A Framework for Maritime Domain Interoperability with Formal Concept Analysis

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ABSTRACT

Interoperability of information systems is the main goal of engineers in 21st century. Maritime domain interoperability is the main requirement of civilian and military agencies for common understanding of the activities in maritime environment. For achieving maritime domain awareness, interoperability between heterogeneous information systems is required, which in turn requires these systems to be connected physically, syntactically and semantically. Alliance forces and law enforcement agencies depend heavily on maritime information systems in their operational activities for decision support and anomaly detection. In our work, formal concept analysis (FCA) is proposed as the core of decision support and anomaly detection in maritime domain. Concept lattices are generated and concept exploration methods are utilized for maritime domain awareness requirements of the alliance. Finally; in this paper, a new framework for maritime domain interoperability is proposed, which properly maps to phases of Semantic Interoperability Framework (SILF) by generation of maritime data model, mapping of the maritime context, utilization of FCA for anomaly detection and upgrade to the national/alliance data model. The proposed framework aims to achieve maritime domain interoperability in a sense of an electronic library approach that can also form the basis for Common Information Sharing Environment (CISE) of European Union (EU). This work is accomplished in the context of Coastal Surveillance Radar System project requirements for the Turkish maritime information system.

1.0 INTRODUCTION

The development of communication technologies has led to the requirement of semantic information exchange between computer systems. This has given rise to a new question: “What is semantic information for a computer system?” For two or more systems to be interoperable, the language of the shared information has to be compromised by all parties and all systems need to fully understand each other. Situational awareness, which is the perception, comprehension and projection [1] of the real world from information systems’ point of view, can only be achieved by the semantic interoperability of the systems. Among the research areas for bringing situational awareness to reality, Maritime Situational Awareness (MSA) steps forward as a promising concept for member nations’ information sharing requirements for maritime interoperability issues.

In this paper, we focus on the importance of interoperability by giving examples from maritime situational awareness with semantic information exchange, and introduce the concept of anomaly detection in maritime domain. Then we propose a theoretical approach for maritime situational awareness concept analysis by defining maritime ontologies as context, utilizing concept exploration as a tool for dynamically aligning the maritime situational awareness concept lattice. Maritime concept exploration browses through the concepts, which give the maritime situational awareness operator the ability to locate required vessels, reach the related information and analyze the maritime situation. Afterwards we introduce the framework for maritime domain interoperability and identify the sub domains with different operational picture requirements. Lastly, we finalize the paper by mapping the phases of Semantic Interoperability Framework (SILF) [2] to the phases of our Framework for Maritime Domain Interoperability with Formal Concept Analysis and conclude with our suggestions and requirements for establishing a maritime information system.

2.0 MSA & SEMANTIC INFORMATION EXCHANGE

According to NATO, "MSA is an enabling capability which seeks to deliver the required information superiority in the maritime environment to achieve a common understanding of the maritime situation in order to increase effectiveness in the planning and conduct of operations." where "The maritime environment comprises the oceans, seas, bays, estuaries, waterways, coastal regions and ports."

Generation of the maritime situational awareness requires the semantic communication between member nations' maritime information systems which leads to a full semantic integration of systems', which is referred as interoperability of systems. NATO definition of interoperability is "The ability to act together coherently, effectively and efficiently to achieve Allied tactical, operational and strategic objectives" and the NATO Architecture Framework (NAF) defines interoperability as "The ability to operate in synergy in the execution of assigned tasks" [3].

Consequently, to enable the member nations' information systems to act together and operate in synergy, information systems need to have a shared communication medium and a fully understood context, in which the systems share information semantically for maritime situational awareness [4]. The shared medium requires a "common language" between the systems, which needs to have a well defined form, meaning and language in context where linguistics is defined as "The study of language in general and of particular languages, their structure, grammar, and history". From the information sharing perspective, grammar of the language has an important role. Grammar defines the semantics of information sharing, where shared datagrams are understood as they are intended to.

Words in a language, both in a natural language or a computer language, gain different meanings as they are used. For instance, words are used as attributes to real world objects, such as an adjective in front of a noun; and, as new phrases are created, the phrases gain different meanings. We need to find a formal way of creating phrases from words by defining their relations, and build semantic sentences from these phrases. Building the sentences requires the logical selection of the words and phrases, adjectives and nouns in natural languages, similar to objects and attributes in computer languages, by a formal methodology. For situational awareness, we will model this methodology in information systems by generation of formal context and performing formal concept analysis on this context. Formal concept analysis is proposed in this paper as the main tool for anomaly detection in maritime domain.

3.0 ANOMALY DETECTION IN MARITIME DOMAIN

Maritime domain consists of several and multi-disciplinary branches, each of which deals with completely different data sets. To achieve Maritime Situational Awareness, each data set needs to be thoroughly analyzed by a formal way. The results of the formal analysis are to be used in not only improving the daily operations such as optimization of maritime commercial vessel routes against piracy operations but also for maritime anomaly detection.

Anomaly detection refers to detecting patterns in a given data set that do not conform to an established normal behavior. The patterns thus detected are called anomalies and often translate to critical and actionable information in several application domains. In maritime domain, a vessel coming from Country A, with a load of Substance 1, may be referred to as a normal behavior, while the same vessel coming from Country B with a load of Substance 1 may be referred to as an anomaly. Our main effort in this paper is to automate the detection of anomalies in maritime domain, through the analyses of the knowledge base generated by domain experts. The knowledge base shall include the experiences of the domain experts and shall be temporally updated according to new maritime incidents, such as the same vessel coming from Country A with a load of Substance 1 may be referred to as an anomaly by time, if the ship gains a criminal record.

Supposedly, a cargo vessel V1, coming from country U1 with a load of white chalk S1 is a normal behavior. But later on, the coast guard receives a notice stating that the load is not white chalk, but illicit cargo. After this event, all cargo vessels coming from country U1 with a load of white chalk becomes an anomaly for a predefined time frame, keeping in mind that the suspicion includes all known related commercial routes, vessel personal lists and ship owners.

This suspicious behavior of all related vessels need to be analyzed and all vessels of interest shall be classified into a set of suspicious vessels, each set containing a different property of vessels such as vessels from Country U1, ships with crew C1, ships with load of white chalk S1. We need to find a formal way of creating data sets and a formal way of navigation through these sets so that we can focus on the suspicious vessels and semi-automate the anomaly detection process. For the arrestment of the offenders in maritime domain, the maritime governmental authorities need to gather all maritime related data into a database, and the information in the database shall be automatically analyzed 24/7 for suspicious behavior, leading to law enforcement operations. One procedure for behavioral analysis by the usage of the time varying knowledge base is called Formal Concept Analysis.

4.0 FORMAL CONCEPT ANALYSIS FOR ANOMALY DETECTION

Formal concept analysis is a theory of data analysis which identifies conceptual structures among data sets, by usage of contexts and concept lattices [5]. This method intends to make ontology building more efficient and allows for discovering necessity for new concepts and relations in an ontology, which leads to an ontology that has these entities described in a way suitable for knowledge exchange. Member nations' semantic information sharing objectives and interoperability goals will be achieved by forming the maritime ontology from the formal context and analysis of the concept lattice [6].

4.1 FORMAL CONTEXT

Before analyzing and sharing the maritime information, all the vessels and properties shall be listed in a worksheet composed of two dimensional tables, for machine readability. The tables shall have related objects in rows, and attributes in columns. For easy machine processing, we shall form the context such that, the context includes the objects' attributes by a simple relation, instead of a complex ontological definition [7].

We will create a maritime ontology, which is simple to process, but detailed enough to include all related maritime information in the formal context of the maritime domain. The created context will not be able to be described in one single table, as we are required to define all attributes of all objects as detailed as required. Cascaded tables will be used for describing this detailed recursive meaning, which will eventually form a computer representation of maritime domain, as an ontology.

The tables starting from the highest level formal context table (level zero) to sub-sub level (level two or more) includes all objects (vessels) in the system and all attributes of the objects. The context shall have objects in rows, and attributes in columns. If the attribute in column needs to be detailed in another table, such as crew, route or anomaly in Table 1: Highest Level Formal Context Table, then this attribute becomes an object in the new table, and a new table with objects in rows and newly detailed attributes in columns is created. The objects and attributes are gathered from maritime information databases.

We must keep in mind that, the related data shall be linked to the knowledge base by domain experts. The data need not be stored in a different database, but the related software shall access the databases online, and fill the cells of the context for a possible formal concept analysis. All these tables are generated and stored in a third dimensional array wrt the changes due to time. We will ignore the time effect in this paper, and focus on the near real time formal concept analysis requirements here.

Finally we will form the worksheet consisting all these tables, and we will be able to browse through the worksheet from a graphical user interface, which will give warnings in pre-defined events and anomalies, such as “Person P3 (Criminal), on a vessel that carries white chalk (S1), from Country U1”, based on the previous experience of domain experts. This anomaly detection will be a software algorithm running on the server as the decision support module. The anomalies will be reported to the user so that the law enforcement agencies can take appropriate action.

For instance, we will create the ontology in a cascaded formal context such as: Vessel V1 has crew C1, cargo S1, route R1 and anomaly A1, while Vessel V2 has cargo S2, route R2 and anomaly A2. Also the context shall include, in another table, Crew C1 has Person P1, P2, P3 and P4, of which P3 has a criminal record. Also the tables will have temporal displacement, such that the routes will change in the next trip, which we will ignore in this paper. The ontology details are simple examples from paper [8], [9]).

The vessel V1 is en route from U1 island to U2 island, and stops by island U4 and suspected region SR1 on the way, while the vessel V2 is en route from U1 island to U3 island, and stops by suspected region SR1 and island U2. In the suspected region SR1, the two vessels V1 and V2 has a contact which creates anomalies A1 and A2 respectively, as shown in Figure 1: Vessel movement scenario and the following context table, sub tables and sub-sub table. “Obj.” refers to objects to be detailed in a new table, while “att.” refers to attributes in the same table.

The context will also be used for forming the concept lattice and browsing through the lattice, so called concept exploration, which is described briefly in the following section

Table 1: Highest Level Formal Context Table

Vessels	IMO # (att.)	Crew (obj.)	Cargo (att.)	Route (obj.)	Anomaly (obj.)	Sensor Data (obj.)	…
V1	…	C1	S1	R1	A1	…	…
V2	…	…	S2	R2	A2	…	…
V3	…	…	S1	…		…	…
V4	…	…	S1	R3		…	…

Table 2: Vessels Sensor Data Sub Table

Vessels	Coordinate	Sensor IMO #	Sensor MMSI #	Navigation Status	Radio Call Sign	Type of Vessel	…
V1	…	…	…	…	…	…	…
V2	…	…	…	…	…	…	…
V3	…	…	…	…	…	…	…
V4	…	…	…	…	…	…	…

Table 3: Crew C1 Context Sub Table

Crew C1 Table	ID #	Citizenship	Clean Criminal Record	Birth date	…
P1	…	U1	✓	…	…
P2	…	U1	✓	…	…
P3	…	U2	✗	…	…
P4	…	U3	✓	…	…

Table 4: Route R1 Context Sub Table

Route R1 Table	From Country	To Country	Midway Stop #1	Midway Stop #2	…
V1	U1	U2	U4	SR1	…

Table 5: Route R2 Context Sub Table

Route R2 Table	From Country	To Country	Midway Stop #1	Midway Stop #2	…
V2	U1	U3	SR1	U2	…

Table 6: Route R3 Context Sub Table

Route R13Table	From Country	To Country	Midway Stop #1	Midway Stop #2	…
V4	U1	U2	…	…	…

Table 7: Anomaly A1 Context Sub Table

Anomaly A1 Table	Contact en route (obj.)	Stopped for 6 hours	No AIS Signal	Route change	…
V1	Con1	✓	✓	✗	…

Table 8: Contact Con1 Context Sub-Sub Table

Contact Con1 Table	Contact	Time Period
V1	N/A	N/A
V2	✓	…
V3	✗	…

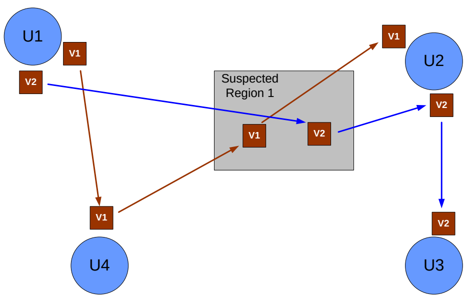

Figure 1: Vessel movement scenario in our case study

4.2 CONCEPT LATTICE

Concept lattices are used to represent conceptual hierarchies which are inherent in data. They are the core of the mathematical theory of Formal Concept Analysis (FCA). There are many algorithms to build concept lattice, while in our work of maritime ontology building, we will only use the context we have previously defined in section 4.1 of our paper, and we will focus on the requirement for a graphical user interface for concept exploration, briefly mentioned in this and the following section.

Suppose our aim is to find the suspected vessel in a set of all vessels. With domain experts help, the system “has learned” the suspected vessel criterions. We construct the concept lattice with previous experience of the domain experts such that: we have a concept (a set of vessels) called vessels that change their route from previously reported route (R1) V1, V3 and V4, set of vessels carrying suspected substance (S1) V1, V2 and V4, set of vessels within limited distance to other vessels (D1) V1, V4 and V5, and set of vessels whose personnel has criminal record (CR1) as V1 and V6.

We draw the concept lattice by linking the sets R1, S1 and D1 and draw a new concept R1S1D1 including the set of vessels V1 and V4. But this is still a large set of vessels, so we need a new concept, linking the set of vessels with a criminal personnel set CR1 including V1 and the concept R1S1D1. Then finally we find a final concept with only one vessel in the set (V1) and report the situation to law enforcement agencies, and check the Vessel V1 for illegal activities.

We have connected the sets on a three level lattice, such that in this example some vessels might not have a previous criminal record, but still might be engaged in illegal activities. The first two levels connects three sets and level two results the vessels V1 and V4, concept R1S1D1. If this set of vessels satisfies the operator, then there is no need for a third level. This connection of sets enables multi level generation of concept lattice, which in turn returns a limited set of vessels, where this limited set enables the operator to physically examine the vessels in the set for illegal activities. Additional levels can be generated by forming new concepts and connecting them, which in turn results very limited number of vessels, even more possible for physical inspection.

The operator can watch some concepts for newly added vessels, and the system can generate alerts for each vessel addition to these concepts. These concepts act as the main decision support module of the maritime information system, and the knowledge of domain experts play a very important role. By time new sets can be generated, as new expertise is gained by law enforcement activities and the system learns to catch maritime anomalies in time.

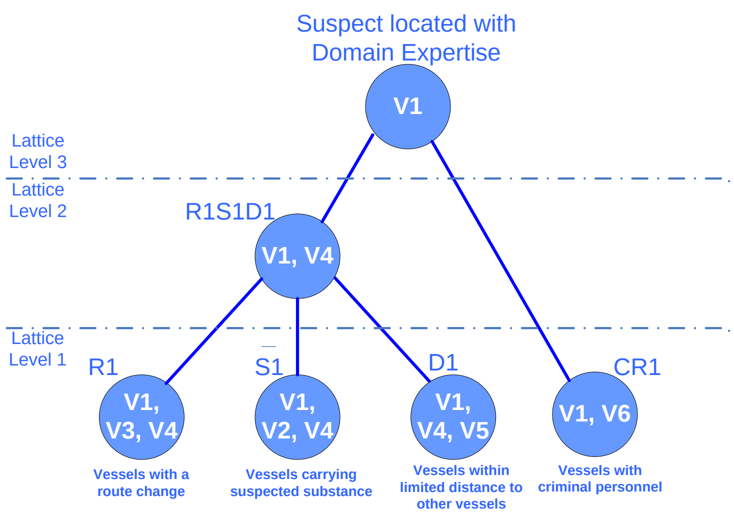

Figure 2: Suspect Location with Domain Expertise via Concept Lattice

4.3 CONCEPT EXPLORATION

Now that we have formed our concept lattice, we need to use the graphical user interface for concept exploration, also known as relational browsing [10]. This latter stage of formal concept analysis, aims to find new concepts, new sets of vessels, that might be advantageous to investigate for law enforcement agencies. After drawing the simple concept lattice, suppose we have new sets of ships:

Vessels carrying explosive (S1): V1, V2, V3, V4, V5, V6,

Vessels coming from country one (U1): V1, V3, V5, V7, V9, V11

Vessels with criminal personnel (CR1): V1, V2, V6, V10

We explore a new concept, by intersecting the S1 and U1 sets, and find the concept S1U1 with elements V1, V3 and V5, then intersect this set with criminal personnel set CR1 to find the concept with only element V1.

If the result V1 does not satisfy the operator, or is known to be a regular vessel, then the coast guard needs to find new sets of vessels for inspection. Concept exploration becomes critical here, where we will explore the concept lattice for new concepts.

The need to find new suspected vessels drives the need to find new sets/concepts. The most common method of finding the new concepts is asking the Question to the set S1U1: “What common properties do the subsets of this concept/set have?” Suppose we get the answer “%90 of the members of the concept S1U1 carry crane”. Then the system can suggest inspecting a new concept from the initial set of vessels, namely a set of vessels carrying crane, which is a regular load for commercial vessels, but can be used as a platform for launching long range rockets in illegal activities. Then we can find the intersection of this set with the set of personnel with criminal records (CR1) by operators’ domain experience. The intersection of this concept with concept CR1 gives the set of suspicious vessels V1 and V10 as a result. Reaching V10 is important here, as the system suggested the operator a new vessel for inspection, in addition to section 4.2 of this paper. More common properties of this concept can also be inspected for further analysis, along with the other common properties of the concept S1U1.

The same operation can be done for other common properties of the concept S1U1, such as “%75 of the members of the concept S1U1 are en route to country U2”. Then similarly, a new concept can be initiated from the initial set of vessels, namely a set en route to country U2, and further analysis can be performed on this set.

The system aids the operator by tightening the sets of suspected vessels, and gives the coast guard and other law enforcement agencies a chance to catch the anomalies. The graphical user interface helps the user to use the computing power of servers for browsing through the vessels and minimizing the set of suspected vessels. Formal generation of the context enables the system for real time formal concept analysis.

A very important requirement of the system described here is to keep the context tables updated from the databases. The system needs to get the required data from the connected databases and generates the tables online. To enable the system for performing formal concept analysis, the updated tables need to be generated and stored with timestamps in a data storage unit, centrally or distributed.

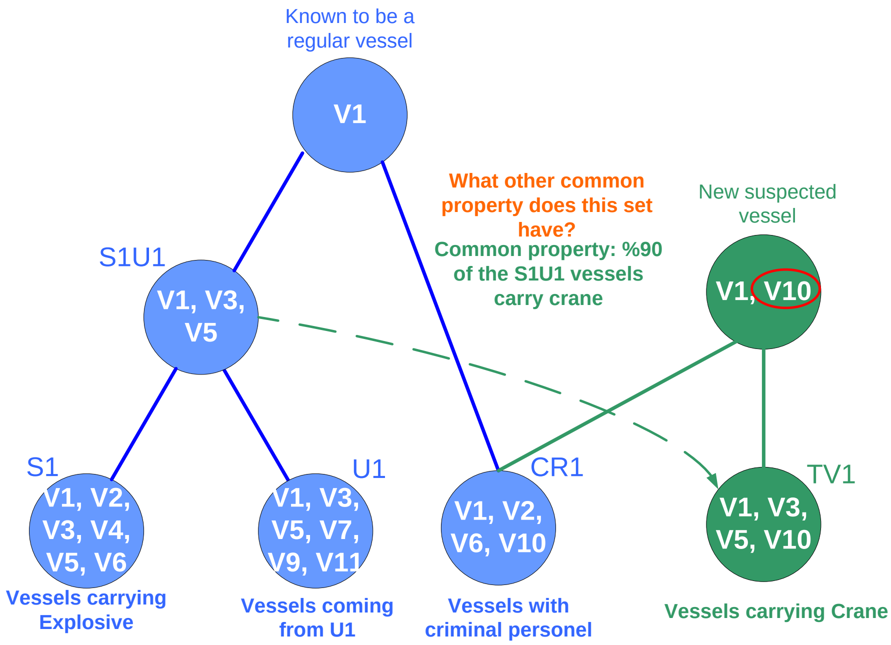

Figure 3: Concept Exploration for automatic suggestion of a new suspected vessel

5.0 FRAMEWORK FOR SEMANTIC INTEROPERABILITY IN MARITIME DOMAIN

Interoperability, in its broader sense, deals with knowledge exchange between different systems, each system with its own vision of the world. Maritime domain interoperability is the semantic knowledge exchange between different maritime information systems, with each system viewing the operational picture from different approaches. Not only does each approach create a new sub domain that focuses on different perspectives of maritime affairs; but also each NATO member nation has a different understanding of maritime affairs according to their operational and national maritime policies. Therefore, they divide the maritime view into sub domains according to national legislations. We will focus in four sub domains of maritime environment and exemplify accordingly.

The most generic classification of maritime domain is achieved as maritime security, maritime navigational safety, protection of the maritime natural resources and maritime commerce. These domains are closely related to each other, but each having their own objective and focus. Security sub domain deals with international cooperation and homeland security issues, including protection of national maritime environment against unauthorized entry and all kinds of attacks including using lethal weapons. Navigational safety sub domain deals with precautions taken for prevention of maritime accidents and events that can cause losses of life, property, injuries and damages. Maritime natural resources sub domain deals with precautions taken for the protection of maritime environment and more specifically prevention of marine pollution. And lastly, maritime commerce sub domain deals with the economy of maritime affairs including national and international transportation. These sub domains are closely related to each other and the domains and related agencies' responsibilities intersect at times. Management of each domain is a challenging task on its own. In order to manage each sub domain and the maritime domain as a whole, interoperability of maritime information systems is crucial.

The framework for interoperability; requires the sub domains to be assessed from a broader perspective, instead of focusing on each sub domain separately. Maritime context is same in all sub domains, but the semantics that relate to this information differ between sub domains. The semantics are derived from maritime context by domain expertise. Each sub domain needs a different way of domain expertise and requires a different operational picture. For instance the objects, surface vessels, and the attributes, properties of the vessels are the same in all sub domains but navigational safety sub domain (and responsible governmental agency) inspects the traffic of vessels while natural resources sub domain focuses on marine pollution. The knowledge extracted from the context differs as each government agency (each sub domain responsible) feels the world in its own experience and responsibility.

The national agencies responsibilities for the maritime domains are complicated, as each agency is responsible for different parts of different sub domains. Also each agency has many heterogeneous information systems [11], which need to be contextually interconnected for performing the responsibilities. Interoperability between different systems, established in different countries, requires a translation mechanism for each country as indicated in SILF. The maritime context, including all maritime related data, shall be applied to a SILF like mechanism, so that when the data is transmitted to the international area, the semantics of the information are protected and all stakeholder countries of information sharing will communicate in the common language with common semantics. Semantic Interoperability Framework (SILF) focuses on the functional interoperability of these systems, assuming the physical and syntactical levels of interoperability are accomplished.

In the preparation phase, according to SILF, the world knowledge is to be transferred to the common ground, for collecting the necessary context information about the participants in the form of semantic descriptions (ontologies). In this phase, our aim is to create the national maritime data model from the data field descriptions of the information in distributed databases of heterogeneous maritime systems in different governmental agencies.

In the configuration phase, the definition of translation rules will be performed by defining the ontology alignment operations. Maritime context will include the abstract ontological definition of the system and the maritime context will be aligned with the data model. Translation rules are utilized to transform the information inside the fields of the maritime data model to and from the maritime context.

In the operational phase, the maritime systems will be exchanging information semantically and the maritime context will be automatically updated from the distributed maritime databases near real time. Each system will be posting and subscribing to the information in the context by service oriented architecture. All sub domains communicate with each other semantically, formal concept analysis is performed on the maritime context and maritime anomalies are detected.

The post-operation phase will be the basis for evaluation and improvement of the system. In this phase the maritime data model will be upgraded to the national/alliance data model. Instead of focusing solely on the national maritime environment; land, air and space information will be included in the national data model, along with the international maritime information systems. The output of phase will also be coherent with the Common Information Sharing Environment (CISE) for the surveillance of the EU maritime domain.

This mapping process is detailed in Figure 4: Mapping of the phases of SILF to Framework for Maritime Domain Interoperability with FCA.

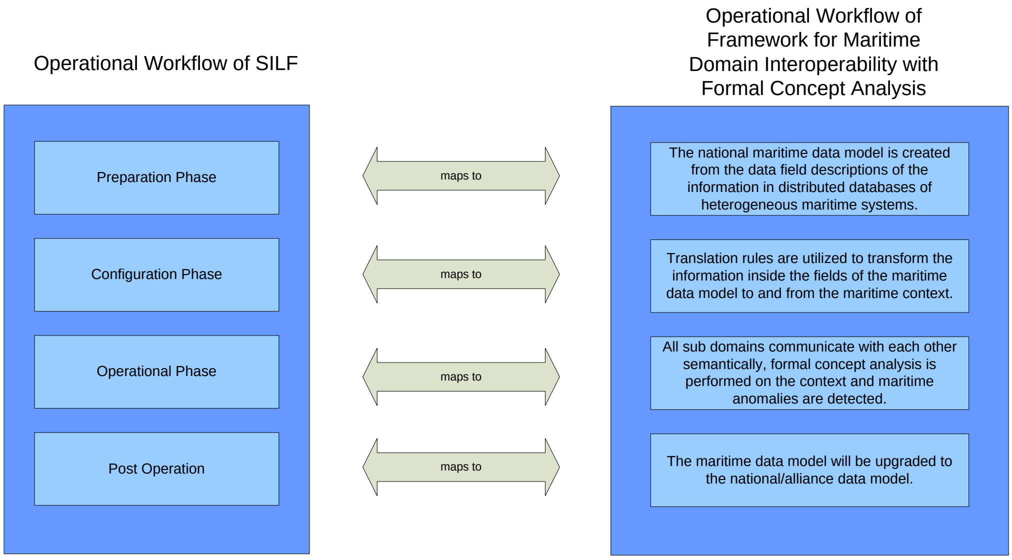

Figure 4: Mapping of the phases of SILF to Framework for Maritime Domain Interoperability with FCA

6.0 CONCLUSIONS

This paper has described a novel mechanism for semantic interoperability in maritime domain with Formal Concept Analysis. Integrating the FCA with maritime/national data model and mapping of the phases of SILF, creates a new framework for maritime domain interoperability.

The generation of the maritime context is fundamental to semantic interoperability. For the systems to be interoperable, they must share information without the loss of semantics, which in our case without the loss of relations to other objects and attributes in the cells of the maritime context tables. The maritime context is the viewpoint of each agency/nation/alliance for maritime environment. The maritime context shall include all necessary adjectives (attributes) for defining the nouns (objects), so that the language will enable the national information sharing requirements, enabling the semantic information sharing. The context will include all elements of the maritime ontology, and each system will access the information from the context, as the shared medium. After the systems reach the required information, they will process the information individually for each system's own requirements. In large scale systems, such as Common Information Sharing Environment (CISE) of European Union (EU), the semantic translator modules in SILF may be required before the information can be individually processed by the systems.

For the goals of the Framework for Maritime Domain Interoperability with Formal Concept Analysis to be achieved, the government agencies owning the data in the distributed databases need to access the maritime context online for performing their required analysis. The maritime context shall include all maritime related information and the agencies need to have their own analysis tools for analyzing the maritime context. These tools will have different capabilities for analyzing and reporting the maritime events. No such tool can satisfy the requirements of all government agencies, so these tools and related graphical user interfaces need to be designed separately but all will have access to the same maritime context. The maritime context shall be shared as an electronic library, not designed as a new system, and each agency shall design its own operational tools for accessing and processing the information in the electronic library.

Maritime environment is very complicated as mentioned in previous sections and requires the integration of many heterogeneous systems. Some of these systems are coastal surveillance systems including construction of radar/EO sites, while some are online local/international databases for maritime related information. Successful integration of all these heterogeneous systems require very customized solutions and the development of a common data model. The nation/alliance wide maritime information system integration projects need to be divided into phases. We would suggest starting from a limited number of sites and databases, and expanding the system to nation/alliance wide in a second phase.

The future work of our framework will be the analysis of the data model definition of maritime systems and interoperability requirements of EU CISE and NATO C2IS systems.

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