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A Practical Framework to Ease Complexity Understanding

Track: C2 Concepts, Theory, and Policy

Mario Couture and Robert Charpentier
Defence Research and Development Canada (DRDC)
2459, Pie-XI Blvd North, Québec, Qc, Canada, G3J 1X5
Tel.: (418) 844-4000 (4285)
Mario.Couture@drdc-rddc.gc.ca

Abstract

To complement the traditional reductionism approaches, many C2 analysts and designers are now considering holistic and middle-out approaches that could better deal with the ever-growing complexity of modern command and control systems. In this article, four "complex conditions" (called modalities) are proposed for studying Complex Systems (CxS) and to characterize their evolution toward superior behaviors. Modalities address multiple features, properties, complex mechanisms that can be linked together into "interaction diagrams", which help understand complex relationships in more holistic perspectives. They form the first version of a practical framework that is illustrated with the NATO C2 Network Centric Operation taxonomy.

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1 Introduction

Nowadays man-made systems used in our societies like the Internet are becoming more and more complex[1], hard to control and predict [Poussart, 2007]. They often involve intricate combinations of people that have different perceptions of reality and that are distributed in scattered organizations. In general, they are made of huge numbers of relatively autonomous "sub-systems" that are willing to work together in different modes[2] in order to achieve common goals using sets of communication means and protocols (herein they are called **components** of complex systems).

Internal rules, values, beliefs, cultures and models of understanding within each component drive or regulate their actions. Their ability to create, modify, adapt, and survive "as a whole system" in face of unforeseen situations depends on specific internal conditions such as the decentralization of planning and control and the flexibility of components to spontaneously re-organize and innovate. Appropriate sets of conditions will also give complex systems (CxS) higher robustness, responsiveness and resilience. They will give them high levels of stability while operating in highly unpredictable and variable environments. Interrelationships between components are at the source of the emergence of complex behaviors such as: self-organization, self-adaptation, self-recovery, self-healing and long-term evolution. It is often said in the literature that the capabilities of the whole CxS are greater than the ones that would be obtained from the sum of individual capabilities.

This ever increasingly "complexification" of our world is enabled by the tremendous evolution of communications. It has (and will continue) to have profound effects on the military Command and Control (C2) [Alberts and Hayes, 2007], imposing new challenges to military organizations. For instance, officers in operations that are addressing complex problems shall have a good understanding of critical complexity aspects of involved systems, and the environment in which they evolve (hostile or not). Moreover, C2 systems operated in theatre must reach levels of sophistication that are at least equal if not higher than the ones of the environment within which they evolve [Bar-Yam, 2005]. Military acquisition must thus adjust accordingly in order to provide systems that will make military operations more efficient and effective in any context[3] and environment. Typically, traditional (and relatively linear) reductionism top-down approaches are not enough to deal with this new complex problematic [CTW, 2006].

This change of paradigm imposed to military community is truly challenging for at least three reasons. First CxT is still evolving; it is the object of intensive R&D all around the world. Basic underlying principles and concepts are not necessarily interpreted the same way by different authors and some concepts and complex phenomenon such as "emergence" are still not completely understood. Second, theoretical concepts are often abstract and their subtleties are difficult to understand at first glance. This is particularly true in military operations where officers are engaged in complex demanding tasks and in contexts and environments involving very high levels of stress. Moreover, our mental models of understanding that are based on traditional linear top-down reductionism approaches are not well suited to understand such highly interlinked and interdependent concepts. A global or holistic approach, which is contextual and relational and that is both top-down and bottom-up (middle-out) appears to be preferable.

[1] The reader is invited to refer to Annex 1 for definitions of some key words of Complexity Theory.
[2] Modes can be for instance: cooperation/collaboration, coalition, competition or conflict.
[3] Context corresponds here to nowadays complex spectrum challenges officers are facing on the battlefield: peacekeeping, humanitarian relief or full scale military actions.

Third, there is not a common and generic complexity framework that could be used at this moment to study CxS. As observed in a recent literature survey [Couture, 2006a-d], the definition of concepts[4] of CxT often vary from one author to another, making the formulation of a consolidated framework difficult at this time. For instance, the concept of aggregation is considered as a fundamental element in [Beech, 2004] while it is considered as one of the basics of CAS (Complex Adaptive Systems) in [Ilachinski, 1996a, 1996b] and [Axelrod and Cohen, 2001] and as a basic complexity parameter in [Holland, 1995]. Also, some of these concepts are sometimes used inconsistently with respect to their natural "domain(s) of applicability". For instance, terms like "adaptation" or "resilience" of CxS should normally be used in reference to the whole system while terms like "diversity of roles" and "interdependence" should normally be intrinsic to components of CxS. These lacks in the literature interfere constantly with the understanding and the use of concepts from the CxT.

So the focus of this R&D work was placed on the formulation of a framework that would structure these concepts and ease the building of integrated picture of understanding. A high priority was placed on the practical aspects of the framework as shown in the next Section of this article. It is proposed to synthesize the intrinsic nature of CxS with the help of interactions diagrams. A set of four modalities (i.e. descriptors to group or structure complex notions of CxT) supports the proposed process to explore interactions between components of CxS.

2 The Complexity Framework (CxF) – a Preliminary Version

2.1 Objectives

The CxF has been designed to address some key requirements:

1. the CxF shall be as **generic** as possible. It should allow addressing a wide spectrum of complex problems in different fields or domains;
2. the CxF shall ease the **understanding of underlying concepts** of Complexity Theory (CxT);
3. the CxF shall **provide a guidance** on how to address complex problems;
4. the CxF shall **facilitate reuse** of any proven solution;
5. the CxF shall **reflect the commonalities** that can be found in the scientific literature.

In order to satisfy these requirements, it was decided to adopt the Santa Fe Institute approach [SFI, 2007; Holland, 1995]. Researchers at SFI focus on the emergence of new order within complex systems (CxS) when they are operating within a state called "Edge-of-chaos" [Langton, 1990, 1991]. Based on a multi-disciplinary approach, they postulate that this new order emerges at the level of the whole when many of its interacting components are willing to improve the global fitness and find new solutions. Their approach involves the study of similarities between different CxS to find underlying principles or premises that would form the basics of a unified CxT. [Holland, 1995] describes the SFI approach in these terms: *The best way to compensate for this loss* ([5]) *is to make cross-disciplinary comparisons of CAS* (Complex Adaptive Systems[6]), *in hope of extracting common characteristics. With patience and insight we can shape those characteristics into building blocks for a general theory.*

[4] The word "concepts" includes here complex notions, properties, mechanisms and phenomena.
[5] We are missing the means for generalizing observations into a unified theory.
[6] A CAS is an "instance" of CxS. The acronym "CxS" is used all along this document.

2.2 Modalities – Key Notions for Studying Complex Problems

The operation of a CxS in specific context and environment will exhibit complex behaviors (i.e. self-organization, self-adaptation, evolution, etc.) only if certain internal conditions are gathered and maintained for a certain period of time[7]. Based on the literature survey [Couture, 2006a-d], four **modalities** were identified. They are "composite conditions" (or meta-conditions) that characterize the evolution of a complex system toward superior behaviors. They are:

1- the **Richness of Components**;
2- the **Richness of Interactivities** between components;
3- the **Shared Motivations and Anticipations**; and
4- the **Outgrowth synergy**.

Each modality will now be briefly described and is illustrated. In Figures 1-4, the horizontal scale (x-axis) defines qualitatively the "degree of complexity" of the CxS defined by elements of the modality. It ranges from highly stable states on the left to unstable chaotic states on the extreme right. The state or region called **Zone of Rich Free-play**[8] is located between these two extreme regions (but more on the right side).

The lower part of these diagrams illustrates the **internal characteristics** used to describe **"**the modality" and the upper part depicts the **enabled outcomes** that are exhibited by a CxS as a result of these characteristics interacting together. The distinction between the upper and lower parts in these diagrams is important. It allows one to discriminate what can be leveraged in a specific CxS to achieve a certain goal (or a desired behavior) from what can only be expected out of a given situation (or a set of conditions). Both parts of the diagram are however closely related and their elements may in some contexts be partly interchangeable. These "generic" figures only list a limited number of characteristics and outcomes. The study of a specific CxS and of their environment will yield to more precise characteristics and outcomes.

[7] For a CxS in operation, these conditions are of course continually changing in function of the environment (among others).
[8] It refers to complex states and includes what is referred to "Edge-of-chaos" in the literature.

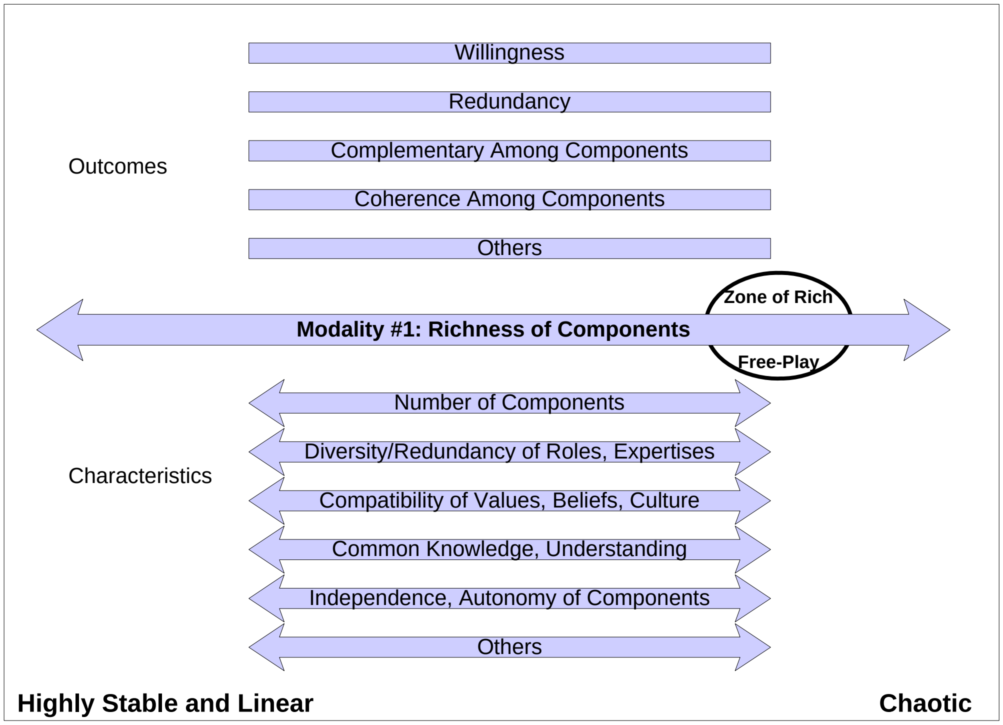

Figure 1- Modality 1: Richness of Components.

Richness of Components is the first modality (Figure 1). It summarizes the number of components and their diversity, compatibility and independence (etc.) that enable the discovery of new solutions or alternate behaviors. For example, a surplus of components will favor redundancy in the CxS. Despite the fact that components are relatively autonomous and independent, willingness to work together toward the achievement of a common mission will be exhibited if some values (beliefs, culture) are shared among an agglomerate of components [Beech, 2004].

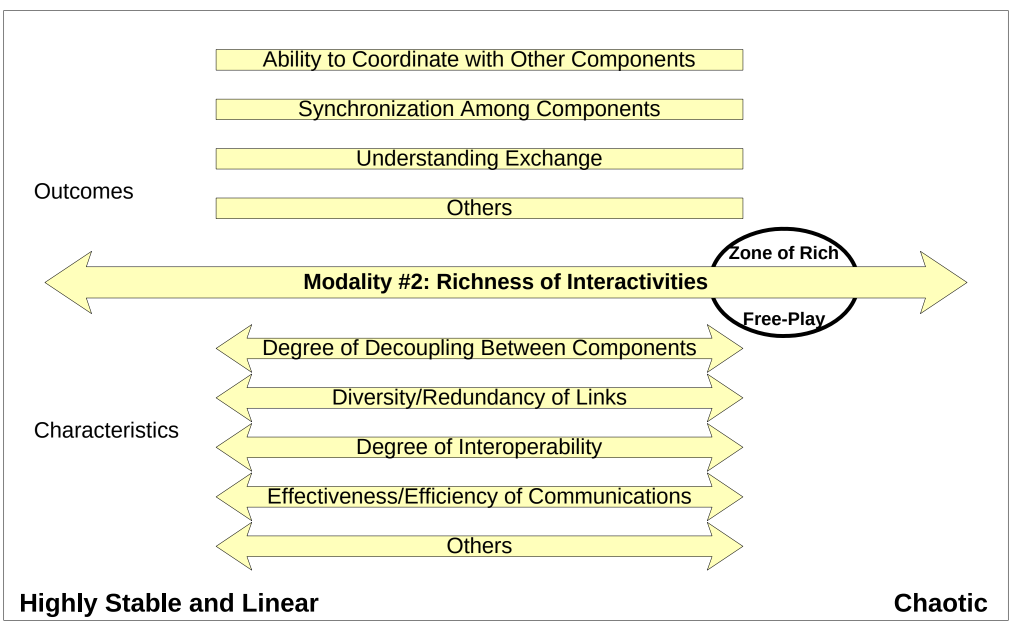

Figure 2- Modality 2: Richness of Interactivities.

Richness of Interactivities between components is the second modality (Figure 2). The degree of decoupling between components, the diversity and redundancy of links, the degree of interoperability, the effectiveness and efficiency of communications are all ingredients (i.e. internal characteristics) that will favor the ability of components to work together, to synchronize and to coordinate. This is depicted in figure 2 using the same qualitative scale (from stable to chaotic) as used in figure 1.

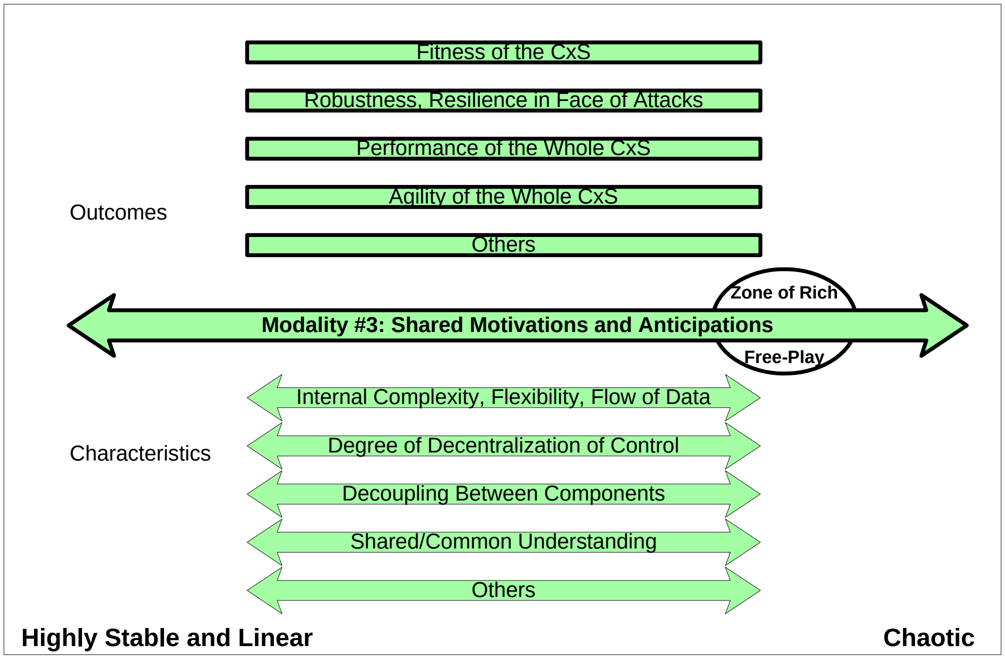

Figure 3- Modality 3: Shared Motivations and Anticipations.

Shared Motivations and Anticipations is the third modality. It builds upon the results of the combination of characteristics and outcomes from Modality 1 and Modality 2. For instance, the robustness and resilience of a CxS in face of unforeseen attacks are motivations (or outcomes) that are related to CxS agility that in turn are enabled by characteristics like decentralization of control, loosely coupled components, availability of critical understanding, etc. The quickness of availability of a second, third or even fourth solution in case of failure of the first one is an example of characteristics that will raise the global performance of CxS in specific situations.

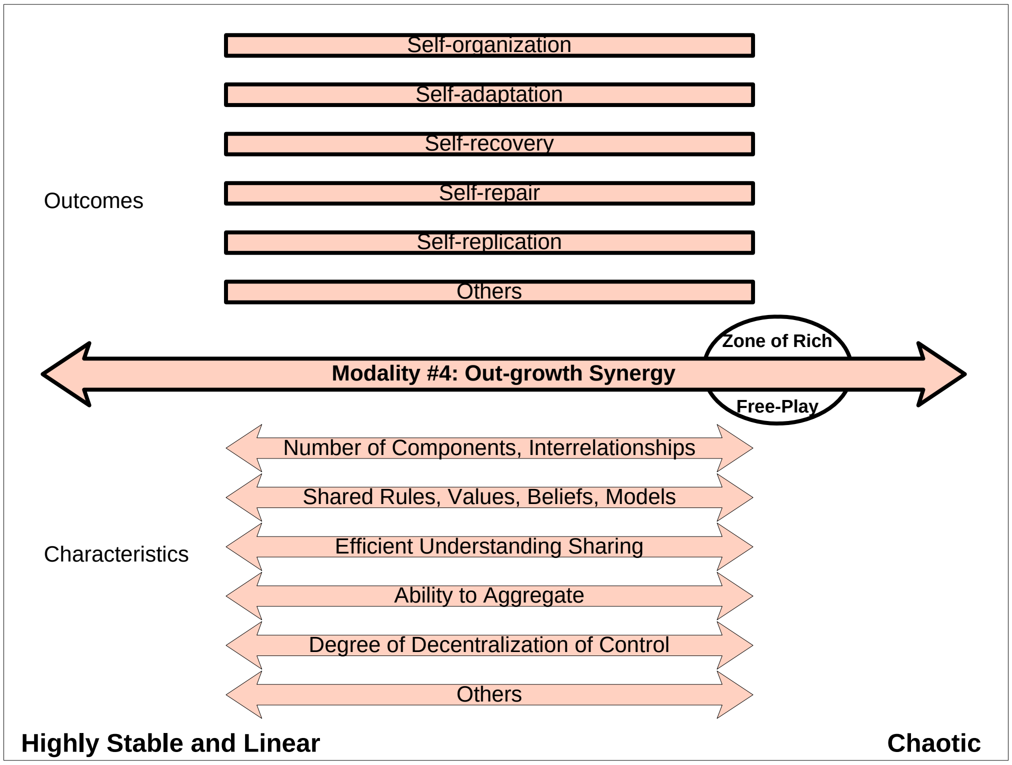

Figure 4- Modality 4: Outgrowth synergy.

Outgrowth synergy is the fourth modality. It represents manifestations of ultimate behaviors like self-organization, self-adaptation, self-recovery, self-repair and self-replication. They are the result of intricate interactions between components that are guided by internal characteristics and by a shared motivation (or anticipation). For instance, a minimal number of components and links between them are needed for emergence to be possible. Supplementary conditions such as internal values, the degree of sharing of appropriate knowledge and understanding, the ability to aggregate and the decentralization of planning and control will give complex behaviors its specific flavors.

There are many advantages of using the set of modalities for studying CxS. One of them is that their characteristics are often simple to manipulate. Modalities ease the identification of critical factors that affect the state of CxS (through the lens of CxT); it also helps establish interrelationships between them. More in depth studies involving characteristics and outcomes of modalities will lead to the identification of sets of critical metrics and ranges of values for each of them. Patterns may be identified for well known CxS that evolve in specific contexts and environments [Couture, 2006d].

The next Section introduces interaction diagrams; a representation that eases the identification and the linkage of characteristics and outcomes of modalities for CxS. Using these diagrams, one can visualize among other things multiple influences and mechanisms that are occurring within CxS.

2.3 Dynamics of Complex Systems Approaching the Edge-of-Chaos

In order to successfully face external unforeseen variability and complex environments, CxS must evolve in the Zone of Rich Free-play (the identified circle in Figures 1 to 4). This region is far from the linear, predictable, rigid and non-creative states and at the same time, away from chaotic states. Life within the Zone Rich Free-play involves a high degree of flexibility to create new solutions to unforeseen problems (i.e. Modality 4); it involves thus CxS to show optimum efficiency and effectiveness (i.e. Modality 3) in face of high variability. CxS evolving in this region continuously re-adjust their components and interrelationships (i.e. Modalities 1 and 2) in function of their context.

The state of a CxS varies thus constantly with respect of time. Internal characteristics and outcomes of modalities describing a CxS can be used to study these changes. They can also be used to find critical factors that will keep its state within the Zone of Rich free-play and that will favor the emergence of desired complex behaviors. Interaction diagram is a simple tool that helps the finding of such critical factors (and interrelationships between them).

Figure 5 depicts an example of the use interaction diagrams. It shows the differences between loosely coupled and tightly coupled components of CxS. The color code used in this diagram corresponds to the one used in Figures 1 to 4; yellow rectangles are related to Modality 2, green rectangle to Modality 3 and orange rectangles to Modality 4. Arrows with the positive/negative (+/-) signs represent positive/negative *contributions* of the originating rectangle to the destination rectangle.

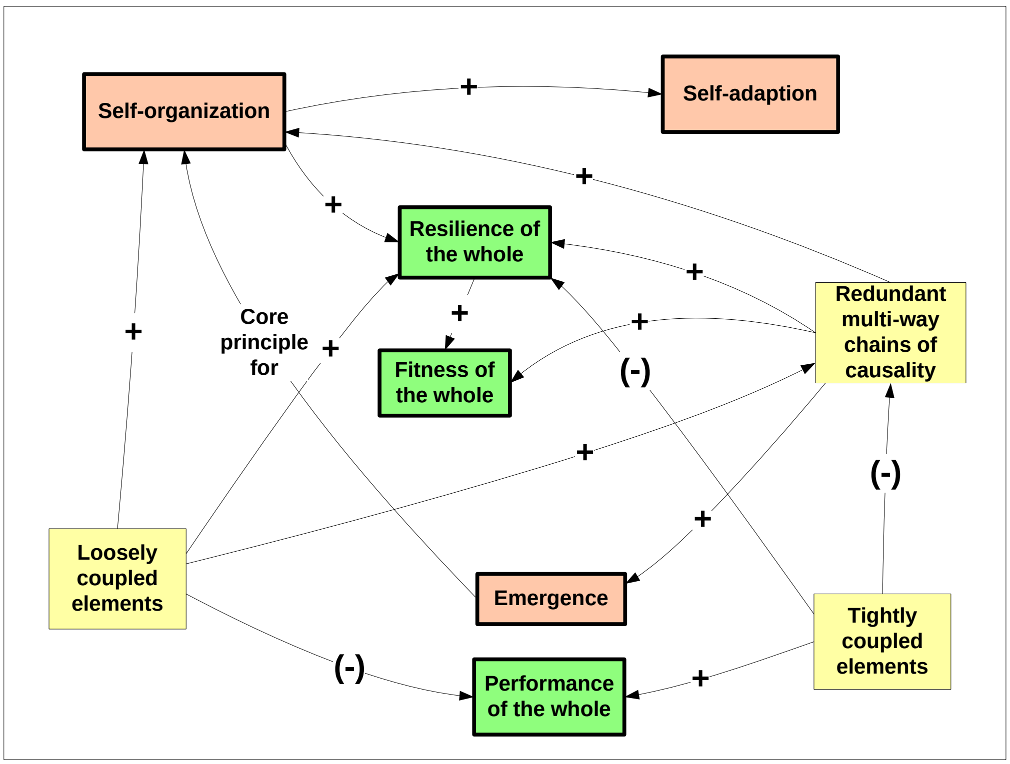

Figure 5- Interrelationships between Elements of Modalities
(Generic example not specific to any domain)

This Figure shows that *emergence* is a core principle for self-organization [Fromm, 2005; De Wolf and Holvoet, 2005], which in turn favor self-adaptation. Loosely coupled components within a CxS contribute to increase the number of choices the latter has to solve problems and being more resilient. The reason for this is that components of a loosely coupled CxS form building blocks (in the sense of [Holland, 1995]) that can be re-combined in many ways, enhancing the probability of finding appropriate solutions to unforeseen problems. Through the process of aggregation and correlation [Holland, 1995] the network develops “redundant multi-way chains of causality” to accomplish its *collective interests* and contribute to the network’s resilience; [Beech, 2004] provides a concrete example. This increased number of choices also contributes to raise the fitness of the whole in its environment because the number of available configurations is also augmented. This higher level of flexibility is often made at the expense of global performance; chances are that loosely coupled components will encounter interoperability or communication limitations for instance, lowering performances of the whole.

On the opposite side, Figure 5 shows that tightly coupled components often involve rigid structures (i.e. linear and highly hierarchical systems that may correspond to highly stable and linear states of Figures 1 to 4). Their performance is increased because their components are made to work in the same ways; interoperability problems for instance were solved at conception. This “rigidness” contributes to lower the degree of resilience and the flexibility of the whole CxS; it has limited “redundant multi-way chains of causality”. Linear systems are less able to re-combine in different configurations when unforeseen problems happen.

CxS usually involve numerous components that are intricately interrelated. It should be noted that the modifications of one aspect of a CxS (one characteristics of one modality for instance) might potentially have hard to predict global consequences, particularly if it evolves in the Zone of Rich Free-play. As an example, eliminating a shared rule within some components of a complex organization may trigger its evolution toward chaos states. Putting back the removed rule after some time will not necessarily restore the system in its original state.

The knowledge of complex critical aspects of a CxS (i.e. understanding the modalities through the use of interaction diagrams) appears to be very important for its management or guidance; this is particularly true for organizations or groups of people [Shetler, 2002]. The next Section illustrates the process to iteratively build meaningful interaction diagrams that are coherent with the nowadays Network Centric type of command and control.

2.4 The Application of the Complexity Framework to Network Centric C2

The world of Command & Control (C2) is currently going through a significant revolution with the availability of Network Centric Operations (NCO)[9]. In this new paradigm, information does not flow according to the traditional chain of command; it is rather free to move among components meaning that data is not “pushed” but instead, it is posted, pulled and smartly pushed according to the need for expertise and understanding, which is distributed and available. Decisions are not anymore centralized into highly rigid hierarchical structures. They are distributed among components of the CxS and there exists degrees of flexibility at the level of components that allow responsibilities to be dynamically re-allocated on the basis of needs, efficiency and relevance, allowing parallel and continuous extensive collaborations. In this context, planning and execution of missions are interactive; they aim at enabling self-synchronization and seeking synergies with focus on effects in multiple arenas. Agility of CxS becomes thus a common and shared goal among components. Agility can be expressed in terms of robustness, resilience, responsiveness, flexibility, innovation and adaptation. These features are actually characteristics/outcomes of the modalities that were described in the previous sections.

Therefore, NCO is an interesting case study that can be used to illustrate the application of the complexity framework (CxF). The proposed example focuses on the “planning” and

[9] This paragraph partially reproduces some aspects of Alberts and Hayes’s (2007) Figure 6, page 63.

"control" aspects of C2 without delving into unnecessary details; the aim of this example is only to provide an overview of the application of the CxF to study NCO.

The first key concept of the CxF that needs to be mapped to NCO is the set of four modalities. In this example, the triplet (**M#/O**) will be used to designate outcomes of modalities. For instance, the triplet M3/O would represent "outcomes of modality number three". The first paragraph of this Section is used as basis for the example. It is reproduced in the following lines with the addition of "bolded words" that correspond to outcomes. Outcomes are then represented in figure 6 under the form of a tree-view, which is aligned with the structure of modalities[10].

> Briefly, the C2 that should be used in NCO is relatively different from the traditional C2. Information does not flow according to the traditional chain of command; it is rather free to move among components (**flexibility, creativity, responsiveness; M1/O, M2/O**) meaning that data is not "pushed" but instead, it is posted, pulled and smartly pushed (**smart communication; M2/O**) according to the need for expertise (**shared knowledge and understanding; M1/O**), which is distributed and available (**availability of data, information, knowledge and expertise; M1/O, M2/O**).
>
> The decision making process is not anymore centralized into highly rigid hierarchical structures. It is distributed among components of the CxS (**decentralization and distribution of decision making, heterarchy, independence, proactive; M1/O, M2/O**) and there exists a degree of flexibility (**flexibility; M1/O, M2/O**) at the level of components that allow responsibilities to be dynamically re-allocated (**ease of reallocation of responsibilities; M1/O, M2/O, M3/O**) on the basis of needs, efficiency and relevance, allowing parallel and continuous extensive collaborations (**collaboration; M1/O, M2/O, M3/O**).
>
> In this context, "planning" and "execution" of missions are interactive (**interactive planning, execution and control; M3/O**); they aim at enabling self-synchronization (**self-synchronization; M4/O**) and seeking synergies (**synergetic; M1/O, M3/O**) with focus on effects in multiple arenas (**able to deal with multiple arenas; M3/O**). Agility of CxS (**agility; M1/O, M2/O, M3/O**) becomes a common and shared goal among components. These authors recognize the dimensions of agility: robustness, resilience, responsiveness, flexibility, innovation and adaptation (**robustness, resilience, responsiveness, flexibility, creative; M3/O**), (**adaptation; M1/O, M2/O, M4/O**).

Other examples of outcomes of Modality 4 that would be desired in our example are: **self-organization**, **self-orchestration**, **self-recover**, **collective learning** and **collective innovation**.

Having found a first version of the set of outcomes for the example, their interrelationships can now be studied. Interaction diagrams would ease this discovery effort by providing the ability to generate visual recursive representations of outcomes[11]. Generally speaking, the proposed process is **iterative** and **incremental** and it is one of **discovery**. It is described in another document that can be made available to those who need to actually build such diagrams.

[10] The same color code as previous figures is used.

[11] The tool used to generate interaction diagrams involves two parts: 1- the visualization part and 2- a repository of data that keep trace of all information and interrelationships between them. The full power of this tool is reached when a search engine and specific key words are repeatedly used to generate multiple views (showing selected aspects) of the whole set of outcomes under the form of interaction diagrams.

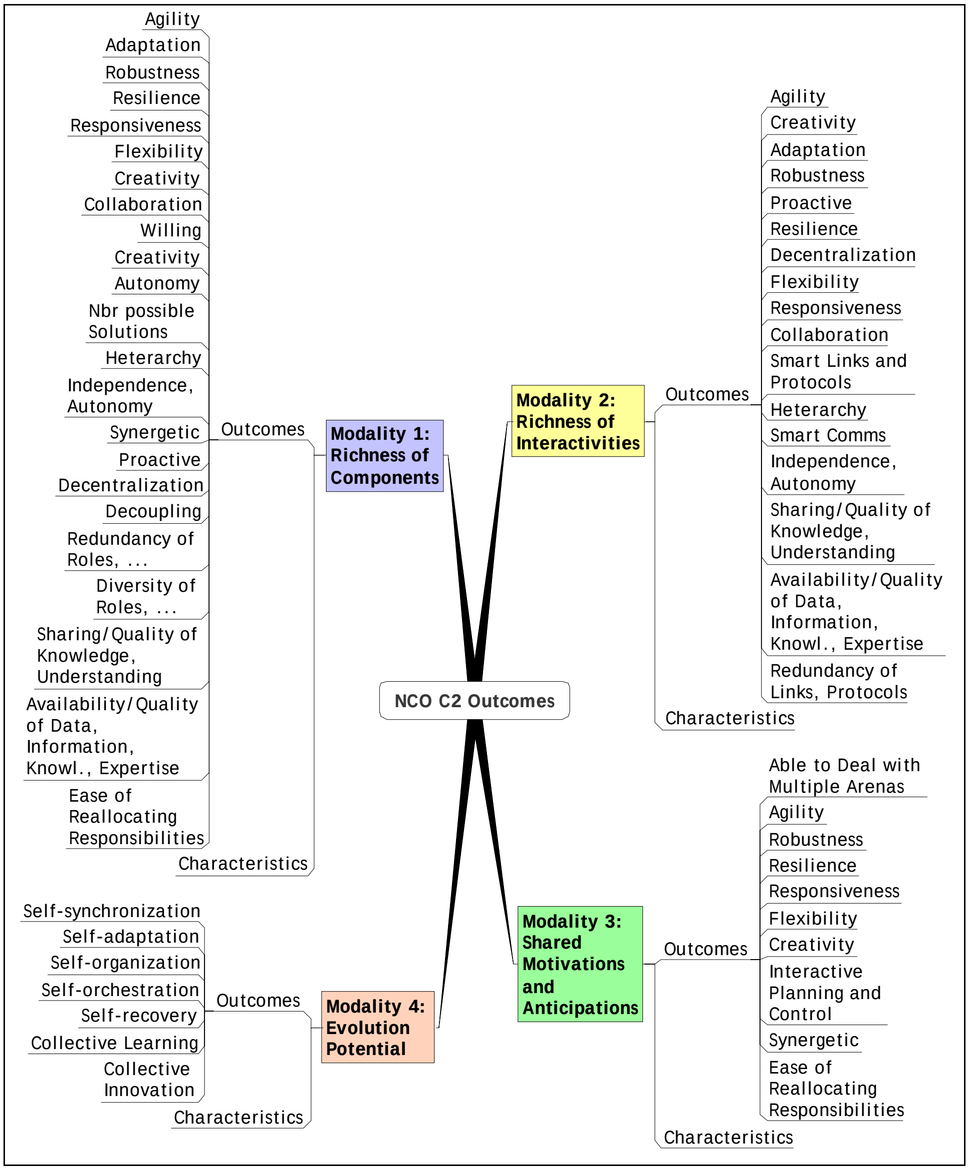

Figure 6- Selected NCO C2 Outcomes; Re-structured According to CxF.

Figure 7 shows the interaction diagram associated to the NCO C2 outcomes[12]. In this example, agility and self-organization are the desired "Motivation" (Modality 3) and "Outgrowth Synergy" (Modality 4) for the systems to be deployed. Global qualities of CxS such as robustness, resilience, responsiveness, flexibility, innovation or creation will contribute to improve agility of the CxS, which in turn will favor the emergence of complex behaviors such as self-organization.

As for the finding of outcomes, the finding of characteristics and interrelationships between them will be made easier if one makes use of the NATO SAS-050 model [NATO, 2007]. This exhaustive decomposition includes not only favorable (constructive) components but it also enumerates some negative characteristics that will interfere with the construction of a desired outcome. The authors of this article truly believe that interaction diagrams must include positive

[12] Only a limited number of outcomes are shown for clarity purposes.

and negative contributions to allow a comprehensive analysis to be performed. Using this structured information, it will also be easier to categorize the C2 CxS in terms of the NATO NEC Maturity Model [NATO, 2006; Alberts and Hayes, 2007]. This will be further documented in a separate report.

In summary, it was shown in this Section that instead of building a traditional linear, pre-determined, rigid C2 system, the proposed process (and CxF) aimed at providing "each component" what it needs for being able to form (with others) a complex system that will manifest the desired emergence of capabilities. This approach is both "top-down" and "bottom-up"; the intent and the desired capabilities originate from the top but the CxS is designed from the bottom.

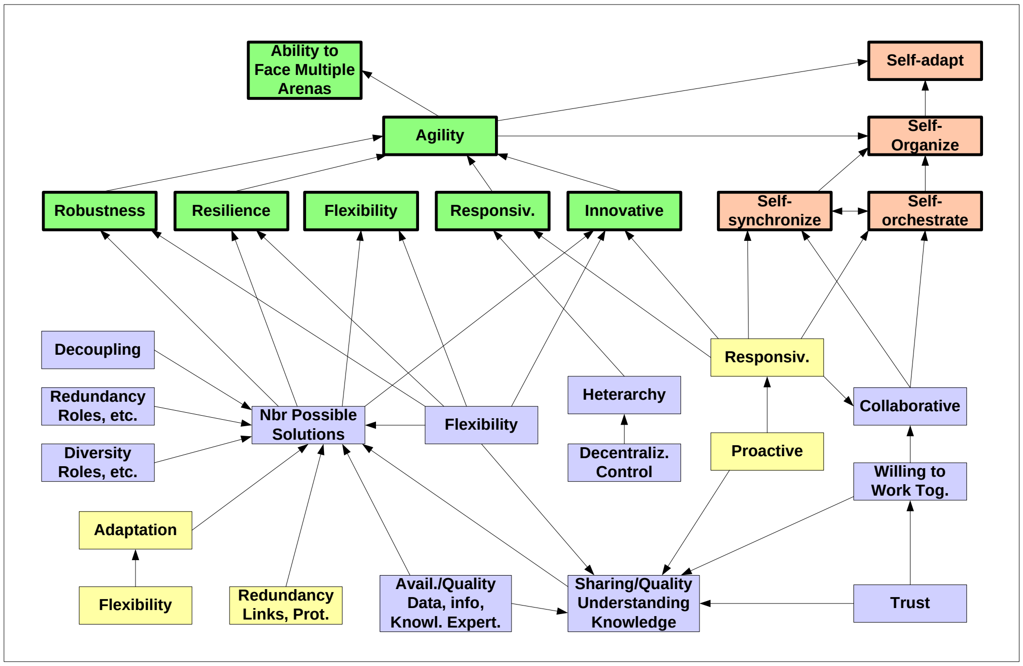

Figure 7- Integrated Set of Outcomes for NCO C2.
(Each arrow represents a positive contribution).

3 Discussions and Conclusion

The analysis of Complex Command and Control Information Systems (CxC2IS) comes with new challenges that are mostly related to the entangled coupling of sub-systems and to the predictability of behaviors emerging from the changes in the environment or in the internal organization. To ease the understanding of CxS, we have proposed the interaction diagram that greatly facilitate the identification the key components of a CxS and helps visualize interactions between these components.

Of course, to be meaningful, the interaction diagram has to be constructed in a rather rigorous manner that will guarantee some coherence in the representation of the reality. This is achieved in our CxF by the definition of four "modalities of complex systems" that are fundamental ingredients needed to achieve high-order emergence like self-organization, self-adaptation etc. Each modality can be expressed in two ways: first as "technical descriptors" (i.e. lower-level, parametrical and/or quantifiable; called "characteristics") and second as "observable manifestations" (i.e. higher-level, rather qualitative but more intuitive; called "outcomes"). This distinction appears to be critical to the coherence of interaction diagrams that must avoid mixing entities that are at different conceptual levels. Also the ability to include "positive and negative contributors" in the same diagram makes the analysis much more revealing and much more comprehensive.

In order to illustrate its capabilities, the proposed CxF was applied to C2IS domain by bridging the description of the C2 NCO (Command & Control – Network Centric Operation) with the four modalities previously defined. Future R&D efforts proposed within the DRDC will be directed toward the identification of metrics and mathematical relationships between the modality descriptors and their manifestation. This will provide some quantification capabilities to the CxF. An implementation of a graphical environment will also be made in order to ease the utilization of the framework in concrete applications.

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Annex 1 – Some Key Definitions

This Annex proposes a short definition for a selected number of key words. The reader will find more details and additional relevant definitions in [Couture, 2006c].

Chaos: *a) Sustained and disorderly-looking long-term evolution that satisfies certain special mathematical criteria and that occurs in a deterministic non-linear system; b) largely unpredictable long-term evolution occurring in a deterministic, nonlinear dynamical system because of sensitivity to initial conditions* [Williams, 2001].

Complex Behavior: *A type of dynamical behaviour in which many independent agents continually interact in novel ways, spontaneously organizing and reorganizing themselves into larger and more complicated patterns over time* [Williams, 2001].

Complex System: *A collection of many simple nonlinear units that operate in parallel and interact locally with each other so as to produce emergent behaviour* [Flake, 1998].

Emergence: *A system exhibits emergence when there are coherent emergents at the macro-level that dynamically arise from the interactions between the parts at the micro-level. Such emergents are novel w.r.t. the individual parts of the system* [De Wolf and Holvoet, 2005].

Evolution: *A process operating on populations that involves variation among individuals, traits being inheritable, and a level of fitness for individuals that is a function of the possessed traits. Over relatively long periods of time, the distribution of inheritable traits will tend to reflect the fitness that the traits convey to the individuals; thus, evolution acts a filter that selects fitness-yielding traits over other traits* [Flake, 1998].

Heterarchy*: A heterarchy is a network of elements sharing common goals in which each element shares the same "horizontal" position of power and authority, each having an equal vote. A heterarchy may be independent or at some level in a hierarchy. Each level in a hierarchical system is composed of a heterarchy which contains its constituent elements* [Wikipedia, 2007].

Holism: *"The idea that the whole is greater that the parts". Holism is credible on the basis of emergence alone, since reductionism and bottom-up descriptions of nature often fail to predict complex high-level patterns* [Flake, 1998].

Middle-out Approach: Middle-out approach combines top-down and bottom-up approaches.

Reductionism: *The idea that nature can be understood by dissection. In other words, knowing the lowest level of details of how things work reveals how higher-level phenomena come about. This is a bottom-up way of looking at the universe, and is exact opposite of holism* [Flake, 1998].