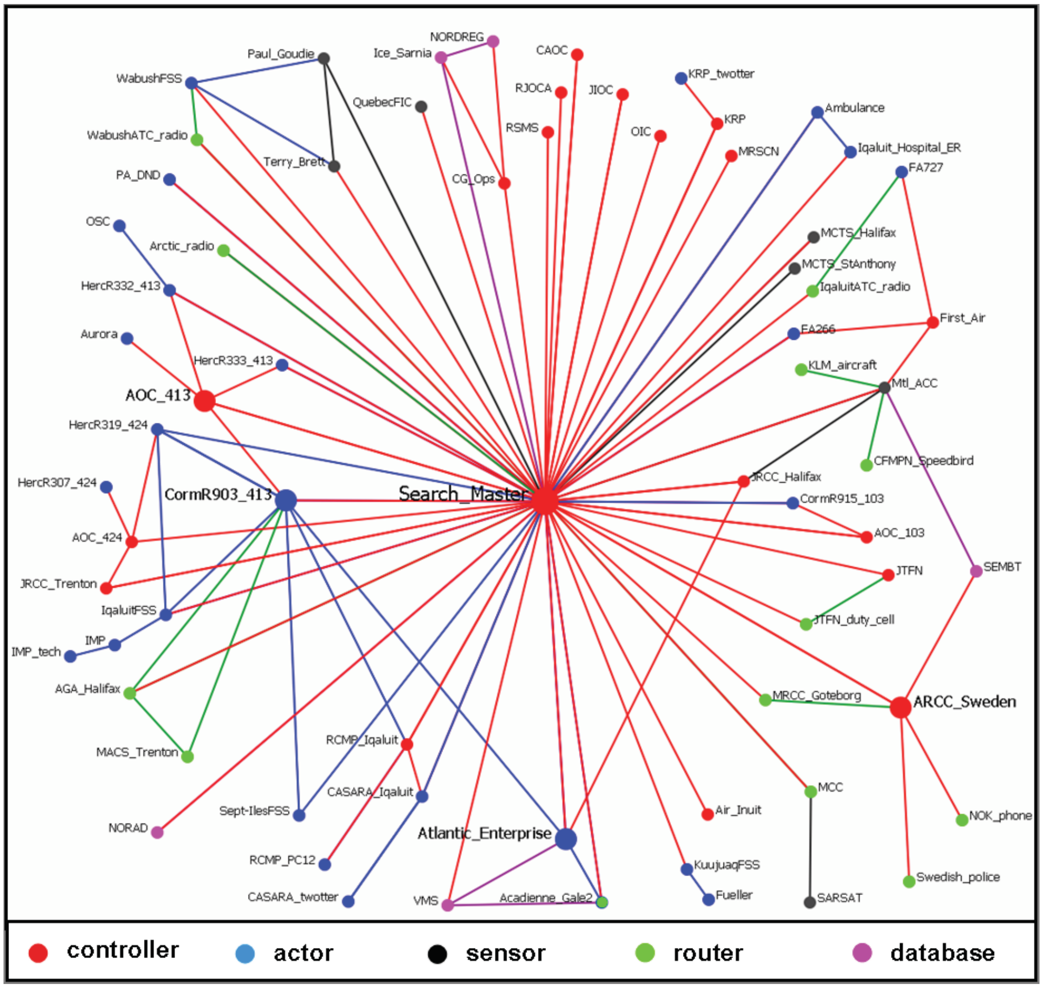

Figure 20: *The A1 Operational net (final snapshot).*

CASARA Iqaluit provided a twin-otter aircraft with spotters. RCMP Iqaluit provided a Pilatus PC-12 single-engine aircraft. Both aircraft participated in the search operation. Katavic Regional Police provided a twotter, as a back up aircraft. The CCG assets included two MCTSs, CG Operations (other than SAR), and database resources. The search and rescue operation was run from JRCC Halifax by CCG (deck) officers on duty.

Since the downed aircraft belonged to a Swedish air company, Swedish authorities participated in the operation. SEMBT is a Swedish aircraft registry that provided information about the aircraft (transponder codes) and the pilots (names and NoKs). The Aeronautical Rescue Coordination Centre in Sweden (ARCC Sweden) handled the NoK notification through creating a special NoK phone number. Swedish police obtained contact information of NoKs and verified the identity and nationality of the pilots. The Maritime Rescue Coordination Center in Goteborg, Sweden (MRCC Goteborg) served as a router between the Search Master and ARCC Sweden. There was intensive telephone and email communication between the Search Master and ARCC Sweden (more than 20 emails sent with updates on the situation in addition to telephone calls).

Figures 18 - 20 show several ad hoc nodes that are not part of the SAR system, but joined the network on an ad hoc basis. These nodes are: NORAD (provided vital radar data on the LKL); the NORDREG ice services for navigation in the Arctic waters and the CCG Ice services office in Sarnia, ON (provided info on the ice cover and weather); AGA Halifax and Military Aeronautical Communications System Installation in Trenton (MACS Trenton in the figure). First Air Commercial Airline Company (self-tasked to do search of the area with two aircraft, FA 266 and FA 727); Air Inuit (provided info on refueling); Iqaluit Hospital and Ambulance (treated the PoB).

A comparison of the Standby network (Figure 17) and the A1 Operational network (Figure 20) indicates that the SARnet model does capture all essential components and structural characteristics of the SAR system.

4.4.2 Network Analysis

For the purpose of this project, we conducted a network analysis of the A1 Operational network, discussed above. The performed analysis involved application of network measures, both at the level of individual components/nodes and at the network level. The node-level measures were applied to identify key network entities, and the network-level measures were used as performance indicators for the network as a whole. Network analysis results are presented below.

According to the node-level analysis, the following five agents repeatedly top-ranked in most of the measures: the Search Master, CormR903 413, AOC of the 413 squadron (AOC 413 in Table 8), Fishing Vessel Atlantic Enterprise (FV AE in Table 8), and ARCC Sweden. (These agents are shown by enlarged nodes in Figures 18 – 20.) The Search Master was ranked first in most of the measures, while CormR903 came second. AOC 413 was ranked in the top three in the 50% of the measures. Atlantic Enterprise and ARCC Sweden scored relatively high on degree centrality measures as well as on shared situation awareness, as compared to other agents.

Table 8 shows agent ranking with respect to selected standard network measures. The meaning of each measure is explained below. Measure values for five agents that top-ranked on each of these measures are given in Tables B.2 - B.5 of Annex B. The *ORA Standard Network Analysis tool [22] has been used to calculate the measure values.

Table 8: *Agent ranking according to selected standard network measures.*

Rank	Total Degree	Betweenness	Eigenvector	Authority	Hub
1	Search Master	Search Master	Search Master	Search Master	AOC 413
2	CormR903 413	CormR903 413	CormR903 413	CormR903 413	CormR903 413
3	AOC 413	Sept-Iles FSS	AOC 413	HercR319 424	FV AE
4	FV AE	JRCC Halifax	FV AE	FV AE	AGA Halifax
5	ARCC Sweden	RCMP Iqaluit	AGA Halifax	HercR332 413	HercR332 413

Total Degree Centrality is the total number of in- and out-links of a node, normalized by the maximum value of this function across all nodes in the network. The minimum value of 0 indicates an isolate (i.e. a node that is not connected within a network), whereas the maximum value of 1 indicates a node with the highest number of incoming and outgoing connections. Agents who are ranked high on this measure are considered to be ‘in the know’, as they have access to the expertise and resources of many others in the network [22]. According to our calculations, the Search Master was ranked first on this measure, while the Cormorant R903 was a distant second (Table B.2).

Betweenness is a centrality measure that computes the fraction of the shortest paths (i.e. paths composed of the minimum number of links) that pass through a node. The computation is done across all node pairs, which include this node on their shortest path. Betweenness identifies which node is the most connected to other parts of a network (i.e. most central to the network as a whole). Entities with high betweenness are positioned to broker connections or serve as gatekeepers between groups [22]. The Search Master had the highest score of 0.648 (Table B.3), meaning that 65 out of 100 shortest connections passed through this node.

Eigenvector Centrality calculates the principal eigenvector (i.e. the eigenvector of the largest positive eigenvalue) of the adjacent Agent x Agent matrix, corresponding to the network. Eigenvector Centrality reflects entity's connections to other well-connected entities. A node is central to the extent that its neighbors are central. In other words, nodes that are connected to many isolates have a much lower score in this measure, than those that are connected to others who are themselves well-connected [22]. Again, the Search Master was ranked first on this measure (Table B.4).

Authority Centrality counts all in-links that connect a node to network hubs (i.e. nodes that have many out-links). Agents that act as authorities are receiving information from a wide range of sources [22]. The Search Master acts as an authority in the A1 Operational network with the highest score of 1, which is 25 times as high as that of the second-ranked agent (Table B.5).

The only centrality measure, on which the Search Master was not ranked in the top five, was *Hub Centrality*. This measure is, in a sense, the opposite to authority centrality. A node is hub-central to the extent that its out-links are to nodes that have many in-links. Agents that act as hubs are sending information to a wide range of others, each of whom has many others reporting to them [22].

In addition to the standard network measures discussed above, the extended graph measures [20] of cognitive demand and shared situation awareness were used in this analysis. Measure values for the top five entities are given in Tables B.6 - B.7 of Annex B. The *ORA Management report [22] was used to calculate these measures.

Cognitive Demand [20] is a measure of cognitive effort expended by each agent. According to [20], agents who are high in cognitive demand can be perceived as emergent leaders capable of replacing the current leader, when needed. Depending on the number of input networks, cognitive demand is calculated as an average of terms, each of which measures an aspect of cognitive effort [22]. The minimum input requirement is an Agent vs. Agent network. In this context, cognitive demand of an agent is the number of other agents with whom this agent interacts, normalized by the total number of agents minus one. According to our calculations, the Search Master has the highest score of 0.57, corresponding to direct interactions with 44 out of 78 other agents. (In total, 79 agents were included in the network.) This value is almost an order of magnitude higher than that of the second-ranked agent, CormR903 413 (see Table B.6). A comparison of measure values given in Table B.6 indicates that there is no other entity in the network capable of assuming the leadership role in this operation.

Shared Situation Awareness (Shared SA) is interpreted in [22] as a measure of how similar agents view a particular situation. For any given pair of agents, this measure computes a value based on their relationships (i.e. links) to others in the network. Relationships may include physical proximity, social demographic similarity, or other similarity. In this study, the communication relationship within the A1 Operational net was considered. In this context, shared SA of agents *i* and *j* is proportional to scalar product of rows *i* and *j* of the adjacent Agent x Agent matrix plus the product of eigenvector centrality values of these agents computed on this matrix (see [22]). To obtain shared SA of an agent, a shared SA value for each dyad of agents is averaged across all dyads that include this agent. Agent ranking with respect to this measure together with measure values is given in Table B.7. According to our calculations, the Search Master has the highest shared SA, which is more than an order of magnitude higher than the average shared SA for this network (cf. Table 9).

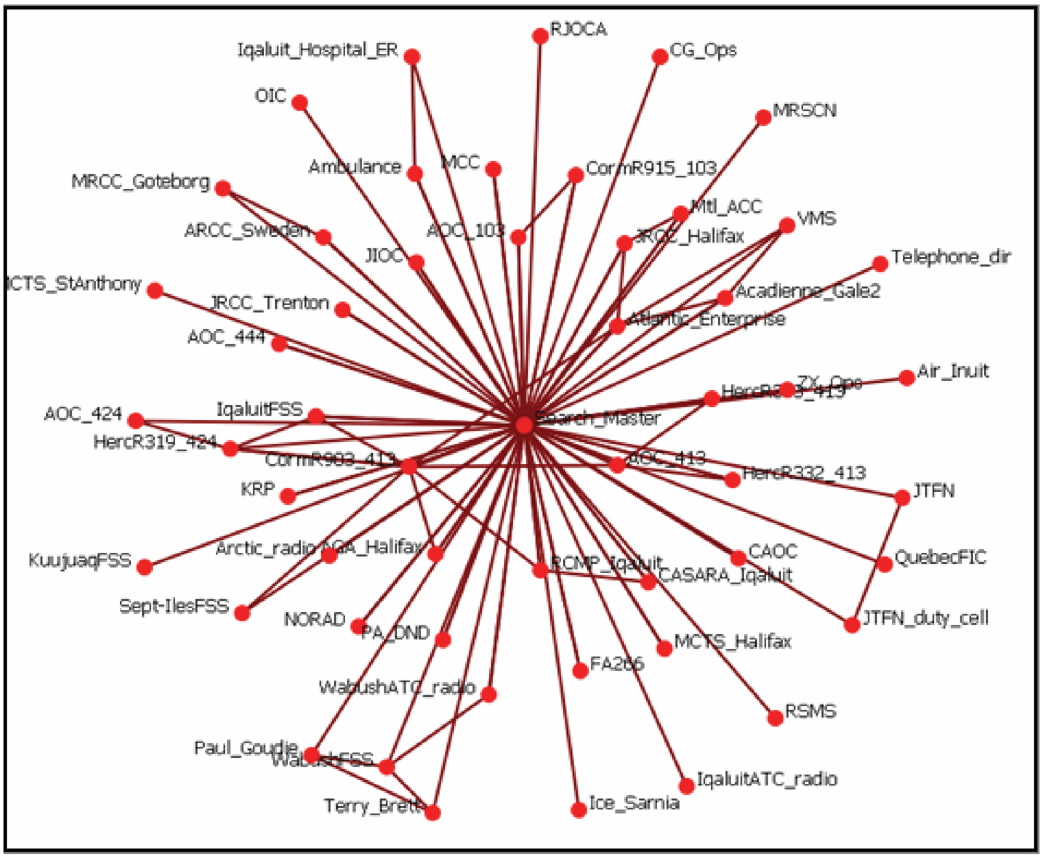

Figure 21: *The Search Master's Sphere of Influence.*

The node-level analysis clearly indicated that the Search Master was by far the most important and influential entity of the A1 Operational network. The Search Master's Sphere of Influence is shown in Figure 21. A Sphere of Influence of a node contains all nodes within the ego network[¶] of this node; it is an important indicator of the node value [22]. The Search Master's Sphere of Influence encompassed 67% of the entire Operational network. For comparison, the Sphere of Influence of

[¶]An ego network of a node is a sub-network of radius 1 that includes all nodes to whom that node has direct connections plus connections between those nodes.

the next most influential node, CormR903 413, contained about 14% of the network. The *ORA Sphere of Influence report [22] was used to derive spheres of influence for key entities of the A1 Operational network.

The network-level analysis results are summarized in Table 9. The *ORA network analysis tool [22] was used to generate the network-level measures. The meaning of each measure is explained below.

Table 9: *Performance indicators for the A1 Operational network.*

Network Density (also known as complexity):	0.022
Network diameter:	16
Characteristic path length:	4.727
Average communication speed:	0.211
Clustering coefficient:	0.175
Average Shared SA:	0.013
Network fragmentation:	0
Critical set size:	1 (The Search Master)
Fragmentation after removing Critical set:	0.795

Network density is the number of network links divided by the number of all possible links between nodes, not including self-references (maximum value is 1.0). It is also a measure of complexity for the network in question. *Network diameter* is the maximum shortest path length (number of links) between any two nodes in a network. It measures how large a network is. For the A1 Operational network, both measure values are low, which is a good feature. It should be noted that expansive dense networks could be costly to maintain and support. Besides, large number of connections could produce a lot of noise in the system. The A1 Operational network is a compact low-density network, where new links appear as needed.

Characteristic path length is the median of the average shortest distances (number of links) connecting each node to all other nodes. *Average communication speed* is the average inverse shortest path length (number of links) between any pairs of nodes in a network. It measures the average speed with which any two nodes can interact. The maximum value for this measure is 1.0. Average communication speed between any two nodes in the A1 Operational network is about 20% of the maximum, which is rather low. However, average communication speed between any two nodes within the Search Master's sphere of influence (or 67% of the network) is close to 0.5 which is high, and the average speed with which the Search Master interacts with 67% of all agents is 1.0 which is the maximum.

Clustering coefficient for the whole network is the average of the local clustering coefficients of all nodes. The local clustering coefficient of a node is given by the proportion of links between the nodes within its neighbourhood divided by the number of links that could possibly exist between them. Clustering coefficient is used to determine whether a network is random or small-world. According to our calculations, the A1 Operational net was neither random nor small-world at any stage of its development.

Average Shared SA for the whole network is the average of shared SA of all nodes. This measure is useful, as a reference point, for determining a relevant shared SA of individual nodes in a network.

Network fragmentation is a measure of network performance that shows the proportion of disconnected entities in a network. The measure value of 0 indicates that there is no disconnected entity in the A1 Operational network. *Critical set* is a set of nodes in a network, whose removal leads to maximum network fragmentation. The size of the critical set (i.e. the number of nodes that it includes) and maximum network fragmentation associated with the removal of this set are important indicators of network resilience to node removal (either due to technical failure or attack). High centralization of the A1 Operational net is a contributing factor to the operational efficiency. However, it can also be viewed as a vulnerability factor. According to analysis results presented in Table 9, the removal of the Search Master will lead to maximum network fragmentation when almost 80% of SAR assets will become disconnected. Therefore, the Search Master is the most valuable asset of the Operational network and must be well protected.

4.5 Refining SARnet

SARnet is not a high fidelity model, but it could be transformed into one with the help of modern network technologies. A straight forward way to achieve a higher fidelity level of the SAR system representation is to add new nodes and node attributes to SARnet using the editing capabilities of the *ORA network visualization and analysis software (see [22] for details). The alternative way to add new nodes or attributes to SARnet is to import Excel table data. Similarly, new links or networks can be created within *ORA using the Editor panel (see [22] for details) or imported as Excel table data. In [15], we describe how the *ORA Matrix Algebra tool can be used to develop new networks from networks already imported into the software.

If required, new node classes can be added using the *ORA "Add New Node Class" button (see [22] for details). For example, one may decide to add the Tasks node class to SARnet to represent various tasks associated with execution of SAR response. Examples include: SAR mission coordination, search from air, ground search, aid delivery, hoisting, disaster scene management, first aid, marine rescue, etc. It would be a useful extension of SARnet, as SAR protocols and procedures could be effectively represented in the model as sequences (or work flow) of tasks. The example of the work-flow network is given in [15].

Environmental effects, such as weather, can have a large impact on the performance of the SAR system. These effects need to be modelled so that their impact can be analyzed. One possible method to model environmental effects is to modify the structure of the airport network through the removal of affected nodes and/or links in simulations. Another method of incorporating environmental effects is to modify the parameters of the links (e.g. link weight). When considering a SAR response time calculation over a series of airport hops, each link in the network can be adjusted with an estimated fly time (e.g. as a function of the weather). Each node can also incorporate a probability of failure (i.e. aircraft unable to land on an airport) based on the weather forecast.

Also, refinement and validation of SARnet can be performed through simulating a series of scenarios against historical data. Historical data for incidents in the High Arctic region can be used for this purpose. Small and large scale scenarios can be modelled with SARnet. A small scale scenario (e.g. a medical emergency on board of a cruise ship) can involve a localized response. A large scale scenario (e.g. cruise ship incident in the High Arctic similar to the 2010 grounding of the Clipper Adventurer) would involve a much greater SAR response with more involved units and greater geographical area of a response.

5 Conclusions

In this report, we have presented a new modelling framework that makes use of modern network technologies (collated into the net-enabled approach in [1, 2]) for representation and analysis of joint interagency systems – a class of socio-technical systems of interest to Defence. Agents or active players in such systems are highly-specialized entities that differ by the roles/specialization and by the environmental domains in which they operate, among other case specific attributes. This study is concerned with the systems that perform two main functions: detection of a significant event and execution of an appropriate response action.

Under our approach, the system is viewed and modelled as a set of inter-linked dynamical networks with embedded heterogeneous agents. Each network node represents a system component and the links between two nodes denote some relationship between those components. The emphasis is given to the relationships (links) and to the dynamics of how these relationships change in the course of a response action.

To accommodate the agent heterogeneity in network models, we have introduced five classes of agents depending on their role in the network: sensors, routers, actors, databases, and controllers; and six environmental domains of operation: maritime, land, air, space, cyber, and cognitive. Sensor agents represent the system surveillance capabilities. They sense, detect, and pass gathered information to designated routers. The role of routers consists of distributing and directing the flow of information within the system. Controllers coordinate a response action and task other agents. Actors accomplish the bulk of tasks, associated with a response action. Databases (which could be read-write or read-only) store information and make it available to other agents. Each agent is encoded as a multidimensional string, where each dimension represents an agent attribute or property. The number of dimensions is not limited and can include as many case specific attributes as needed.

The agent heterogeneity gives rise to the Operational network, which provides a conceptual representation of a step-by-step execution of a response action. The Operational network is the most important network in the model, as its measures serve as performance indicators for the entire system. As long as the system can create an efficient operational network, it can be considered efficient. The concept of the Operational network provides a useful and powerful tool for system analysis.

The Canadian Arctic Search and Rescue (SAR) system has been chosen to illustrate the utility of the modelling framework. The resulting dynamical network model, SARnet, incorporates essential components and structural features of the Arctic SAR system.

The following node classes have been included in SARnet:

- *Agents:* SAR assets that play active roles in SAR response;
- *Organizations:* various organizations responsible for delivery of SAR services in the Arctic;

- *Knowledge:* skill sets, protocols, and procedures relevant to SAR;
- *Resources:* resources required to support SAR operations; and
- *Locations:* geographic locations relevant to Arctic SAR.

The following networks have been constructed to represent various relationships between system components (Table 7):

- *Interagency net:* represents the inter-agency structure of the SAR system (Figure 8);
- *Organizational net:* links organizations with their respective SAR assets (Figure 9);
- *Knowledge net:* links SAR assets with their respective areas of expertise (Figure 10);
- *Resource net:* links SAR assets with resources, representing the 'who has access to what resource' relationship (Figure 11);
- *Location net:* links locations with SAR assets and Arctic survival kits, located there (Figure 12);
- *Airport net:* links CFB Trenton and 114 Arctic airports (Figure 13); and
- *Standby net:* represents the standby posture of the SAR system, linking agents based on working relationships (Figure 17).

Unlike other networks in SARnet, the airport network has not been imported into the model as table data, but has been computed using the network generation technique that we have developed and described in Subs. 3.3.2.

SAR assets (agents) are represented in SARnet by 90-dimensional strings of data, where each of the 90 dimensions represents a particular agent property or attribute. The first 15 dimensions are reserved for five agent classes, six environmental domains, and four SAR domains: Air SAR, Maritime SAR, Ground SAR, and Joint SAR. The latter four attributes represent the traditional subdivision of SAR service providers. The remainder specifies the number of agent classes with subclasses (in this version of SARnet, 1); mobility factors (in this version, 2: mobile or portable); availability factor; agents' skill sets (29 in this version); access to resources (12 types of resources are currently included), 26 affiliations; 2 standby times (working hours and quiet hours); and latitude and longitude of the home unit location. The last four variables are continuous, whereas others are either binary (0,1) or categorical (0,1 and $*$ for N/A). Assortative networks have been used in this report to visualize and then explore multidimensional agent attributes.

For the purpose of model validation, we have developed the Operational network of a real A1 incident (air with lives at risk), which occurred in the Arctic in December 2008. The resulting network dynamics is illustrated in Figures 18 – 20. A comparison of the Standby net and the A1 Operational net has shown that the SARnet model adequately captures all essential components and structural characteristics of the real system. Network analysis results have identified the key system entities and structural features, contributing to the successful outcome of the December 2008 operation. Some inefficiencies (e.g. 'dead-end' calls to controllers that did not have any available

SAR assets and multiple land-line calls to access a CCG database regarding ice conditions at the LKL) and the ways of how these inefficiencies could be overcome through automation of parts of the SAR Mission coordination process have also been identified.

SARnet is a prototype dynamical network model that implements modern network technologies, creating a virtual laboratory in which various aspects of system performance can be efficiently evaluated. The visualization and computational capabilities of the SARnet model provide useful and powerful tools for operational-to-strategic level analysis of joint interagency systems.

In addition to the network-based tools explored in Subs. 3.3, the model allows for a straightforward application of the Generative Network Automata (GNA) – a novel network simulation technique for automated generation of new networks depending on the dynamical state of the nodes [54]. The GNA techniques are being incorporated into SARnet for automated generation of the Operational network on the Standby network.

A rapid expansion of air and maritime transit through the Arctic region puts an emphasis on assessments of current and required Arctic capabilities. The GNA-empowered SARnet model will facilitate such assessments. The following important questions of system analysis should be answered through incorporation of the GNA techniques:

- *Resilience to technical failure or attack:* Will the system degrade gracefully or will it fall apart after one or several nodes are removed?
- *Strategic readiness:* Can the system create the Operational network capable of handling an incident that is out of the ordinary, because of its size or severity?

It is our hope that the SARnet dynamical network model will find useful applications in Operational Research and Analysis.

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Annex A: SARnet Agents

Tables A.1 – A.4 show SARnet agents and their respective classes for each of the four SAR domain: Maritime (2.2), Air (2.3), Ground (2.4), and Joint (most joint components are described in 2.1). Some agents are meta-nodes that represent several entities of the SAR system with similar attributes. For instance, the CRPG_patrol meta-node represents 56 CRPG patrols operating in the North. Similarly, CCGAS represents 14 CCGA vessels currently operating in the Arctic waters. The meta-node agents are marked by ∗ in Table A.1 – A.4.

Table A.1: *Air SAR assets included in SARnet.*

SAR Asset Name	SARnet ID	Agent Class
424 Squadron Air Operations Centre	AOC_424	Controller
435 Squadron Air Operations Centre	AOC_435	Controller
413 Squadron Air Operations Centre	AOC_413	Controller
103 Squadron Air Operations Centre	AOC_103	Controller
440 Squadron Air Operations Centre	AOC_440	Controller
CH-146 Griffon helicopter with the crew	Griffon∗	Actor
CH-149 Cormorant helicopter with the crew	Cormorant∗	Actor
CC-130 Hercules with the crew	Hercules	Actor∗
DHC-6 Twin Otter STOL with the crew	Twotter	Actor∗
2-member SAR tech team	SARtech_2men_team∗	Actor
Inuvik CASARA unit	CASARA_Inuvik	Controller
Norman Wells CASARA unit	CASARA_Norman_Wells	Controller
Hay River CASARA unit	CASARA_Hay_River	Controller
Yellowknife CASARA unit	CASARA_Yellowknife	Controller
Cambridge Bay CASARA unit	CASARA_Cambridge_Bay	Controller
Rankin Inlet CASARA unit	CASARA_Rankin_Inlet	Controller
Iqaluit CASARA unit	CASARA_Iqaluit	Controller
Whitehorse CASARA unit	CASARA_Whitehorse	Controller
Teslin CASARA unit	CASARA_Teslin	Controller
CASARA Aircraft	CASARA_aircraft∗	Actor
Aircraft of Opportunity	ACoO	Actor
NAVCAN	NAVCAN	Sensor
CASARA Telephone Directory	CASARA_Tel_dir	Database RO

Table A.2: *Ground SAR assets included in SARnet.*

SAR Asset Name	SARnet ID	Agent Class
2 CFLAWC 6-member teams	CFLAWC_6men_team1(2)	Actor
1st CRPG patrols (x56)	CRPG_patrol*	Actor
CF Health Services Support Team	HSS_team	Actor
On-Scene Coordinator	OSC	Controller
Hay River RCMP	RCMP_Hay_River	Router
Yellowknife RCMP	RCMP_Yellowknife	Router
NRC Canada Research Station	NRC_Research_Stn	Actor

Table A.3: *Maritime SAR assets included in SARnet.*

SAR Asset Name	SARnet ID	Agent Class
CCG secondary SAR vessels (x4)	CCGS_secondary*	Actor
CCG icebreakers (x6)	CCG_icebreaker*	Actor
Hay River CCGA	CCGA_Hay_River	Controller
Yellowknife CCGA	CCGA_Yellowknife	Controller
Cambridge Bay CCGA	CCGA_Cambridge_Bay	Controller
Rankin Inlet CCGA	CCGA_Rankin_Inlet	Controller
Inuvik CCGA	CCGA_Inuvik	Controller
Fort Resolution CCGA	CCGA_Fort_Resolution	Controller
Fort Chipewyan CCGA	CCGA_Fort_Chipewyan	Controller
Aklavik CCGA	CCGA_Aklavik	Controller
Pangnirtung CCGA	CCGA_Pangnirtung	Controller
CCGA vessels (x14)	CCGAS*	Actor
Vessel of Opportunity	VoO	Actor
MCTS centre at Inuvic	MCTS_Inuvik	Sensor
MCTS centre at Iqaluit	MCTS_Iqaluit	Sensor
INNAV	INNAV	Database RW

Table A.4: *Joint SAR assets included in SARnet.*

SAR Asset Name	**SARnet ID**	**Agent Class**
JRCC Trenton	JRCC_Trenton	Controller
JRCC Halifax	JRCC_Halifax	Controller
Aeromedical Evacuation Coordinating Officer	AECO	Controller
Canada Command Press Information Centre	PIC	Actor
Forward Operating Base	FOB	Controller
SAR Mission Coordinator	SAR_Coordinator$*$	Controller
Search Master	Search_Master	Controller
SAR Mission Management System	SMMS	Database RW
Meteorological Service of Canada	Meteo	Database RO
SARSAT	SARSAT	Sensor
LUT	LUT	Router
Canadian MCC	MCC	Router
SAR Telephone Directory	Telephone_dir	Database RO

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Annex B: Network Analysis Results

Network Dynamics: Table B.1 provides quantitative estimates that trace the development in time of the A1 Operational network, discussed in Subs. 4.4.1. In particular, we look at the agent heterogeneity and at the distribution of agents according to agent classes, environmental domains and SAR domains.

Table B.1: *Network development after 1, 3, 6, 12, and 18 hours (final).*

	1 hour	**3 hours**	**6 hours**	**12 hours**	**Final**
Node count:	28	40	55	61	79
Link count:	41	64	91	100	140
Link weight:					
Max.	4	6	6	7	12
Min.	1	1	1	1	1
Average	1.37	1.48	1.53	1.71	1.96
Network composition:					
Actors:	7 (25%)	10 (25%)	15 (27%)	20 (33%)	32 (40.5%)
Controllers:	10 (36%)	15 (37.5%)	19 (35%)	20 (33%)	21 (26.5%)
Databases:	4 (14%)	4 (10%)	4 (7%)	4 (7%)	7 (9%)
Routers:	5 (18%)	7 (17.5%)	10 (18%)	10 (16%)	12 (15%)
Sensors:	2 (7%)	4 (10%)	7 (13%)	7 (11%)	7 (9%)
Number of agent types*:	14	17	20	21	23
Network entropy♯ (normalized♯♯):	0.92520	0.89210	0.90540	0.88870	0.86274

*Agent types are agent groupings, according to the first 15 positions of string σ. Agents that are identical in $[\sigma_1, \ldots, \sigma_{15}]$ (i.e. five agent classes, six environmental domains, and four SAR domains) belong to the same agent type. The number of agent types can be used to measure the agent heterogeneity. As one can see from the above table, the agent heterogeneity increases in the course of the operation.

♯Network entropy is defined as follows:

$$S = -\sum_{k=1}^{K} X_k \ln X_k, \tag{B.1}$$

where K is the number of agent types and X_k is a fraction of agents of type k $(k = 1, \ldots, K)$.

Then ♯♯normalized network entropy is:

$$\overline{S} = \frac{S}{S_{max}} = \frac{S}{\ln K}. \tag{B.2}$$

Note that $\overline{S} \in [0,1]$. The minimum value $\overline{S} = 0$ corresponds to a network composed of one agent type. The maximum value $\overline{S} = 1$ corresponds to a network composed of agents evenly distributed between all K agent types (i.e. $X_k = 1/K$ for $k = 1, \ldots, K$). As $\overline{S}$ approaches 1, the agent distribution becomes uniform. According to analysis results presented in the above table, the distribution of agents between agent types becomes less balanced in the course of the operation.

Key Entities: The following network analysis results have been generated by ORA* [22] to identify key entities of the A1 Operational network, discussed in Subs. 4.4.1.

Total Degree Centrality:

Table B.2: *Agent ranking with respect to Total Degree Centrality.*

Rank	Agent	Value	Unscaled
1	Search Master	1.000	212
2	CormR903 413	0.113	24
3	AOC 413	0.094	20
4	Atlantic Enterprise	0.085	18
5	ARCC Sweden	0.085	18

Betweenness Centrality:

Table B.3: *Agent ranking with respect to Betweenness Centrality.*

Rank	Agent	Value
1	Search Master	0.648
2	CormR903 413	0.084
3	Sept-Iles FSS	0.051
4	JRCC Halifax	0.050
5	RCMP Iqaluit	0.048

Eigenvector Centrality:

Table B.4: *Agent ranking with respect to Eigenvector Centrality.*

Rank	Agent	Value
1	Search Master	1.000
2	CormR903 413	0.401
3	AOC 413	0.400
4	Atlantic Enterprise	0.363
5	AGA Halifax	0.328

Authority Centrality:

Table B.5: Agent ranking with respect to Authority Centrality.

Rank	Agent	Value
1	Search Master	1.000
2	CormR903 413	0.040
3	HercR319 424	0.018
4	Atlantic Enterprise	0.051
5	HercR332 413	0.015

Cognitive Demand:

Table B.6: Agent ranking with respect to Cognitive Demand.

Rank	Agent	Value
1	Search Master	0.570
2	CormR903 413	0.076
3	AOC 413	0.063
4	Iqaluit FSS	0.051
5	HercR332 413	0.038

Shared Situation Awareness:

Table B.7: Agent ranking with respect to Shared Situation Awareness.

Rank	Agent	Value
1	Search Master	0.467
2	ARCC Sweden	0.075
3	AOC 413	0.069
4	CASARA Iqaluit	0.055
5	Atlantic Enterprise	0.050

List of symbols/abbreviations/acronyms/initialisms

ACC	Area Control Centre
ACoO	Aircraft of Opportunity
AGA	Air-Ground-Air
AOC	Air Operations Centre
C2	Command and Control
C&A	Central and Arctic Region
CASARA	Civil Air Search and Rescue Association
CCG	Canadian Coast Guard
CCGA	Canadian Coast Guard Auxiliary
CE	Capability Engineering
CF	Canadian Forces
CFACC	Combined Forces Air Component Commander
CFB	Canadian Forces Base
CFLAWC	CF Land Advanced Warfare Centre
CI	Critical Infrastructure
Comd 1 Cdn Air Div	Commander 1 Canadian Air Division
CRPG	Canadian Ranger Patrol Group
DNA	Dynamic Network Analysis
DND	Department of National Defence
DRDC	Defence Research and Development Canada
EC	Evolutionary Computation
ELT	Emergency Locator Transmitter
FOB	Forward Operating Base
FSS	Flight Systems Services
GA	Genetic Algorithms
GEO	Geostationary Earth Orbit satellite
GIS	Geographic Information Systems
JRCC	Joint Rescue Coordination Centre
ICSAR	Interdepartmental Committee on SAR
INNAV	Information System on Marine Navigation
LEO	Low-altitude Earth Orbit satellite
LKL	Last Know Location
LUT	Local Users Terminal
MAJAID	Major Air Disaster
MAJMAR	Major Marine Disaster
MCC	Mission Control Centre
MCTS	Marine Communications and Traffic Services
MRSC	Marine Rescue Sub-Centre
NAVCAN	Navigation Canada
nmi	nautical mile
NoK	Next of Kin
NORAD	North American Aerospace Defense Command

NRC	National Research Council
NSP	National Search and Rescue Program
NSS	National Search and Rescue Secretariat
OGD/A	Other Government Departments/Agencies
OIC	Officer In Charge
*ORA	Organizational Risk Analyzer
OSC	On Scene Coordinator
PA	Public Affairs
PCP	Primary Care Paramedic
PG0	Partner Group 0
PoB	People on Board
PR	Public Relations
RCMP	Royal Canadian Mounted Police
RO	Read Only
RW	Read Write
SA	Situation Awareness
SAR	Search and Rescue
SARSAT	Search and Rescue Satellite Tracking System
SKAD	Survival Kit Air Droppable
SLDMB	Self-Locating Datum Marker Buoy
SMMS	SAR Mission Management System
SRR	Search and Rescue Region
STOL	Short Takeoff and Landing
VMS	Vessel Monitoring System
VoO	Vessel of Opportunity

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This report discusses a new network-based modelling framework that we have developed for representation and analysis of joint interagency systems. Agents in such systems differ by the roles they play in the system, by the environmental domains in which they operate, and also by other case-specific attributes. The agent heterogeneity gives rise to an Operational network, which represents a step-by-step execution of a response action to a particular incident. The network measures of the Operational network serve as performance indicators for the entire system. The utility of the presented modelling framework is illustrated using an example of the Canadian Arctic Search and Rescue system. Under our approach, the system is viewed and modelled as a set of inter-linked dynamical networks with embedded heterogeneous agents. Each agent is encoded as a multidimensional string of data, which represents agent attributes. The resulting dynamical network model, SARnet, provides visualization and computational capabilities for system analysis and exploration. The visualization capabilities of the model are used to examine the architectural make-up of the system and to explore its multidimensional agents. The computational capabilities are applied to analyze the Operational network of a real incident in the Arctic. The presented modelling framework is applicable to a variety of joint interagency systems. SARnet is a prototype dynamical network model that implements the presented modelling framework, creating a virtual laboratory in which different aspects of system performance can be efficiently evaluated.

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