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Developing a Framework for Linking Clustering Coefficient to Loose Coupling of Hardware and Software Systems

<u>Topics</u>
C2 Technologies & Systems
Networks & Networking
C2 Metrics & Assessment

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Abstract

This paper will discuss the concept of the Clustering Coefficient as is used with regard to the connectivity between people or organizations. The paper will use an example of a hypothetical group of people as would be found on a small project team to determine a possible best range for the coupling coefficient to resolve the optimal number of tight and loose connections. The concept of diminishing marginal returns and the tradeoff between tight and loose connections will be examined to determine how tight connections may actually destroy options on exchanging information with other people, and thus lower the value of the organization. The concept of the coupling coefficient will then be applied to discuss the concept of Loose Coupling as is often applied to hardware and software systems, or systems of systems. The goal of this section of the paper will be to determine a framework to examine the level of coupling between subsystems in a system of systems, and to then determine to what degree a system is coupled, with possible implications to the difficulty and costs for spiral developing the subsystems. Coupling to standards will be presented as analogous to limiting the tight connections between people.

Introduction: As part of looking at valuing networks and applying this concept to organizational design, the concept of clustering and the clustering coefficient became apparent. Unfortunately, while the concept is discussed, rarely is a formula found to readily apply to an organization or an actual network. Additionally, the application of the clustering coefficient is scratched upon but not deeply investigated. This paper uses a previously developed method for calculating the coupling coefficient and applying it to a hypothetical group to determine the levels of a coupling coefficient that aid and hinder group performance. This author believes that social networking theory and systems engineering concepts can be closely linked. As such, this paper attempts to move past the idea of a coupling coefficient to provide a possible method to evaluate loose coupling between technical systems.

Clustering: Clustering is a measure, or at least a heuristic, to define the level of connectivity between a group of people. The Clustering Coefficient (CC) is the measure for this level of connectivity. As described in "Linked"m (Barabasi, 2002), if 4 people are all closely connected then the CC = 1.0. Essentially:

CC = number of close links/ number of possible close links
Number of possible close links = N(N-1)/2

As an example, "Linked" says that if there are 4 people then there are 6 possible close links. Some readers may confuse this with what is commonly referred to as the "N(N-1), or the N^2 problem." This problem is how people describe the pre-networking challenge that occurred when the DoD tried to have all of the nodes in a certain mission area connect to all other nodes in that mission area. The N(N-1) was based on using half-

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duplex radios and needing to be able to transmit and receive at the same time. In "Linked" they show only 6 links between 4 nodes because they appear to assume full duplex links. This explains why the above formula divides the N(N-1) by 2.

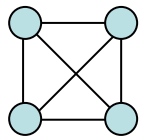

Figure 1 Linkage between 4 Close Friends

From the above example, if each of the 4 people are all close friends, then CC = 6/6 = 1.0. In reality everyone won't be close friends. If only 4 of those links were considered to be among close friends, then the CC = 4/6 = .667. Generally speaking, many people would look at these examples and believe having a CC = 1.0 is optimal. Surprisingly that is not the case. When everyone in a group is very close to each other, they usually primarily exchange information with each other. This limits their information sources and limits the knowledge the group has access to. As pointed out in "Linked" and "The Agile Organization" it is optimal to have some closeness within a group along with having what are called weak connections to outside groups, thereby making more information available to more people. "Linked" related this to the results of job searches, and that most people don't learn about job openings from their close friends but really learn about openings from "friends of friends". This mixture of a close knit group of people along with weaker outside links to other groups is referred to as a Small World Network.

Optimal Clustering Coefficient

While various readings have discussed the CC, the author has yet to find one that goes deeply into discussing how to optimize network performance to have a Small World Network that takes into account:

- How the formula for CC can be amended to take into account the optimal range of tight connections.
- How the formula for CC can be amended to take into account the benefits of medium and weak connections.
- How the answers to the CC and the above questions relate to the survivability of a Small World Network.
- How a formula can evaluate the gradual degradation of performance as various links are removed in a Small World Network.

The next challenge is to determine the optimal CC, or at least a range for the CC to provide an optimal Small World Network as judged by performance. The below table shows the range of CC values for the number of close connections in a group of 4 people.

Close Connections	Clustering Coefficient	Maximum # of Hops	Average # of Hops	Resiliency of Network

1	.167	Undeterminable	Undeterminable	0
2	.333	Undeterminable	Undeterminable	0
3	.5	2	1.5	Minimal to 0
4	.667	2	1.33	Good
5	.833	2	1.17	Best
6	1.0	1	1	Good to Avg

Table 1 Range of Clustering Coefficient Values

Table 1 introduces the concept of resiliency of the network. For this paper, resiliency is defined as the combination of the percentage of links that need to be destroyed to harm the small world network, and also still have connections available for outside connections. In this way resiliency relates to keeping the immediate group connected to each other and to the outside world. Further research may discuss the time frame that a small world network can be separated from the larger network before experiencing significant degradation in performance, but that discussion is beyond the scope of this paper.

We have already stated that in a group of 4 people, the odds are that they all won't be close friends, and that according to the Small World networking theory it isn't optimal to have them all be close friends. Reviewing the table we can intuitively consider that only 1 or 2 close connections will eliminate the chance for strong connectivity between the team no matter how many hops the information must traverse and therefore eliminates any chance for good performance by a team of 4 people. That leaves us to consider the relative merits for having 3-5 close connections. Evaluating this situation may required the determination of the longest number of hops required for information to transfer between the two most disconnected links, and the average number of hops required for information to transfer between any two people in the network.

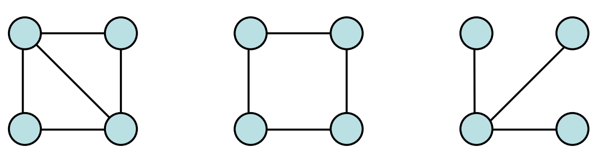

Figure 2 Diagrams of 5, 4, and 3 connections

As shown in figure 2, going below 3 connections for a group of 4 people means the group is not fully connected. The diagram of 3 connections also shows that the network has collapsed into a star or a serial connection between the nodes. Both of these constructs are very fragile because the loss of the hub means the network will disintegrate. The diagram of 4 connections shows that no node must act as a hub, and in this case the network would need to lose 2 connections (50%) to leave any node unconnected. The diagram of 5 connections appears to have the most resiliency since it would take at least 2 connections, and sometimes 3 connections to leave any node unconnected. In this case eliminating the correct 2 connections (40%) is still all that is required to start harming the

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network, although in some cases it would take the removal of 3 connections (60%) to start harming the network. From a resiliency standpoint, there is some benefit to the extra connection (5) if the threat to the network is random and statistically based. Against a knowledgeable enemy there may be no benefit to 5 connections.

While the above discussion relates to the resiliency of the internal network nodes to each other, it fails to take into account connectivity to the outside world. When viewing the tightest connectivity between the 4 nodes, it is apparent that each node can handle up to 3 tight connections. A second look at the 5-connection diagram reveals that 2 nodes would still have the capacity for an additional connection to the outside world, while analysis of the 4-connection diagrams reveals that all 4 nodes have the capacity for at 1 additional tight connection to the outside world. There appears to be a tradeoff between additional tight connections between the nodes of the group and the opportunity cost of having connections to the outside world.

Diminishing Marginal Returns on the Number of Connections

Many discussions on networks imply that more connections are better. This thought seems to disagree with the concept of diminishing marginal returns. While every person reacts differently, each person likely has a maximum number of other people that maintain close contact with. For each of us there is a point where we not only receive diminishing returns by attempting to maintain an additional close connection (with all of the time and effort involved) but also a point where that additional connection provides negative returns. A person has reached the point of diminishing marginal returns when the value added by the new connection is less than the value added by the last connection. A person has reached a point of negative returns when the new connection lowers the total information content value, possibly because this connection takes time away from those old connections. On the other hand, each person can likely maintain far more weak connections than they can one close connection. Possibly when a person reaches diminishing marginal returns on their total Small World Network value, and definitely when a person reaches negative marginal returns on their close connections sub-network, then the person should consider which close connections to sever or at least to weaken to optimize the value of the close sub-network and the overall Small World Network.

$$\text{Diminishing Marginal Return: } \Delta V_n < \Delta V_{n-1}$$

$$\text{Negative Returns: Total Value } (TV)_n < TV_{n-1}$$

Real Options and Network Connectivity

Each connection to a node represents an option that the node operator, and the network overall, can leverage when needed. Therefore the strength of each connection should be reviewed from the standpoint of diminishing marginal returns and diminishing total returns. Looking back at the 3, 4, and 5 connection networks, we should now consider the alternatives to substituting a close connection for a weak connection, or for multiple weak connections. Adding strong connections to a node impacts the number of weak connections that node can support and the network can utilize. The network topology should be reviewed to take into account the likely increasing value of adding multiple weak connections in the place of some strong connections. This evaluation should take place at the point where the addition of another tight node shows a decreasing marginal utility. Since a review of the resiliency of the networks has shown that the 3 connection network has little survivability, that network should be removed from consideration. The question now becomes the relative merits of moving from a 4-5-6 connection network. These networks are equal in the greatest number of hops between any two nodes, and are very comparable in the average number of hops between two nodes. The 6 connection node has a maximum and average hop length of 1, clearly the lowest number of any network choice. On the other hand, the Small World theory has shown that having all nodes tightly linked lessens the networks resiliency due to a failure to have outside connections. Additionally, there is a cost to each of those network connections. So far basing our analysis on resiliency, average hops, maximum hops and cost of network design shows the optimal network will be either the 4 or 5 connection network. The choice now comes down to which network provides the greatest number of possible weak connections. As previously discussed, it appears that each node can accommodate 3 tight connections. In this case the 4 connection network offers the chance for weak connections attached to all 4 nodes. While the replacement coefficient for weak connections compared to strong connections has not been determined, the author expects this coeeficient to be $\geq$ 2.0. Applying an estimate of being able to replace 1 tight connection with 2 weak connections, then the diagram with 5 tight connections means that 2nodes can each support up to 2 outside connections, giving the group 4 weak connections to the outside world. A similar analysis of the 4 connection network shows that each node can provide 2 connections to the outside world, giving the group 8 connections to the outside world. Each of those outside connections offers a Real Option (RO) the group can exercise as needed to gain information from other groups. Additionally, the network's resiliency increases with a weak connection (as opposed to no connection) because the weak connection offers the chance to still connect between its own nodes, just taking more hops than possible with tight connections.

Quality of Information

While the previous discussion has focused on the number of connections and delineating between whether those connections are tight, medium or loose, another consideration is the quality of information passed over each connection. This quality of information determines if the connection, independent of the tightness rating, has a positive or negative value. This might also relate to how teams are developed and used. For instance, some people are more outgoing and extroverted than others. Those people may or may not have the highest quality of information, whereas the situation can often exist

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where an introverted person has a very high quality of information but lacks the personality to readily share that information. In these cases, managers should try to tightly link a person with a high quality of information with a more extroverted person to thereby maximize the value of the network for those people that are close knit and those that have a number of loose connections.

	Tight Connection	Loose Connection
High Quality Information	+	++
Low Quality Information	--	-

Table 2 Relative Value of Connection

Relationship to the Clustering Coefficient (CC)

The prior analysis can be done via easy diagrams and calculations for a small network of only 4 nodes. The challenge now becomes how to apply the CC to larger networks. Software exists to analyze networks by basically inputting information on who talks to whom, and can provide a calculation for a clustering coefficient. The challenge now becomes determining how to use this information. From the above example the author has developed the hypothesis that a network will have good performance if

$$.6 \geq CC \geq .75$$

A CC below .6 appears to indicate that the network topology offers the chance for too few close connections for the Small World Network to operate efficiently, and going below a CC = .6 risks the network collapsing into a star. A CC greater than .75 appears to be a point that the network may have too many close connections and has lost the RO provided by have more weak connections that that link to other information sources and the resiliency that comes with a Small World Network.

The challenge now becomes whether a formula can be developed to aid in the use of the above heuristic to judge a network's topology. Bringing the previous discussion on options into account, a revised formula for the Clustering Coefficient and Optimal Network Design might yield:

Optimal Network Design Π (union of)
$.6 \geq CC \geq .75$
$\text{Network}_2 >$ # of Weak Links than Network_1

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CC = number of close links/ number of possible close links
Number of possible close links = N(N-1)/2

Relationship to Loose Coupling and Platforming

The definition and a formula for Loose Coupling (LC) have proven to be very difficult to develop. In some instances, just making the intellectual distinction between tight and loose coupling is difficult. Previous discussions on LC have often implied that any tight coupling can be bad for the overall system. To the contrary, some tight coupling can prove to be good. For instance, relating back to research performed by Konstantinos Kalligeros (Kalligeros 2006) in his PdD dissertation, platforming (standardization) can be both good and bad.

Platform design → managerial flexibility
→ faster/cheaper deployment of more variants
→ modularity → operational flexibility (in design/use)
→ interface standardization → interchangeability
→ learning organization, focused innovation

but

Platform design → strategic commitment and sub-optimality
→ locking-in with expertise and supply chain
→ dominant standards → limiting innovation
→ not enough "extent" for changing future requirements
→ "local" sub-optimality

Therefore, there is likely a range of platforming opportunities that exist that can provide options for system design for mass production and for mass customization. While each major system or enterprise should be evaluated on a case by case basis, this author hypothesizes that the use of Design Structure Matrices (DSM) can be developed for technical systems should be evaluated in much the same way that a network engineer or sociologist should evaluate the clustering coefficient.

For the purpose of example, lets apply this thought to a system that has 30 subsystems. Using the previous discussions from the clustering coefficient (CC),

CC = number of close links/ number of possible close links
Number of possible close links = N(N-1)/2

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A system of 30 subsystems would then have 435 possible connections between subsystems. The question then becomes whether the heuristic discussed earlier for human and communications networks applies here. It is highly unlikely that a good systems engineer would then want to have 261 to 327 (.6 to .75) subsystems tightly linked together. This is still a level of integration and complexity that will make system evolution very difficult. On the other hand, the concept of coupling may relate more to ensuring that each system is connected to at least 1 other system in an electronic or mechanical manner. The author contends that systems that only connect via a “sneaker net” are not really connected at all. Therefore, a loosely coupled system will have each subsystem technically connected in some manner to at least one other subsystem.

The Design Structure Matrix

A Design Structure Matrix (DSM) is a compact representation of a digraph (i.e. directed graph) that depicts the relationships among the components in a system (DSM Web Site 2006). Systems engineers use DSMs to illustrate relationships among subsystems.

The rows and columns in the DSM are analogous to nodes in the digraph and correspond to system components. The cells in the matrix are analogous to edges in the digraph and represent the relationships among the system components. As in a digraph, the relationships tracked by a DSM are directional. Thus the relationship of component A to component B is distinct from the relationship of component B to component A.

This study employs DSMs to articulate how changes made to components affect other components in a system. The relationships in the DSMs indicate whether a given component will require modification if another specified component is upgraded. These relationships are stated as dependencies. Figure 3 shows the three possible types of dependency relationships.

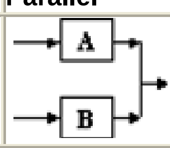
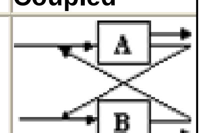
<table>
<tr><th colspan="4">Three Configurations that Characterize a System</th></tr>
<tr><td>Relationship</td><td>Parallel</td><td>Sequential</td><td>Coupled</td></tr>
<tr><td>Graph Representation</td><td></td><td></td><td></td></tr>
<tr><td>DSM Representation</td>
<td><table><tr><td></td><td>A</td><td>B</td></tr><tr><td>A</td><td></td><td></td></tr><tr><td>B</td><td></td><td></td></tr></table></td>
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Figure 3. DSM Component Relationships (DSM Web Site 2006)

In the first relationship depicted in the figure, changes to the system components do not interact with one another. Thus component B is independent of component A (and vice versa) with regard to modifications. Upgrades to either component can be made independently. In the sequential (also known as dependent) relationship, changes to one component require modifications to another component in order to maintain a working system. The figure depicts that component B is dependent upon component A. Thus, if component A is upgraded, then component B will require modifications to keep the system operational. Finally, in the coupled relationship, components A and B are interdependent and therefore coupled.

Figure 4 depicts a DSM for a generalized connectivity between a satellite terminal to satellite to satellite terminal. While some users of DSMs insert a "1" or an "X" in the boxes that indicate a relationship between to subsystems, this author has chosen to use an "H" to indicate a high degree of coupling, a "M" to indicate a medium degree of coupling, and a "L" to indicate a low degree of coupling. Each of this linkages, or couples, indicate an increased level of complexity since each relationship will impact the initial design and any efforts to upgrade one of the subsystems since that will impact the other subsystem as well. These linkages are similar to linkages between nodes in the social network that was discussed earlier in this paper. Tight couples between subsystems can lead to customized design rules between each of the subsystems, and thus make the total system very tightly coupled and very difficult to design, maintain and upgrade. Additionally, tight couples between components or subsystems are similar to the tight couples in a social network. Each subsystem has a theoretical limit on the number of other subsystems that it can maintain tight couples with, and thus may limit any additional couples, whether tight, medium or low, with other subsystems.

		1	2	3	4	5	6	7	8	9
Baseband -- User 1	1		L	H						H
Input Port -- User 1	2			H						
Terminal -- User 1	3	H	H		M	H	L			
Uplink Channel -- User 1	4			H		H	M			
Satellite Communications Payload	5			M	L		L			
Downlink Channel -- User 2	6			M	M	H				
Terminal -- User 2	7			H	L	H	M		H	H
Output Port -- User 2	8							H		
Baseband -- User 2	9	H		M				H	L	

Figure 4. Generalized Satellite Terminal – Satellite – Terminal DSM

Standards and Interfaces

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While the previous discussion focused on subsystems being coupled to each other, the system should also be evaluated by the number of standard interfaces that are used. Standards, especially those that the consumer base (not just this customer) has most readily accepted would be analogous to a strong connection. For instance, the linkage between computer systems and networks should then be evaluated at each of the 7 layers of the Operational System Interconnect (OSI) model. Therefore, each subsystem could have up to 7 strong connections to standards but still be loosely coupled to other subsystems since changes in one subsystem that still maintain coupling to the interface standards won't impact the other subsystems. Of course a subsystem can support multiple standards. The benefit of coupling to standards means that the degrees of complexity for a system are decreased.

The OSI stack provides a somewhat idealized linkage to standards. Many systems of systems are built with Commercial Off The Shelf (COTS) products. Those products are often built to commercially accepted standards. Frequently a commercial product will gain significant market share and come to dominate the market place. As designers choose to platform on specific COTS products, the overall system can unfortunately become tightly coupled to the product line. This is obviously good for the provider of the COTS products because now the consumers, and the system-of-system designers/owners, will need to upgrade at various intervals, often less than 5 years in time, to maintain interoperability with the given COTS product line. Therefore, while platforming on the COTS products appeared to provide the system with the option to leverage research & development efforts of COTS providers, the ability to continually exercise that option has a cost related to the upgrade cycle. Users of such COTS products can gain back flexibility, and decrease the level of complexity, but developing processes to possibly skip some upgrades and possibly only exercise an option on every other upgrade to the COTS product. In essence, the upgrade process returns some of the value of the option for the user.

Coupling Coefficient

Now, lets revisit the earlier discussion on the coupling coefficient. That discussion really went to whether the nodes exchanged information often, sometimes or not at all. Having common standards (a common language, transmission protocols, computer applications, encryption techniques, etc.) all can facilitate this connectivity, but cannot make the connectivity happen between humans. On the other hand, the discussion on loose coupling that is related to hardware or software systems assumes that humans want these systems to exchange information. In that case, the Coupling Coefficient for hardware and software systems should really focus on the ability of the systems to exchange information, relate to the coupling to common standards, and relate to the upgrade cycle of COTS products used in the overall system design. *Therefore, the coupling coefficient formula for hardware and software should relate to the tightness of coupling for each system to other systems, to standards, and to upgrade cycles. For computer networks, the*

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coupling to standards would be evaluated at each layer of the OSI stack if each layer is required to exchange information. The use of standards has the possibility to greatly decrease the number of tight couplings in a system of systems.

Therefore, a system can be tightly coupled to another system if the coupling is accomplished using a non-standard linkage. Systems are loosely coupled to each other if they are linked using a standard that is readily available to and used by the consumer base for this product. Therefore, systems don't necessarily need to use standards linked directly to Commercial Off The Shelf (COTS) products. Ideally, each of the subsystems that must exchange information, or are even expected to exchange information, should be linked at each level of the OSI stack to a standard that is readily available to and used by the consumer base. Readers should note that a focus on the use of COTS standards and their products can actually cause a system to be tightly coupled to a product line and the subsequent development cycle.

Determining a Formula for Coupling Coefficient
A formula for a Coupling Coefficient needs to include a variety of factors. Starting with the DSM, designers can see how many close connections a system, or system-of-systems will have. As such, determining the Coupling Coefficient needs to start with the following:

$$\text{Coupling Coefficient} = \sum_{\substack{i=1 \\ i=1}}^{n} S_i S_j$$

The use of standards can often decrease the levels of complexity, but may also raise the levels if the standards are not used judiciously. Using a computer network and the OSI stack as an example, a poorly designed system that has 30 subsystems could end up with a a worst case of (30X30-30)7 = 6,090 tight couplings. While possible, that level of errors is statistically unlikely. On the other hand, the optimal solution using the OSI stack and common standards means that the total system of systems might be tightly coupled to only 7 standards. This would appear to be a perfect use of standards.

$$\text{Coupling Coefficient} = \sum_{i=1}^{7} OSI_i \left[\sum_{\substack{i=1 \\ i=1}}^{n} S_i S_j \right]$$

As previously discussed, the use of COTS products can provide the designers with an excellent option to utilize commercially developed research and development. The use of COTS also can force system owners and sustainers to deal with required upgrade cycles. These upgrade cycles must be considered when determining the coupling coefficient for a system or system-of-systems. While no definite formula has been developed for the linkage to COTS product upgrades, this author hypothesizes that the tightness of the coupling decreases with the years between required system upgrades. Therefore, the portion of the Coupling Coefficient formula may equate to

$$\text{COTS Portion of Coupling Coefficient} = \sum_{i=1}^{n} S_i S_j \,/\text{Years to upgrade}$$

$i = 1$

Given the above formulas, the total Coupling Coefficient is tied to the system to system linkages, the use of standards, and the use of COTS products. While the DSM presented in Figure 4 only shows technical subsystems, a DSM can be adjusted to show standards used. Evaluating the DSM according to standards used for each subsystem will indicate if designers have judiciously used standards to tightly couple subsystems to a group of accepted standards and thus decrease the number of total tight couples. Given the example of the computer network and the OSI stack, the number of tight couplings can either greatly explode or greatly decrease to only a handful. While engineers often refer to standards, in the computer and networking area a COTS product(s) can become the defacto standard. As such, the system, or subsystems within, can become tightly coupled to the COTS product line. Engineers and sustainers have the opportunity to evaluate this tight coupling and the upgrade cycle to determine if some upgrades can be skipped, and therefore the impact of tightly coupling to COTS products can be diminished, but will still be additive to the overall coupling coefficient.

Summary

It appears that the concept of the coupling coefficient can be applied to physical networks in a manner that is similar to how the clustering coefficient can be applied to human networks. An example of applying the clustering coefficient to a network of 4 nodes was used to evaluate the impact of tight and loose connections on the resiliency of a Small World Network. The need to decrease tight couplings was related to opening up Real Options for the network participants to exercise to gain information from outside sources, and that the increase in tight connections is stopped at the point of diminishing marginal returns. At that point future connections should be loose instead of tight, and should be used to connect to other Small World Networks. For technical systems the concept of a coupling coefficient was presented. The coupling coefficient relates to the number of subsystems that are directly connected, to the use of standards in the system design, and the impact of using COTS products. The use of standards represents opening up each of the subsystems in an information exchange to freely evolve as needed within the boundaries of still working according to the technical standard. This use of standards provides the opportunity for sustainers to upgrade a system as technology provides possible new solutions. COTS products present the option to use product upgrades developed for many customers, but also presents a challenge of maintaining a minimally acceptable interoperability with new upgrades to those COTS products, whether the customer desires these upgrades or not. While much of this paper focuses on determining the tight couplings and trying to decrease the number, some tight couplings will still need to be maintained, if even only to technical standards. Here the number of required tight couplings is linked to the degrees of complexity for the systems. Reducing the total number of tight couplings and the number of different types of tight couplings will decrease the complexity of the system.

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