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Complexity and fragility in system of systems

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Abstract: SoS are an ensemble of complex systems, which have the potential for an extraordinary amount of structural complexity, even temporarily, as a result of interconnections and couplings that can vary in strength. Because of this, SoS can be vulnerable to sudden catastrophic collapse as a result of small and insignificant partial functionality losses in one of the constituent systems. This paper provides an analysis of the response SoS to uncertainties in the form of partial failures, which is complemented by the presentation of a measure of structural complexity for SoS. Experiments with the development of random graphs to simulate SoS show that a partial failure initiated in one system has a high possibility of leading to a collapse of another system of SoS, sometimes even before leading to total failure in the originating system. After pinpointing the effect of the complexity of today's system of systems (SoS), we present a first-step understanding of why unanticipated failures find more potential and more pathways to their occurrence when interventions in SoS operations, standards or processes are conducted without enough insight and without consideration of the fundamental nature of complexity. We then demonstrate a condition where the incremental changes actually lead to failure of the SoS to meet its performance parameters.

Keywords: system of systems; SoS; complexity; coupling; failure propagation; complexity systems engineering.

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1 Introduction

With the explosion of information technologies, it has become possible to establish systems that meet a diverse set of goals and a heterogonous set of capability objectives. These are system of systems (SoS), created through the coupling of a number of constituent systems (CSs), each of which is a system in its own right (Keating et al., 2003). SoS are federated collaborating structures that, more than any other bonding mechanism, are linked by information exchange/sharing (Maier, 1998). An SoS is not defined in terms of some fixed top-level application; rather it is understood to enable the continual introduction of new applications (Abbott, 2006). This distinguishes SoS from most systems as traditionally understood. SoS have the following distinct characteristics from monolithic complex systems (Nielsen et al., 2013; Jamshidi, 2009): autonomy of CSs, their managerial independence, their geographic distribution, evolution (openness) and versatile operational contexts (Mekdeci et al., 2011). Nielsen et al. (2013) disagrees with Maier (1998) that SoS are so dispersed that the only bonding mechanism between CSs must be in the form of information exchange; energy supply systems are examples of SoS that exchange material and energy. Other examples to the contrary of the claim by Maier (1998) are socio-technical systems which include movement of people, as well as information. Nonetheless, most commentators agree that 'the main' bonding mechanism in SoS is information exchange; however other forms of connectivity cannot be excluded.

Within the SoS literature, emergence refers to the behaviours that arise as a result of the synergistic collaboration of CSs. In SoS, emergent behaviours deliver a higher functionality than that which is delivered by the constituents separately. Unlike emergence in monolithic complex systems that is achieved by capability sharing between constituent elements, the emergence in SoSis achieved through alignment of CS goals and information sharing mechanisms. The distinction between 'SoS' and 'complex system' is related to the nature by which they attain goals. While the operational goals of complex systems tend to be focussed on only a few objectives, the goals of SoS are diverse and heterogeneous. Complex systems achieve their goals by introducing new functionalities or capabilities whereas SoS aim at high-level operational capabilities as well as operational attributes (system qualities/attributes or ~ilities such as reliability, maintainability, robustness, etc.) beyond those of the CSs (Mekdeci et al., 2011; Office of the Under Secretary of Defense for Acquisition and Technology, 2008). In complex systems resources and capabilities are shared between CS elements – which is often necessary for mission success – whereas SoS tendency is more towards a goal-sharing paradigm, rather than capability and resource sharing. For this reason, SoS requirements are often cast in terms of broader capability objectives. CSs follow independent goals in heterogeneous contexts (Mekdeci et al., 2011) that are complementary in SoS grand scheme and stated missions. This complementarity of goals is the main challenge of SoS engineering that requires a subtle balancing of CSs objectives with that of the SoS (Office of the Under Secretary of Defense for Acquisition and Technology, 2008).

1.1 Scope and approach of the paper

SoS engineering is premature (Sousa-Poza et al., 2008), and developing slowly primarily due to a lack of coherence and congruence between perspectives of academia, military and enterprise as to how an SoS is created (Keating and Katina, 2011). Keating and Katina (2011) suggest a framework for focusing the development efforts into: philosophical, theory, axiological, axiomatic, methodological, method, and application. The focus of this paper is theoretical development. The golden rule for creating a SoS is to use an architecture based on open systems and loose coupling (Office of the Under Secretary of Defense for Acquisition and Technology, 2008). The open-system paradigm allows evolution of CS capabilities to align increasingly with the goals of SoS, and the loose coupling ensures robustness and resilience of the SoS as a whole, as well as protection for the openness of CSs. A tight coupling of CSs negates the initial purpose of the SoS, which is the maximal exploitation of CSs capacities towards a greater goal/mission of SoS. Furthermore, tight coupling of complex CSs leads to ultimately fragile system. Normal accident theory (Perrow, 1984), for example, states that system complexity and coupling, readily present in all highly technological systems, lead to accidents which are commonly branded as normal. These accidents are a result of catastrophic potential of complex systems with tight coupling combined with human operator error in highly technological systems. By using the term 'normal' Perrow (1984) sought to convey the notion that accidents of catastrophic nature should be normally expected wherever complexity and coupling are present. Perrow (1984) defined tight coupling as "processes happen very fast and can't be turned off, the failed parts cannot be isolated from other parts and there is no other way to keep the production going safely. Then recovery from the initial disturbance is not possible; it will spread irretrievably for at least some time". Reason (1990) later noted that organisations seek to prevent failure, often by measuring errors, with the intention of preventing them from reoccurring. However, this helps "it raises some further questions: how can we best gauge the 'morbidity' of high-risk systems? Do systems have general indicators, comparable to a white cell count or a blood pressure reading, from which it is possible to gain some snapshot impression of their overall state of health?" (Reason, 1990). Dekker (2011) discusses the nonlinear relationships in complex systems where small events can produce large results. Dekker also discusses the ignorance of components about the behaviour of the system as a whole, and that the components do not know the full effects of their local actions. Based on this introduction, this paper seeks answers for the following fundamental question:

1 How can complex systems fail due to small, unnoticeable failures in their components? We seek to explain the relationship between system complexity and system fragility, or simply present a rigorous evidence-based support for normal accident theory.

2 How does this relationship impact SoS? Here we want to find out whether SoS is impacted by the fragility that is seen in complex systems.

3 Does evolvability, as a pillar of the SoS architecture, make it more or less fragile and how?

4 What are the consequences of the current risk management practices for system fragility?

In order to answer these questions, this paper presents a relatively simple graph-theoretic method, which provides a complementary means for the analysis of SoS response to uncertainty. In support of normal accident theory, we demonstrate the scale impacts of complexity and coupling on system failure that is demonstrated with fresh evidence from experimentation with graphs. We have chosen to use the word collapse, rather than total failure and the like, for this paper, since it more closely describes a likely result of imposing closer coupling. Since a SoS is rarely designed to perform the function or functions that it is tasked to provide, it is possible that collapse may not mean complete dissolution of the SoS, but some degraded operation mode, where the component systems largely maintain their coherence yet the SoS does not function as desired in its SoS role. For example, consider the SoS that provides electrical power for a nation. This SoS contains systems to design, contract, build, outfit, test and deliver to service the electrical generation and distribution systems of the nation's electrical grid. It also contains systems to recruit, train, retain and advance the workers that man and maintain those ships systems from early in-service until the components are retired from service. The SoS also contains systems that provide sensors, networks and communications systems allowing the components to act in consort with other components. The systems that comprise the SoS often operate independently, and connections can be difficult to observe.

A model of the relationship between close coupling and the possibility of system failure in complex systems is presented. Closer coupling is shown to increase the possibility, and not the probability, of collapse, and also shorten the likely duration of system trajectory to a total collapse. Coupling and complexity create grounds for fast propagation of uncertainties, which is a fast magnification of small errors into large failure. A fragile system is one in which the propagation is too fast and a large failure comes sudden and as a surprise, as a result of small disproportionate stimuli (error). Thus a fragile system is prone to collapse and has a high potential for sudden failure. We show that there are many different ways that can lead to the collapse of a complex system. Thus reducing the uncertainties surrounding the system as well increasing the reliability of system capabilities does not guarantee safety, simply because of high sensitivity to (or intolerance of) small, insignificant errors. We show this by means of a simulation with graphs.

We then turn our attention to the structural complexity of SoS. It is shown that the complexity of SoS is almost equal to that of largest CS. However, because the CSs are complex systems themselves, anything beyond loose coupling of these systems can create extreme levels of complexity that in turn create the possibility for unpredictable emergent catastrophic events. We show this with two simple experiments with randomly generated large graphs representing the structure of SoS all the way down to the components of CSs. In the first experiment, it is shown that the overall structural complexity of SoS is sensitive to the degree of coupling between CSs, and can rapidly increase with the increase in coupling. In the second experiment we show that SoS with tight coupling is very unpredictable by facilitating fault propagation between CSs, and that the faults eventually become untraceable to their origin. Finally, expressing a theory of complexity escalation, confirms grounds for normal accidents can be sown by repeated responses to detected risks and uncertainties in the design and during operation of human-machine systems, a behaviour that is mostly observed in SoS essentially because of their evolution. We provide two examples of how through evolution of CSs they become more closely coupled, leading to increased system complexity.

2 On relationship between complexity and surprise

A simple mathematical notation of coupling can be provided by a square matrix of size $n \times n$, $A = [a_{i,j}]$ where n is the number of system elements/components, and each off-diagonal element of matrix $a_{i,j}$ corresponds to the amount of coupling between components i and j. The elements i and j can also be task processes with specific inputs and outputs. In task oriented and procedural systems (such as organisational systems) $a_{i,j}$ is the amount of amount of information that needs to be exchanged between tasks. In hard physical systems $a_{i,j}$ is determined by physical adjacency, material, energy and information transfer between components of the system.

Coupling can be linear or nonlinear [or complex according to Perrow (1984)]. A linear coupling remains consistent with time or with change in the value of systems parameters or other couplings, so $a_{i,j}$ does not change in value, thus matrix A preserves its form for the entire operation of the system. This is however not the case for almost any system. Consider a vehicle for example. The coupling between engine and transmission is an increasing and nonlinear function of both velocity and acceleration of the vehicle. For example, if an error occurs in the engine causing large vibrations, this is not likely to propagate to the transmission system and cannot cause damage to the gearbox when the gears are not engaged. However, when the car is moving, the vibration propagates to the transmission through the gearbox. The severity of this propagation, or coupling, of vibration varies for different speeds, road conditions, and accelerations.

Assume that for a system the coupling matrix is always constant. A failure or error f_i can occur in a component or element or procedure i at any time during the operation. We can think of f_i as the percentage of error in the output or percentage of lost functionality in i. Then given the coupling matrix A (that is a positive matrix) the error or fault or failure can propagate to other components, elements and procedures, like j and cause a functionality loss or error $f_j = f_i \times a_{i,j}$. If we combine all the *initial* partial component failures in a failure vector F_0 of size $n \times 1$ then we have:

$$F_1 = AF_0 \tag{1}$$

where F_1 is the failure status at a moment or an instance after the first error(s) occurred and $F_1 \geq F_0 \geq \delta \times 1_{n\times1}$. Assuming the coupling matrix A is unaffected by the partial failure and assuming the errors go undetected then the failures keep on propagating until an instance t when a component or procedure is totally failed, preventing the entire system to function. Under these strong assumptions the following simple recursive formula holds:

$$F_t = AF_{t-1} = A^2 F_{t-2} = \ldots = A^t F_0 \tag{2}$$

where $F_t \leq 1_{n\times1}$. t is the time to complete propagation of error/fault, and we refer to t as time to failure (TTF). Note that this is a different notion than the TTF for a component that is the expected TTF as a function of component's reliability. By a singular value decomposition of A we have:

$$A = U_1 S V_1 \tag{3}$$

where U_1 and V_1 are unitary matrices $(U_1^{-1} = U_1^T)$ and S is a diagonal matrix with singular value of A on its diagonal. We also know that:

$$A^t = U_t S^t V_t \tag{4}$$

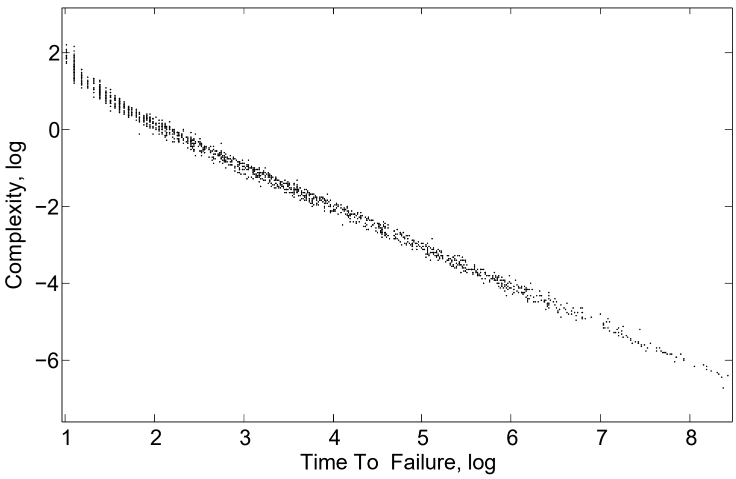
where $|U_t| = |U_1|$ and $|V_t| = |V_1|$. Substituting (4) back in (2) we arrive at:

$$F_t = V_t S^t U_t \left(F_0\right) \tag{5}$$

Since F_t has a maximum of 1 (or 100% failure) it is not too difficult to see that S and t have an inverse relationship, which is essentially common sense, in that a larger S leads to smaller t. Larger S also means greater overall coupling or complexity that leads to faster error growth due to propagation (see Figure 1). The complete error propagation time is still dependent on the occurrence of the initial error F_0 and also on the location of this initial failure in the failure vector (which corresponds to the identity of element of the system with an error). However, simulation results show that on average t (or mean TTF) has a pseudo-log-linear relationship with maximum singular value of A (σ_0)

(Efatmaneshnik and Ryan, 2014; Efatmaneshnik et al., 2012; Bradley et al., 2015). An analytic proof of this statement is beyond the scope of this paper, although we might provide such proof in a future paper. We refer to σ_0 as complexity of system with A as its coupling matrix.

Figure 1 TTF versus complexity (on a log-log basis) have a pseudo-linear relationship



To demonstrate the relationship between complexity and TTF we proceed with an experiment. Consider a system with 100 functional units with their functional relationships/couplings recorded in a square matrix *A*. The entries of A can be the percentage that every two functional element are functionally dependent. However, for simplicity we assume that the entries are either 1 or 0, i.e., there either exist a functional relationship or not. We create the matrix *A* from *G*(*n*, *p*) model of Erdos-Reyni random graphs (where n = 100, and p takes values between 0.01 to 0.5). We used 20 different amount of p, and for each p we created 10,000 instantiations from *G*(100, *p*), a total of 200,000 instantiations. Then for each instantiation we ran 100 simulations with assigning a small error of 0.00001(or 0.001%) respectively on each of 100 functional nodes, and measuring TTF for each case. Then the mean TTF was calculated for each instantiation of *G*(100, *p*), and was plotted against its complexity. The result is a pseudo linear relationship on a log-log scale and can be seen in Figure 1. Note that in this simulation we did not make any assumption about the probability of the occurrence of the partial error. Thus the result does not regard the probability of failure, but only the possibility of propagation and its rapidness however rare a partial failure might be. In the following section we discuss this in more depth.

2.1 Fragility

Fragility is the quality of being easily broken and being highly vulnerable to collapse. The opposite of fragility is often taken as resilience that is, the quality of bouncing back to operation after a failure. Resilience is much like plasticity, the quality of being stretched and not broken, the quality of being ductile. There has been much written about the differences between resilience, survivability, reliability, and robustness (for example see (Madni and Jackson, 2009) and the references therein). Westrum (2006) has argued that application of at least two of the following warrants resilience (Madni and Jackson, 2009; Westrum, 2006):

1 *Avoidance:* is the prevention of a disruption. Avoidance goes beyond traditional system safety considerations (Madni and Jackson, 2009) in that it encompasses the *anticipation* of a mishap based on the ability to detect 'drift' towards system brittleness, a harbinger of potential accidents.

2 *Survival:* is the ability of a system to resist destruction or incapacitation in the face of a disruption.

3 *Recovery:* is the ability of a system to survive a major disturbance even with degraded performance.

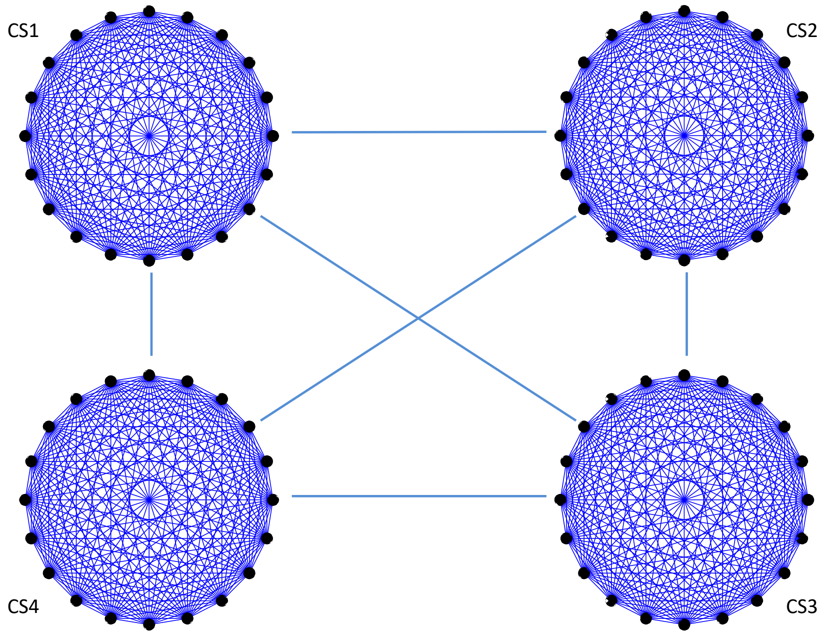
Given these definitions, one can argue that if avoidance is achieved, then the need for survival and recovery are indeed reduced. However, avoidance is achieved through intervention, namely detection and isolation of threats/errors/failures, so as to avoid their propagation. If complexity is very high there is potential that the error will propagate so fast that intervention becomes impossible, and a collapse becomes likely. The obvious reason for this is that fast propagation reduces the fault detectability, and increases the chances of a surprise failure.

2.2 Structural complexity of SoS

Structural complexity is degree to which system elements are coupled and interact in nonlinear ways. In a systemic hierarchy the nature of interactions vary at different layers of the hierarchy. For instance inside the CSs dependencies are information or material flow, energy flow and physical adjacency are the cause interactions. However at the grand SoS level interactions between CSs are of *operational nature* (Autran et al., 2008) requiring mainly information flow. This does not mean that for instance material or energy transfers should not happen between CSs. It is evident that physical adjacency accounts for very tight couplings or in other words causes high interaction intensities. It is also evident that information flow is subtler in nature and causes less intense interactions than material and energy flow. Because an SoS is highly dynamic and open, the SoS structural complexity is not a static measure, but can change with time, as CSs change their size (perhaps as the result of adding new capabilities) or as CSs change their level of interactions to higher or lower levels of cooperation/coordination. In the dynamic nature of a SoS can also result from changing the composition of functional dependencies between CSs in response to changes in circumstances. In SoS re-configurability is even performed without planned intervention (Nielsen et al., 2013).

Regardless of the kinds of interactions and dynamicity of SoS, we can say that SoS at any instance of its operation is a structure with strong coupling inside the CSs and loose coupling between CSs. Figure 2 shows a graph with such property. It is composed of four identical complete sub-graphs with 20 nodes. There is only one link between each pair of sub-graphs. In this section we study the structural complexity of SoS and its relation to amount of coupling between CSs with an experiment. The purpose of this experiment is to gain insight about change in the level of SoS structural complexity with variations in the intensity of coupling between CSs, or their interaction complexity. We will also look at the effect of SoS couplings on failure propagation.

Figure 2 Shows a typical SoS structure made of 4 CSs (see online version for colours)

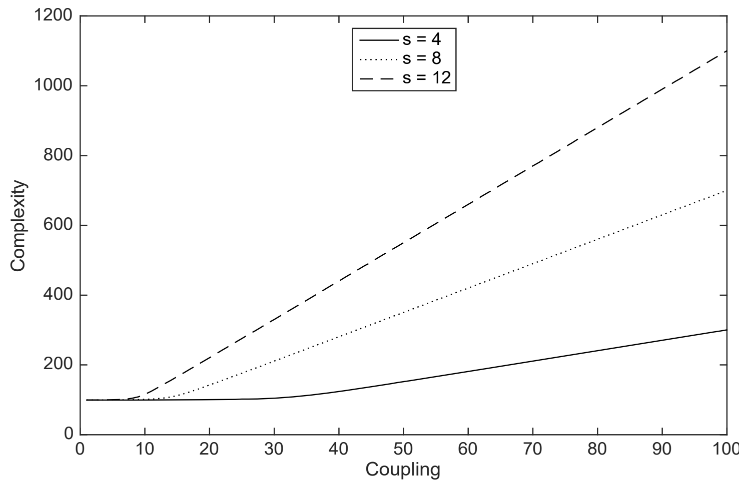


Note: Each CS is a complex system however the couplings between CSs are usually sparse, loose and weak.

In this experiment, CSs are simulated by complete graphs (have all possible links) with 100 nodes. The weights of interactions inside the CSs are all 1, which makes structural complexity of CSs equal to 99, when the complexity is measured according to maximum singular value. Figure 3 shows the result of this experiment, when the strengths of couplings between CSs change between 1 and 100. In case of a loose coupling (*coupling* = 1), the SoS overall complexity is 99.0309, slightly above that of each individual system. This means that with loose coupling, one can coordinate the goals of CSs for a bigger purpose; however a higher degree of capability sharing creates tighter couplings. The SoS complexity can increase 10-fold in response to increase in communications between CSs when there are 12 CSs in SoS. Since the CSs are complex themselves, the management of this complexity can become intractable. Also we can argue that with loose links, the SoS complexity is almost independent of its size (number of CSs). This means that inclusion of more and more systems into a SoS cluster is managerially feasible given that the loose link formula is adhered to, and if not, the inclusion of new systems can increase exponentially the overall SoS complexity.

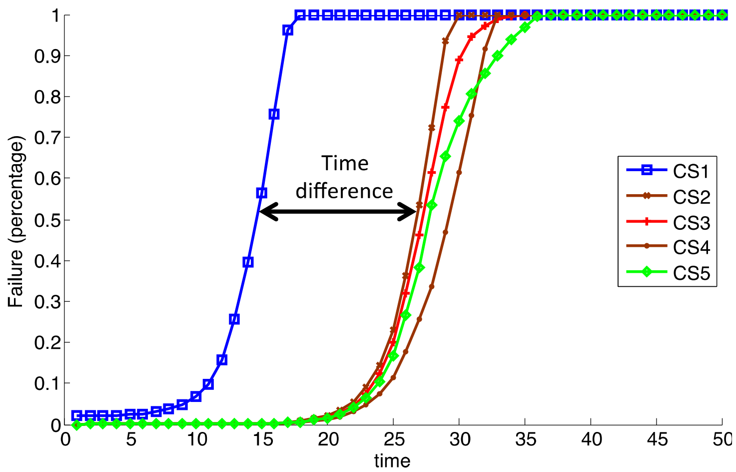
In Figure 4 we place a small partial failure of 0.001% on one of the nodes of ones of first CS in an SoS with five CSs and loose coupling of 1 between them. Then we monitor the failure growth in all CSs by tracking the amount of the largest failure in each CS. The failure grows in CS1 earlier than all other CSs. This means that the difference of TTF between CS with an initial error and the rest of the CSs is large relative to TTF itself, which in turn implies resilience of SoS in the presence of threats to one of CSs. If the coupling between the CSs is high the difference in TTF becomes very close to zero.

Figure 3 SoS overall complexity increases with tightness of communication between the CSs



Note: *S* is the number of CSs in SoS.

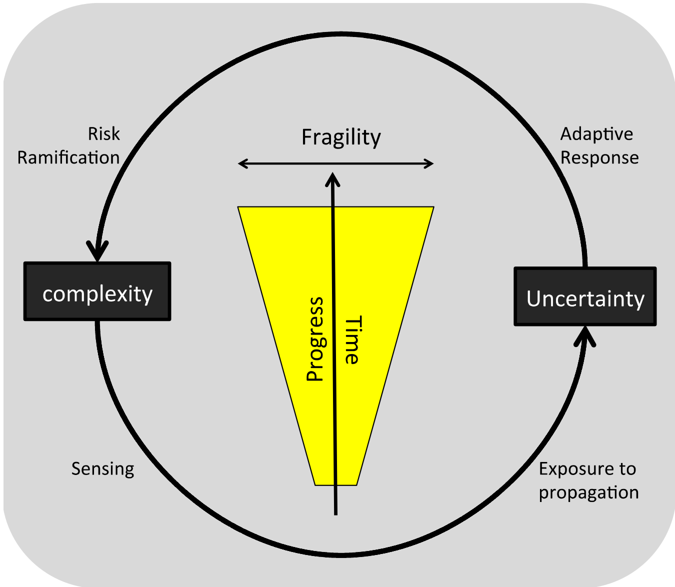
Figure 4 Difference in TTF or time difference between failures of CSs is positive and large for SoS with loose coupling (see online version for colours)



3 Complexity-uncertainty escalation

The central question is how might coupling inadvertently be made closer in an already complex system? Do classic risk mitigation schemes transform our systems towards less or more complexity over time? Any attempt towards risk management potentially increases the structural complexity and coupling that in turn creates more sensitivity to uncertainty and susceptibility to uncertainties and risks that the system was robust to beforehand (Figure 5).

Figure 5 Complexity-uncertainty spiral (see online version for colours)



One way for this increased potential for risk might be as a result of increasing the number of elements in the rule set of subordinate systems. This concept will be proposed in this paper to lend a real-life case where coupling was increased. Such an example could be a task executed by the subordinate system that initially appears relatively simple, such as welding pipe, and moves the task to the regime of a complicated or complex task that is no longer executed well enough for the SOSE function. To support the notion of complexity-uncertainty escalation, in the next two sub-sections we provide real examples directly experienced by one of the authors where complexity and coupling have increased as a result of risk management activities.

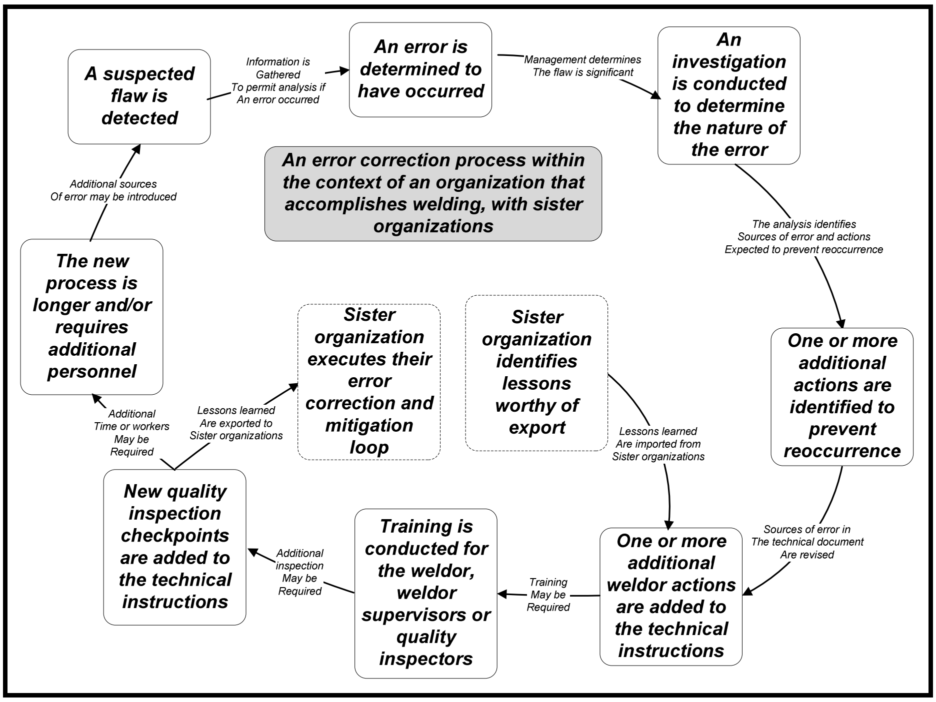
3.1 An industrial example: repair of naval vessels

How would a rulemaking process increase complexity and uncertainty? We will examine an example of an industrial process that would appear to be limited to a specific component of the systems comprising the SoS, but has SoS implications. We will examine the system response to a problem in the pipe welding area in a large industrial organisation that is responsible for maintenance of warships. This industrial organisation is one component in a much larger SoS where its role is to repair and modify large pieces of equipment used by other organisations in harsh environments. This industrial organisation has codified many of its processes ranging from the industrial shop operations to engineering and information technology. It has developed a robust quality assurance capability and its leaders espouse the belief in continuous process improvement. Because the large pieces of equipment are used in harsh environments, the industrial organisation subscribes to structured standards designed to ensure the repaired equipment is fit for purpose and will operate in the complete range of harsh environments for specific periods of time.

One process used extensively by the industrial organisation is welding. A variety of different metals are permanently fastened together using various welding processes. Welding often occurs inside the large pieces of equipment, which must be protected to prevent damage to other components. Further, the weldments frequently form part of the pressure boundary required for successful operations in the aforementioned harsh environments. While most welds are accomplished flawlessly, there are occasional faulty welds, usually detected by a range of measures spanning visual inspection, non-destructive testing, or records review of the completed work as documented in the weld record card. Occasionally, the welder will recognise a flaw and self-identify the problem. The industrial organisation has a process to categorise flaws, determine the immediate corrective action and determine if the flaw is in error that requires initiating a formal problem resolution process. For this example, the flaw is postulated to have been identified, classified by the organisation, it is determined that it bears further action immediately.

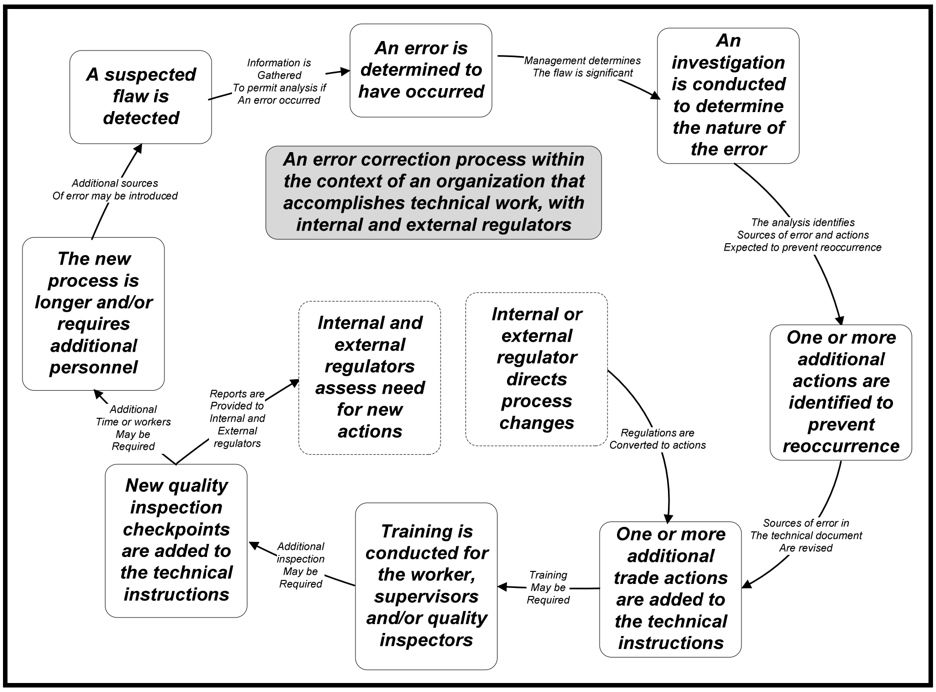
The industrial organisation has a workgroup that assesses each flaw that merits higher analysis and action. Their first assessment is to classify the flaw as to the presence of human error. That human error could be welding proficiency, error in the technical document prepared by a technician for the welder, issuance of improper weld wire not detected by the welder or his supervisor, or any number of other failures humans can make. The flaw may have also been introduced by a mechanism other than human error. In this case, we postulate that the workgroup has assessed that this flaw is at least partially due to human error and designates the requirement for further corrective action. The further corrective action will be a formal critique, which will include all of the workers involved, the immediate supervision, representatives from engineering and the project management team. At the critique, the flaw and its possible causes are reviewed, and potential actions to prevent recurrence are presented, discussed and selected actions to incorporate in one or more processes are decided upon. For this example, we will postulate that one or more additional actions (requirements) will be added to the welding process document. The engineering or shop management may elect that additional training be conducted for the specific welder or all welders and their supervisors before any further welding is performed. It is also possible that instead of immediate training, a decision may be made to include the new requirements in the periodic requalification training attended by all qualified or qualifying welders. The document used by the welder submitting the flawed work will be retrieved from the worksite and updated to the new requirements by engineering department personnel prior to work being allowed to resume. As part of the error elimination process, the engineering group may specify additional inspection requirements for this process. The welder, the welder supervisor, or quality control inspectors may perform the inspections. This is an ongoing process, with relatively frequent opportunities to enter the loop. The welding process is now more closely coupled than it was prior to flaw being detected and highlighted to the error correction and remediation process. This process is depicted in Figure 6.

Figure 6 Internal system of response to flaws in welding



One might rightly ask: how does this process affect the SoS? The answer lies in the relationship of the individual welding processes, and all the other industrial processes with the delivery date of the large piece of equipment back to its operational owner. Each addition to each industrial process has the opportunity to lengthen the critical path for the repair period. Thus, while on an individual basis, the revisions may seem trivial, cumulatively they can add up to lengthening the repair process, thus affecting the SoS. However, one additional method of imposing coupling has not yet been discussed. Returning to the organisational training, this industrial organisation is only one of a number of similar organisations. A flaw of large magnitude and the corresponding actions to permanently prevent the flaw from occurring again are transmitted to the system's other organisations for incorporation in their welding (or any other industrial processes). Thus the larger system is also now more closely coupled, as all the other industrial organisations replicate the process of error detection, response, and development of corrective actions along with instantiation of permanent measures to prevent recurrence. Thus all the industrial organisations are contributing to increasing coupling, both internally and exporting it across their system boundaries industrial organisations. Before we move on, one last method of imposing coupling should be discussed. This industrial organisation is part of a larger system that incorporates regulators, both internal and external. The internal regulators observe problems both inside the industrial organisations that they oversee and other organisations outside their purview. Occasionally, the internal regulators are stirred to take action by either the severity of a particular flaw, or a pattern indicating some larger action is required. In a similar fashion, external regulators, usually governmental, may impose some rulemaking across the whole industry or selected sectors/businesses. Functionally, these two sources are essentially injecting coupling into the industrial organisation's system, which will eventually be translated to a later return of the large equipment to their owners. A depiction of the interaction of internal and external regulators is show in Figure 7.

Figure 7 Interaction of internal and external regulators in coupling



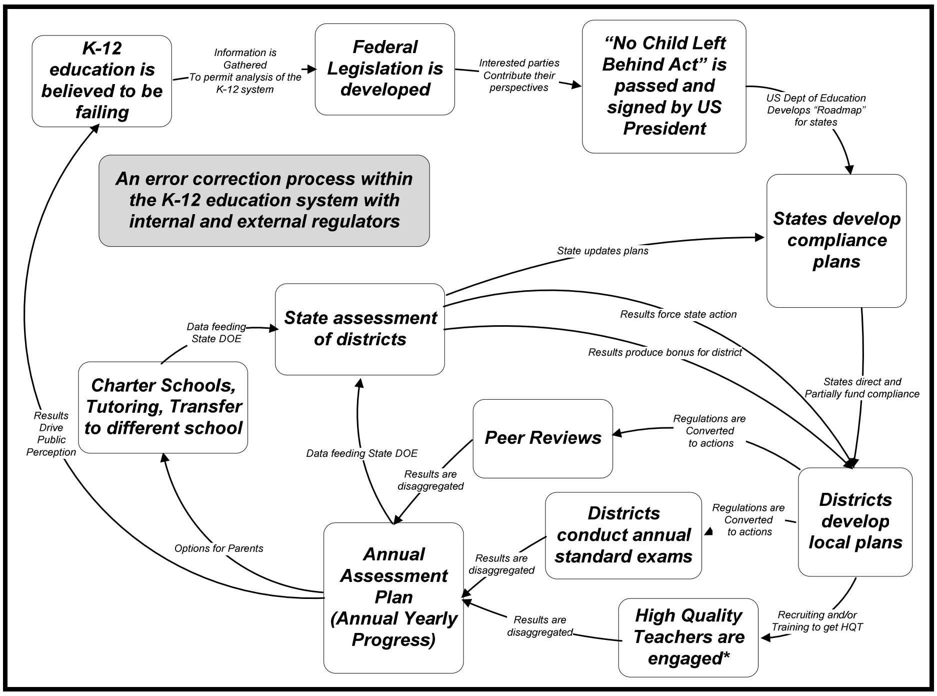
Another question remains to be discussed. The process of remediating flaws was designed with preventing flaws from reoccurring, why is it now perceived to be a problem itself? One would expect the total number of flaws to be reduced over time, with less rework, and improved schedule and cost performance. The answer to this question is that while the probability of anything going wrong is decreased by the risk mitigation measures, the possibility of a negative event is increased by tighter coupling of SoS processes. However, this does not mean that something will necessarily go wrong. Thus while possibility of the error is collectively increased its probability is not. This means that other potential errors (probably unforeseen to this point) have the possibility or opportunity to propagate through this tighter coupling. Thus although one source of uncertainty or error is reduced (that of welding) the system is now collectively more fragile. Since this notion is not attended to at the SoS governance level (which means that the possibility of collective error is deemed to reduce) any upcoming error will be a surprise, simply because such incident has been implicitly assigned a low possibility.

3.2 A policy example: no child left behind act

In the late 1990s, a frequent topic for policy makers in the USA was the K-12 education system, and its reported failure to produce graduates with the requisite skills for America to succeed in the 21st century. These conversations propelled a bi-partisan effort in the

US Congress to update the Elementary and Secondary Education Act (ESEA). These efforts resulted in the passing of the No Child left Behind Act (NCLBA) of 2001 (Manna, 2004). The NCLBA provided requirements for states and districts that were believed led to improved education outcomes. For those districts (or individual schools) that do not meet the AYP goals, parents are required to be offered a number of options for their children, including Charter Schools, Tutoring or transfer to another school (presumably with better AYP scores). Figure 8 is a simplified depiction of the system created by the NCLBA. Like the previous example, it depicts an error correction process. On its face, this system can make sense and lead to better outcomes for students. Though it is currently depicted as an open loop, we begin with the widespread belief that the K-12 education system is failing America. This belief energises interest groups to collect data and lobby the US Congress for action (i.e., legislation). The problem is perceived to be big enough that it merits action and the US Congress develops draft legislation. In hearings and informal sessions, various interest groups lobby Congressional and their staff to modify the legislation which is passed and signed into law by the US President.

Figure 8 Idealised NCLBA system reflecting learning partnerships



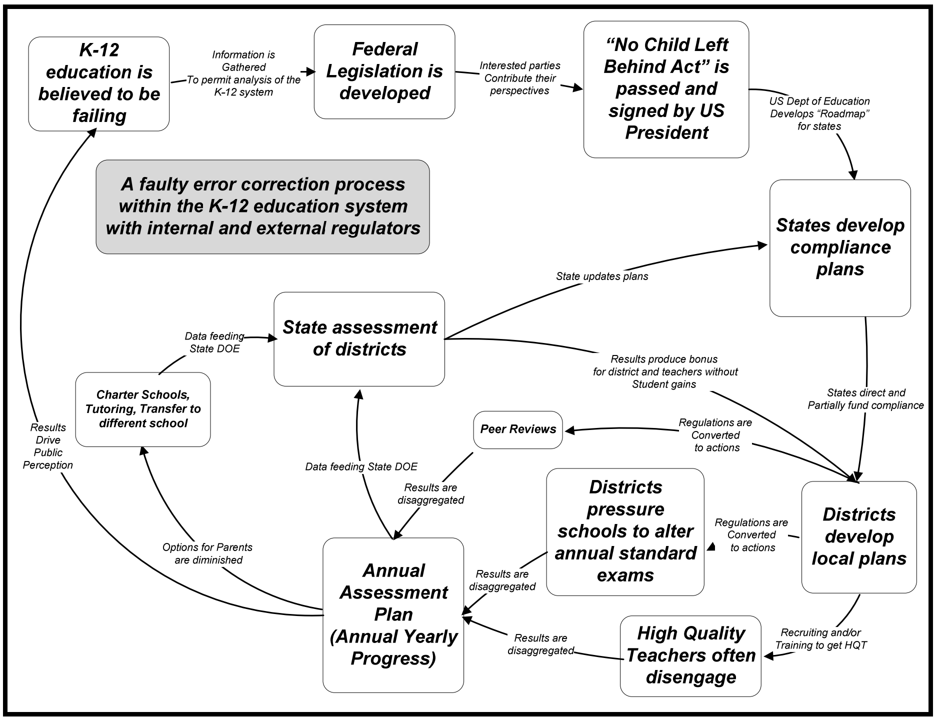
At its heart, NCLBA is a punitive system with 'high stakes testing at its centre' (Acker-Hocevar et al., 2006). The US Department of Education (USDOE) developed a 'roadmap' for the states, as well as supporting regulations and rules (Spellings, 2005). These regulations require the states and districts to each develop and execute plans to be compliant with the NCLBA. The primary carrot for the states and districts is funding from the USDOE, which supplements the local and state funding. State and district plans include elements for improving the quality of instruction, measurement of student progress (taken as a token of teacher quality) and peer reviews to assist schools in detecting and improving upon weaknesses (Sunderman and Orfield, 2006; Moloney, 2006). "NCLB is the primary federal policy tool to deliver educational services to children of low socioeconomic (low-SES) status and limited English proficiency (LEP), otherwise called English Language Learners (ELL)" (Acker-Hocevar et al., 2006).

The primary measurement of student progress is a set of annual, standardised exams. These exam results are the arbiter of follow-on actions and determine the fates of superintendents, principals and teachers. These actions include tutoring or transferring to other schools (Fusarelli, 2007). For districts with declining or poor steady scores, NCLB causes states to invoke a plethora of corrective actions, few if any of which, are viewed positively by superintendents, principals and teachers (Moloney, 2006; Shirvani, 2009). These include establishment or support of charter schools, tutoring programs, or transfer of students to better performing schools. For districts with improving scores, the results can be bonuses, improved funding and promotions. Acker-Hocevar et al. (2006) sought schools that responded to the underlying NCLBA requirements by developing a system that improved student outcomes. Working within the Florida's Sunshine State Standards, they identified nine schools that had significant fractions of the student groups targeted by NCLBA, and met a set of criterion demonstrating meeting those state standards over a sustained period of five years (Acker-Hocevar et al., 2006). Once the schools were identified, an interview protocol was developed to help identify the key characteristics leading to that success. A systems alignment model had been previously developed to explain school success (Acker-Hocevar et al., 2006) and this model served as the framework for this research. Acker-Hocevar et al. reorganised their model into organising (visible) variables (accountability, resources, instruction, information management and personnel) and sustaining (less visible) variables (culture and climate, leadership, communication, and parent and community involvement) were the key elements for the success of each school. The language dominating the interviews was filled with positive approaches, recognition of cultural differences and challenges being met in a forthright manner, and less focus on punishment (Acker-Hocevar et al., 2006). An idealised version of the relationship between the elements is contained in Figure 8.

This contrast between punishment and reward has led some districts to a path of falsification and cheating (Sadler, 2013; Freeman, 2014). In these cases, notably Atlanta Public Schools (APS) and the School District of Philadelphia, the district itself conspired to direct teachers and principals to cheat on the standardised exams. In prosecutions associated with APS, the first indictment named 34 individuals, including the superintendent and "4 high-level administrative aides, 6 principals, 2 assistant principals, 6 testing coordinators, 14 teachers, a school improvement specialist and a school secretary" with charges including racketeering; theft by taking and false statements (Freeman, 2014). Figure 9 illustrates the visible modifications to the idealised system made in the APS case.

These results are not unique, but they occurred far faster than might have been expected. Khan suggests that the collapse was due to the inherent feedback, where altering this year's exams created a higher standard for the next year, which required more test alterations (Khan, 2014). Returning to our theme, the system becomes more brittle by adding requirements. In the NCLBA cases, it took only a very few years for the system to change to a state that essentially led to collapse. The state of Georgia took control of APS, installed a new superintendent and senior leaders. Large numbers of school administrators and teachers were discharged from the system. This case suggests that when we turn to modelling, these systems, we clearly need to understand the accelerants.

Figure 9 Depiction of no child left behind in the K-12 EDUCATION SYSTEM reflecting APS approach to exam falsification



4 Conclusions

In this paper, we have begun to explore potential for modelling the effect of tightening coupling with the purpose of being able to detect the boundary between effective operation of the SoS and what we have called collapse, where the collapse is instigated by lower level components of the SoS, potentially invisible to the higher level until it is too late. Detectability of threats and faults is one of the major factors that enable resilience engineering. In this paper we presented the concept of TTF as a general concept applicable to any networked (flat or hierarchical) system, as well as time difference of failure that solely applies to hierarchical systems such as SoS. TTF is an indicator of rapidness of failure propagation. If the TTF is short the failure appears as a surprise collapse of the SoS. If it is longer it might be detected and averted by resilience engineering techniques. In all cases of short TTF, short time difference of failure, and positive time difference of failure, formulating resilient responses is difficult if not impossible; because of:

1 the lack of a presumed window of opportunity to detect the threat

2 the lack of resources to react to threats from all systems of SoS at the same time

3 the difficulty in detecting the origin and source of failure.

We also showed by some real world examples that complexity of SoS increase overtime, because of their openness to future development of CSs and also because of risk management activities. These mean that the SoS becomes more fragile over time due to creeping increase of complexity. Currently, most discussions in this arena are driven by after the fact, backward looking hindsight. Few tools exist to assist the SoS operators in predicting the impending collapse. Thus, the authors believe that developing models that give such insights would be valuable.

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