Modeling and Analysis of Interoperability Risk in Systems of Systems Environments

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This article describes the use of a set of modeling and analysis techniques in an interoperability risk probe that found gaps in the ability of a North Atlantic Treaty Organization (NATO) modernization program to react to changing demands. The modeling and analysis techniques were used to create models of the people, processes, and technologies of the program and to represent the way demands were placed on this complex socio-technical system. Analysis of the models revealed interoperability risks that were manifested in the linkages between operational requirements of functional capabilities and the way in which those capabilities were being maintained. The risks identified in this probe were typed as mission, composition, and performance risks. The structural models produced by the techniques bring a welcome engineering rigor to the process of examining interoperability.

A National Defense Industrial Association report suggests that modeling can aid the DoD throughout the system of systems (SoS) development life cycle [1]. Model-based dynamic system analysis provides insight into otherwise unobservable dimensions that can help characterize an SoS. One of those dimensions is interoperability risk, which is manifested in the linkages between operational requirements of functional capabilities and the way in which those capabilities are maintained.

This article describes a model-based interoperability risk probe[1] of a NATO modernization program. Using a rapid assessment engagement format, the Software Engineering Institute (SEI) modeled the NATO program as a system of social and technical systems. The probe involved workshops and interviews conducted over a two-week period, followed by analysis of the data gathered. In the probe, we interpreted SoS and interoperability in a broad sense. We examined the hardware and software in the context of its operational and sustainment environments. Therefore, the SoS examination included the many ground and airborne systems and the diverse organizations (social systems) required to operate and sustain the NATO program. In this article, we are emphasizing the modeling and analysis techniques employed over the specific details of the case, because those details are confidential to NATO[2].

The risk probe emphasized the importance of demand on a systems of systems environment. If demand is stable and pre-identified—large nation-state military threat scenarios, a huge and stable demand for sport utility vehicles, or the best health care that money can buy—traditional hierarchical structures and monolithic systems work well. However, demand conditions can change—terrorism has redefined military threats, ever-increasing gasoline prices have affected consumer choice in automotive vehicles, and health care costs have skyrocketed—forcing market-driven demand responses from systems of systems.

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An assumption underlying the techniques is that interoperability issues are—and should be—strongly influenced by the need/desire to be reactive to changing demands. As a result, these modeling and analysis techniques find gaps in an organization's ability to react to changing demands. The goal is to model complex emergent patterns of behavior (and gaps therein) that are not directly intended by any single governance entity within a complex SoS. The techniques model physical and social aspects of enterprises associated with the conception, construction, fielding, operations, and evolution of complex systems and systems of systems. An enterprise can include multiple organizational entities, often under different management and ownership structures. The techniques model the roles and interrelationships of the enterprise's physical and social elements across organizational entities and their ability to form, use, and evolve automated systems within the systems' operational context of use—both today and for the future.

The techniques probe three general categories of risk:

1. Performance. The risk that subsystems within system elements will not interoperate in the ways needed to respond to demand.
2. Composition. The risk that a set of systems that need to interoperate within a given SoS cannot be made to interoperate in the ways being demanded of them.
3. Mission. The risk that an SoS will not function within its operational context of use in the ways demanded of it.

NATO Interoperability Probe Approach

In the NATO probe, we used workshops and small group interviews to examine

Table 1: Perspectives Represented in the Workshops

Client Perspective	Description
Physical	The physical realization of a complex system or SoS within its operational context-of-use.
Cognitive	The knowledge associated with the acquiring, building, or evolving of a complex system or SoS.
Effects-based	Mission or business effects, current and future, that the capabilities provided should support.

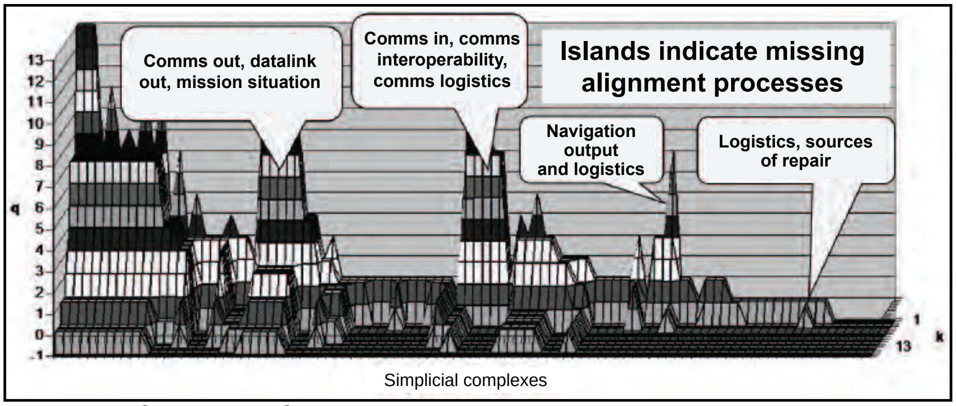


Figure 4: Orchestration Landscape

esis was that NATO's focus was biased toward managing the capabilities (white/blue) in a way that was divisive to the ever-changing demand versus the mission driver (red/black) relationship. Rotating through the color quadrants, we probed for structural (what, how) and influential (who, why) aspects. This generated a wall full of sticky notes to jump start the visual modeling.

The visual models were constructed interactively in the workshops using Microsoft Visio with a custom stencil of symbols and rules applied to assure that only the allowed symbols and appropriate connectors were used within and between layers of the model. This consolidated visual model representation contained five interlocking layers:

1. Structure/Function. The physical structure and functioning of resources and services.
2. Hierarchy. The formal hierarchies and standards under which both the non-digital and digital aspects of the whole are held accountable.
3. Trace. The digital processes and software that interact with the physical processes.
4. Demand. The organization of customers' needs as demands on the way the enterprise is organized.
5. Synchronization. The lateral relations of synchronization and coordination within the enterprise and between the enterprise and its customers.

In between client sessions, these visual model entity-relationship diagrams were analyzed for patterns (complex or emergent[3]) that facilitate the structuring of the entities according to the stratification (from services to mission environments). The patterns revealed aligning structures between the mechanisms that determined the organization's ability to react and manage itself (e.g., governance, actors, design authority—the determining structures) and those mechanisms that carry out the directives of the determining structures (e.g., systems, processes, agents—the determined structures).

> *"The patterns revealed aligning structures between the mechanisms that determined the organization's ability to react and manage itself."*

Model Matrices

The stage-one, entity-relationship-style diagrams rapidly became eye charts, too complex to analyze directly. The views conveyed the global complexity of the situation, providing a structural snapshot of the dynamic characteristics of this complex SoS. However, they did little to indicate specific interoperability risks among those characteristics.

In the probe's second stage, we took advantage of the defined semantics and rule-based approach of the diagramming technique to convert the diagrams into a stratified matrix. The conversion was done using an automated utility that leveraged recognizable patterns in the entity/connector relationships (e.g., a hierarchical unit that controls a synchronization of activities produced a derived entity called an orchestration). The conversion layered the connection information embedded in the diagram's semantics from the point of view of the different demands being placed on the systems; see [4] for details of this procedure.

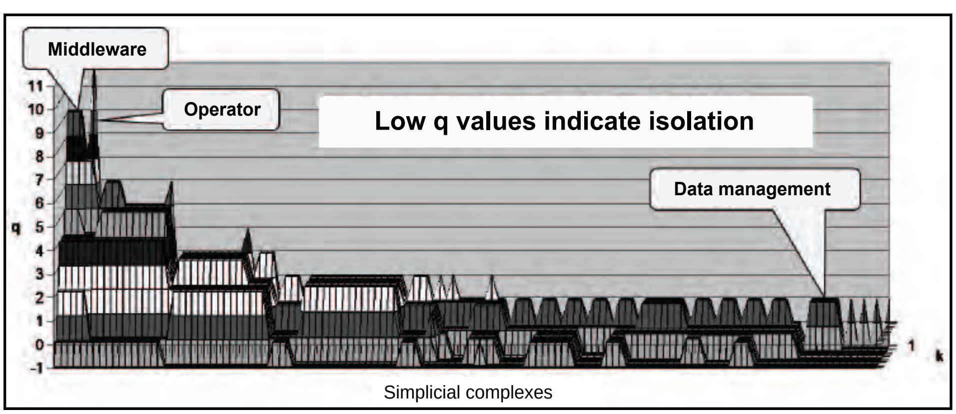
The NATO six-level stratification is illustrated in Figure 1. The core levels—the sub-matrices labeled 1-6 (the darker shaded boxes)—form a value stratification that progresses from low-level services, systems, and know-how to high-level mission environment descriptions (this progression is represented by the connecting arrows in Figure 1). The other numbered matrices model the aligning structures that facilitate the overall enterprise's ability to react to the mission environment. The major axes are composed of the simple and complex objects[4] that model the enterprise's assets, capabilities, and processes.

Figure 1 also includes some exemplars of the entity types that populated the various sections of the matrix, such as mission situations, drivers, demand situations, constituent capabilities, events, processes (such as change notification), know-how, and outcomes.

Interoperability Landscapes

In the third stage of the probe, we analyzed the stratified matrix and produced interoperability landscapes. The landscapes depict the connectedness of the entities, sorted so that neighboring entities show commonalities and differences in their degrees of connectedness. An interoperability landscape (like the one in Figure 2) enabled us to visualize relationships and gaps within the visual model representations, viewed from different

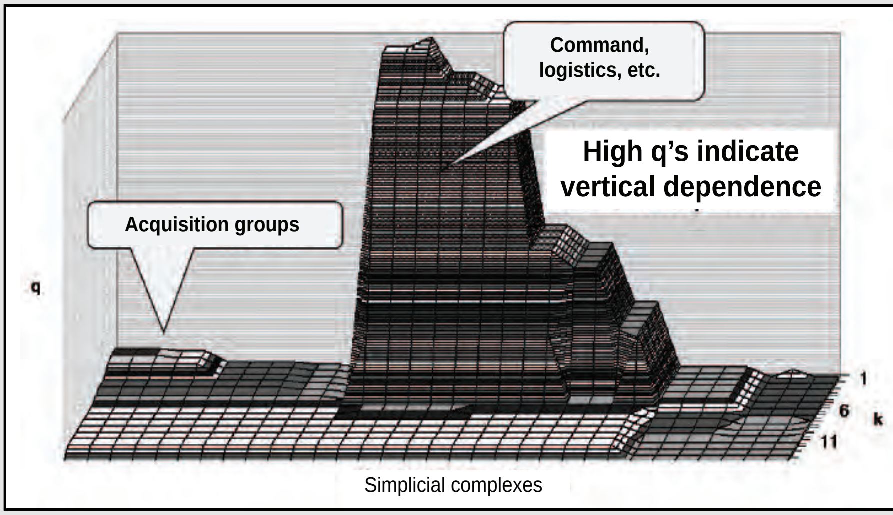
Figure 5: Performance Risk Landscape



perspectives codified by the matrix. The columns in the landscape (Ron Atkins'[5] simplicial complexes) are organized so that entities connected through a shared number of interoperating activities are next to each other in terms of their height and depth dimensions. The height dimension (q in the landscape) describes the number of shared underlying activities; the higher the q between columns, the more related they are. The depth dimension (k) describes the number of other related columns there are at that level of q. For example, the landscape in Figure 2 shows peaks separated by valleys. These valleys illustrate the gaps between the different levels of shared activity. From this landscape and its underlying matrices, we gained insight into which 17 relationships generate the high peaks and which 10 events share services in the broad plateau on the left of the figure.

Indirect Management Control

The slicing process can be customized and creatively applied. For example, when the first-line management structures were suppressed, the impact of indirect management control jumped out. It also revealed the significant separation between the acquisition organization and the line command structures. This figure shows the vertical command dependencies in this SoS.



Outcomes About NATO Interoperability Risks from the Approach

Using the modeling and analysis techniques approach described in this article, we constructed models of the people, processes, and technologies that made up the NATO modernization program and represented the way demands were placed on their use. Using those models and representations, we developed an objective view that reflected the major interoperability challenges faced by the program, using interoperability landscapes to discover and illustrate those challenges. We categorized those challenges as Type III Mission Risks, Type II Composition Risks, and Type I Performance Risks.

Type III Mission Risks

Projecting[6] from Level 6 (mission environments) in the matrix, we examined how the SoS interoperates within its demand-driven, operational context-of-use.

Figure 3 is the three-dimensional depiction of our mission awareness landscape. This particular example shows that the predominant mission awareness integration point was the system operator and the operator's display console. The rest of the social and technical systems for areas such as development, support, and acquisition were virtually unaware of mission-demand complexity. That is, these systems did not interoperate in response to demand situations; for those that should have, the Type III risk was high[7].

Type II Composition Risks

Entering the matrix at Level 4, the orchestration level, we examined whether the systems interoperated in the ways being demanded of them.

After ordering and ranking, the resulting orchestration landscape (see Figure 4) revealed obvious islands of high connectivity with broad regions of separation. The specific entity groupings were examined to determine if the separations were warranted. For example, gaps revealed that hardware configuration management was quite separate and poorly orchestrated with software version management. The depth of the valleys indicates that the baseline connective tissue (of aspects such as change management and revision control) was far from seamless in this SoS.

The model (at the modeled fidelity) is good at indicating missing connections; it conversely indicates the presence of connections (peaks) but does not speak to the sufficiency of those connections. Therefore, gaps tend to be truer signs of interoperability risks (because it is hard to interoperate when one has no connection) than peaks are guarantees of interoperability (because high connectivity does not necessarily mean interoperability). However, both gaps and peaks are good indicators of worthy areas for further investigation.

Type I Performance Risks

Entering the matrices at Level 3, the operational capability level, we examined how the subsystems within system elements were or were not connected.

The performance risk landscape (shown in Figure 5) revealed the degree of isolation between the many structural entities in this SoS. Once again, we found a high likelihood of connectivity gap-driven risks; these gaps required further examination to determine the severity of consequences before declaring specific risk significance.

In our three categories, we identified interoperability risks and visually reinforced their presence by the landscape topologies. The objects and relationships depicted in the landscapes were familiar to the client and served to:

- Facilitate constructive dialogue about mitigation strategy.
- Justify and prioritize follow-on activities, such as detailed impact analysis, model refinement and validation (through detailed, bottom-up fact finding), and cost analysis in targeted areas.

Conclusions About the Modeling and Analysis Techniques

The examination of interoperability is a challenge in understanding complexity. The structural models produced by the techniques bring a welcome engineering rigor to the process.

In part, the effectiveness of this set of model-based analysis techniques can be attributed to the way they stress the need to speak in the client's language. The technique starts with client artifacts and builds visual representations (entity-relationship-style diagrams) that are understood by the client. While they quickly become eye charts that are too complex to convey anything other than the global impression of complexity, these diagrams do employ rules of object-connector relationships that facilitate a transformation of the data into a stratified matrix, supporting empirical analysis. Overall, the techniques produce a rapid (nominally two days per model) snapshot of interoperability risks from the perspective of the interviewed stakeholders.

Of great merit in the techniques is the attention paid to understanding the relationship of the operational context and the supplied technologies, capabilities, and governance mechanisms[8]. By identifying gaps in their alignment, the NATO interoperability probe team identified critical risks that are often overlooked.◆

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Notes

1. The techniques used were a demonstration of Boxer Research Limited's (BRL's) Projective Analysis (PAN). The SEI and BRL have since integrated uses of PAN into the SEI SoS Navigator suite of products. PAN has been applied in enterprises in such domains as manufacturing, health care, defense, and telecommunications [2]. For example, PAN has been used in support of Through Life Capability Management practices [3] for the United Kingdom Ministry of Defense. Projects under the European EUREKA program, jointly funded with the Department of Trade and Industry in the UK, with City University (London) as a subcontractor, further developed parts of the technology.
2. This article has been drawn, with permission, from two SEI special reports [4, 5] and from information about PAN available at [6]. We have used figures utilized in our NATO research. To protect NATO's confidentiality, some actual specifics have been removed: For example, the vertical marks above simplical complexes in the landscape figures each represent an item with a name that has been removed.
3. The patterns are represented by model-generated entities emerging from more complex interactions than are represented by simple entity-connector-entity constructs (e.g., markets, orchestrations, and super-channels).
4. Tangible assets, such as control modules or design expertise, are named *simple objects*. Patterns of relationships that form outcomes or mission situations are named as *complex objects*.
5. The form of description behind this matrix format uses the mathematics of Ron Atkins' Q-analysis. An introduction to this can be found in [7]. The simplicial complexes are derived directly from the named entities in the visual model and from the patterns of objects generated by the stratification process.
6. *Projection* is the systematic process used to examine the matrix representation of the modeled SoS; it is described in detail in [4]. The technique uses the stratification to provide *entry points* at different levels of complexity. This provides a means by which the interoperability issues can be decomposed at different levels of complexity.
7. If the consequence of the detected condition is not serious (i.e., benign), the risk may be considered low [8].
8. The technique models the structure-determining processes of the organization-in-context as well as the structure-determined processes of the systems the organization uses.

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