13th ICCRTS: C2 for Complex Endeavors

C^2OLISEU – A META-MODEL FOR RESEARCH AND DEVELOPMENT OF COMPLEX NETWORK CENTRIC OPERATIONS

Topic 7 – Network-centric Experimentation and Analysis

Topic 8 – C^2 Architectures

Topic 9 – Collaborative Technologies for Network-Centric Operations

André Luiz Pimentel Uruguay, MS*[1], STUDENT
Paulo Cesar Guerreiro da Costa, PhD [2]
Nilton de Oliveira Lessa, MS [1]
Carmen Lúcia Ruybal dos Santos, PhD [1]

[1] Instituto de Estudos Avançados
Rodovia dos Tamoios, Km 5,5
São José dos Campos, SP 12228-001 - Brazil
[auruguay; nilton.lessa; carmenl]@ieav.cta.br

[2] Center of Excellence in C^4I
The Volgenau School of Information Technology and Engineering
George Mason University
4400 University Drive
Fairfax, VA 22030-4444 - USA
(703) 879-6687
pcosta@gmu.edu

*Point of Contact: André Luiz Pimentel Uruguay

+55-12-3947-5345 / +55-12-9121-5695 (mobile)

auruguay@ieav.cta.br

C²OLISEU – A Meta-Model for Research and Development of Complex Network Centric Operations

Abstract

Complexity in net-centric systems is a clear and increasingly present trend in C2 development. Yet, support for research and development inside the dynamics of complex net-centric systems has been relatively shy. Addressing this issue, the present work introduces C²OLISEU, a meta-model designed to express concepts associated with network-centric systems operations, providing a meta-model that encompasses the four key domains of network centric operations: social, cognitive, information and physical. For the social and cognitive domains, a set of basic concepts is derived from well-established paradigms in computational organization theory and artificial intelligence. Concepts within the information domain are conveyed via a subset of the DoDAF framework's concepts for the operational and systemic views of C² architectures. Finally, as a means to consistently support the physical domain, the meta-model includes a preliminary set of C² metrics derived from the classic principles of war. We argue that C²OLISEU metrics will help to better characterize complex and adaptive systems trajectories, thus enabling the study of edge organizations. Further, by using concepts derived from DoDAF, the C²OLISEU meta-model greatly improves the understanding of research results by both systems engineers and managers, thus eliminating unwanted cognitive entropy and fostering the innovation process.

Keywords: NCW, Computational Organization Theory, Complex Systems, Cognitive Agents

Introduction

Kossiakoff and Sweet (Kossiakoff and Sweet 2003) define the function of Systems Engineering as to guide the engineering of complex systems. The word *complex* here is meant to indicate systems with numerous and diverse elements that have intricate interrelationships. The behavior of such systems cannot be understood solely in terms of its respective constituents deeds, making reductionist, divide-and-conquer approaches simply ineffective. In fact, it is the very interaction of its constituents that introduces complexity within a given system. The reductionist methodology fails entirely to capture the structures that arise specifically due to interaction (Crutchfield,1990).

The definition of complex systems fits well to cases in which several entities are supposed to operate geographically dispersed in an uncertain, partially observable environment, trying to accomplish a global goal in a synergetic way. Good examples are application domains such as transportation, disaster relief and defense.

The concept of network-centric systems was created to handle the complexity of these areas. *Net-centricity* is based upon the thesis that robustly networked entities can be more effective by improving information sharing. Better quality of information provides for better situational awareness and, thus, more agile decisions. These tenets form a chain of premises crossing four key domains: physical, information, cognitive and social (Signori 2002).

Considering the above domains collectively for the development of net-centric information systems is a daunting task. The physical domain has solid grounds within the physical sciences. Also, many paradigms already exist to represent information. Most systems engineering methodologies encompass good separation and integration of physical and information-related concerns. However, cognitive, social and organizational issues still remain absent.

On top of the above, institutions in developing countries often have limited resources for research and development of complex systems, which encompasses operational analysis and systems engineering. In the Brazilian case, there is also an intrinsic design requirement of keeping the architecture of complex systems flexible enough to accommodate an ever changing public infrastructure (e.g. civilian and military air traffic control systems having to cope with recent regulatory changes).

The main goal of the present work is to present a set of concepts and its respective interrelationships, named C^2OLISEU (from the acronym, in Portuguese, for Concepts for Operational Applications and Systems Engineering), to describe network-centric architectures. The central idea behind this conceptual framework, expressed as a meta-model, is to foster innovation among complex systems researchers by providing them with a tool that is simple and flexible enough to be used within a broad range of application domains, yet ensuring that standard architectural concepts for further development and engineering are rigorously met.

The next section introduces the subject of architectural frameworks, as well as the importance of executable architectures and its relevance for research. Also, topics of cognition and organization are presented as conceptual enhancements for these frameworks. Then, the C^2OLISEU framework, the relationship among its concepts and the four NCW key domains, a notional agent, and some basic processes to enable simulation are presented. Finally, we explore interesting issues from a brief set of simple metrics based on Graph Theory, validating the contribution of the framework for research.

Background

Architectural Frameworks

Due to its distributed nature, net-centric systems architecture is always a central point of concern. Viewing a system as a network implies that we are paying attention to its architecture, intending to study its structure and organization. To facilitate comparisons among these systems, many architectural frameworks were created to standardize the description of system architectures, such as Zachman (Zachman 1987), DoDAF (DoD Architecture Working Group 2007) and MoDAF (MODAF Partners 2005).

DoDAF, expressed in Figure 1, is composed of different views of the architecture. The *operational view* describes the tasks, activities, operational nodes and information exchanges, with no systemic, technological or even material consideration. The *systemic view* is comprised of the systems, subsystems, and interconnections that realize the requirements expressed in the operational view. Lastly, the *technical standards view* contains all current and future standards and norms to be employed in building the architecture.

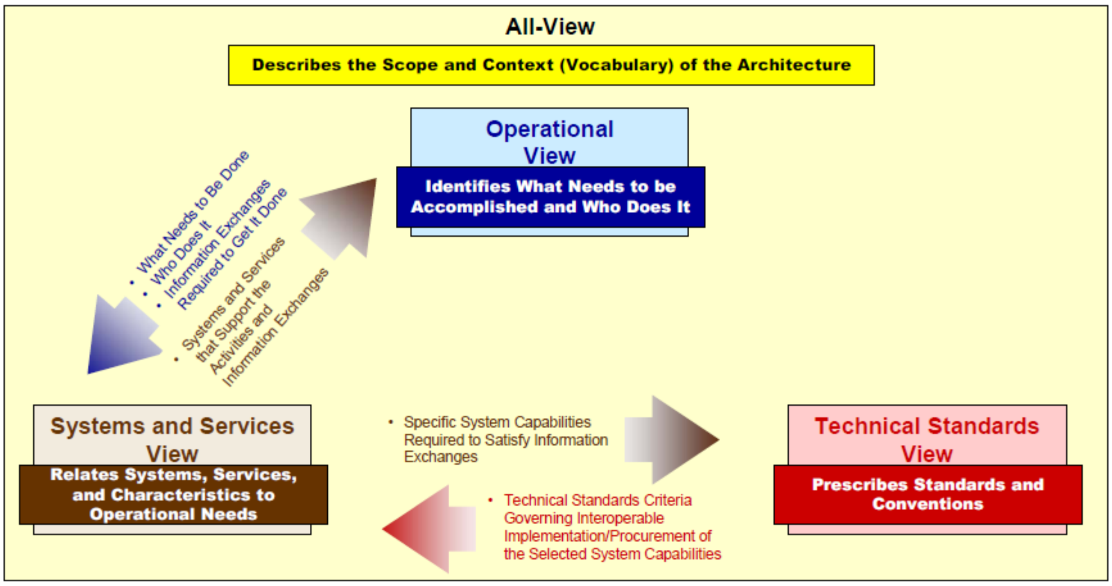

Figure 1 - The DoD Architecture Framework Views and Relationships

The basic concepts of the operational view are: *operational nodes*, which perform *operational activities*, consuming, producing and exchanging *information*. The requirements for information exchange are expressed by the concept of *needlines*. Similarly, the systems view is composed of *system nodes* performing *functions* that consume, produce, and exchange *data*. The data exchange is performed by *data links*.

Because DoDAF is a mandatory standard for any proposal to DoD involving architectural descriptions, most of the computer-aided systems engineering tools incorporate its concepts and diagrams. Also, industry is already able to handle DoDAF documents, provided by a systems design office, as input for detailed design and implementation.

If researchers were able to express their results in a format easily understandable by industry personnel, e.g., for rapid prototyping and experimentation, the innovation cycle would become more agile. This makes DoDAF a quite interesting language to formally express new concepts resulting from operations research. However, one of the drawbacks of using DoDAF architecture descriptions is its static nature. Although the framework describes process-related concepts, such as operational activities and system functions, the ability to make accurate performance predictions is paramount to dynamically evaluate the behavior of these processes in association with a specific architecture.

Given that modeling and simulation are powerful techniques to study the dynamics of large and complex systems, executable architectures can be considered an important feature. Also, DoDAF specifies the documents and data, i.e., the format for describing architectures, but nothing is mentioned about how to develop integrated architectures.

To help solve these limitations, the Activity Based Methodology (Ring *et al.* 2004) was developed at MITRE to enable the transition to executable process models and their associated time dependent behavior. The methodology is based on the DoDAF Architecture Description Specification Model (DADSM), shown in Figure 1, which consists of a subset of DoDAF concepts and relationships in order to assure consistency between the different views and to remove ambiguity in DoDAF documents.

In the model, core concepts are derived from both the operational and systems views. For the operational view, each *operational activity* that produces and consumes *information* is performed at an *operational node*. Similarly, for the systems view, each *system node* performs systemic *functions* that produces and consumes *data*.

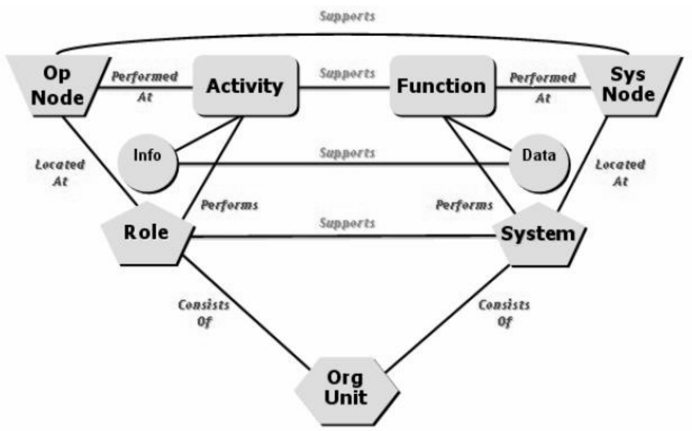

Figure 2. The DoDAF Architecture Description Specification Model

DADSM dynamically executable models of architectures are derived from attributes of both activities and systems, such as duration and its statistical time distribution, average wait time before processing, continuation strategy, activity cost, and input/output conditions. Cognition is expressed as the required skills to perform each process. Finally, organization is mentioned only as a means to express linkages of property and control over operational and system nodes.

Cognition

The very fact that the International Command and Control Research and Technology Symposium (ICCRTS) has for many years held a separate track for cognitive analysis can be seen as a clear indication of how hard it is to understand, due to the human nature, the cognitive domain. Even more difficult is to abstract the cognitive functions in a computational, executable model. The need to express cognitive activities is vital for assessing the quality of decision making. Cognition can be understood as the property of an entity to make decisions based on internal models (instead of direct perceptions) of the environment, of other entities, and even of itself.

Grisogono (2007) cites some characteristics of adaptivity for the purpose of building complex adaptive C^2 systems: 'intelligent' context-sensitive behavior, resilience, robustness to perturbations, flexible responses, agility, innovation, and system learning from experience. Of these characteristics, context-sensitivity, flexibility, innovation, and learning clearly fall within the cognitive domain.

Interestingly, resilience, robustness and agility seem to be results of good networking and systems architecting.

Rational cognitive behavior, as long as applicable in command and control, can be defined as the production of actions towards the goals of an agent, based upon its conception of the world (Bratman *et al.* 1988). These conceptions can be meant as the beliefs an agent has, so the inference mechanisms already conceived for decision-making can only be applied over its internal models. Furthermore, one cannot suppose that the beliefs conveyed by these models are always faithful results of the agent's perceptions.

In fact, one important objective of any command and control system is to provide consistency between the beliefs of its many elements, preventing these beliefs from being corrupted by any factor, be it generated by humans or nature. As a consequence, combining social networks with cognitive science and multi-agent systems is considered a key advance in extending network analysis to the dynamic realm (Carley 2003).

In most of the cases, the cognitive elements of a system are humans, although artificial cognitive computational agents can already be implemented in software. Many techniques exist to support the engineering process with cognitive aspects (Bonaceto and Burns 2005). Bonaceto and Burns (2004) mention three challenges to C2 systems engineering: smaller organizations, better coordination and faster execution. They also present a large set of methods, each one representing more or less opportunities to meet the three goals.

The concept of net-centric operations aims for agile decisions, which makes time a critical issue. In the work of Bonaceto and Burns, since the purpose is to attain faster execution, the techniques related to computational cognitive modeling are those that denote higher applicability. Those are techniques based on logical descriptions of cognition, expressed as abstract internal architectures of an agent.

There are many abstract cognitive agent architectures, one of the most employed being the *Belief-Desire-Intention* (BDI) agent (Rao and Georgeff 1995). In this architecture, *beliefs* are all that the agent knows about the world, *desires* are its goals, and *intentions* are the commitments the agent does in trying to accomplish its goals. In essence, an intention is a stack of partial plans selected to be performed with respect to the feasibility of the agent goals, and the external context, expressed by its beliefs.

Based on this, *beliefs* and *goals* are expected to be the most important concepts to express the autonomy and intentionality of the networked entities. *Beliefs* and *Goals* in C^2OLISEU are black box concepts, adequately providing for many different instantiations. However, in order to define metrics for the cognitive domain, a closer look at them, and how they fit in the overall net-centric, command and control context, seems a relevant task.

When talking about network-centric systems operations and C2 architectures, it is important to keep in mind the OODA loop designed by John Boyd (see Hammond 2001 for details). Although many other models have been proposed along the years, the OODA loop can be seen as representative for different abstractions about the traditional human behavior in the battlefield. Even if the main focus on network-centric systems is to advance the concept of war, Boyd's model still stands as an important reference for experiments and analyses in the field. C^2OLISEU has two constructs for the cognitive domain: *Beliefs* and *Goals*. *Beliefs* can be related to the *Observe* and *Orient* steps in the OODA loop and *Goals* to its *Decide* part.

What was presented so far was aimed at identifying some important pathways for defining *Beliefs* and *Goals*, giving us an initial idea about what each of those concepts should encompass. It can be seen, for example, that *Belief* is not just the direct result of sensor devices and communication links but that all the data, or information, received by an agent just makes sense when they can be interpreted in the light of the operation been conducted and the agent's particular situation. Furthermore, to be fully operational, the agent's comprehension is not enough but it has to be able to perform *Inference of Intention* and *Threat Assessment*, what in turn refines and extends its *Belief* content. Possible *Belief* contents are representations for sensor and communication data, cues, and expectancies.

Goals, in the context addressed here, normally relate to COAs generation and selection. As a result, most of its contents are defined by doctrine. Each agent will possibly have a set of default COAs already defined, which is triggered by a set of preconditions that must hold for the COA to be applied.

Difficulties, mainly related to availability of human subjects, have increased the use and interest in closed-form computer simulation. Here, computational agents are used to estimate human behaviors in real settings, and the resulting representations can be narrowed by focusing on the important points in the agent's profile and on the aspects of the scenarios.

For the cognitive domain, closed-form simulations imply in a computational representation for *Beliefs* and *Goals*. Many cognitive analysis techniques have been used for assessing human subject's behaviors in particular domains, e.g., hierarchical goal analysis, cognitive task analysis, and SAGAT. Normally, the techniques are devoted to uncover some central cognitive aspects such as the definition of goals, workload, or situational awareness (SA). Together they can help to populate the specific contents of *Beliefs* and *Goals*. However, as already mentioned, much of this content is likely to be categorized as representations for sensor and communication data, cues, and expectancies, for the *Belief* representation, and as COA instantiations, in the case of *Goals*.

Even with similarity of categories and contents, the resulting computational implementations can be very distinct, rending metrics for comparison difficult. Given the nature of the cognitive constructs outlined here, it is possible to lessen this problem by the use of Graph Theory to represent *Beliefs* and *Goals*. Graphs are general structures and, as such, consonant with C^2OLISEU focus. A sound set of mathematical and statistical metrics is defined for graphs, and its meaning has to be instantiated for the net-centric, command and control context. The whole body of knowledge pertaining to Belief Network Theory and Petri Nets can be of much use in the implementation of *Beliefs* and *Goals*, respectively.

The timing and the soundness of decisions are key concerns for military operations. In terms of graphs, time can be assessed indirectly through the many ways for measuring distance in graphs, ranging from Hamiltonian distance to statistical measurements. Soundness could be related to the quality of Beliefs that the agent holds. The agent *Beliefs* can be compared to the "simulation ground truth" or other agents' *Beliefs* set, providing information about the quality of sensor and communication technology being used, or on the relative degree of SA obtained by each agent.

Organization

A major issue for the study of complex, net-centric systems is the way by which an entity groups with others in a social context, i.e., the idea of organization. However, in many representations of C^2 systems, organizations are, at most, barely mentioned for the very purpose of illustrating which one is in charge of each element of the architecture.

To ensure useful models, any framework must have a richer representation for such an important factor. Types of networked organizations such as terrorist groups or transnational crime are of real value on interacting with allied or friend forces, so an organization must be considered beyond formal institutions, somehow as a set of constraints over the entities' behavior (Dignum and Dignum 2001), an important element that can empower or constrain an individual entity. Moreover, its structural and functional specifications are important sources of requirements for net-centric systems, something that should not be disregarded.

Several paradigms exist to formally express organizations. Table 1 presents some of them, with their main concepts. To keep our meta-model simple, yet interoperable with most of the paradigms, only the most important concepts are derived from them. *Roles* express the constraints an agent must accept in order to be part of an organization. *Relationships* express how the roles influence each other's behavior, based on the norms of the organization. These concepts for cognition and organization, although simple, are thought to be adequate for the purpose of C^2OLISEU. Obviously, for more advanced studies on human behavior other paradigms shall be used.

Table 1. Organization Paradigms and Main Concepts

Paradigm	***Main Concepts***
AALAADIN (Ferber and Gutknecht 1998)	Roles, Groups and Agents
MOISE (Hannoun et al. 2000)	Roles, Groups, Missions, and Relationships
MOISE+ (Hübner 2003)	Roles, Groups, Missions, Relationships, Goals

The C^2OLISEU Framework

Overview

As previously mentioned, the framework is intended to serve as a tool for research and development of net-centric systems, mainly focused on operational analysis and systems engineering. Our approach is based on a set of layers, each representing a key NCW domain, as shown in Figure 3.

We kept some original ideas of the Architecture Description Specification Model, using the main concepts of DoDAF for operational and systems views. Also, although with different definitions, two of the five core principles of the Activity Based Methodology (ABM) presented by Ring *et al.* (2004) were adopted: alignment of operational and system architecture objects and existence of four core operational/system architecture entity objects. The other principles are more related to systems engineering tools and were not included in C^2OLISEU. Table 2 summarizes the definitions for each concept of the meta-model.

Table 2. C^2OLISEU Concepts and Definitions

NCW Key Domain	***Concept***	***Definition***
Social	*Role*	Is a set of constraints a given entity must accept in order to become a member of an organization. These constraints can be expressed as *Goals,* which the organization expect the *Node* to achieve.
	Relationship	Indicate how two *Roles* interact between themselves. Some instances of relationships can be command, coordination, coalition, control and acquaintance.
Cognitive	*Belief*	Is a fact known by each *Node*, be it *Operational Node* or *System Node*. It is a result of the perception applied to *Information*/*Data* collected by the *Node.*
	Goal	Represent the intentionality of a *Node*. It is a desire, an objective the *Node* is supposed to pursue.
Information	*Operational Node*	Nodes that perform *Roles* determined within the organizational structure.
	Operational Activity	Actions performed in conducting business of an enterprise
	Information	Refinement of *Data* through known conventions and context.
	Needline	A requirement that is the logical expression of the need to transfer *Information* among *Operational Nodes*.
	System Node	Nodes with the identification and allocation of resources (e.g., platforms, units, facilities) required implementing specific roles.
	Function	*Data* transforms that supports the automation of O*perational Activities* or *Information* exchange.
	Data	Representation of individual facts, concepts, or instructions in a manner suitable for communication, interpretation, or processing by humans or by automatic means (IEEE 1990).
	Link	Represents the physical realization of connectivity between *Systemic Nodes*.
Physical	*Object*	Represents an entity in the physical domain. It is the instantiation of physical matter associated with a node or a set of nodes.
	Energy	It is the expression, in its many forms (electromagnetic, acoustic, thermal, mechanical), of the relationships between objects in the physical domain.

An implementation of the framework in a simulation software is also planned, having two modes of operation: *operational*, with only the operational view of the information domain; and *systemic*, encompassing both operational and systemic views.

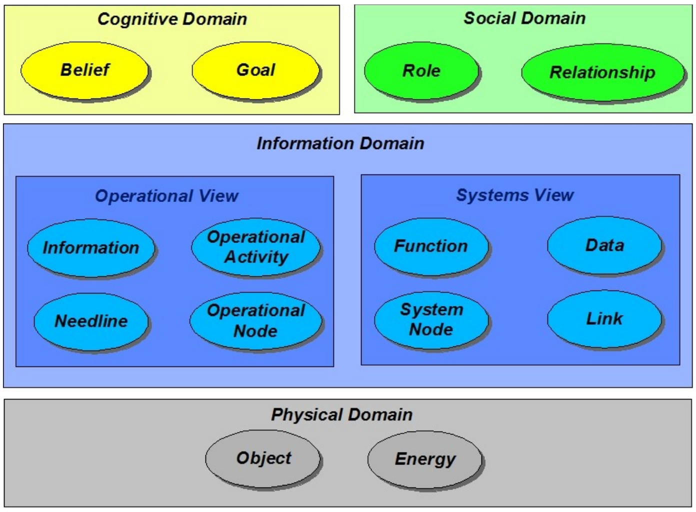

Figure 3. The C²OLISEU Framework

A Typical C²OLISEU Agent

In the cognitive domain of C²OLISEU, the concept of an agent is not made explicit. Instead, the basic external processes of sense-making, communication and action are executed by involving instances of several concepts of the framework. As an example, since we already know how to develop and deploy systems with artificial cognitive agents, cognition is a property of Nodes, either Operational or Systemic.

Figure 4 describes, at a high level of abstraction, a notional C²OLISEU agent. Each *Node* can commit to perform *Roles* in order to be a member of an organization. Committed Roles can impose the accomplishment of certain Goals by the Node. Since the Node can have any degree of autonomy, it can also have individual Goals. Also, as member of an organization, a given Node is subject to the Relationships between its Role and the role of other nodes, dictated by the organizational structure in the social domain.

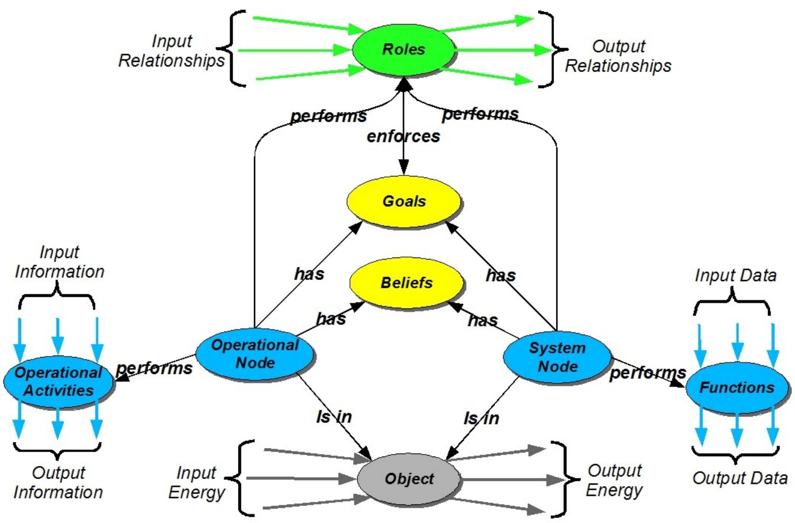

Figure 4. A C²OLISEU Agent Architecture

A Node can also have Beliefs, which we can assume as part of the context it knows. Once a Node has its Goals defined, it can use its Beliefs to select an Operational Activity (if an Operational Node) or a Function (if a System Node) to try to accomplish the Goals it has just committed to. This is very similar to the deliberation process used in BDI agents found in some cognitive development environments, e.g., JACK Intelligent Agents (Lucas and Goss 1999, Wallis *et al.* 2002), and provides great flexibility to accommodate different degrees of autonomy for the Node. Also, the possibility of a Node to learn a new Operational Activity or Function can enable models to exhibit adaptivity (Grisogono 2007).

Figures 5, 6 and 7 depict the three basic processes of sense-making, communication, and action, respectively, as activity diagrams in UML standard format. For each diagram two different possible threads can be seen, one for each simulation mode: operational and systemic.

Each Operational Activity or Function consumes and produces Information and Data, respectively, just like as conceived in DoDAF. Each Node can have its own repository and collect the Information/Data from the external environment. It can also receive this Information/Data by communicating with other Nodes, via Needlines, in the operational case, or via Links, in the systemic case.

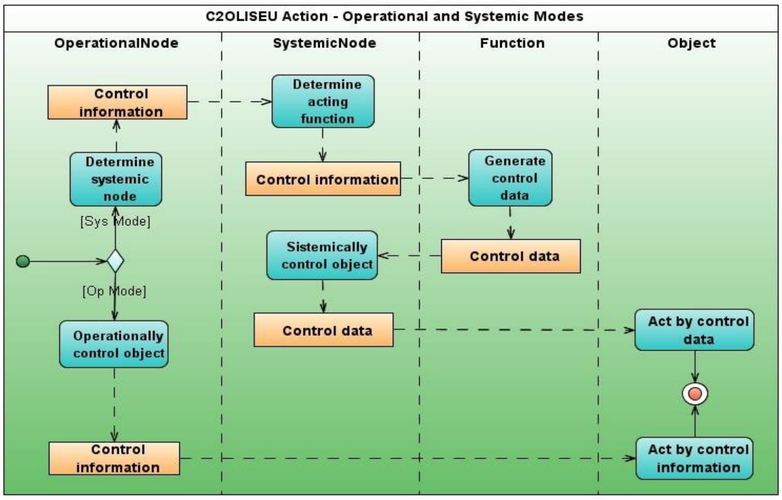

Figure 5. C^{2}OLISEU Action Activity Program.

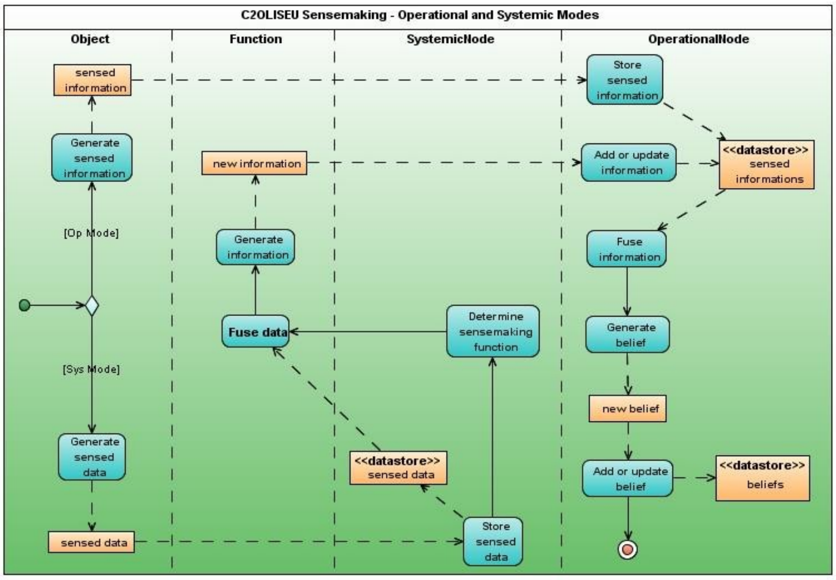

Figure 6. C^{2}OLISEU Sense-Making Activity Diagram.

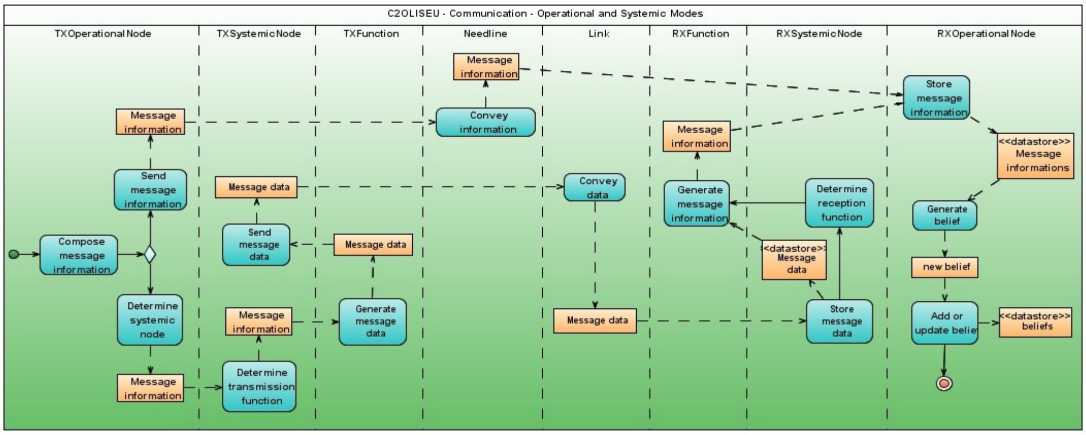

Figure 7. C^{2}OLISEU Communitation Activity Program.

In the physical domain, Objects are containers for Operational Nodes and System Nodes. They provide the condition for physical existence and proper working of each Node. Once an Object is destroyed, all the Nodes it contains cease to exist. Each Object can emit and be subjected to emission of Energy, in its various forms (electromagnetic, mechanical, thermal, etc.). The concept of Energy here is to provide more detail for the processes of sense-making and action. Communication between Nodes is primarily abstracted using the related concepts from DoDAF: Needlines for the operational mode and Links for the systems mode. Nonetheless, this does not prevent the use of more detailed models for communication. The framework is flexible enough to accommodate a third mode of operation, namely the physical mode, extending communications to the physical domain.

Finally, to evaluate the framework proposed here, we used the five key requirements a complexity framework is supposed to address (Couture and Charpentier 2007). Table 3 summarizes our evaluations.

Table 3. Complexity Framework Key Requirements

Key Requirement	***Evaluation***
Be as generic as possible, it should allow to address a wide spectrum of complex problems in different fields or domains.	Yes. C^{2}OLISEU framework is domain-independent, able to deal with problems involving organization, cognition and information sharing in a distributed environment.
Ease the understanding of underlying notions of complexity theory.	To be determined. It depends on future research.
Provide guidance on how to address complex problems.	To be determined. It depends on future research.
Facilitate the reutilization of any proven solution.	Yes. C^{2}OLISEU framework makes use of evolved representations to express organizations, cognition and systems architectures (DoDAF).
Reflect and make use of the commonalities that can be found in the scientific literature dedicated to Complexity Theory.	Yes, partially. C^{2}OLISEU framework makes use mostly of concepts from Network Science. Since the interest is on systems dynamics, further research will incorporate further metrics to deal with it.

The concepts hereby presented enable the representation of three key domains in layered graph formats. Table 4 presents the definitions for nodes and edges of these graphs for each layer.

Table 4. Graph Entities Definitions for the NCW Key Domains

Layer Name	***Node Definition***	***Edge Definition***
Social Domain	Role	Relationship
Information Domain	Operational Node Systemic Node	Needline Link
Physical Domain	Object	Energy

Metrics

Metrics for systems net-centricity can be derived from the framework, using some well know parameters from Network Science, although the techniques for analyzing networks' structures and their effects on system behaviors are at present still in its infancy (Newman 2003, 2). Previous work already made use of network metrics to evaluate architectures. To cite a few, Warren (2001) used node criticality to analyze the vulnerability of C^2 systems; Dekker and Colbert (2004) studied the influence of network robustness using graph connectivity; and McMaster, Baber and Houghton (2005) used social network analysis to evaluate an emergency response system.

All these studies focused on communications network, with a minor attention on organizational structure. The C^2OLISEU framework stands out from the above by introducing an integrated approach to encompass communications network architecture, organizational structure, and processes using social roles and relationships, cognition, and physical entities. All these elements and associated effects are made distinct by an explicit separation, although still interrelated, within the four NCW key domains.

C^2 metrics are a complex subject, being another classic track of the ICCRTS. Therefore, it is outside of this paper's scope to present a full set of metrics encompassing the whole NCW Conceptual Framework. Instead, we present a research issue using simple graph metrics of centrality, as a means to demonstrate the framework's value for research.

One of the most attractive general network attributes so far is centrality. In fact, providing more "power to the edge" intuitively means more decentralization, in contrast with the common doctrine jargon of "centralized planning, decentralized execution" found, for instance, in both US and Brazilian Air Forces' Doctrines (Brazil, 2004). Yet, figuring out what centrality means in each NCW key domain is in fact a question to be tackled by careful research. Although military organizations are hierarchically centralized, technology is continuously providing means to do things in a more decentralized way. As a consequence, determining the optimal degree of centrality within the social/organizational and the information domains is no trivial task. In some cases, too much capability at the edge may actually inhibit self-organizing behavior and negatively impact the mission of the networked whole (Chen 2003).

As an example, we cite some centrality metrics from network science as a starting point to elicit the influences of centrality in the social and information domain. The basic types of graph centrality metrics are based on three graph features (Freeman,1978): degree, betweenness and closeness. For the formal description of those metrics we use the following convention for a graph G: $G = (N,E)$, being N a set of nodes v_i and E a set of edges $e_{i,j}$, connecting the nodees v_i and v_j.

Degree-based centrality are based on the graph theory concept of *degree* of a node, the number of links departing or arriving at one node. This is viewed as an index of its potential *communications activity* in the network. The general formula for degree-centrality is

$$C_D(n_k)=\sum_{i=1}^{n} a(n_i,n_k)$$

where $a(n_i,n_k) = 1$ if and only if there is an edge connecting n_i and n_k, and 0 otherwise.

The betweenness-centrality is based upon the frequency by which a node falls between pairs of other nodes on the shortest paths connecting them. This is useful as an index of the potential of a point for *control of communications*. Its general formula is

$$C_B(n_k)=\sum_{i}^{n}\sum_{j}^{n} b_{ij}(n_k)$$

where $i \neq j \neq k$ and $b_{ij}(n_k)$ is the betweenness of node n_k, which can be determined by

$$b_{ij}(n_k)=\frac{g_{ij}(p_k)}{g_{ij}}$$

where g_{ij} is the number of paths between nodes n_i and n_j, and $g_{ij}(p_k)$ is the number of those paths crossing node n_k.

Finally, closeness-centrality is based upon the degree to which a node is close to all other nodes in a network. This is also related to the control of communications, but it shows how much a node can communicate without the need of relaying. It is also known as a metric of *independence*, meaning its avoidance of the potential control of other nodes in the network, or *efficiency*, because of the low distance between nodes. It is determined by

$$C_C(n_k)=\frac{1}{\sum_{i=1}^{n} d(n_i,n_k)}$$

where $d(n_i,n_k)$ is the geodesic distance between nodes n_i and n_k.

Interestingly, all the above metrics show the minimum value for circle and fully connected networks, and the maximum value for star networks. Among these three extreme cases, it is clear that they differ noticeably in their rankings. The differences are relevant to the point that it demands attention to the purpose of the metric: communications activity, control of communications, independence or efficiency.

Those metrics were presented for individual nodes of a graph, but they can also be averaged for the entire graph. Their absolute values, which are dependent on the size of the graph, can be made relative by dividing them by their maximum values for each graph size. We believe that further research on the many combinations of these graph metrics applied to the C^2OLISEU framework can generate useful metrics for net-centric operations. As an example for the social domain, if we take the authority or the command relationships, the distribution of degree-centralities can help determining at which degree a given network is a hierarchy. Also, adapting betweenness centrality to include the capacities of links in the systems view can uncover eventual bottlenecks in communications networks.

Conclusion

The C^2OLISEU Framework for research and development of complex net-centric systems was presented, with the purpose of supporting the efforts of operations research and systems engineering. In order to consistently capture phenomena from all four NCW key domains, the framework uses concepts of information systems, cognition, and organization.

For the social domain, a set of paradigms from computational organization theory was presented, in order to support the selection of the concepts of *Roles* and *Relationships*. For the cognitive domain, it was argued that artificial cognitive agents, such as those proposed within the BDI architecture, are more suitable for meeting the requirements of cognitive systems engineering for agile, timely C^2 systems. As a way of enhancing the transition of results from research to engineering, the information domain took concepts from the DoDAF, a defense-wide standard that is broadly accepted by industry. For the physical domain, the objects and energy associated with the well-known laws of Physics provide enough expressivity for the framework's objectives.

In essence, the C^2OLISEU agent architecture uses elements taken from the BDI architecture in a consistent fashion as a means to enable the construction of executable architectures. The framework also includes a set of basic processes, derived from agent theory, of sense-making, communications, and action, which were presented here as being essential for capturing the relationships between the NCW key domains, a major advantage provided by C^2OLISEU.

Finally, a set of graph metrics for centrality was presented as indicative of the potential of combining the body of knowledge on this area with the C^2OLISEU framework to achieve an enhanced insight on relevant research questions regarding organizations and information systems.

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