NAVAL ENGINEERS JOURNAL December 2019 | Vol. 131 | No. 4

NEJ

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Republic of Korea Navy, ROKS Sejong the Great (DDG-991), center, in formation with ships from Carrier Strike Group Five (CSG 5) during exercise Invincible Spirit. Invincible Spirit is a bilateral exercise conducted with the ROKN in the waters near the Korean Peninsula, consisting of routine operations in support of maritime counter-special operating forces and integrated maritime operations.

U.S. NAVY PHOTO BY PETTY OFFICER 3RD CLASS NATHAN BURKE/RELEASED

Realizing Flexible Ships: Lessons from Allies to Improve the U.S. Shipbuilding Affordability, Capacity, and Schedule

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Abstract

Flexible and adaptive ship designs that are properly built and configured in a modular fashion save production and maintenance costs and provide rapid upgrade capability. U.S.-allied navies have adopted a modular approach to accommodate mission payloads for many currently deployed ships and future ships in development. The purpose of this paper is to present innovative concepts and practical lessons from South Korea, Japan, and Taiwan that could assist the U.S. Navy in quickly recognizing the benefits of introducing Flexible Warship design features and modular payloads into new and existing ships. These flexible features or enablers will achieve improved affordability, extend service life, increase deployment time, and expand mission capability. Our Pacific allies' ship building programs have been summarized from a global view:

- **Top Shipbuilding Tonnage Producers**
- **US Allies with Rapid Shipbuilding Capacity**
- **Destroyers in Korea and Japan using Modular Weapons Features for Production**
- **Taiwan Navy's 16 warship programs plus its Coast Guard's 169-cutter acquisitions in 2018**
- **Three Taiwan Modular Warship examples: DDG(X), FFG-Cutter, and Corvette-Cutter**
- **Larger Hull Margins Improve Ship Acquisition Affordability, Schedule, and Capability**
- **Flexible ships need Flexible Modular Combat Systems**

Traditionally, when U.S. surface ships are designed to the lowest weight and highest equipment density with little upgrade margin, they are often considered an "optimized" procurement choice. This weight-based cost model often results in expensive ships with short service lives, long deployment delays, and lack of upgradability. By building less dense ships and using modular weapons payloads, Pacific allies have chosen these characteristics for both their new ships and their purchases of older soon-to-be-decommissioned ships to significantly increase their service life after upgrades.

These three Pacific allies' approaches for evaluating flexible ship design features and building affordable ships can supplement traditional U.S. surface ship development. It is important for the U.S. Navy to plan, design, build, and operate flexible warships with an understanding of both the upfront cost of installing flexible architecture and the cost savings these features enable throughout the ship's life cycle.

Introduction

How can the U.S. Navy practically increase its annual shipbuilding tonnage? Existing U.S. DOD naval shipbuilding spending is already a significant portion of the defense budget and therefore unlikely to substantially increase. To build a greater number of ships more efficiently, it is important to study how other countries with higher ship tonnage production than the U.S. can affordably build and maintain their fleets. This paper recommends to U.S. ship designers, estimators, and builders a profitable solution that incorporates the design flexibility and the business model practices used by Japan, South Korea, and Taiwan to reduce their ship building costs.

This study primarily examines our Pacific allies' ship building production and practices. It also identifies the types and quantities of flexible features used by these countries. First to be examined is their approaches to building large surface ships for their navies. It will be followed by a more detailed study of Taiwan's Navy and Coast Guard investing heavily in modular ship construction, flexible features, modular payloads, and modular Combat Management Systems (CMS) across all ship classes. Finally, Taiwan's business practices for bringing a ship from design through construction will be compared with their initial cost estimates to see how well they were able to forecast

[1] Abbott On Call, Inc.

their costs and construction schedules. At the end, the lessons learned from our Pacific allies will be summarized and suggested for U.S. naval implementation.

Global Shipbuilding Tonnage Ranking

Many countries are known for using flexible architecture enablers and modular payloads in their ship designs. Table 1 provides a list of the top shipbuilding countries that produce commercial ships and warships.[1] Their lessons learned will provide insight on the true cost savings potential of using flexible features, payload modules, and technologies on U.S. Navy surface ships.

During World War II, the United States had to increase warship building tonnage output tenfold by converting some commercial shipyards into naval shipyards.[2] During a major naval conflict mobilization, naval ships would be mass produced at converted commercial shipyards. Under these circumstances, other countries with greater existing commercial and naval shipbuilding infrastructure will have the capability to produce warships more rapidly than the U.S. in times of conflict. The total 2015-2017 warship building displacement for China was approximately 370,000 tons while the U.S. was around 175,000 tons, see Table 2.[3] In 2019, China is estimated to build around three times more warships in terms of displacement compared to the U.S. How can the U.S. prepare to practically meet the challenges of naval readiness?

Several of the countries listed in Table 1, namely Philippines, Romania, Brazil, and Vietnam do not build or operate large destroyers over 7,000 tons in size. Therefore, these countries are not included in the next comparison. Table 3 was created to compare the top seven countries that produced large quantities of modern high-quality large warships in 2018. The U.S. is currently ranked No. 7 in terms of Annual Gross Tonnage. There are several valuable lessons that the U.S. Navy can learn from these Peer-Competitors especially regarding Flexible Design enablers.

Historical World War II experience shows that a country's total potential warship building capacity during a conflict can be estimated by converting approximately 20% of the country's annual general shipbuilding's gross tonnage within two years. The manpower for shipbuilders comes from the country's population, but it would take years of professional training and logistical infrastructure development to build modern warships unless a country already generally builds a lot of ships. This table also compares several economic data points for these countries. The Foreign Exchange (FX) reserve means immediate cash funding that can be used to import foreign warships and combat systems to fill in the development gap and production lag. One question that is often asked is, "How does a U.S. worker's income compare to the incomes of workers from these other countries?" to see if that is a major factor in ship building costs between countries. By comparing countries' Gross Domestic Product (GDP), the total economic power of a country, with Purchasing Power Parity (PPP) per capita means the adjusted annual income of an averaged citizen can be calculated. We see that an American worker's adjusted income is not that much higher than other countries except China.

Looking at Table 3, the second through sixth ranking countries (Republic of Korea, Japan, Taiwan, Germany, and Italy) are U.S. allies who seek a strong U.S. Navy to maintain a stable peaceful world situation. The shipbuilding industry is impacted by economic cycles and governments' reactions to those cycles. There is also the challenge for the shipyards to keep production levels constant for maintaining a strong pool of talent and making a profit. The U.S. Navy and the American shipbuilding industries can learn valuable lessons from other countries especially the three Pacific allies.

Ranking	Country	Annual Shipbuilding Gross Tonnage (GT), Avg. 2014-2017
	Total Economies	66.0 M
1	China	23.5 M
2	South Korea	23.4 M
3	Japan	13.1 M
4	Philippines	1.71 M
5	Taiwan	0.579 M
6	Romania	0.543 M
7	Germany	0.445 M
8	Italy	0.353 M
9	Vietnam	0.422 M
10	Brazil	0.297 M
11	United States	0.285 M

TABLE 1. World General Shipbuilding Tonnage Ranking.

*Calculated by Jang from UNCTAD Data

Total Annual Warship Full-load Displacement Tonnage Produced	CHN	USA
2009-2011 (three years)	130,000t	140,000t
2012-2014 (three years)	245,000t	246,000t
2015-2017 (three years)	370,000t	175,000t
2018-2020 (three years) [estimated]	600,000t	200,000t
Total Shipbuilding Gross Tonnage 2015-2017	70,500,000	855,000
Annual Warship/Overall Production Tonnage Ratio 2017	.005 [low]	.205 [high]

TABLE 2. Warship Construction Rate Comparison.

*Compiled from Childs 2018

Country	Annual Gross Tonnage	Population	FX Reserve (US$)	Avg. Adj. Worker Annual Salary (US$)	Mi. Budget (US$)	Mil $ % of GDP
1 CHN	23.5M	1,415M	3.08T	16,624	216B	1.90%
2 KOR	23.4M	51M	0.40T	41,388	34B	2.70%
3 JPN	13.2M	127M	1.26T	44,426	48B	0.90%
4 TWN	0.58M	23M	0.46T	52,305	11B	2.16%
5 DEU	0.45M	82M	0.20T	52,801	44B	1.20%
6 ITA	0.35M	59M	0.12T	40,030	24B	1.52%
7 USA	0.29M	326M	0.12T	62,152	626B	3.10%

TABLE 3. Data on the Top Shipbuilding Countries Producing Large Modern Warships.

*Compiled based on Wikipedia and 2018 UNCTAD info

Comparison Of International Large Surface Combatants

Three major U.S. allies in Asia Pacific are developing new Large Destroyers similar in complexity to the future U.S. Navy Large Surface Combatant (LSC) program. Examining how these programs develop and progress through construction may provide lessons that might be applied to achieve better cost, schedule, and performance on the LSC program.

Aegis Destroyers of South Korea and Japan

For South Korea and Japan, the focus of this section is on their Large Surface Combatants. This study looks at large destroyers from these countries' Aegis DDG programs since their ships have nearly identical combat systems as those on U.S. Navy ships. These larger ships were more spacious and more affordable to design, build, operate, and upgrade than the densely-packed U.S. DDG-51 class Aegis destroyers. The reader can compare their acquisition contracted costs listed on public websites to the costs of recent U.S. Navy destroyer contracts listed in the annual Congressional Research Report.[4] Their larger size, lower volumetric density, and better growth margins permitted faster construction times, lower construction costs, and affordable life-cycle costs even with small production quantities.

Destroyers of South Korea

The biggest ship construction company in the world will be the newly merged Hyundai-Daewoo in South Korea as of early 2019, of which occupies approximate 20% of global general shipbuilding tonnage. Warship construction tonnage occupies a relatively small percentage of the overall shipbuilding tonnage in this country. The Korean Navy has been operating and incrementally building surface combatants for decades. Its KDX-III class Aegis destroyer shown in Figure 1 is the expanded versions of the U.S. Navy DDG-51 class. However, the design of the KDX-III Batch I destroyer has a far larger hull with 2000 more tons of full load displacement than the U.S. Navy DDG-51 Flight IIA ships. The Korean Aegis destroyer has more missile launchers, weapon type selections, payload growth margins, and reserved stability when compared to the original U.S. version.

The updated version KDX-III Batch II shown in Figure 1 will provide many future options such as laser point defense weapons and long-range land-attack missiles. In addition to its larger size, it has more automation thereby reducing the planned crew size from 400 in Batch I to 200 in Batch II. Three KDX-III Batch II hulls are currently under construction after receiving positive feedback on three KDX-III Batch I sister hulls from its operators. Delegations of the Korean Navy and shipbuilders are frequently seen in maritime conferences and exhibitions in the United States to learn and incorporate the latest warship technologies especially flexibility and modularity features into the future Korean warships.

Destroyers of Japan

As the third biggest ship construction country in the world, warship construction occupies a tiny percentage of the overall shipbuilding tonnage in Japan. The Japanese Maritime Self-Defense Force (JMSDF) has inherited the tradition of the Imperial Japanese Navy in operating and building capable surface combatants. The Kongo Class Batch I destroyer shown in Figure 2 is similar to the DDG 51 Flight II. It is an expanded variant of the Aegis destroyer class with a larger hull incorporating increased ceiling clearances between decks to allow installation growth margins for distributive systems. It has added a Fleet Command center with additional staff accommodations. JSDMF and Mitsubishi Heavy Industries had revised the U.S. original designs to make them more efficient to construct and operate, e.g. using popular and affordable Metric-based steel materials and replacing certain U.S. subsystems with Japanese-produced modules.

The enlarged Kongo class Batch III is called the Maya class. Its lead ship, Maya, was launched in August 2018 and will enter service in 2020. As shown in Figure 2, it adds a helicopter hangar and is larger than the comparable US DDG-51 Flight

Image: Wikipedia.org — Image: Navy Recognition

Current: KDX-III Class Batch I	Future: KDX-III Class Batch II
"US Navy DDG-51 Flight IIA is 9,200t full load (1997-2024) in comparison;" $1.8B in 2011 Wikipedia	**"US Navy DDG-51 Flight III is 9,600t full load (2018) in comparison;" $1.8B in 2018, Expected to enter Service in 2023** CRS
KDX-III Batch I is: • Longer, less dense, 2,000 tons heavier • Launch SM-2; with 32 additional VLS • Compatible with Aegis DDG capability • Unit cost at US$923M in 2010 Wikipedia	KDX-III Batch II is: • Larger by approximately 2,000 tons • Automation for a crew size to 200 • Launch SM-3 BMD; with 32 additional VLS • Adds directed energy weapons option • Compatible with latest Aegis DDG capability • Unit cost at US$1.1B in 2019; Expected delivery starts in 2023 DAPA

FIGURE 1. Korean Aegis Destroyer Programs

Image: Wikipedia.org — Image: Navy Recognition

Current: Kongo Class Batch I	New: Maya Class Batch III
"US Navy DDG-51 Flight II is 8,400t full load, (1995-1999) in comparison" Wikipedia	**US Navy DDG-51 Flight IIA is 9,200t full load, (1997-2024) in comparison;" $1.8B in 2011** CRS
Kongo class is: • Larger, less dense, 1,000 tons heavier • Higher ceiling clearances to install more distributive systems • Added Fleet Flagship Command Facilities • Compatible with Aegis DDG capability • Unit cost at US$1.12B in 1993	Maya class is: • Larger, adds helicopter hanger versus Kongo class, 1,250 tons heavier • Adds directed energy weapons option • Compatible with latest Aegis DDG capability • Unit cost at US$1.5B in 2018. Expected to enter service in 2020.

FIGURE 2. Japanese Aegis Destroyer Programs

IIA. It is designed to fit future weapons such as laser point defense system modules and a modular gun station that can fit a railgun as described in its initial 2015 planning. Until the first U.S. DDG-51 Flight III and Korean KDX-III Batch II destroyers enter service around 2023, the Maya class will possibly be the most powerful Aegis destroyer variant in service.

Modular Destroyers of Taiwan

As one of the top five biggest shipbuilding countries, warship construction occupies a rather small percentage of the overall shipbuilding tonnage in Taiwan. In order to build up their navy, the Taiwanese decided to purchase and modify recently retired U.S. warships at a bargain price. The Taiwan Navy currently operates four 9,800-ton DDG-993 Kidd class destroyers and (22) 4,000-ton frigates. Taiwan's Navy started to operate destroyers in 1970 by using former U.S. Navy Gearing-class destroyers. They later purchased four former U.S. DDG-993 Kidd class destroyers that had been decommissioned early in the 1990s. These ships were purchased by Taiwan for $183M per hull in the 2000s, see Figure 3. These ships had a large hull volume and lower equipment density which allowed adequate displacement growth margins.

Current: Keelung DDG-1801 Class (former US Kidd DD-993, 9,800t)	Future: TW DDG(X) Class (est. up to 16,000t full load)
"US Navy DDG-51 Flight IIA is 9,200t full load, (1997-2024) in comparison;" $1.8B in 2011 Wikipedia	**"US Navy DDG-1000 is 14,800t full load, (2018) in comparison;" $7.4B in 2010 (including R&D); Still under testing in 2019** CRS
Keelung Class is: • Larger displacement by 600 tons • Same hull size as U.S. CG-52 cruisers • Lower density interiors to allow HM&E growth • Added indigenous combat systems and weapons with constant updates • Secondhand ship unit cost was $183M including upgrades in 2005	TW DDG(X) is: • Mk41 or equivalent VLS for TK3 BMD missiles • HF-2E & HF-3 supersonic cruise missiles • Two modular radar systems • Taiwan's non-Aegis Modular Combat System • Adds directed energy weapons • Unit price and schedule are not openly published

FIGURE 3. Taiwanese Aegis-equivalent Destroyer Programs

By incrementally replacing or upgrading the original U.S. components with their domestic parts using component modularity concepts to modernize old equipment, adding domestic weapon systems to enhance firepower, and implementing the Taiwanese-developed Open Architecture (OA) Modular Combat Management System (CMS) to incorporate Command, Control, Communication, Computers, Collaboration, and Intelligence (C5I) and Network-centric Cooperative Engagement Capability (CEC), their warship service life was extended for another 20 years or more. Through integrating different ship systems from Taiwan, the U.S., and other countries, Taiwan became proficient at upgrading ships using component modularity and its domestic "Modular Combat System" which will be described later in this paper. The outward appearance of the vessels and systems may seem similar to the original, but their internal subsystems have been replaced with domestic components with newer functions.

In 2016, Taiwan had decided to develop a new generation of the large destroyers to replace its existing 9,800-ton DDG-993 Ex-Kidd class destroyers. The new Taiwanese ship, tentatively called the DDG(X) design, is being developed with limited information released to the public. A concept model is shown in Figure 3. Its 16,000-ton size estimate is based on open source materials, public-released conceptual figures, and its cost-displacement trend. From two recent examples, new Taiwanese Navy heavy frigates were initially described as 4,000-ton displacement ships in 2016. The full displacement has since been revised to more than 6,200 tons in late 2018. A similar pattern occurred with their 10,000-ton class Landing Platform Dock (LPD) design in 2016 as shown in Figure 4. The contracted full displacement size was increased to 16,000 tons as of late 2018. In addition, the scheduled times of entering service for first two 16,000-ton LPD vessels have been accelerated to 2021.

Shipyard production tonnage values in China, Korea, and Japan are an order of magnitude larger in comparison to the current U.S. shipyard production levels, as shown in Table 2. The next three ranking countries that operate and produce large surface combatants are Taiwan, Germany, and Italy. For the United States to consider catching up, the U.S. needs to find a suitable pattern with a similar production scale to imitate initially. Since the flexible warships of Germany and Italy were already extensively described in our 2015 ASNE Day paper,[5] these two countries will not be described further by this paper. This search leads to a more in-depth study of Taiwan, a country that is already in the process of mass producing modern warships.

Building A Flexible Fleet By Modularity—Taiwan

This section describes how Taiwan applies flexibility, Open Systems Architecture (OSA), and modularity to design, build, operate, and upgrade their naval fleet.

Background on the Reasons Taiwan Uses Modularity

Taiwan, also known as the Republic of China (ROC), is an island of nearly 24 million people with a strategic importance in its location, economy, and geopolitics. Taiwan is a small democratic country that is roughly the size of the state of Maryland. It is located by the southeastern Chinese coast with a disputed maritime border of roughly 1,950 km with China,

Image: Wikipedia.org

Image: NCSIST.org.tw

Current: Hsu Hai LSD-193 (ex- US Pensacola LSD-38, 14,200t full load)	Future: Newbuild TW LPD Class (16,000t full load)
"US Navy LPD-17 Class is 25,300t full load, (2000-2019) in comparison;" $1.6B in 2012 Wikipedia	**"US Navy LPD-17 Class is 25,300t full load, (2000-2019) in comparison;" $1.6B in 2012** Wikipedia
• TW LSD: Large displacement margin: allowed life cycle growth • Added more indigenous combat systems and weapons • Paid $6.3M for 1 used ship in Dec 1998 FAS	• TW LPD has a 76mm gun, ASW MH-60, modular medium-range AAW & SUW missiles • Unit cost at $78M excluding combat systems in 2018. First 2 ships are expected to enter service in 2021 within 30 months

FIGURE 4. Taiwanese Landing Transport Dock Programs

similar in length to the U.S.-Mexico border (1954 km). Taiwan is surrounded by the Taiwan Strait on its west, the East China Sea on the north, the South China Sea on the south, and the Western Pacific on its east. Although Taiwan has never been governed by the Chinese Communist Party (CCP) of the People's Republic of China (PRC), the Beijing-based CCP has threatened Taiwan to be reunified with PRC under peaceful surrender or by force since 1949, which is the year that the CCP took control of the mainland China.

Internationally, most nations cut off diplomatic relationships with Taiwan due to Chinese pressure. Until summer 2019, most countries have not been willing to import and export complete defense platforms and weapon systems with Taiwan since the 1970s. Taiwan's surface warships consist of decommissioned U.S. Navy ships, unarmed international warship hulls with Taiwanese-installed combat systems, and domestically built warships. The conventional culture of operating a costly modern navy had to be challenged, modified, and improved in order to afford operating a capable fleet. Old ships had to be repaired and upgraded to extend their service life, and eventually replaced. New ships needed to be designed and built within budget, accelerated schedules, and limited resources. As a result, the creative Taiwanese Navy was forced to apply naval flexibility, modularity, and Open Systems Architecture (OSA) from components to subsystems. Their naval platforms even share combat management systems (CMS) with all armed service branches to save costs in time, training, logistics, and technological development. More Taiwanese modular fleet details will be described in the following sections.

Affordable Cost for Sixteen New Warship Programs—Taiwan Navy

Taiwan has around 47,000 active professional naval personnel including 9,000 marines. Its fleet operates 4 destroyers, 22 frigates, 4 submarines, 1 corvette, 12 patrol ships, and 30 missile boats. In 2016, Taiwan decided to build a new generation of their fleet to meet its urgent security needs. The estimated total budget for most of these new ship programs was around US$17B in 2016. Most shipbuilding bids would be based on fixed price contracts, tough performance tests, and accelerated schedules. By compiling the open source data, there are 16 new warship programs ongoing as of late 2018 as shown in Figure 5.[6] Over 100 navy vessels are under shipbuilding contracts as of January 2019. The new shipbuilding program will add a minimum of 4 destroyers, 10 heavy frigates, 2 helicopter carriers (LHD)s, 8 submarines, 4 LPDs, 12 corvettes, and 60 missile boats to the existing fleet before 2039. Taiwanese shipyards usually deliver warships ahead of the original schedule. Most of its existing major warships will also be upgraded to extend their useful service life to at least 40 years. Most of these ships are fitted with Taiwan-developed modular weapons such as Sky Bow TK-3 a 100km-ceiling Ballistic Defense Missile (BMD) Surface-to-Air Missiles (SAM), Brave Wind HF-2E 600km-range land attack cruise missiles (LACM), and Brave Wind HF-3 400km-range Mach-3.2 supersonic anti-ship cruise missiles (ASCM).

Furthermore, the Taiwan Coast Guard (TCG) has announced a total of 141 new cutter vessels in September 2018 with an additional 28 Search and Rescue boats ordered in July 2018 to be entering service before 2027 as shown in Figure 6.[6]

FIGURE 5. Taiwan Navy New Warship Programs in 2018 (entering service before 2039)

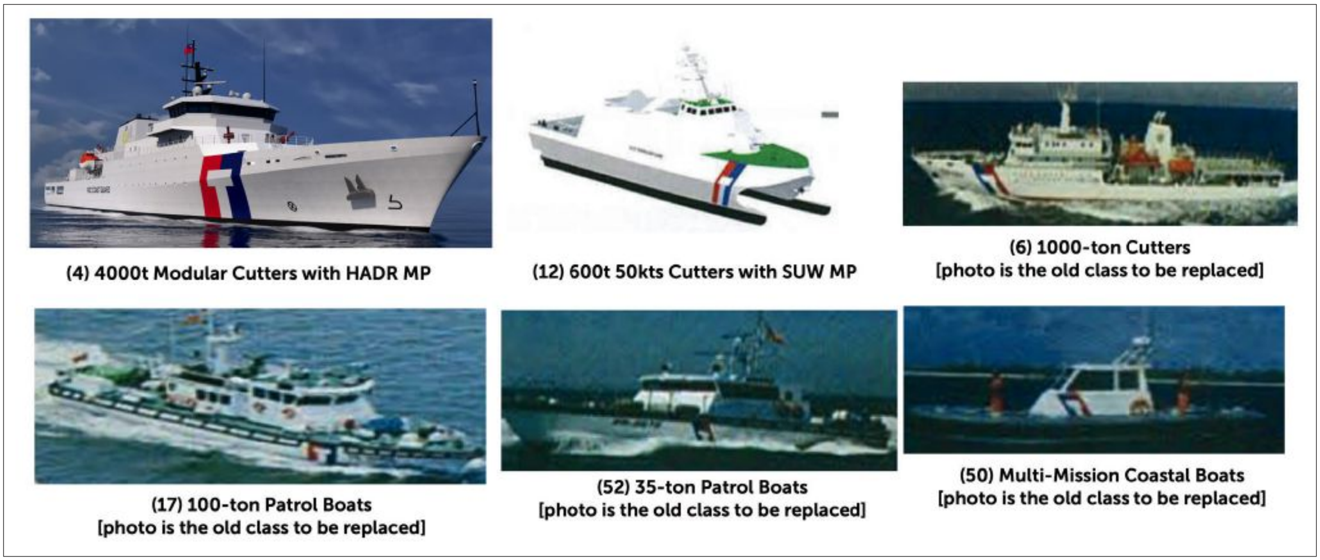

FIGURE 6. Taiwan Coast Guard New Cutter Programs 2018-2027 (Compiled by AOC, Inc,).

Several new Taiwan Coast Guard vessels are fitted with pre-installed distributed wiring and piping systems in their modular zones that enable them to be fitted with modular Surface Warfare mission packages including C5I sensors and cruise missiles within a couple of days.[7]

A Lower Density Ship Provides More Flexibility and Affordability—Taiwan CG

Since the 1990s, the U.S. Navy generally presented weight-based Ship Work Breakdown System (SWBS) cost estimates derived from decades of domestic naval surface shipbuilding

Year Lead Ship Entering Service	Ship Class Name	Initial RFP—estimated size (tons)	Yard As-built Displacement Full Load (tons)	Price excluded NCSIST-provided combat systems and weapons
2001, 2005	CG-116 Taipei (2ea)	500	742	
2001	CG-117 Taichung (4ea)	600	827	
2008	CG-123 Kinmen (2ea)	500	688	
2011	CG-126 Tainan (1ea)	2,000	2,105	
2011, 2013	Hsun-Hu No. 7 (3ea)	1,000	1,915	
2013	CG-127 Xinbei (1ea)	2,000	2,077	
2014	CG-128 Yilan (2ea)	3,000	3,719	US$86M each
2015	CG-131 Miaoli (4ea)	1,000	1,899	
2017	RV Legend (1ea)	2,000	2,581	US$28M each
2019	Fast Missile Boat (60ea)	50	80	US$20M each
2020	100-t Patrol Boat (15ea)	100	Ext. >140	US$6M each
2020	Corvette-Cutter (12ea)	600	750	US$39M each
2020	Frigate-Cutter (4ea)	4,000	5,000	US$98M each
2021	LPD-Cutter (2ea)	10,000	16,000	US$78M each
2022?	100-t Patrol Boat (17ea)	100	Ext. >140	

TABLE 4. Taiwan CG Cutter RFP-Estimated vs. Yard-delivered Displacements, 2000-2018.

*TCG was founded in 2000; Compiled by Jang from open source documents, e.g. Wikipedia

data for surface ships. These estimates are proportional to the weight of the ship systems regardless of design maturity and construction steps. For example, while C5I and Armament systems are relatively low-weight (11% of ship weight), they account for 50% of the total ship cost. Comparatively, steel occupies 50% of the ship weight and accounts for only 8% of the ship cost.[8] This weight-based approach results in a dense ship that is expensive to build, operate, and upgrade. Therefore, the current U.S. weight-based cost estimate system faces challenges in estimating flexibility costs and savings.[9]

Throughout the past years, the U.S. naval engineers and cost estimators have been trying to prove that a slightly larger Flexible Warship with lower density can be more efficient to design, build, and operate.[10] Japan, Korea, and Taiwan destroyer programs have proven that the theory is achievable. Table 4 provides the data from a study that looked at almost 20 years of TCG Cutter acquisition programs since its founding in 2000. When acquiring a new ship, the TCG would release a request for proposal (RFP) specification to multiple shipyards detailing the requirements of the ship they wanted to build. The RFP would include capability and expected ship displacement. In every case, the winning shipyard's as-built displacement was larger than originally expected and they were able to furnish the TCG with a fixed price contract. The shipyards were always able to successfully deliver these fixed price ships. This leads to the conclusion that a larger ship with lower density is easier to design, predict construction costs, and build within budget than a densely designed ship with an arbitrary displacement limit.

A ship with a lower density and a slightly larger design margins usually serves longer and can be more survivable during peacetime and wartime. For example, ramming or grounding are popular naval tactics among ships especially in the age of cyberattacks. When this occurs to a densely equipped warship, it does not have enough reserve buoyancy to handle the situation. A small hull damaging incident may cause the loss of the entire vessel with the many lives aboard. Incorporating a few more tons of steel structure to make the hull would make the ship less dense, and therefore would provide a low cost safety insurance policy for a billion-dollar warship.

Mission Flexibility by Modularity—TCG Patrol Frigate

The Taiwan Coast Guard needs four large long-range cutters with built-in hospital facilities with convertible flexible mission compartments that can accommodate additional in-patient beds for humanitarian assistance and disaster relief (HADR), see Figure 7.[6] Due to Taiwan's lack of official diplomatic recognition, it is less politically sensitive for TCG cutters to visit international ports than its Navy ships. These cutters are also able to protect Taiwan's large commercial ocean-going fleet operating in the East and South China Seas, Pacific Ocean and beyond. Since this is a coast guard ship design, it does not carry missiles during peacetime. During wartime, these frigate-sized cutters with flexible mission compartments may be able to carry out HADR missions in addition to Fleet Command, C5ISR, and Search-And-Rescue duties in the Western Pacific.

Image: TaipeiTimes.com

Image: Janes.com

New TCG 4,000t Patrol Cutter (est. 5,000t full load):

"USCGC WMSL-750 is 4,600t full load (2005–2019) in comparison;" $735M in 2013

TCG Cutter has:

- Built-in hospital facilities and MH-60 helicopter hanger
- Large flexible compartments can be converted into additional hospital beds; these *modular spaces* can also be used for other TBD missions
- Open Architecture (OA) with pre-installed SWAP-C with some sort of Flexible Infrastructure (FI) to allow rapid medical package installations
- Unit cost at $98M in the July 2018 fixed-price contract. 4 new ships ordered.
- Lead ship will be launched in 18 months before 1/2020

Modular law enforcement and hospital packages allow flexibility to visit international ports

FIGURE 7. Taiwan Coast Guard 4000-ton Modular Patrol Cutter with Medical Facilities and Anti-Ship Missile Mission Package.

Reconfigurable mission modularity is applied in the form of the various Mission Packages. The vessel is designed with large Size, Weight, Access, Power & Cooling (SWAP-C) margins and pre-installed Hull, Mechanical and Electrical (HM&E) distributed systems to allow adequate life cycle growth. A different mission package can be installed within a couple of days. The ship is equipped with an Open Architecture (OA) Combat Management System to allow rapid insertion of C5I sensors and weapon installations if needed. The fixed contract price for a ship hull excluding the combat system is US$98M in 2018, and the lead ship is expected to be launched by the CSBC Taiwan Shipyard within 18 months of ordering. The combat systems and mission package will be separately provided as Government-Furnished Equipment (GFE) that will be integrated by National Chung-Shan Institute of Science and Technology (NCSIST). By applying mission modularity, both Taiwan Coast Guard and Navy requirements can be met by a shared ship design.

Hull Commonality, Modularity, and Scalability – Corvettes, Cutters, and FACs

The concept of hull commonality and modularity are applied in the 600-ton vessel case, as shown in Figure 8. A prototype 570-ton 45-knot stealth corvette was constructed and has been undergoing testing at sea since 2014. After a few years of service, several lessons were incorporated into the later batches of 11 Navy-operated corvettes and 12 TCG-operated patrol cutters. First, the same hullform was widened and lengthened to provide better seakeeping and then additional air defense missiles were added. This evolved into a class of 11 Taiwan Navy corvettes. Second, the Taiwan Coast Guard used the same enlarged hull with some topside modifications to be constructed into 600-ton class patrol cutters with a pre-installed HM&E infrastructure to fit 16 anti-ship cruise missile modules within 12 hours. An optional automated minelaying racks module could be installed on its aft flight deck to deploy advanced mines. The Taiwan Ministry of Defense realized that its coast guard high-speed vessels were more frequently deployed than its navy ships. The Taiwanese have focused on sharing flexible surface vessels with modular topside weapon stations. These 600-ton high speed vessels can be used as coast guard cutters during peacetime while retaining the rapid conversion capabilities into warships during mobilization. Since the same vessels are shared between the Navy and the Coast Guard, significant life cycle cost savings and effective warfighting capabilities are achieved.

Applying hull scalability further, the 600-ton corvette parent hull form was scaled down into a smaller 80-ton high-speed stealth missile catamaran as shown in the left column of Figure 9. The lead vessel serves as a combat system test ship for the mission systems integrator NCSIST. The test ship was ordered, constructed, tested, and transferred to the NCSIST ownership service in May 2019 after only 7 months from the start of construction. During its three sea trials, the tiny 80-ton watercraft was able to reach over 38 knots during rough wave heights of up to 3 meters.[11]

In addition, sixty Micro class 50-ton stealthy Micro Class missile attack crafts will be built using scaled-down hullform modularity, as the preliminary concept picture is shown in the right column of Figure 9. These boats can hide in fishing ports, commercial marinas, and inside the coastal caves that were secretly built to dock Taiwan's 500 landing craft (e.g. LCM) within a few miles of the Chinese mainland coast during the 1960s. These less-than-6-feet-draft missile crafts are operated by three sailors

Image: TheDiplomat.com

Image: DIIC.com.tw

Image: LTS.com.tw

Prototype: Tuo River Corvette (1ea 570-ton)	New: CG Patrol Cutter (12ea 600-ton)	New: AAW-SUW Corvette (8 to 11ea 700-ton)
• Stealth catamaran, 40+ knots • Has 76mm gun, CIWS, torpedoes, and flight deck • Modular weapon zone carries 8 HF-3 Mach3.2 supersonic missiles and 8 HF-2 subsonic missiles • Unit cost was $80M in 2014	• Share common hull with 700-ton naval variant • 40mm gun/70mm MRLS modules; Large fuel tanks • Converts in 6 hours to install modular Anti-Ship Missile Mission Package • $25M per hull in 2018 • Price excluded combat systems	• Share common hull with coast guard variant • 76mm gun, 12 ea ASCMs • 16ea 60km-range TC-2N SAM • Automated mine-laying modules on aft flight deck • Sea Oryx SeaRAM CIWS • $46M per AAW hull in 2018 • $177M/hull for AAW package • First ship launch in 2021

FIGURE 8. Taiwan Coast Guard Large Modular Patrol Cutter-Corvette

LTS.com.tw

Shop2000.com.tw

Child: Modular Test Ship (1ea 80-ton)	Micro Class Fast Missile Boats (60ea 50-ton)
• Use scaled catamaran hull modularity with Tuo River corvette. 38+ knots in 3m waves • Reconfigurable bay to test modular combat systems components by NCSIST • Carry four missile launcher modules • Lead ship delivered in May 2019 • Ordered, built, tested, and delivered in 7mo.	• Shares scaled parent hull modularity. • 1.5m draft. Operated by 3 sailors. • Modular zones carry up to 4 missiles, remote control gun, Stinger SAM, and UAV, etc. • Fixed unit cost at $16.7M in 2018. Up to six yards to be selected for rapid production • NCSIST-furnished weapons priced separately

FIGURE 9. Hull Scalability—Corvette into Test Ship and Fast Missile Crafts.

and can launch at least two 150km-range anti-ship missiles even while in port. This scalable modular approach achieves cost savings in time, manpower, money, and technological development.

Centralized Modular Combat Systems Integrator—NCSIST

Taiwan's National Chung-Shan Institute of Science and Technology (NCSIST) serves as the primary weapons system provider for the country. In a recent interview published in Naval Forces Issue II in 2019 with Admiral (ADM) Chen, a retired Republic of China Navy officer, he discussed NCSIST and how the organization is responsible for the total life cycle of weapon systems. In the past, Taiwan depended on using excess or old equipment from other countries. NCSIST developed the skills and technology necessary for keeping these systems operational when Original Equipment Manufacturer (OEM) parts were no longer available. After Taiwan received the retired Gearing class destroyers with Fleet Rehabilitation and Modernization (FRAM) upgrades from the U.S. Navy in the 1970s, they worked with Honeywell to develop the Modular Combat System (MCS)—its own distributed, Open Architecture (OA) modular combat management system using commercial off

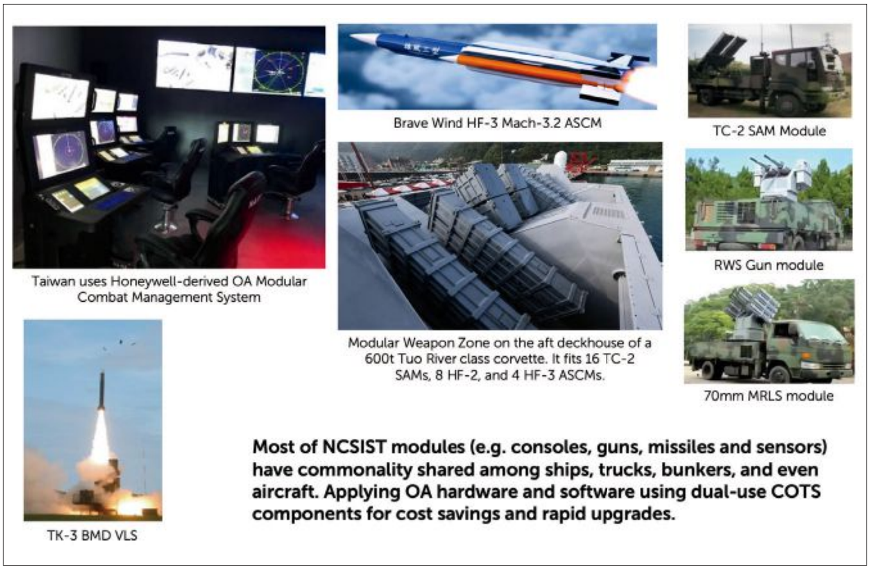

FIGURE 10. NCSIST Joint Weapon Systems and Modular Combat Management System

-the-shelf (COTS) components. ADM Chen said, "Maybe it wasn't the very best, but it was suitable and affordable, and we could improve it because of OA."[12]

The weapon hardware systems used today by Taiwan are integrated and networked by NCSIST using this same modular Combat Management System (CMS) software. This allows all their warships: logistics ships, minehunters, frigates, and destroyers, no matter the size or the mission, to integrate different weapon systems scaled to the size of operator consoles and missions that they need. This keeps older combatants including former U.S. FFG-7, DDG-993, and FF-1052 class ships upgradable to incorporate the latest weapon systems developed by Taiwan. The flexibility of OA software and hardware modularity also allows other reconfigurable but unarmed ships purchased from European and Asian countries to be upgraded and retrofitted with capabilities they did not originally have.

These weapon systems are fully integrated by NCSIST on multiple platforms at sea, in the air, and with coastal defense sites as shown in Figure 10. This gave the command and control sites the ability to see a complete real-time battlefield picture and matrix their sensor grid and weapons grid together. Many of the Taiwan Navy weapon modules such as guns and missiles are using component modularity and commonality to share parts and CMS software with the Taiwanese Air Force and Army to simplify logistics and lower unit costs during both development and production.

NCSIST develops, manufactures, and conducts sales of Dual-Use Technologies. It assists local companies in making profits through commercialization and transfer of some of NCSIST-developed technologies to domestic commercial industry. Since Taiwan is subject to restrictions for exporting complete weapon systems and has a limited domestic market, it has focused on component modularity to boost its production quantities. Although a military missile system cannot be exported, a dual-use electronic component can be exported to replace outdated components in the international market. Therefore, the electronic components need to be modular, dual-use, and be compatible with U.S. and international standards in order to make a profit and maximize international market share.

Recommendations

Some Naval Flexibility lessons from Japan, Korea, and Taiwan are as follows:

1. All three countries revised the original U.S. Navy destroyer/frigate designs with *enlarged hulls* to create lower density ships to lower production unit cost and add new capabilities.
   - Original U.S. ship design examples are DDG-51, DD-993, FFG-7, and FF-1052 classes. If acquired as retired vessels, they would be modified with flexible modular zones. When they built new hulls, they built larger hulls with additional modular spaces to incorporate flexible functions to meet changing needs such as weapons and C5I.
   - Korean KDX-III lengthened DDG-51 design to add firepower (32 VLS cells) to assist land battles.
   - Japan Aegis enlarged DDG-51 design to add Fleet C2 facilities for 1,000-nm offshore operations.
   - Taiwan chose lower density ships with larger hulls to convert/add modular zones with flexible mission packages to meet to changing needs.
   - More buoyancy reserve also increases survivability against collisions and battle damages.
2. Flexibility and Modularity design features allow rapid upgrades, mission flexibility, and long service life with enhanced performance.
   - Taiwanese corvettes' flexibility, modularity, scalability, and commonality enable sharing of vessels, personnel, R&D time, and mission modules between its navy and coast guard.

- Taiwan purchased decommissioned U.S. warships (e.g. DD-993, FFG-7, and FF-1052 classes) after the U.S. Navy retired them early due to upgrade difficulties. After Taiwanese conversion by adding modularity, same vessels have extended service life with new enhanced mission capabilities.
- Most Taiwan Navy's modules and CMS software could be shared with its ground forces.
- Taiwan uses OA modularity and COTS components to allow rapid affordable tech upgrades.
- Modules can be swapped out quickly without needing costly in-shipyard service repairs.

3. Fixed-price contracts are used in most cases without arbitrary ship size limit values.
   - Shipyards need some flexibility to increase the ship size to meet increasing mission requirements, as long as the cost does not increase significantly.
   - Incorporate a supplemental Flexibility Process-based cost estimate model into existing U.S. Navy Weight-Based cost model. Use inputs from production experts to more accurately determine schedule impacts and estimate cost savings.
4. Implement centralized configuration management of all modular Open Systems Architecture (OSA) Modularity interface standards on flexible zones:
   - Taiwan's NCSIST controls and manages Open Architecture modular interface standards across different ship classes throughout their entire platform life cycle. All newbuild warships need to be tested to meet modularity requirements before acceptance.
   - NCSIST has implemented common software and hardware modularity across multiple platforms (Land, Air, and Sea platforms) to maximize cost savings in time, manpower, money, and technologies.
   - NCSIST tests subsystem components to ensure compatibility with the U.S. and NATO parts to allow modular production, emergency substitution, common logistics chain, and potential export orders.
   - U.S. Navy has implemented partial modularity to specific warship programs (e.g. AEGIS, LCS, DDG 1000, FSF-1, etc.), but it needs to have common modular interface standards across ship classes to reap more benefits and cost savings.

All these Pacific navies took the 1980-era U.S. Navy as their pattern to build a strong navy. All are open to use proven U.S. and international military standards, hire experienced American engineers as consultants, obtain licensing transfer of American or foreign technologies, revise U.S. original designs to build enlarged hulls, purchase proven American naval systems, and share co-production with the foreign parent-design shipyards. A similar international cooperative business model is already practiced by the U.S. aerospace industry and its allies on the Boeing jets, satellites, F-35, and other defense/commercial programs. The U.S. Navy and shipbuilders can consider expanding cooperative programs with these Pacific allies to strengthen the American shipbuilding industry.

The U.S. Navy is not the only navy faced with affordability problems that impact shipbuilding plans. Flexible ships with reconfigurable force packages provide one of the key solutions used by international navies including Taiwan, Germany, and Italy to address budget constraints. Not only were more ships built for a given acquisition budget, flexibility provided the ability to cover a wider range of missions due to the ease of payload reconfiguration. Foreign navies have concluded that Flexible Warships can reduce costs without reducing capability, and that if budget constraints limit near team capability these navies can easily choose a lower capability that they can afford (i.e. can be upgraded later if money becomes available during the life cycle of the ship).

Much progress has been made over the last 40 years in developing flexible warships including significant work accomplished for the Littoral Combat Ship program.[13] As the U.S. Navy moves forward to developing future large flexible multi-mission warships, the "lessons learned" from domestic and foreign navy flexible warships designs can help reduce the uncertainty and risk of U.S. Navy implementation of their own Large Flexible Warships. As proven by our Asian Pacific allies, flexible ship architecture and modularity work well for lowering construction and upgrade costs of modern warships when properly applied. NEJ

AUTHOR BIOGRAPHIES

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REFERENCES

[1] UNCTAD.org, Ships Built by Country of Building, 2014-2017, Annual. By Gross Tonnage

[2] Doerry, Norbert, and Phil Koenig, "Naval Shipbuilding Expansion: The World War II Surface Combatant Experience," SNAME Maritime Convention, October 2018.

[3] Childs, Nick and Tom Waldwyn, "China's Naval Shipbuilding: Delivering on Its Ambition in a Big Way," IISS.org, May 2018.

[4] Navy DDG-51 and DDG-1000 Destroyer Programs: Background and Issues for Congress. Updated May 7, 2019

[5] Abbott, Nicholas, Tony Jang, Darren Leap, and Alexander Schaps, "Flexible Warships in Foreign Navies: Applications for Future U.S. Navy Surface Combatants", ASNE Day, March 2015.

[6] EWDefense.com, "Taiwan's Indigenous Shipbuilding Projects in 2018", Asia-Pacific Defense Magazine, Jan 2019 Issue, pp.12-15.

[7] DIIC.com.tw, "Taiwan Coast Guard's New 600-ton Cutters Started Construction at Jong-Shyn Shipbuilding in Kaohsiung in January 2019," Defense International Magazine (in Taiwanese language), February 2019, page 20.

[8] Sumrean, Nidak, "Ensuring Affordable Warfighting over the Life Cycle," ASNE Day 2012, NAVSEA 05C presenation, February 2014.

[9] Keane, Robert Jr., and Barry Tibbits, "Too Little, Too Much, Just Right," SNAME Maritime Convention, October 2018.

[10] Jang, Tony, Lois Pena, and Nicholas Abbott, "Realizing Flexible Ships: Flexibility Cost Savings Estimate for U.S. Navy," presented at ASNE Modular Adaptable Ships Symposium, Systems, and Ships conference in DC, November 2018.

[11] Lee, Chung-Wei, "NCSIST's 'Glorious Star' Test Ship Delivered to Accelerate Taiwan's Indigenous Naval Weapon R&D Progress,", PEOPO.org, 20 May 2019.

[12] Lundquist, Edward, "Do It Yourself – The National Chung-Shan Institute of Science and Technology's Combat Capabilites for Taiwan," Naval Forces, No.II/2019 Issue, pp.58-61, March 2019.

[13] Abbott, Jack W. and Michael R. Good, "Foundations and Leaders: Jack W. Abbott. Start researching modularity in naval ship design and you'll find that all roads lead back to this guy", SNAME Marine Technology magazine special issue on "Modularity and Flexibility", pp.10-13, January 2019.