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CLOCKSPEEDS IN ARCHITECTURE: EVOLUTION, DEAD-ENDS, AND DISCONTINUITIES*

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The United States Navy DDG-1000 shipbuilding program was drastically cut back in 2008 before the first ship of the class had been launched. The platform was deprecated by recent emerging threats from China using improved technologies that countered the DDG-1000 capabilities. The system development and capabilities are examined through the lenses of various systems engineering tools and project management frameworks. The analysis illustrates how system developmental rates can be used to introduce disruptions to a system in opposition.

Keywords: Obsolescence; black swan; clockspeed; architectural disruption; TRIZ.

1. Introduction

The DDG-1000 evolved from changes in the Navy's mission and purpose following the end of the Cold War in 1991. Prior to that huge shift in the world political balance, naval strategy revolved around establishing and maintaining open ocean (or "blue water") superiority (Mahan, 1890), and supporting nuclear deterrence. With the fall of the Soviet Union, the Navy had to redefine its role in a new world without a primary adversary. The whitepapers ... *From the Sea* (O'Keefe *et al.*, 1992) and *Forward from the Sea* (Dalton *et al.*, 1994) articulated the new "peacetime" strategy of operating in a joint operational environment to provide crisis response, forward presence projection, settling regional conflicts, control of the seas, sealift capability, and sea-based support, and littoral (or "brown water") warfare with fire support.

SC-21, the program to define a surface combatant for the 21st century, was established in 1994. Its purpose was to develop a guided missile platform with the

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capability to provide Naval Gun Fire Support up to 100 miles inland for joint operations. This platform was designated DD-21. This met the Congressional mandate that the Navy provide fire support for Marine forces; a duty previously handled at the required ranges by battleships. The program was halted in early 2001 and then revived in 2002 as DD(X). This new class was later renamed DDG-1000 (Eversoll, 2009).

Planning for SC-21 was conducted prior to 2001. The attacks of 9/11 demonstrated that while wars between large and globalized powers will probably not happen in the immediate future (Friedman, 2007),[a] war still exists in an asynchronous form that uses nations as bases but not as direct belligerents. This situation is discussed in *The Pentagon's New Map* (Barnett, 2004) as a conflict between globalized and non-globalized areas of the world. Despite these external issues the DDG-1000 program continued development with little change.

On 14 March 2008, Allison Stiller, Deputy Assistant Secretary of the Navy for ships, and Vice Admiral Barry McCullough, Deputy Chief of Naval Operations for resources and requirements, testified to the House Armed Services Seapower subcommittee that the DDG-1000 program was on track and would meet US Navy requirements for littoral warfare (McCullough and Stiller, 2008b). Their report was consistent with previous Navy testimony regarding the DDG-1000 program. Trade article reports in July 2008 stated the Navy was cutting back the program from 12 to two ships and was intending to restart the DDG-51 Aegis destroyer line (Cavas, 2008a, 2008b). On 31 July 2008 Vice Admiral McCullough and Stiller again testified to the same subcommittee (McCullough and Stiller, 2008a). This time they presented reasons for the sudden change to effectively end a program that had been in development for almost 15 years. A key point in the public testimony was information relating to China's development of ballistic anti-ship missiles and Chinese developed anti-ship cruise missiles successfully used by Hezbollah against an Israeli ship. The program was cut back with only three ships scheduled to be built.

Problem investigation

The eventual cutback and virtual cancellation of the DDG-1000 after 15 years and billions of dollars of development raises questions on whether the program should have been cancelled much earlier. The answer found in systems engineering is — maybe, but probably not.

DDG-1000 development pursued implementing ten major technology advancements. That was a considerable challenge; previous ship classes had developed two or three at most. Schedule slippage did occur based on some technologies not maturing as fast as expected but overall the platform was expected to be operable.

The areas of investigation are to look at the speed of development related to requirements, the schedule risk of interdependent technology development, and the

[a]Friedman has famously asserted "War has never been declared between countries that both have McDonald's".

impact of disruptive developments. We will show how various systems engineering management frameworks can be used to evaluate the conflicts between architectures and disruptions.

2. Relevant Concepts to this Study

Architecture clockspeed

As architecture is developed there is a race between achieving a practical implementation and producing obsolescence. The concept of clockspeed (Fine, 1998) and its attributes applies to these type of dilemmas. Fine originally presented the notion of clockspeed as a characteristic for industries (Fig. 1). Moore's Law (Moore, 1965), which describes the doubling of components on integrated circuits every two years, is a commonly known clockspeed. We suggest clockspeed is also an attribute of architectures and can be thought of as the cycling rate for system/product/architecture life cycles.

Another facet addressed in Fine's concept is volatility amplification, also known as the bullwhip effect. As represented in Fig. 2, small perturbations in customer requirements cause accelerated changes upstream in the supply chain.

Both the double helix and the bullwhip effect represent the balancing act of maintaining an effective and efficient supply chain with the outside pressures and competition from markets, competitors, and technology.

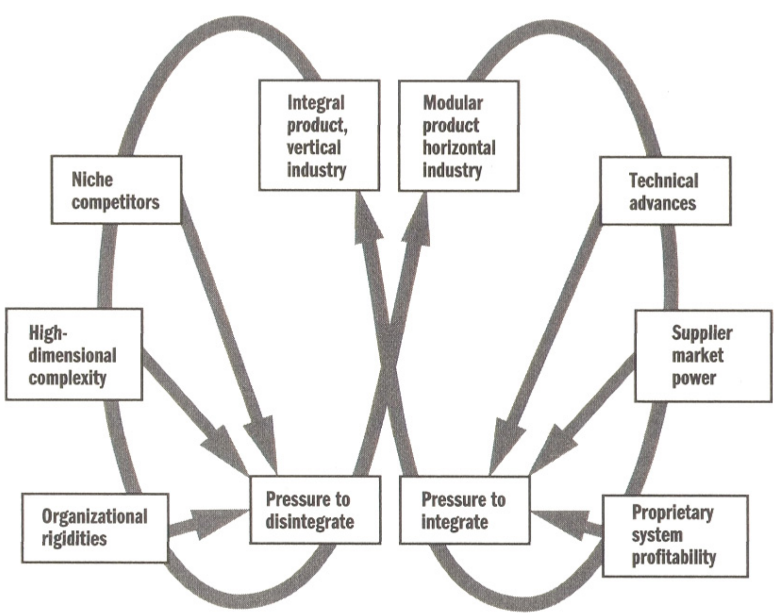


Fig. 1. Clockspeed double-helix (Fine, 1998).

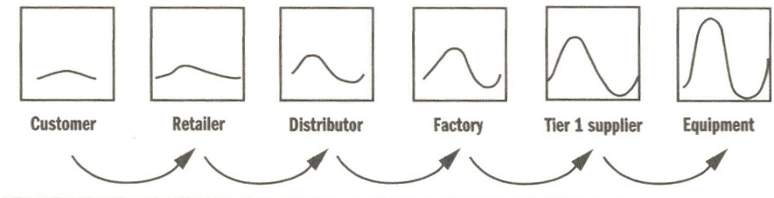


Fig. 2. Bullwhip effect of supply chain volatility (Fine, 1998).

If one were to consider architecture development and management science as equivalent to a self-contained industry targeted to meeting requirements, it will have a clockspeed. The clockspeed will be dependent on the clockspeeds of its subordinate technologies and their interactions. Increased complexity, diversity of technologies, and number of interfaces increases the difficulty in making changes and improvements to one part of an architecture without negatively affecting another part. These interface interdependencies can be mapped as critical paths. As the quantity of critical paths increases, the architecture risk multiplies and the clockspeed slows.

Architecture relevance

Projects that have high risk in technology, system architecture, complexity, and size are more prone to long clockspeeds (Alach, 2008; Charette, 2008; Fine, 1998). Advanced programs, specifically in the military, have technology roadmaps where development is targeted not for the present level of technology but for future levels of capability. This dependence on unproven and untested future technologies assumes the risk that the chosen solutions will remain viable and relevant. We define relevance as the degree of applicability to requirements. Relevance can encompass obsolescence, however obsolescence is a utility within the architecture that is no longer able to perform its required function, either by availability or affordable repair (Herald *et al.*, 2008). Relevance can be affected by complete shifts in requirements, even if there are no underlying obsolescence issues present. From the other perspective, a major obsolescence issue can destroy effectiveness, making the architecture irrelevant.

Outside forces impact architectural relevance. Black swans (Taleb, 2007) describe the occurrence of improbable events and can quickly erase an architecture's relevancy.

The abrupt end of the Cold War in 1991 is an example of a black swan, as are the terrorist attacks of 9/11. In the case of the end of the Cold War, the Western military, especially the US Department of Defense (DoD), had an established strategy of nuclear deterrence and maintaining a ground defense in Western Europe against Warsaw Pact invasion. They had no contingency plan to deal with the situation where the purpose for that strategy had disappeared. Outside of trying to retain funding against demands for a "peace dividend" and repositioning itself to handle drug interdiction and international peacekeeping missions, the military had trouble defining its purpose. For 9/11, the US, its allies, and even antagonist nations found normal daily events thoroughly disrupted. In the US, no planes flew; financial markets closed — as though the world reacted by slowly stopping. This disruption in the US rippled through the worldwide air traffic and financial systems.

Architecture discontinuities

Discontinuities for architectures are abrupt, nonlinear changes. We have identified two types: environmental and developmental.

Environmental discontinuities

The environmental discontinuity occurs when the operating environment or disruptive architectures (Christensen, 1997) literally change the game board. This disruption may undermine any given architecture's relevance. Disruptive technologies can also erode an architecture's relevance over time. The distinction between a discontinuous and erosive disruption is related to the rate that a disruption's relevance overtakes the existing architecture. This dependence on the related clockspeeds can be measured in business cycles, months, or years.

The Napster file-sharing program provides an example of an environmental disruption. By introducing a means to easily share and distribute music files, Napster disrupted control of the traditional distribution channel within a few months. The Napster model of disruption has been shown to contribute to the decline of retail music stores (Zentner, 2006b). This disruption was fought through legal means to restrict the use and spread of this technology (Carroll, 2002). The October 2001 introduction of Apple's iPod and its supporting iTunes store firmly established the electronic model of music distribution (Hormby and Knight, 2007), replacing retail music stores for many customers.

Developmental discontinuities and TRIZ

The other type of discontinuity is a developmental discontinuity. This occurs when application of new inventions and concepts change an architecture in place of incremental improvement by evolutionary progress. The practice, known as TRIZ (Altshuller, 1984; Altshuller *et al.*, 2000; 2001; 2006a, 2006b), provides a framework called the Evolution Potential to chart this form of disruption. Mann (2006a) has shown how these evolutionary jumps in a system or architecture have a consistent rate over time.

TRIZ is an invention development heuristic that matches contradictions in operations to appropriate methods to eliminate the contradictions. This system, arguably a form of a pattern language (Alexander, 1979; Alexander *et al.*, 1977; Cloutier and Verma, 2007; Gamma, 1995; Leitner, 2007; Otto and Wood, 2001; Rantanen and Domb, 2002), provides a means to explore potential architecture deficiencies and then map out solution sets for them. A particular tool from the TRIZ discipline charts discontinuities in architecture development and their relative strength to TRIZ principles in a radar type chart (Mann, 2006a, 2006b). The system engineer can map out the rate of inventive change of one architecture against another, as well as compare which inventive principles have been applied and which have not. This helps explore areas where unexploited principles may have great effect.

Black swans

Taleb's "black swans" (Taleb, 2007) introduced the notion that the most important events are those we never plan for; they fall outside the normal Gaussian-like distribution, i.e., the "law of averages" which most have been trained to expect. It is known that $> 99\%$ of the events that will occur during a project fall within 3-sigma of the mean. The chance of an event, which falls outside that distribution, is so remote that it generally can be ignored safely.

However, when black swans occur, their disruptions cause radical changes and reactions from the norm. Large-scale black swans have changed the course of history. Examples include the stock market crash of October 1929 (which led to the Great Depression), the crash of the US stock market on 19 October 1987, where the Dow Jones index lost 22.6% of its value, and the explosion of the Space Shuttle Challenger on 28 January 1986.

3. Methodology

This study exists to investigate and explore the impact of clockspeed, architecture discontinuities and black swans on the development of large, complex systems. All sources used for this study are available in open source, and are cited in the bibliography. Conclusions are drawn from observation and analysis.

4. Case Overview

11 September 2001

The major black swan event of the early 21st century was the set of terrorist attacks of 11 September 2001. The result of the attacks forced globalized nations to immediately change their strategies and operations for dealing with terrorism. The eventual war front in Afghanistan was not a littoral target due to geography. While DDG-1000 has yet to be completed or deployed, the geography of the Afghan and Iraqi wars underscores that many areas of potential conflict exist where littoral platforms have no utility.

China

Even though the DoD looked to China as a long term adversary following the end of the Cold War, neither its long term strategies nor the Navy's post-Cold

War planning documents (Dalton *et al.*, 1994; O'Keefe *et al.*, 1992) anticipated China's explosive economic and technical growth starting in the 1990s. China's use of its new wealth to expand its naval operations and to develop aircraft carrier capability for force projection was a surprise. China has also worked hard to increase its missile technology. For strategic as well as economic reasons, China has been providing its anti-ship cruise missiles (ASCM) technology, specifically the C-802, to hostile nations such as Iran, who in turn has provided its version of the missile to non-national groups such as Hezbollah; changing the Naval battle space (Hilburn, 2006). Longer term disruption exists in China's progress in increasing its capabilities with ballistic cruise missile (BCM) (Cavas, 2008c) and land attack cruise missile platforms (LACM) (Chase, 2008).

Technology, time, and money

Several of the technologies for DDG-1000 are new and innovative. Timelines are extending, as the technology roadmaps have not met their expectations. With higher technology and more time required, budgets balloon. In July 2008 the Congressional Budget Office (CBO) testified the first two DDG-1000 class ships are estimated to cost US$3.2B each (O'Rourke, 2008). This has put pressure on the DoD and the Navy to reduce the quantity of platforms planned to be built. It is safe to say the financial crisis of 2008 will create additional budgetary pressures on the DDG-1000 as well as other DoD programs under development (Cavas, 2005, 2008a).

DDG-1000 architecture development

DDG-1000, as planned, incorporated ten new critical technologies (Appendix A). Normally the Navy introduces only two or three technologies on a new platform. Incorporating untried technologies has a compounding effect on the architecture development and integration that extends throughout the supply chain. In the case of the DDG-1000, the interactions and dependencies of these ten new technologies, each inserted along different stages of the supply chain, served to create a compound and interconnected bullwhip effect, which was discussed in Sec. 1.

The architectural dependency of so many new technologies added development complexity and time. With development time extended, the DDG-1000 architecture clockspeed slowed dramatically. This slower speed created two pressures. Cost increased which increased risk of program elimination (Cavas, 2005, 2008a, 2008b, 2008c, 2008d; O'Rourke, 2006a; Weiner, 2005). Time was allowed for opposing interests to develop systems that were able to counter the DDG-1000's capabilities. Both pressures — affordability, and a disruptive technology — diminished the relevance and effectiveness of the platform. "The complexity of military systems stems increasingly from their interconnectedness to other systems" (Charette, 2008).

One type of counter system, anti-ship cruise missiles (ASCM), were demonstrated in 2006 when Hezbollah fired an Iranian version of the Chinese C-802

"Silkworm" ASCM and damaged an Israeli corvette (Hilburn, 2006; O'Rourke, 2008). The disruptive issue here was the unprecedented use of ASCM technology by a non-national force in an asymmetric warfare role.

McCullough's testimony to Congress also indicated the design fell short of being able to deal with threats from ballistic anti-ship missiles and the DDG-100's inability to fire and control SM-3 missiles for theater missile defense. The ballistic anti-ship missiles are thought to be a type of medium-range ballistic missile (MRBM) with homing or cruise capability. The inability of using SM-3 missiles for missile defense against new threats created a significant operational deficiency for the Navy (Axe, 2008a, 2008b; Cavas, 2008c; O'Rourke, 2006b; 2008).

These counter systems had sufficient potential in lethality and effectiveness to disrupt the DDG-1000 architecture at much less than the cost of a major weapons platform.

Boyd (1976) defined being able to circumvent the speed of action of an opponent as moving with their Observe, Orient, Decide, Act (OODA) loop (1976; Osinga, 2006). The Navy's grand strategy was disrupted by cheaper, faster innovations (Christensen, 1997) whose clockspeeds ran inside the DDG-1000 OODA loop. Progress in the development of achieving platform effectiveness had been overcome by faster external events.

At this time the circumstances and countering technologies indicate that a fire support littoral warfare platform may not be able to be effective. Survivability is a Top Level Requirement (TLR) mandated by law ("P. L. 95–485 (1978)") and implemented as a Navy doctrine ("OPNAVINST 9070.1 (1988)"). Additionally, US Army doctrine for fire support (FM 6-20-30) holds that "the first priority of the ship is self-preservation". In this case, survival of the DDG-1000 indicated it could not operate in areas defined for its mission. Until there are counters to the present threats of the ASCM and MRBM in the littoral, the Navy is working to increase its bluewater anti-ballistic missile capabilities. The resultant of this was the decision to restart the DDG-51 line to provide the Ballistic Missile capability.

5. Analysis

Impact of clockspeed on architecture project management

As stated, increasing the number of technologies in an architecture multiplies critical paths and risk. Kendrick (2003) provides a means to show this increased risk. An example of a project with two critical paths is shown in Fig. 3 (Kendrick, 2003). Assuming that critical paths ADJ and CHL each have expected durations with a 50% chance of success or failure, we can analyze their combined risk.

Kendrick shows in Fig. 4 the risk matrix for these two critical paths in conjunction. The risk of being late becomes 75% and the chance of completing early and on time becomes 25%. These number change as:

$$2^n, \quad \text{where } n = \text{number of critical paths}$$

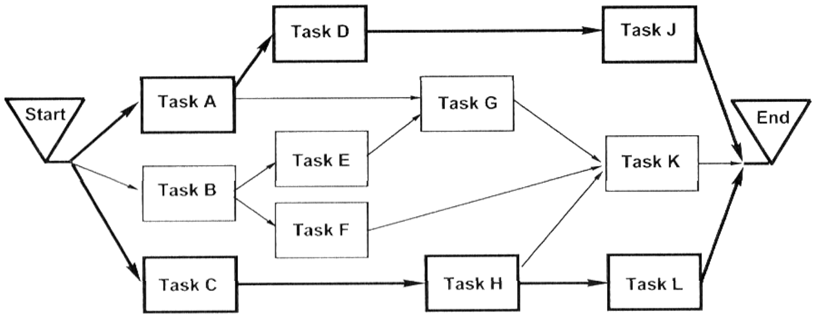


Fig. 3. Project with two critical paths (Kendrick, 2003).

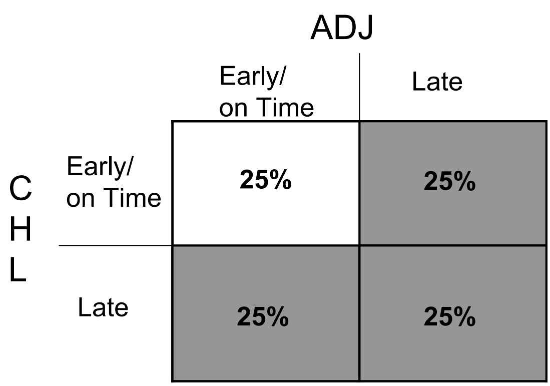


Fig. 4. Project risk matrix (Kendrick, 2003).

For instance, three critical paths would have a 12.5% chance of early/on time completion:

$$(0.5)^3 * 100\%$$

For a complex architecture, these critical paths may represent component technologies. In the case of the DDG-1000, the architecture has ten advanced technologies related to its requirements (Appendix A). A rough order of magnitude estimate of architectural risk can be made by assuming all ten technologies are of equal importance. Using this metric, the raw probability is 0.098% that all ten technologies achieve target capability on schedule. Stated otherwise, the clockspeed slows to match critical path risk.

This type of raw risk illustrates the difficulty for complex architectures to maintain relevance. Even though the future cannot be predicted, various tools and frameworks may be used in conjunction to assess relevance and manage the architecture. Providing clockspeed as an input to these can aid in planning and risk management.

Disruptive technologies

One aspect of architecture clockspeed is the rate of adoption and development. A helpful model illustrating innovation adoption is the logistics S-curve (Rogers, 1983) shown in Fig. 5. It is divided into four phases: early adoption, fast adoption, saturation (ubiquity), and decline (Gorbea *et al.*, 2008). The concept is important since lifecycle curves apply not only to architectures but also to disruptive and antagonistic forces that challenge them.

Christensen (1997) typically presents technology improvement as a linear trend while recognizing that there is an underlying lifecycle curve and that improvements are discrete events. The linear diagrams are trendlines and provide a helpful model for comparison as shown in Fig. 6. We will be following his example.

A typical Christensen model is shown in Fig. 7. The horizontal axis represents time and the vertical axis represents a particular characteristic. The following figures show two technologies, the dashed line (1) is the established one and the dotted line (2) is a new disruptive technology.

The established technology is eventually superseded in capability by the newer disruptive technology. In this example, we show a hypothetical market requirement threshold. This model is admittedly simplistic and the danger exists of comparing the incorrect parameter. In Fig. 8, the disruptive technology may never exceed the capabilities of the older technology based on the criteria selected. This does not mean it will not overcome it in the marketplace. An example of this is the competition between VHS and Betamax videotape formats. Betamax was considered technologically superior while in other areas such as cost and licensing, VHS held an advantage. Consumers accepted less cost for acceptable performance. The market decided the technical capability comparison was of marginal value compared to the economic cost.

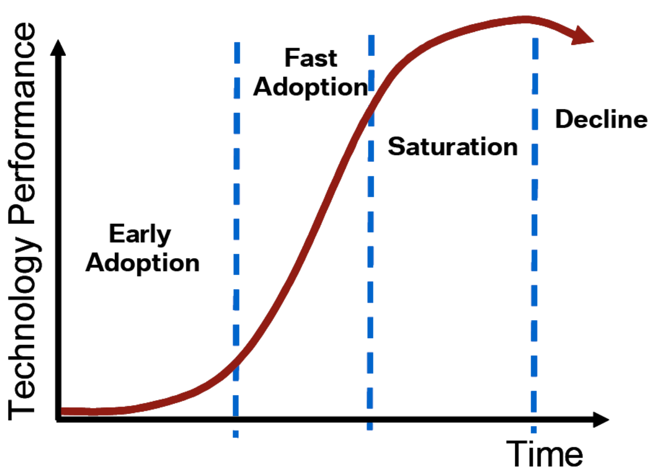


Fig. 5. Innovation lifecycle S-curve (Gorbea *et al.*, 2008).

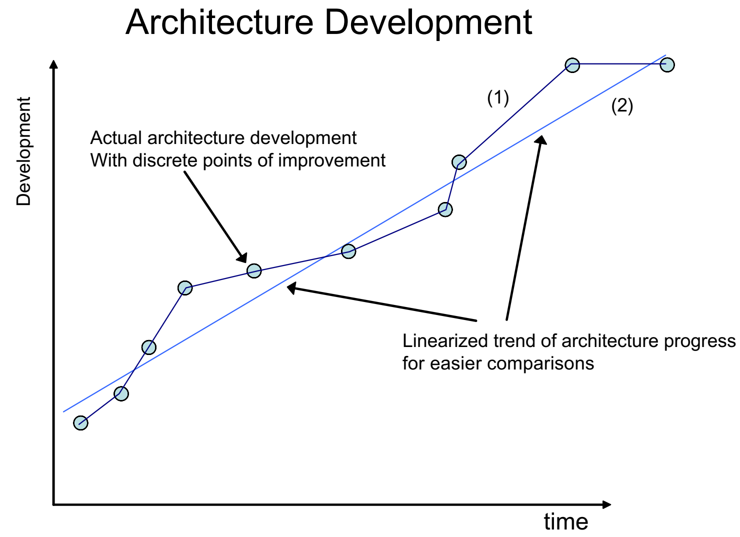


Fig. 6. Linearization of architecture development.

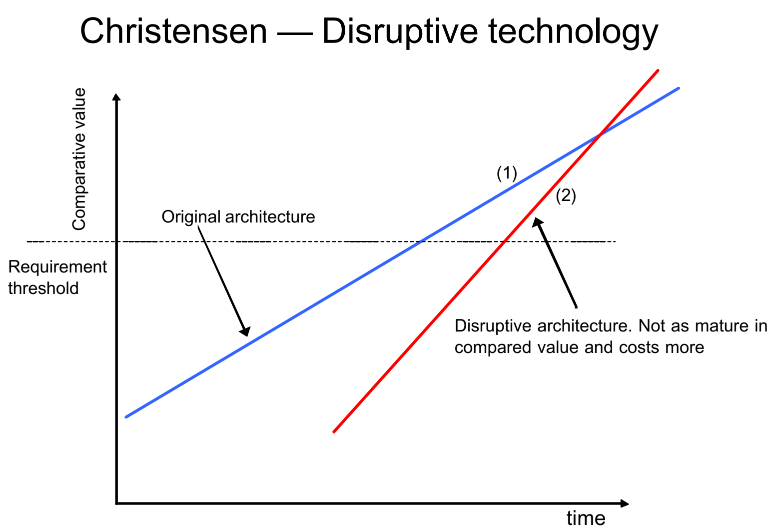


Fig. 7. Disruption in marketplace (Christensen, 1997).

Figure 9 illustrates the relative scale for a technology or architecture to have relevance in the market. There is a period between initial deployment and full market buy-in (saturation in the S-curve) where there is an architectural and hence market deficit.

From here, we will explore how this may be exploited by illustrating the effects of various disruptions. For simplicity of representation, we will show disruptions as

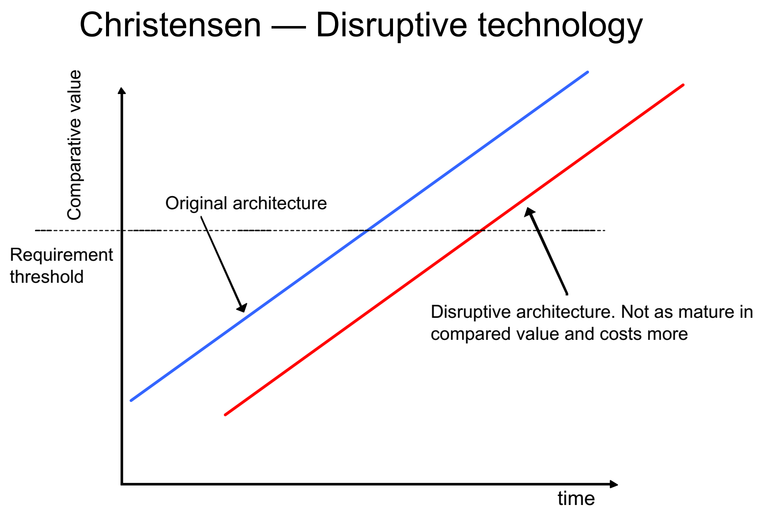


Fig. 8. Disruptive technology with lesser capabilities than original for the selected criteria.

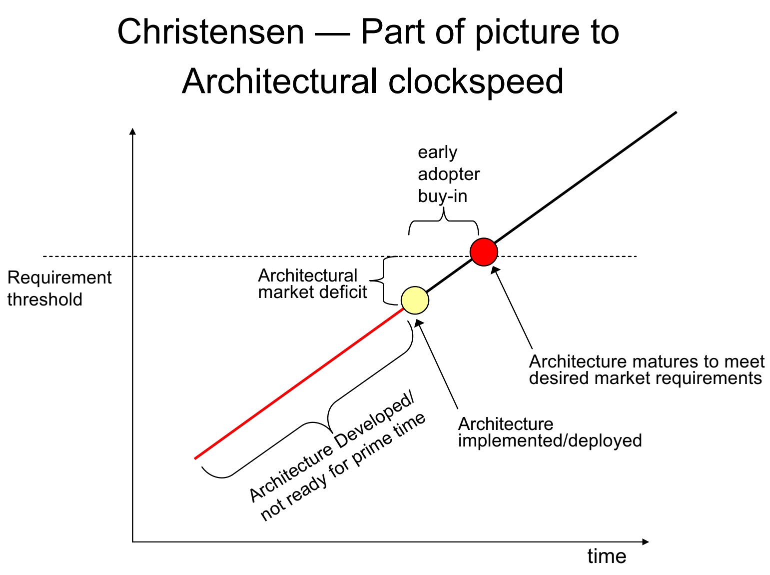


Fig. 9. Technology innovation as part of clockspeed.

instantaneous state changes. In the real world, this disruption would more likely match the S-curve. In Fig. 10, we see the effect a disruption causes to a system architecture when it occurs early in the lifecycle. The vertical axis now represents a ratio scale of one characteristic relative to another. This is effectively adding another dimension for comparing the architectures. The early disruption has the

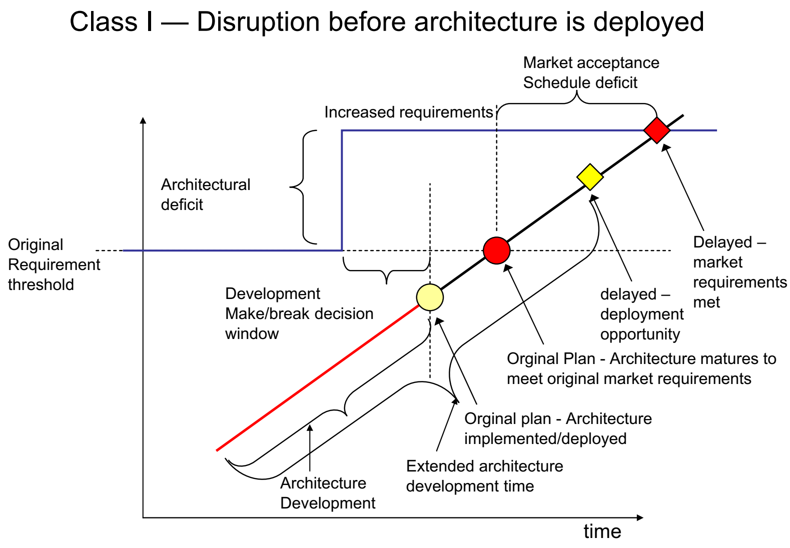


Fig. 10. Class I disruption, development window.

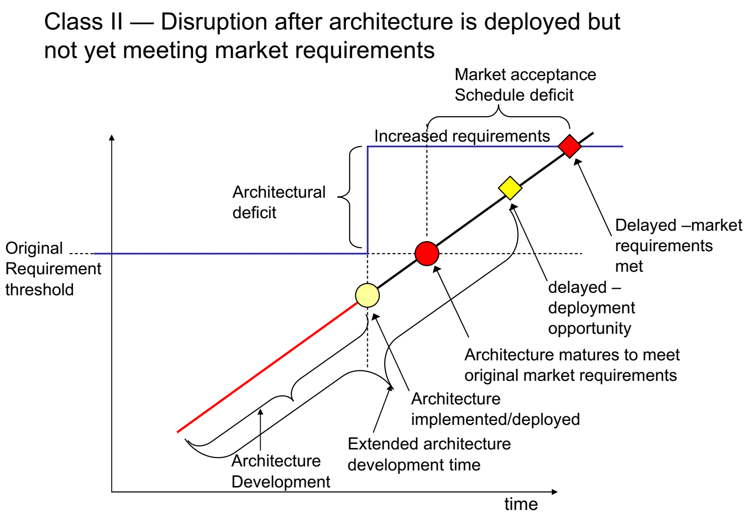


Fig. 11. Class II disruption — early market period.

effect of creating a higher capability level the architecture must reach for market acceptance. This occurs during the development period so there may be time to adapt the architecture. We have defined this as a Class I disruption.

Figure 11 is a Class II disruption. The architecture has entered the market at the time of the disruption. The recovery period is similar to a Class I. This is more serious since most of the development work has been completed.

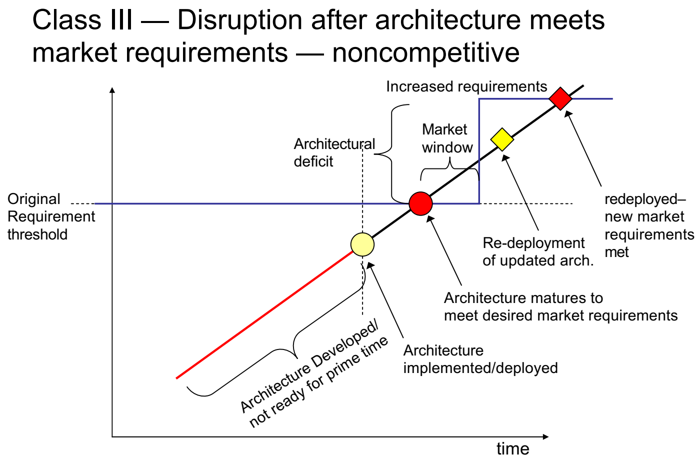


Fig. 12. Class III disruption — noncompetitive.

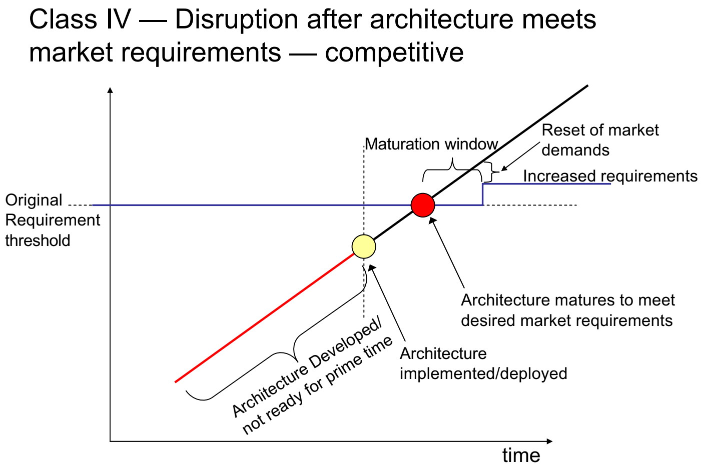


Fig. 13. Class IV disruption — competitive change.

A Class III disruption is one that occurs after the architecture is deployed and has market acceptance. The Class III disruption, shown in Fig. 12, is competitive with the established architecture, which requires an update and redeployment.

The final type of disruption, Class IV in Fig. 13, occurs when an architecture exceeds the new requirements, a disruption adds to the market. This type of disruption marginalizes architectural relevance.

These models illustrate how disruptive technology succeeds against one type of criteria. As previously shown in Fig. 9 the appropriate criteria must be analyzed to establish a context with the disruption.

These notional models show how an innovation can compete with established technology with large market share. The established technology is more capable but only along particular criteria; the innovation wins on criteria with more intrinsic value. These situations illustrate in concept the circumstances affecting an architecture and difficulty in countering a disruptive technology. The disruptive classes and examples will be useful when looking at the case of the DDG-1000 case.

Project management frameworks for managing clockspeed

Some tools and frameworks used for architecture management are: the Novelty, Complexity, Technology, and Pace (NCTP) framework (Shenhar and Dvir, 2004); System Operational Effectiveness (SOE) (Verma and Plunkett, 2000); and System Readiness Levels (SRL) (Sauser *et al.*, 2006). TRIZ methods can be used to explore means to disrupt an architecture and use the knowledge gained to increase the architecture's robustness.

The NCTP framework provides a means to evaluate and guide management of complex projects (Sauser, 2006; Shenhar and Dvir, 2004, 2007). NCTP maps out an envelope of project or architecture characteristics and maps this characterization to suggested modes of management styles. These envelopes can also be used to compare one architecture to another. Application of NCTP framing to an architecture suggests that the "Pace" element is tied to the architecture clockspeed. This will be explored further when we use NCTP to map the DDG-1000 and ASCM architectures.

SOE (Verma and Plunkett, 2000) combines several technical and logistical measures to provide a more complete view of effectiveness (Fig. 14). This provides a state of the architecture but does not provide a comparison of effectiveness to the architectural relevance. An extension to this model may provide that feature.

The obsolescence management framework (OMF) (Herald *et al.*, 2008) can be used to give insight to the obsolescence aspect of architecture relevance. As a tool it addresses the availability and process efficiency sections of the SOE model.

SRLs are a relatively new concept that measures the integration factors between individual Technical Readiness Levels (TRL) (Mankins, 1995). SRLs are the combining of weighting factors called Integrated Readiness Levels with the interrelated TRLs.

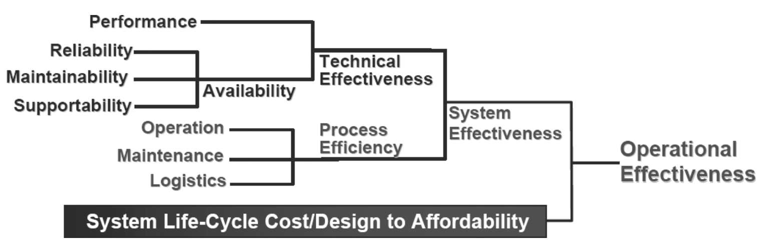


Fig. 14. System Operational Effectiveness (SOE) (Verma and Plunkett, 2000).

We suggest further work could be applied towards using these tools to assess architecture relevance for the present state.

While predicting the future is out of the bounds of any heuristic or analytical method, due to the fast divergence of solutions, TRIZ methods can be used in the form of thought experiments to "debug" architectural relevance. Architectural functionality can be treated as contradictions to the outside world. With this perspective, the systems architect can work through TRIZ inventive methods to "defeat" the architecture. That analysis can be applied to the architecture to counter the "defeat" mechanism and increase its relevance.

Dis-affecting system architecture from disruptive technologies using TRIZ

As shown, faster paces can be used to disrupt technologies that are more advanced. Being able to anticipate disruptions may allow an architecture to avoid them and maintain relevancy. However, solution sets searched via trial-and-error have two problems: they either quickly diverge and fracture into multiple paths, or, a similar tactic is tried in various ways. The second problem is like the old saying "*If your only tool is a hammer, all problems start to look like a nail*". People tend to draw on their past experiences and that can blind them to alternative solutions.

TRIZ (the theory of inventive problem solving) methodology (Altshuller, 1984; Altshuller *et al.*, 2000) is a systemized approach of invention that proposes to avoid these problems. It takes specific problems (contradictions in TRIZ jargon), generalizes them to known solution sets in order to create a specific solution from the generalized form.

The TRIZ framework shown in Fig. 15 maintains a contextual relation to the problem (Domb and Detmer, 1999). The process starts at the bottom left block and the process goes counter-clockwise.

In Fig. 16, we use the quadratic equation from algebra to illustrate a specific example (Ramos). What is not shown is the process of working through the contradiction matrix and applying the inventive principles.

A few of the tools and principles used in TRIZ are the contradiction matrix and inventive principles for technological contradictions (Appendix B), separation principles for physical contradictions, and patterns of system evolution.

There are four general separation principles for physical contradictions: separation by time; separation by space; separation of the system and its components; and separation by condition (or phase).

Altshuller proposed that constant application of invention will cause systems to evolve through distinct phases. The TRIZ patterns for systems evolution consist of the following stages or levels:

(i) Increased ideality
(ii) Stages of evolution
(iii) Non-uniform development of system elements

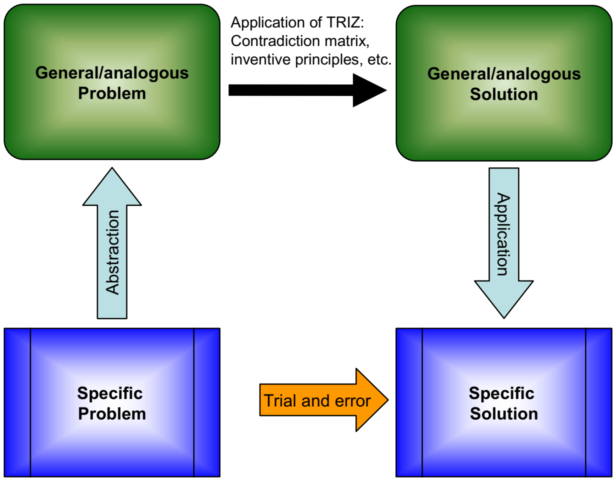


Fig. 15. TRIZ process.

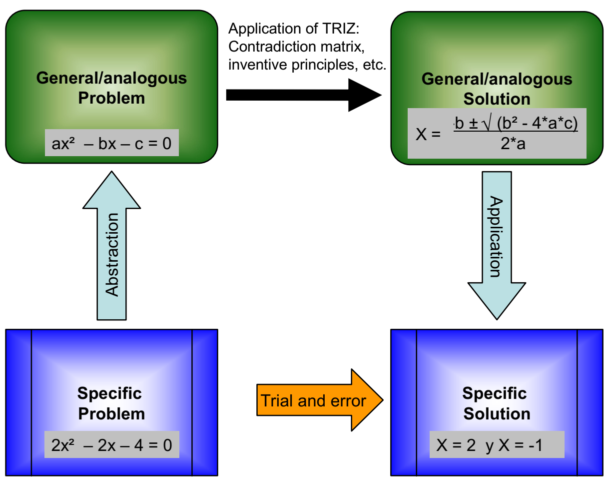


Fig. 16. TRIZ example.

(iv) Increased dynamism and controllability
(v) Increasing complexity, then simplicity
(vi) Matching and mismatching of parts
(vii) Transition to micro-level and use of fields
(viii) Decreased human interaction (increased automation)

Altshuller described the lifespan of an evolutionary pattern as a curve that happens to correspond to the Rogers' S curve. As innovation progresses, one level of evolution nears its end of capability as another starts to gain (Fig. 17).

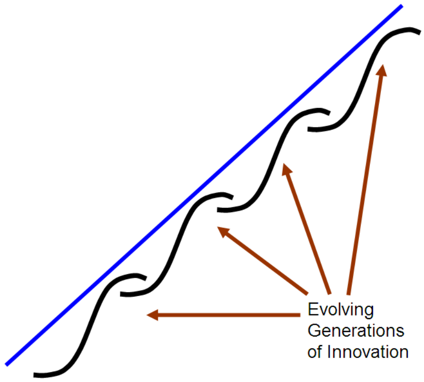


Fig. 17. TRIZ evolution progress.

Following an independent path from Fine, Christensen, and Rogers, Altshuller's TRIZ system developed concepts similar to clockspeed and architectural disruptions. An article by Michael Slocum (2009) provides more information on these patterns and progressions of system evolution.

TRIZ and DDG-1000

In addition to being a framework for inventiveness, TRIZ methodology allows past solutions to be analyzed and deconstructed. This type of examination will be used to explore and understand a disruptive threat facing DDG-1000. The contradiction matrix and the system evolution scale will be used to indicate where development should proceed to improve not necessarily the DDG-1000, but its mission which is to provide fire support for the Marines.

A Chinese puzzle

From the Chinese viewpoint, DDG-1000 as a long-range fire support platform was an unacceptable threat to national security. In the TRIZ, vernacular DDG-1000 is the contradiction to the environment. The specific problem is framed: "*How do we keep a US$3.2B warship from getting near our shores and hitting targets up to 100 miles inland*?"

The specific solution, as implied by Vice Admiral McCullough, is to implement ballistic cruise missiles. They are cheaper than US$3.2B (O'Rourke, 2008) per missile with a significant probability of high impact success (force multiplier). Additionally, operators and crews for BCMs operate remotely from the missile's point of impact. Threats to missile personnel are much less likely than threats to a ship's crew.

Looking at this from a TRIZ lens, the primary general solution is to force the contradiction (DDG-1000) away from the littoral region. This follows the generic principle of separation by space. The specific inventive principle invoked is the 2nd inventive principle of extraction and segregation. Further analysis can identify the level of system evolution in the missile system. This will help map out the development roadmap that the enterprise will follow.

Going back to the general answer, separating by space creates a boundary area that keeps adversaries at bay. This has historical antecedents in Chinese military thought from *The Three Strategies of Huang Shih-kung* (Sawyer, 1993). The use of the Great Wall and the Russian steppes as barriers to invasion over the centuries are working examples.

From an evolutionary point of view, the BCMs and LACMs represent the fourth-level of systems evolution; increased dynamism and controllability. Flexibility, agility, and the ability to precisely control the systems are the hallmarks for this level. The next level in the evolution would tend towards increased complexity that is integrated into the architecture to make its appearance seem simple.

DDG-1000 comprises numerous systems and technologies into a complex architecture. We have already shown how the integration of multiple different technologies introduces greater system clockspeed risk. This corresponds to the third-level of system evolution — non-uniform development of system elements.

The system evolution scale indicates DDG-1000 or its replacement architecture will evolve to level four and demonstrate greater agility and control of the platform. A replacement architecture will be suggested when the discontinuities in the DDG-1000 architecture create too many deficiencies when compared to newer technologies and capabilities.

The ten DDG-1000 technologies can be individually examined for their level on the system evolution scale. This is beyond the scope of this paper but is suggested for later study.

Going back to the missile conflict, the contradictions to explore are not with DDG-1000 but with the fire control and littoral support mission it supports. The missions are at risk because of the contradiction — technically and physically — that Chinese missiles pose.

Physically, littoral fire support should not be in the place and time that a missile will hit it. This may be simplistic but it may suggest that a surface ship for fire support is not feasible. Another way of looking at this is that something should be in the way of the BCMs to stop them. This line of thought leads to ballistic missile defense (BMD).

The following principles are suggested when using the TRIZ technology contradiction matrix and comparing the "*complexity of a device* (36)" with "*time of action of a moving object* (15)":

4: Asymmetry
10: Prior action
15: Dynamicity
28: Replacement of mechanical system

Asymmetry might mean to attack or neutralize the missile with another system that operates outside of its normal envelope. Prior action might not be feasible; this could be sabotage or something more technical such as the BMD program. Dynamicity could be expressed as several robot boats capable of providing littoral and fire support separate from the command ship. Replacing the mechanical system seems ill-fit to the issue but provides a direction to pursue thought experiments.

The use of TRIZ does not mean relevance will be maintained. As the development spiral is followed, there is always a chance of a discontinuity. These can also be considered black swans (Taleb, 2007).

Mapping DDG-1000 using NCTP

As initially described, NCTP (Shenhar and Dvir, 2007) maps Novelty, Complexity, Technology, and Pace in a project as orthogonal qualities based on descriptive levels along each axis. Each quality is simplistic, the closer to the chart's center and becomes more complex or involved further out on the axis. Risk and expense correspondingly increase as the described area increases. This model is generally used to provide a means to assess and select management methods suited to project characteristics.

NCTP can also be used to compare fundamental differences in projects or architectures. In this case, NTCP was used to compare the DDG-1000 architecture to that of countering (disruptive) technologies (Fig. 18). In doing this we chose to map minimal and maximum bounds to create an area effect for the architectures.

DDG-1000 is a system of systems. While many of its parts are complete systems in their own right, its infrastructure and support enterprise also extend it to an array in complexity. The technology ranges from mere high technology to new super high-tech. The compound effect of coordinating some technologies rates it as super high-tech. The novelty comes close to being a breakthrough with the combination of extended range, command and control, low observability, and innovative radar systems. At the minimum, it is a novel platform. These three factors are driven mainly as a function of design. Pace however, is defined differently.

Pace for this platform has been two-fold. As a large acquisition program it has been treated as a regular program with a schedule of development appropriate for such a large program. From a technical point of view, the pace needed to work with technology development roadmaps requires it to be able to use projected technologies. From a tactical point of view, planners realized they had a critical window to develop and deploy to meet the relevancy equation. Architects and users wanted fast and competitive pacing (if not faster) but the procurement system tended to slow down to regular pacing.

Mapping ASCMs to NCT

For the disruptive ASCMs, we see in Fig. 19 that they are a system bordering on an assembly technology that is evolving toward medium-tech. At most, it is a platform

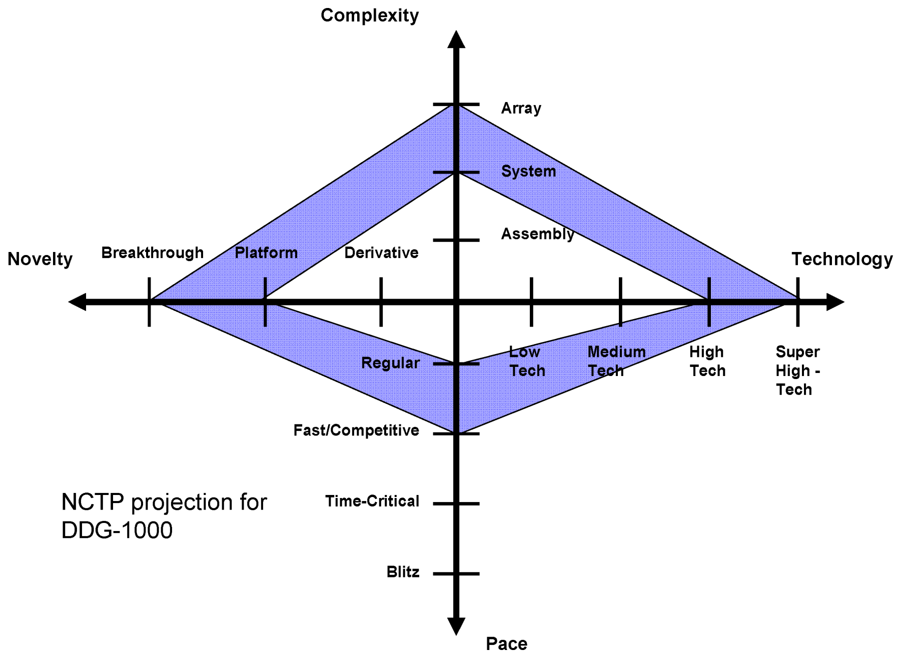


Fig. 18. NCTP profile for DDG-1000.

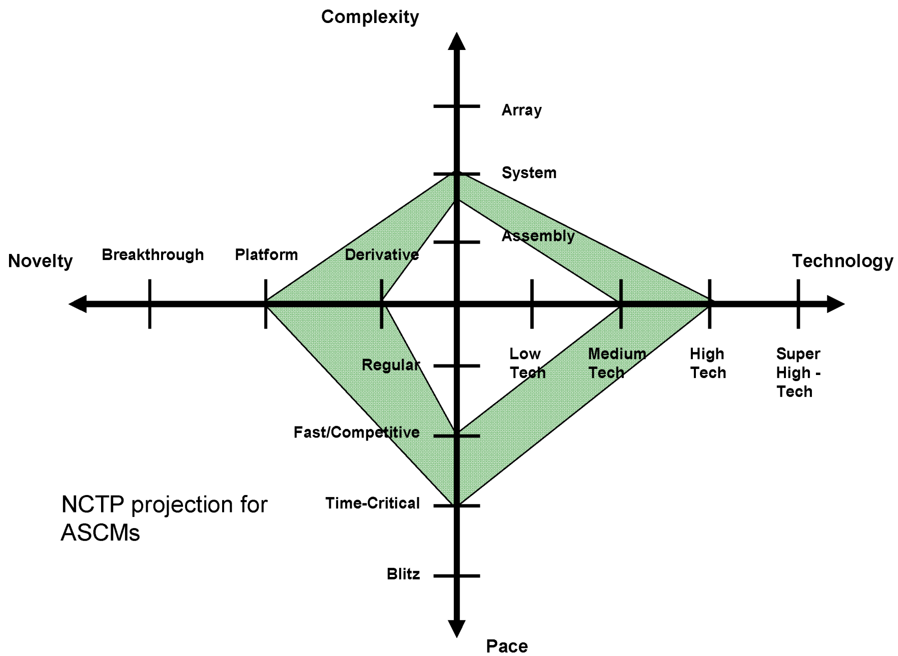


Fig. 19. NCTP profile for ASCMs.

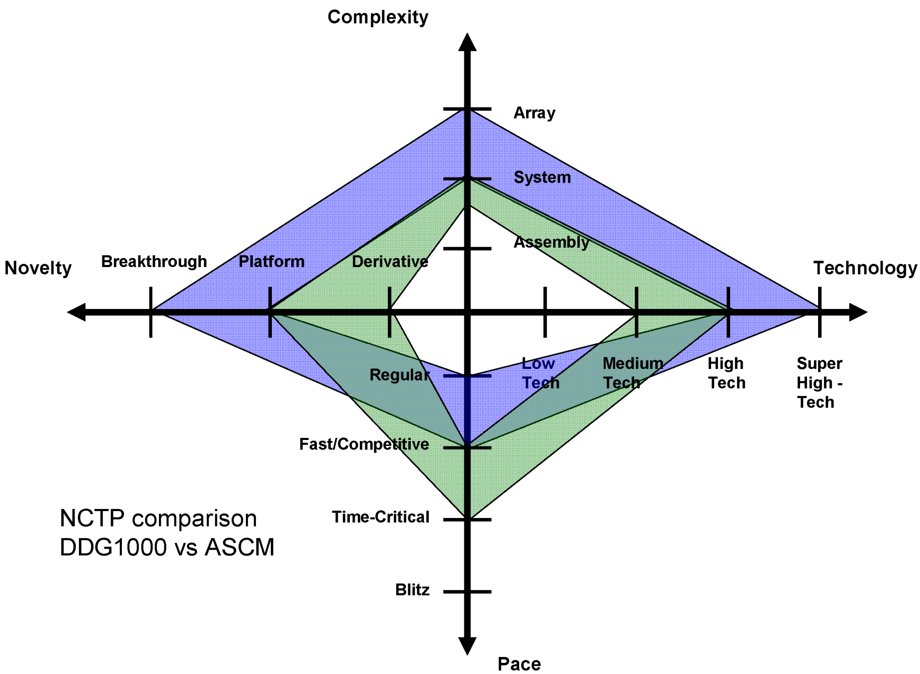


Fig. 20. DDG-1000 versus ASCM.

in novelty but is really derivative. The assumption was made that this was meant to be developed quickly for maximum impact.

The comparison between the two platforms (Fig. 20) is illustrative. The ASCM, using lower and more common technology and having greater pace pressure than the DDG-1000, is able to capitalize on providing sufficient capability sooner than the DDG-1000 can adapt.

The notional ballistic anti-ship missile profile appears as Fig. 21. This is based on speculation that the aggregate technologies exist to the point they are high-tech or slightly above that. The other supposition is that China can prioritize for accelerated development at greater than a competitive but less than a blitz pace. The NCTP overlay of the BCM compared to the DDG-1000 is shown in Fig. 22. Again, this shows the case where lesser novelty, complexity, and technology were accepted in order to achieve a higher pace/clockspeed.

6. Solutions, Implications and Recommendations

Today's DDG-1000 faces a Hydra-like beast of losing relevancy due to geography, advanced land based counter measures, schedule, and cost. The situation presented is that if a theater is too far away, there is no relevance for a littoral platform. For areas that a littoral platform would have relevance, the missile technology exists to deny operations in the littoral. These two environmental disruptions augment

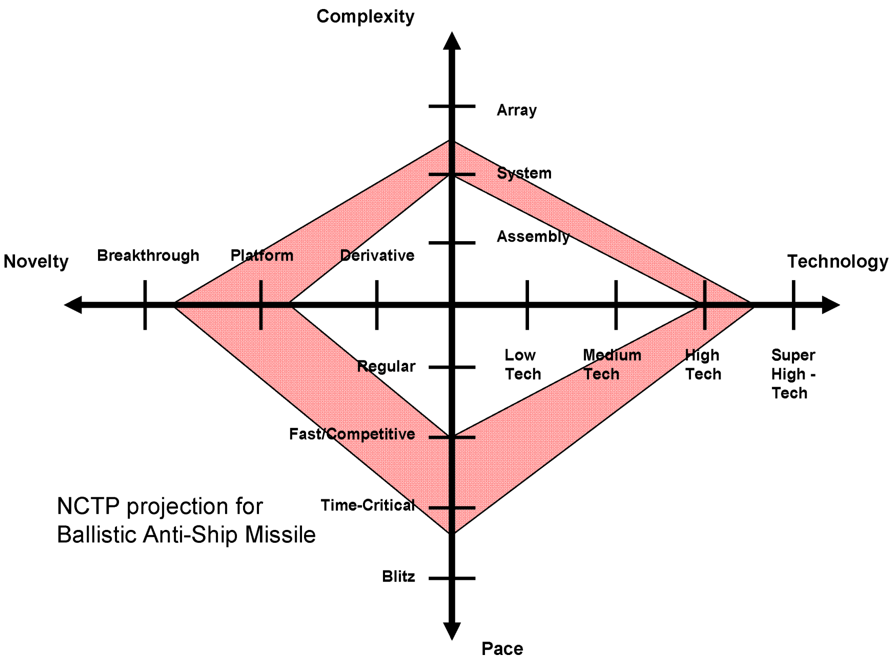


Fig. 21. NCTP for ballistic missile.

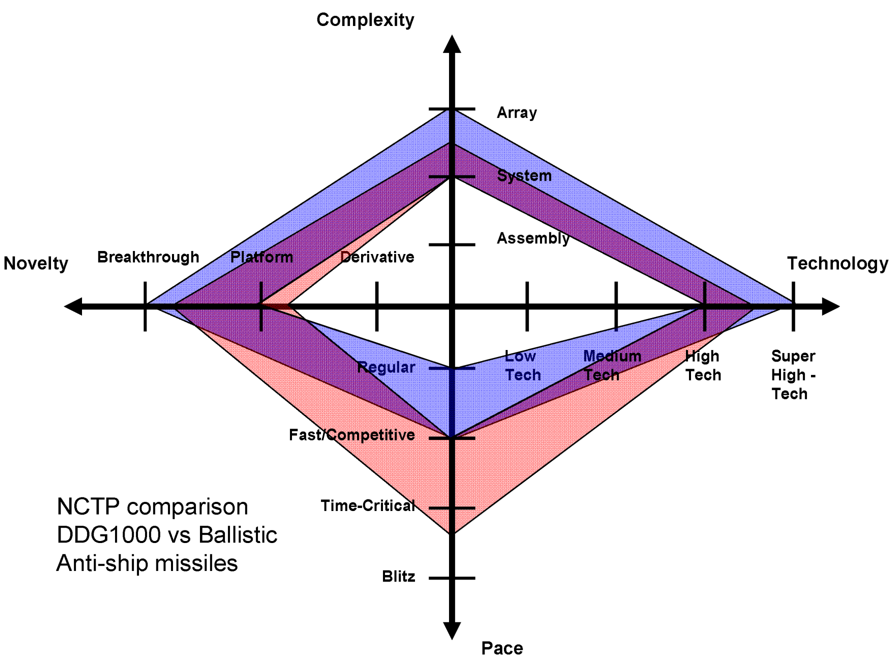


Fig. 22. DDG-1000 versus ballistic missile.

each other in diminishing relevance and effectivity of a littoral platform such as DDG-1000 with minimal air defense capability. The development extensions and increased costs have their own impact.

The issues involving the DDG-1000 ship class and its challenges were examined through the lens of clockspeeds. The long development time provided an opportunity for other architectures to introduce discontinuities to DDG-1000 and increase the risk of program failure. The dimension of time gives each architecture its own heartbeat. This requires systems engineers and architects to consider clockspeed as both a limit and a driver in the effort to maintain architectural relevance.

This case study has demonstrated the impact of clockspeed on complex system architectures. As with any other system characteristic, these clockspeeds must be understood at some level to avoid failure. Failure is generally a disruption that decreases the architecture's relevance. In the course of this paper, an ontology for the basic types of disruptions that occur during an architecture's development and life was developed.

TRIZ has been shown to have concepts and practices that help identify and manage clockspeed effects, and it is proposed that these techniques should be used as a means to "debug" architectures in order to maintain their relevance and extend their life.

Further, it was demonstrated how tools and frameworks such as SOE, SRLs, and NCTP can be expanded to consider clockspeed as an input, and that disruptive technologies and architectural discontinuities can be created and exploited by making trade-offs in the NCTP trade space along the pace dimension.

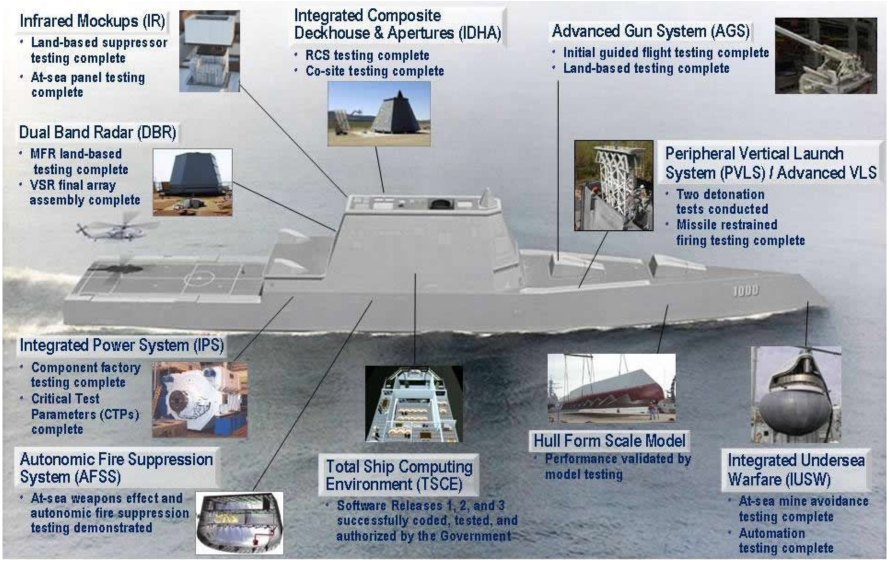
Note. An earlier version of this paper received the Stevens Institute of Technology, School of Systems and Enterprises, 2009 Excellence in Research Award for Exceptional Research and Written Work in a Master's Project.

Appendix A — The Ten Advanced Technologies to be Inserted into DDG-1000[b]

1. Integrated Power System (IPS)
2. Total Ship Computing Environment (TSCE)
3. Dual Band Radar (DBR)
4. Integrated Undersea Warfare System (IUSW)
5. Composite Deckhouse and Apertures
6. Peripheral Vertical Launching System (PVLS)
7. Advanced Gun System (AGS)
8. Wave-Piercing Tumblehome Hull
9. Infrared Mockups
10. Autonomic Fire Suppression System (AFSS)

[b]From http://www.ddg1000.com/overview/ accessed 4 January 2009.

Display of Technologies[c]



Appendix B — TRIZ Inventive Principles

1. Segmentation
2. Extraction, Separation, Removal, Segregation
3. Local Quality
4. Asymmetry
5. Combining, Integration, Merging
6. Universality, Multi-functionality
7. Nesting
8. Counterweight, Levitation
9. Preliminary anti-action, Prior counter action
10. Prior action
11. Cushion in advance, compensate before
12. Equipotentiality, remove stress
13. Inversion, The other way around
14. Spheroidality, Curvilinearity
15. Dynamicity, Optimization
16. Partial or excessive action
17. Moving to a new dimension
18. Mechanical vibration/oscillation
19. Periodic action

[c]From http://peoships.crane.navy.mil/DDG-1000/CriticalTech_hover.htm accessed 4 January 2009.

20. Continuity of a useful action
21. Rushing through
22. Convert harm into benefit, “Blessing in disguise”
23. Feedback
24. Mediator, intermediary
25. Self-service, self-organization
26. Copying
27. Cheap, disposable objects
28. Replacement of a mechanical system with “fields”
29. Pneumatics or hydraulics
30. Flexible membranes or thin film
31. Use of porous materials
32. Changing color or optical properties
33. Homogeneity
34. Rejection and regeneration, Discarding and recovering
35. Transformation of the physical and chemical states of an object, parameter change, changing properties
36. Phase transformation
37. Thermal expansion
38. Use strong oxidizers, enriched atmospheres, accelerated oxidation
39. Inert environment or atmosphere
40. Composite materials

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