Addressing the Challenges of Transferring Ship Designs into Production

A thesis submitted for the degree of Master of Science in

Engineering with Finance

by

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I, Rafael Castillo, confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

September 2020

Student number: 18146932

Total number of words: 11,975

ABSTRACT

"ADDRESSING THE CHALLENGES OF TRANSFERRING SHIP DESIGNS INTO PRODUCTION"

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There are numerous reasons that allow to say that shipbuilding industry is a complex business. Only between 2015 and 2019, 46.1% of worldwide Shipyards ceased their work. In commercial shipbuilding, this has been found to be due to an overproduction of Ships that peaked around 2009, surpassing the demand by a significant margin.

For different reasons, Shipyard closures have also affected traditional Naval Shipbuilding companies, in most cases due to financial unviability, causing massive job losses, leading to social unrest and political turmoil in the United Kingdom.

This fact has led the country to develop the National Shipbuilding Strategy, a document that sets the path towards reversing this trend. Two naval projects have been signalled to be its immediate goals: T26 frigates, being built by BAES, and T31e frigate, to be delivered by BABCOCK.

To gain understanding on how financially stable today's UK Naval Shipbuilding enterprise is, this project provides an analysis of UK significant Shipbuilding companies, comparing their key financial ratios and valuation, where possible, from 2015 to 2019.

On another branch of the investigation, it intends to further understand the large number of risks affecting today's naval shipbuilding projects. This is performed through identifying risks from relevant previous investigations, and presenting them to a broad group of experts for them to rank according to the level of threat they represent for the delivery of a project within time, schedule and expected capabilities.

Most significant risks are found to be unrealistic cost estimations, instability of operational requirements, budget being exceeded largely beyond plan and undesired changes in design, due to errors.

Subsequently, several potential mitigation measures are discussed. Among them, it is found that enhancing the behaviour of the learning curve performance is one of the most applicable measures for naval programs.

Finally, a model to estimate potential benefits that this factor could introduce on T26 and T31e programs is put in place, where for a 14-ship program it is projected that savings for up to 986 M GBP and 392 M GBP respectively could be achieved, with a learning curve factor of 90%.

ACKNOWLEDGMENTS

To mi wife Blanca, and my two kids, Elisa and Rafael. You three mean the world to me.

To the Chilean Navy and ASMAR, for giving me the opportunity to live a life full of joy by allowing me to have the most amazing jobs.

To Professor Catriona Savage, for her guidance, patience, and timely advice.

To Chrystian Dyreborg @ OMT, for all the efforts in transmitting his immense knowledge in ship design and production.

To Howard Matters, for taking time to deliver crystal clear answers on complex subjects, showing that there is no replacement for experience and knowledge, even in this automated world.

To Professor Stavroula Balabani, for her continuous support.

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Glossary of Terms

A/A	Anti/Air Warfare
ASW	Anti-Submarine Warfare
CGT	Compensated Gross Tonnage
DDG-1000	Zumwalt Class Destroyer, US Navy
FSS	Fleet Solid Support Ship
GP	General Purpose
IFEP	Integrated Full Electric Propulsion
HOE	Human and Organizational Errors
LCS	Littoral Combat Ship, US Navy
MEWG	Maritime Enterprise Working Group
MoD	Ministry of Defence
NSS	National Shipbuilding Strategy
QE II	Queen Elizabeth II Aircraft Carriers
RFA	Royal Fleet Auxiliary
RN	Royal Navy
T23	Frigate Type 23
T31e	Frigate Type 31e
T45	Destroyer Type 45

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1. Introduction

Shipbuilding plays an important role in the generation of wealth and work posts on several countries' economy. However, despite its significance, the number of operational shipyards worldwide has declined in the last decades, and more sharply in recent years, as can be observed in Figure 1.

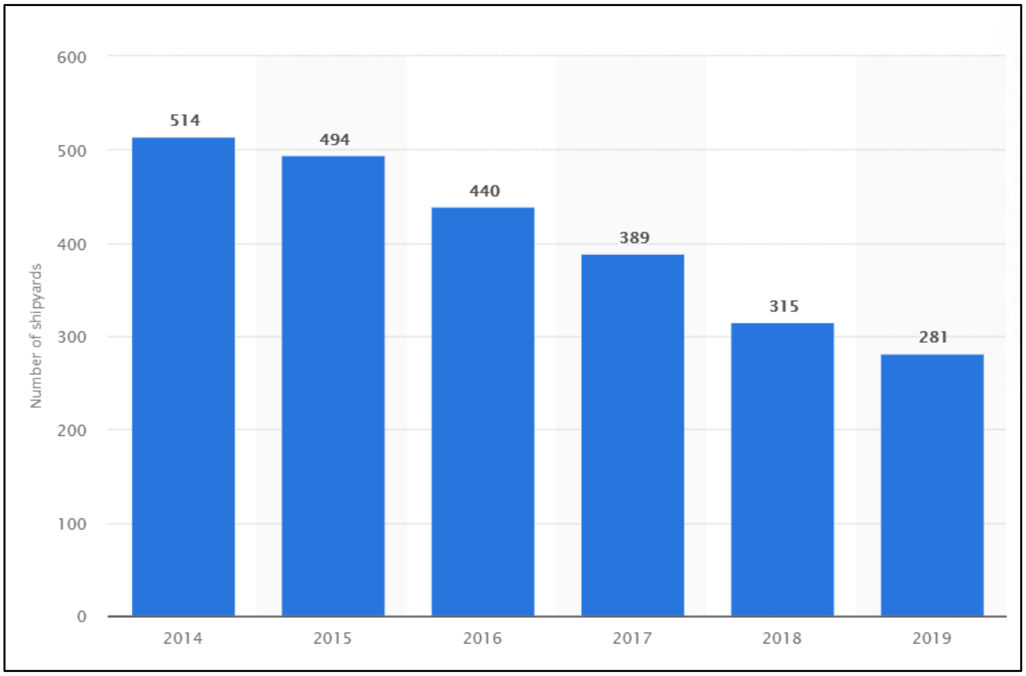

Figure 1. Operational Shipyards Worldwide 2014-2019 (source: www.statista.com)

One of the reasons for the decline in this industry can be found in a great imbalance between the production and demand for ships that have had place in the last 15 years. This factor can be appreciated in Figure 2, where the ideal situation is to have a zero value, a negative value indicates demand is greater than offer and a positive value does the exact opposite. This last behaviour has been predominant with particular strength from 2005 onwards (OECD, 2017).

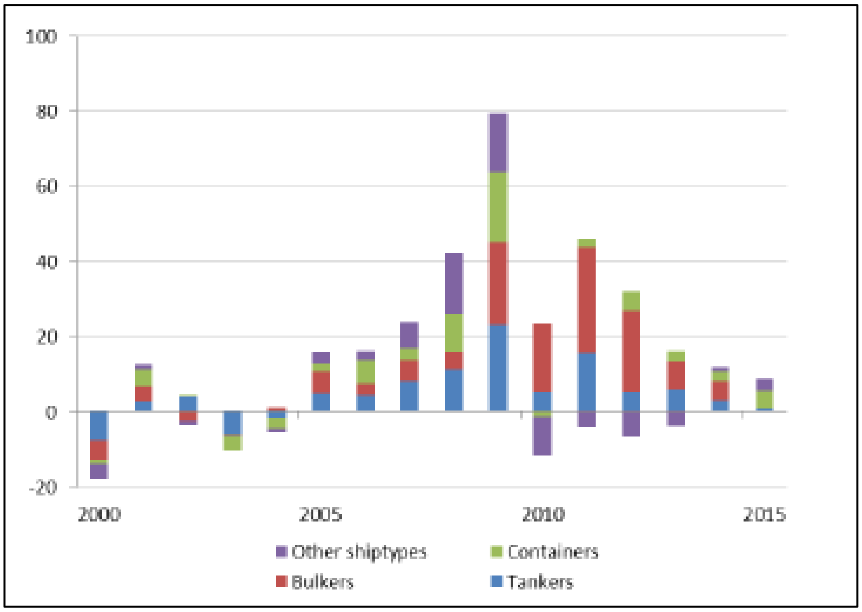

Figure 2. Gap between vessel completions and requirements 2000 – 2015 (OECD, 2017)

The decreasing number operational of shipyards is a reality that is also truth in the UK. However, the main cause for the detriment of UK's Shipbuilding Industry is not necessarily related only to this factor, since from the decade of 1960 onwards commercial shipbuilding industry decreased its relevance, as in Table 1 (Mickeviciene, 2011), causing the building of naval ships to be the most important component of UK's Shipbuilding enterprise.

This trend has caused several of UK's Naval (or mixed Naval-Commercial) Shipbuilding Companies have experienced extreme hardship, as will be discussed on Chapter 4.

Table 1. Leadership in Shipbuilding through history

Duration of the leadership	Country	Stage of business cycle	Causes
1860's – 1950's	G. Britain	Lost leadership	Failure to modernize shipbuilding industry
mid1950's – mid1990's	Japan	Post-maturity, weakening of competitive power	Ageing and high cost human resources. Reduced by shipyards R&D budget to less than 1%. The gap between the demand and supply for steel, increased prices of steel.
From mid1990's	S. Korea	Post-growth, maintenance of competitive power	High cost human resources. The gap between steel demand and domestic supply increased steel prices. The appreciation of Korean Won has worsened the competitiveness of Korean shipbuilding.
Since 2010, earlier than it was planned	China	Acceleration of growth	The lowest labour cost. Ambitious State programmes for the development, growing shipyards capacity, governmental subsidies.

The impact of Shipbuilding Industries closing on unemployment and internal economy has attracted the attention of relevant political actors, and has also been the driver for the development of extensive plans to try to reverse this trend, as will be discussed on section 2.2.

Given the described scenario, this project was designed with the following aims and objectives:

AIM:

UK was before 1950 the world leading Shipbuilding Industry, position that was lost to Asian economies due to several reasons, among them an inability to modernize, leading to uncompetitive costs. Nevertheless, Naval Shipbuilding Industry continued to be a relevant actor in the economy (see 2.1).

However, this segment has also faced enormous difficulties, risking its competitiveness and the very survival of mid-size companies, due to issues such as inaccurate cost estimations, over costs, changes in designs specifications and many others.

Hence, it is the aim of this project to address identify and rank the drivers that preclude a Naval Ship's design to be delivered successfully in terms of schedule, budget and expected operational capabilities.

This process is intended to outline potential mitigation measures against Shipbuilding Industry Risks, that can help to effectively ensure a future sustainable operational balance for remaining Shipbuilding companies.

OBJECTIVES:

a. Summarize pre-National Shipbuilding Strategy Situation
b. Review significant shipbuilding projects, identifying main risks to their completion within defined scope of time, budget, and operational capabilities.
c. Evaluate Financial Health of UK Naval Shipbuilding Companies
d. If Possible, benchmark against comparable foreign competitors

Comments on the level of satisfaction of aim and objectives can be found in Chapter 10

2. Literature Review

Numerous aspects can be reviewed to preliminarily understand the reasons behind the significant decline of the UK's relevance within the Shipbuilding Enterprise. This phenomenon has been a great concern for public authorities and has driven the publication of the National Shipbuilding Strategy in 2017.

Some of the aspects that are investigated are the impact of Naval Shipbuilding in the country's economy, RN and RFA procurement of ships as drivers for UK's shipbuilding enterprise, and past project's experiences.

2.1 Naval Shipbuilding impact on economy

Several estimations about the contribution of Naval Shipbuilding to the UK's prosperity have been made. One of the most recent attempts has been conducted by appointment of the MoD. This research has found that Shipbuilding and Ship repairing activities are estimated to contribute in today's terms with 2.0 Bn GBP annually, with maritime and naval sector employing directly and indirectly a total of 111,000 workers, including shipyards, supply chain employees, and other relevant enterprises. The same source has suggested that a stable naval construction plan, driven by the RN and RFA requirements, can provide an added value of at least 1.5 Bn GBP annually to the country's economy, being also able to support more than 25,000 direct jobs (Ministry of Defense, 2017).

Further development on the subject has been provided by IPSOS MORI, one of MoD's sources, whose findings can be summarized as in Table 2 (GMB Union, 2018).

Table 2. IPSOS MORI socio economics metrics

Aspect of Prosperity	Effect for 100 shipbuilding jobs created	Measure
Employment	Warship spend per gross job (at shipyard)	£10m-£13m
	Net increase in employment	19 jobs
Education	Gross apprenticeships created	25 - 33 apprentices
Income	Net increase in GVA per annum	£4.3m
	Net increase in wages per annum	£1.8m
Unemployment	Reduction in JSA claimants	16 claimants
	Reduction in LT JSA claimants	9 claimants
	Reduction in OOW benefit claimants	11 claimants

Despite the different estimations, one aspect that is hard to challenge is that the impact of Naval Shipbuilding decline is very clear and present on the country's workforce. As a recent example, BAES, UK´s major defence services provider, and as will be shown on later chapters, one of the strongest financially, closed its Portsmouth installations due to its unviability in 2012, causing the loss of 1,775 jobs.

This and other facts have sparked intense political debates around UK's Shipbuilding Industry. At the time of this closure, the then Secretary State of Defence, Phillip Hammond, expressed that, based in today's fleet size reality, the country can afford to have only one shipbuilding facility, branding any other policy as going into "fantasy economics".

Different views have caused different opinions on very relevant subjects, one of them being the sustainability of shipbuilding in the Clyde, and its impact on the Scottish economy. (Brooke-Holland, 2016).

Strong involvement of both government and parliament, due to the uncertainty of the viability of UK's shipbuilding enterprise, caused Sir John Parker, Naval architect and former CEO of Anglo American, to be commissioned to provide an Independent report, meant to outline the source of problems within UK's naval shipbuilding projects, and provide a cornerstone for the development of the National Shipbuilding Strategy.

2.2 National Shipbuilding Strategy

Sir John Parker's report conclusions, published in 2016, are summarized in 11 points, as seen in Table 3.

Table 3. Sir John Parker's Conclusions (Parker, 2016)

Order	Cause
a	Lack of an overrriding Master Plan for each project from the sponsor with key dates expected to be met by the RN Client
b	A lack of assured Capital budget per RN ship series, subject to annual arbitrary change, with accumulative negative impact on time and cost with accompanying increased risk of obsolescence;
c	Poor linkages across the 'Total Enterprise' including industrial capability and capacity;
d	A lack of empowered Governance to grip early trade off debates in design and specification to remain within project cost to meet the assured budget, including rigorous evaluation of cost of design standards;
e	Senior decision-makers have, previously, been engaged too late in the process and not always with high quality information and costing data;
f	Loss of continuity (as people move on to new roles) with new people naturally imposing their preferential views;
g	The MoD has lost expertise in both design and project contract management;
h	Unanticipated cost growth from suppliers;
i	Delays to projects are accumulative;
j	Inadequate evaluation of risk contingency in each project;
k	There is insufficient focus on controlling 'preferential' engineering costs and in understanding costs associated with incorporating key naval standards.

The same report made a preliminary estimation, based on the data on Table 4, which determined that 40 light frigates could be potentially exported in next 10 years, with a strong competition in this market's segment from at least 14 other offerors. T31e program (see 2.3) was, partially based on these calculations, defined as "the pathfinder... for invigorating and sustaining the industrial base in the UK", through the conquering of a relevant share of this export market.

Table 4. Estimation of Ships being planned worldwide (Parker, 2016)

Vessels	OPV	Corvette	Frigate	Total
In service	777	259	469	1505
On order	135	40	69	244
Being planned	276	67	158	501

Based on Sir John Parker's findings, the National Shipbuilding Strategy was designed and published in 2017, with a vision that remarks the importance of modularity, interoperability, and innovation as drivers for the future Shipbuilding Industry. The strategy also declared three main objectives, namely: (1) achieve the building complex naval ships on regular schedules, (2) maximize naval platforms exports possibilities and (3) ensure RN core capabilities (see 2.3).

Several definitions were taken to pursue the defined objectives, from design and management perspectives.

Organizations such as the MEWG (Maritime Enterprise Working Group) were set in place, to provide a common and steady platform of work that would conduct periodical reviews of the effectiveness of the strategy's implementation, with representatives from the RN, MoD, Industry, Universities, and other relevant institutions.

Economic Service life of naval platforms was defined to be studied, and more likely, shortened, to enhance their exportability during service life, providing further demand to industry to replace sold platforms. In the same direction, minimum and well justified bespoke solutions are expected on following projects, with commonality of equipment installed, where possible, to enhance in-service support and decrease overall costs.

2.3 The Royal Navy and RFA as drivers for UK Shipbuilding Enterprise

As today, the Royal Navy has 19 surface combatants in operation, divided into 13 T23 frigates and 6 T45 destroyers. T23 frigates were designed by BAES and built by YSL and Swan Hunter shipyards in a period comprising years 1985-2000, whilst T45 destroyers were designed by BAES and built by the same company between years 2003-2010. Since their incorporation to service, T 23 frigates have provided the backbone of UK's naval fleet in General Purpose and ASW roles, whilst T45 destroyers have provided the A/A required capability.

19 surface combatants has reportedly been found by experts, among them former First sea Lords, to be an extreme low figure to accomplish worldwide RN commitments, an issue that was particularly stressed during the crisis produced by the seize of the unescorted UK flag Tanker "Stena Impero" by the Iranian Navy in July 2019 (Nicholls, 2020). Despite these political and/or operational implications, the latest definition requirement is still to have 19 operational combat platforms in 2030. Therefore, at this point, it is unlikely that major, trend changing workload to UK shipyards, will derive from RN contracts.

Nevertheless, to achieve both RN and RFA Fleet Modernization, a plan to spend 19 Bn GBP over the next decade was put in place in 2017.

8 ASW T23 frigates are to be replaced by 8 T26 platforms, whilst 5 GP T23 are to be replaced by at least 5 T31e multirole vessels, with no upper limit on the maximum number of these frigates to be built.

2.3.1 T26 Frigate Project

T 26 is an ASW frigate of an approximate worth of 1.0 Bn GBP per ship. It has been designed by BAES and will be built by the same company as main contractor in its Clyde facilities. It is intended to replace the currently operational 8 T23 ASW, with an initial contract for 3 platforms.

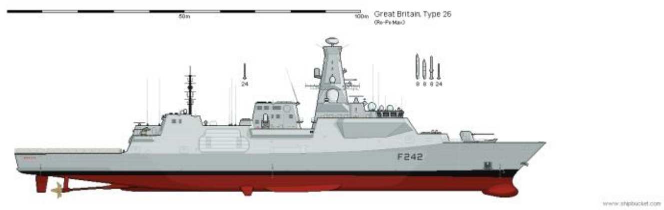

Figure 3. T26 Frigate Drawing (source: www.shipbucket.com)

T 26 design has currently been successfully exported to Australia and Canada; however, the latter seems to be revising its acquisition process due to the program’s cost of 60 Bn USD (Pugliese, 2020).

2.3.2 T31e Frigate Project

T31e is a multirole frigate, with an estimated worth of 250 M GBP per ship, which accounts for one quarter of the valuation of each T26 unit. They are to perform GP roles, allowing T45 and T26 to become the main surface group components for the 2 new QEII carriers, whilst OPV’s currently performing defence tasks return to perform their design, constabulary roles.

Babcock has been awarded the role of main contractor to deliver a minimum of 5 new T31e frigate, with first of the class initially planned to enter service in 2023, this date has already been postponed until 2027.

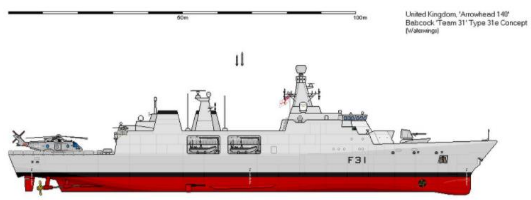

Figure 4. T31e Frigate Drawing (source: www.shipbucket.com)

This project has been signalled as the cornerstone of the NSS in terms of exportability, according to its key aims (Ministry of Defence, 2017):

Table 5. T31e frigate key aims

6 TOP MESSAGES

1. Deliver 5 ships, with first entry into service from 2023;
2. Meet the price of £250m per ship, including development costs, risk and profit, whilst minimising the GFX burden and cost of ownership to the MOD;
3. Accept a firm price contract for a first order of five ships;
4. Maximise the UK prosperity footprint and export potential of your offering, without compromising on cost and time;
5. Develop as much adaptability, modularity, openness, and agility within your proposals. This should be a ship that navies around the world want to own; and
6. Achieve a UK focused Design and Build Strategy that maximises UK content.

2.3.3 Fleet Solid Support

Regarding RFA, there is a necessity of acquiring 2-3 FSS, a type of Ship meant to provide logistic support to the RN at sea; An International bid towards this goal was being carried in accordance with NSS definitions; however, on November 2019, the government cancelled the ongoing process (Hollinger, 2019).

UK's Government policies dictate that complex ships are to be built in the UK; however, there is no clear definition to what a complex ship is. This is an outstandingly important issue to define whether FSS, and any auxiliary ship in the future, will be built locally, providing a much-needed extra demand for British Shipyards, or abroad.

Nevertheless, it must be noticed that the expected value of the FSS program is 1.9 Bn GBP for three ships, and therefore, unlikely to sustain local Shipbuilding Industry in the long run, especially if this alternative is in the form of a team of numerous shipyards; previous research have demonstrated fragmentation on low scale projects has detrimental effects on a project's outcome (RAND Europe, 2005).

Despite the relative lower financial magnitude of RFA acquisitions programs, previous experience seems to demonstrate that better long-term plans could contribute to enhance UK's shipyards participation in the segment.

During TIDE class procurement process, no UK companies participated on the final bidding process, partially since all relevant shipbuilders were by the time compromised with tasks related to the completion of QE II class carriers (GMB Union, 2018).

This precluded UK shipbuilder's potential participation on a 452 M GBP contract.

2.4 Naval Shipbuilding Past Projects Performance

Recently finished projects can provide a good source of information regarding the challenges faced by International Naval Shipbuilding Industry. Two aspects are analysed here: the delivery on expected capabilities, and the delivery on budget/time.

2.4.1 Delivery on Expected Capabilities

Two most recent British projects are the construction of 6 anti-air type 45 frigates and 2 Queen Elizabeth aircraft carriers. Given that aircraft carriers are a very special type of naval vessels, that due to their magnitude make work fragmentation between shipyards a reasonable policy, it is deemed as a better alternative to revise the outcomes of T45 destroyer project, a ship that is much more on the scale of the expected future demand.

T45 destroyers were designed as an A/A platform, to replace the ageing T42. Since their delivery to the naval service, they have faced several technical issues, being the more relevant the one that affects the reliability of their technically novel IFEP propulsion plant.

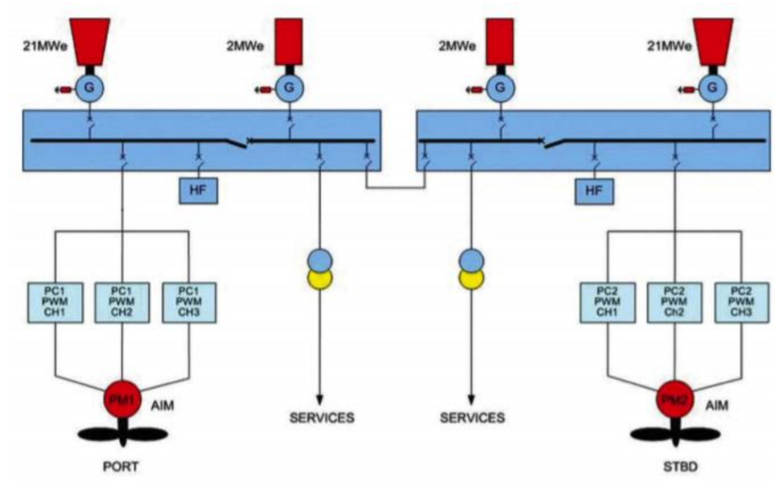

Figure 5. T45 Single Line Propulsion Diagram (source: Journal of Naval Engineering)

JNE Volume 45 Book 3 Paper 11 Problems arising in WR21 turbines have caused on several occasions' loss of all electric power at sea, causing operational detriment and unavailability of the platforms to a degree that it triggered a Parliament enquiry in 2016. This instance found serious shortcomings in both testing procedures and technical specifications of the system (UK Parliament, 2016).

The required upgrade is of a degree of complexity that could not be addressed within the standard scope of time or budget available for corrective maintenance. This originated Project Napier, led by BAES, which is expected to correct underlying issues by performing necessary modifications in conjunction with Rolls-Royce, main propulsion turbine's supplier (Chutter, 2018).

From an International perspective, S-80 case can be addressed, a program of 4 submarines for the Spanish Navy. This platform was fully designed by Navantia, state owned Spanish Shipyard company, after terminating its partnership with DCNS valid throughout the construction of 14 Scorpene submarines.

The first submarine was due to be delivered originally on 2012; however, in November of the same year, management team admitted that flaws on basic design had led to a platform's weight not compatible with its buoyancy, of a magnitude unable to be corrected by the use of design margins. General Electric was contracted to review the design and develop a joint solution, achieved by adding three "light" sections that allow to reach the necessary balance.

Several experts have aimed at the very high risks of the project, since Navantia had not made a submarine's basic design on its own for several decades (Carrasco Santos, 2020).

The flaw caused the estimated delivery of the first hull being delayed 10 years, with a cost increase of 93.4% (2,135 M EU to 4,129 M EU), that besides correcting buoyancy issues, needs to fund increasing port installation capacities, due to the platform's increased length, and a life extension program for the already obsolete S-70 class (Araluce, 2020).

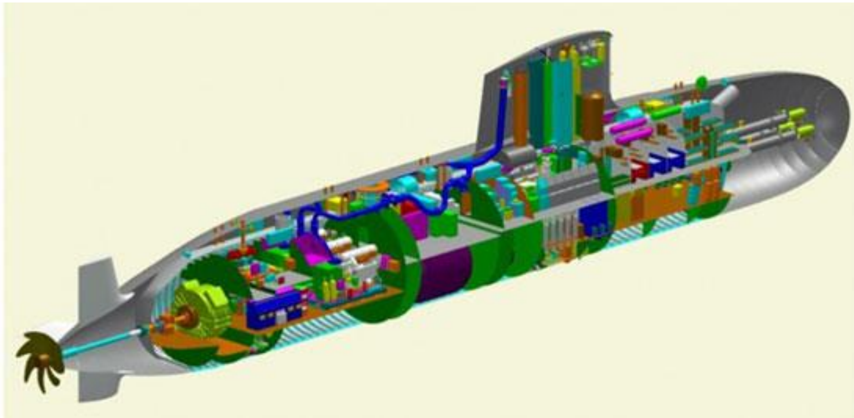

Figure 6. Navantia S-80 Submarine Layout (source: Spanish Mod, online)

No statements have been made relating to the submarines maximum speed and autonomy; however, basic naval architecture knowledge suggests that both characteristics should be noticeably affected.

2.4.2 Delivery on Quantity, on Budget, and on Time

Several works have highlighted the tendency of naval shipbuilding programs to be delivered at a significantly higher cost than planned, well behind schedule and, more than often, providing fewer ships than planned.

This can be observed in Table 6, where several contemporary naval programs characteristics are compared. Among the most interesting data, it can be noticed that not even half of the programs delivered as many ships as expected, with an average of 35.0% of planned ships being built. When addressing schedules, conceptual design to detailed design average period is 3.8 years, and detailed design to first deliverance or acceptance is 8.9 years.

Table 6. Comparison of Program Characteristics (RAND Corporation, 2014)

		Ships					
Difference	Metric	DDG-51	LPD-17	SSN-774	DDG-1000	CVN-78	Type 45
Program initiation[a]	Start of concept refinement	February 1980	November 1990	August 1992	June 1995	March 1996	[b]
Unit cost	PAUC	$1,084 ($M, BY 2006)	$1,352 ($M, BY 2006)	$2,536 ($M, BY 2006)	$3,659 ($M, BY 2006)	$9,307 ($M, BY 2006)	£944 (£M, TY)
R&D funding	% RDT&E funding of total funding	6%	1%	8%	35%	14%	[b]
Quantity	Planned quantity	62	9	30	7	3	12
Production rate	LRIP quantity	9	No LRIP	18	7	3	3
	Annual rate (min/max)	1/5	0/2	1/2	1/1	0/1	0/1
Production strategy	Allocation of production work	Dual shipyards, whole ships	Single source	Dual shipyards—modules	Dual shipyards—modules	Single source	Dual shipyards—modules
Design phase time	Conceptual design to detailed design (months)	30	42	11	96	47	[b]
	Detailed design to first delivery/acceptance (months)	91	110	113	89	141	96
Size	Full displacement (long tons)	9,515	2,5883	7,008	15,656	112,000	7,900
	Overall length (feet)	510	684	377	610	1,092	500
Crew	Accomm. (A) or crew (C)	312 (A)	396 (A)	132 (A)	158 (C)	4539 (A)	190 (C)

Keeping these figures in mind, it is not surprising that one of the most significant findings in Sir John Parker's Independent review, cornerstone for the development of UK's National Shipbuilding Strategy, was the significant difference on average schedules when comparing naval projects with civil undertakings, as can be observed in Table 7.

Table 7. Timescales comparison for Shipbuilding Projects (Parker, 2016)

Ship	Start of life Displacement [1] (Tonnes)	Concept Phase start	Contract	Time concept to contract (years)	Delivery ship 1	Delivery of class	Time contract to delivery of class (years)
'Mega cruise ship'	c180,000 (Gross Registered Tonnes)	2014	2015	1	2018	2020 (4 in total)	5
Polar Research Ship	c15,000 (Gross Tonnes)	2014	2015	1	2018	n/a (1 in total)	3
Military Afloat Reach and Sustainability tanker	31,485	2001 (in a different programme boundary)	2012	11	2017	2018 (4 ships)	6
Type 21	2,750	c1967	1969	2	1974	1978 (8 in total)	9
Type 23	3,386	c1978	1984	6	1989	2001 (16 ships)	17
Type 26[2]	6,900 (Basic)	1997	n/a	>19	n/a	n/a	n/a

2.5 Learning Curve in Naval Shipbuilding

Naval Industry has complexities of its own, being one of them that normal naval programs build a number of platforms that is not able to make large scale economies when purchasing systems and equipment, item that accounts for more than 50% of the expenditure on Surface Combatants (see 8.1).

When observing Figure 7, it can be noticed that very few programs achieve a number of ships above 8. Even in the largest naval fleets, like US Navy, programs that surpass 20 units are very scarce, namely Ticonderoga Destroyers and Arleigh Burke Frigates.

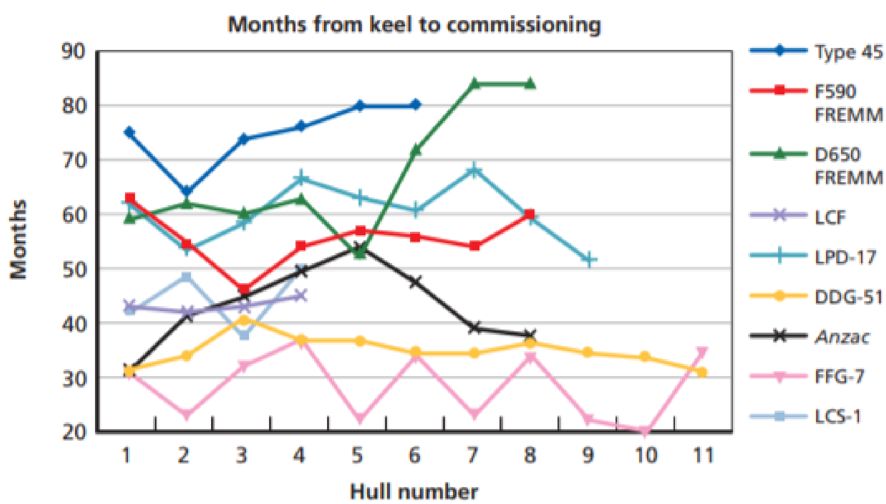

Figure 7. Time from keel to commissioning on relevant naval shipbuilding projects (RAND Corporation, 2015)

However, this fact does not necessarily preclude the effectiveness of the learning curve effect, since on general terms, it exerts a greater effect on the first few hulls, as observed in a general curve in Figure 8.

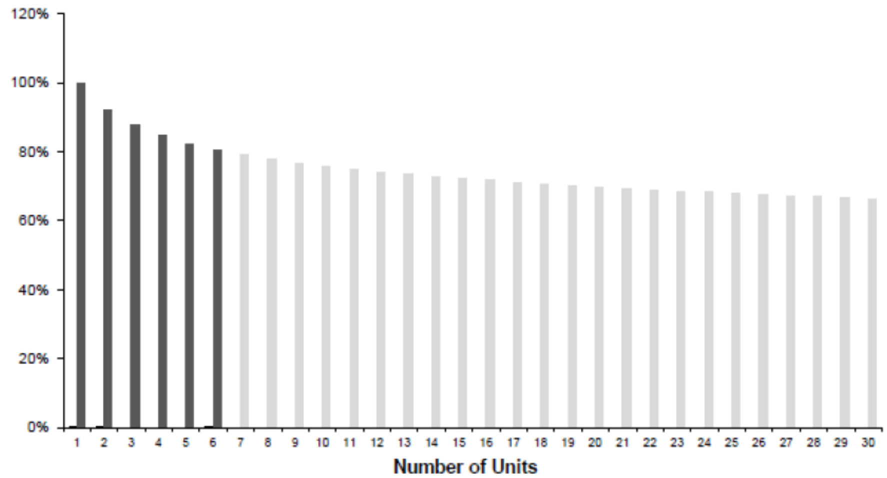

Figure 8. The learning curve for naval production (Centre for Operational Research and Analysis, 2017)

This and other complexities that will be discussed in following chapters make naval shipbuilding projects to be very prone to underperform in several areas, being the most relevant: delivery of fewer ships of a planned class, with fewer capabilities than those expected and at with significant delays from planned schedule.

2.6 Contracts in Shipbuilding

A contract is an agreement between two parties where a contractor commits to perform a service for a customer, normally in return for a payment (Nicholas & Steyn, 2017). From this transaction perspective, contracts can be classified as in Table 8. Each category and subcategory of contract will provide a different set of advantages/disadvantages to customer and contractor.

Table 8. Generic Types of Contract (Nicholas & Steyn, 2017)

Main Category	**Subcategory**
Fixed Price Contracts	Fixed Price Contract
	Fixed Price with Redetermination
Cost-Plus Contracts	Cost Plus Fixed Fee
	Guaranteed Maximum Price
	Time and Materials Contract
Incentive Contracts	Cost Plus Incentive Free Contract
	Fixed Price Incentive Fee Contract
	Other Incentive Contracts

To manage the procurement of a naval shipbuilding program, several acquisition strategies can be adopted. Their main difference is which organization takes the responsibility for each step of the process, from concept refinement to test and trials. Main acquisition strategies are as in Table 9.

Table 9. Example Acquisition Strategies and Organization in Lead Role, by Design (RAND Corporation, 2014)

Acquisition Strategy	Concept Refinement	Preliminary Design	Contract Design	Detailed Design and Construction	Test and Trials
Government design	Government	Government	Government	Industry	Joint
Industry design (sole-source—prime)	Government	Industry	Industry	Industry	Joint
Competitive design (down-select to single prime)	Government or industry (multiple firms)	Industry (multiple firms)	Industry (multiple firms)	Industry (single firm)	Joint
MOTS (turn-key)	Industry	Industry	Industry	Industry	Joint
Alliance	Collaborative	Collaborative	Collaborative	Collaborative	Joint

Both the type of contract and the acquisition strategy will have a major impact in the result of a project, not only for the delivery on schedule, on budget and on capabilities, but also on the health of the shipyards as a sustainable organization, as will be further discussed (see 7.1).

3. Methodology of the Study

Methodology used for analysing the problem can be summarized as in Figure 9, where green boxes represent those aspects that could be developed according to the original plan, and red boxes represent those who had to be heavily modified due to COVID 19 exceptional circumstances.

Initial research was done on the basis of an extensive literature research and online databases investigation; its findings have been outlined in chapter 2. After this step, two separate branches of investigation were defined.

On the upper branch, a financial analysis of companies that are relevant for the UK Shipbuilding Industry was performed. This list included 6 shipbuilding/ship repair companies and one design and engineering office, and deliberately excluded companies in the chain of supply since naval activity is in rare cases (if any) the major share of their revenue. This analysis allowed to determine which companies are, from a financial point of view, improving, stable or not improving. Findings are outlined in chapter 4.

On the lower branch, an identification of previously identified risks associated to Ship Design and Shipbuilding Industry was performed as a first step, and subsequently, a survey was designed to obtain opinions electronically from UK and foreign experts on their relevance; findings are as in chapter 5 and 6. This branch differed greatly from what was originally planned, since risk identification and ranking was meant to be done by visiting several shipbuilding industrial facilities.

Risk mitigation measures to those risks identified as more relevant were investigated and discussed in chapter 7 and chapter 8, from a financial/administrative and engineering perspective respectively. This sections value was greatly enhanced by discussions with industry experts from ASMAR, OMT and MoD.

One of the most effective mitigations, able to reduce the significance of several of the identified risks, was found to be the learning curve effect. Hence, in chapter 9, a model was developed to preliminary estimate savings on currently ongoing UK Naval Shipbuilding projects due to its effect.

Chapter 10 provides conclusions of the study and points for discussion.

Chapter 11 outlines what in the author's opinion could contribute to further develop the subject of Risks and Mitigations in the Shipbuilding Industry.

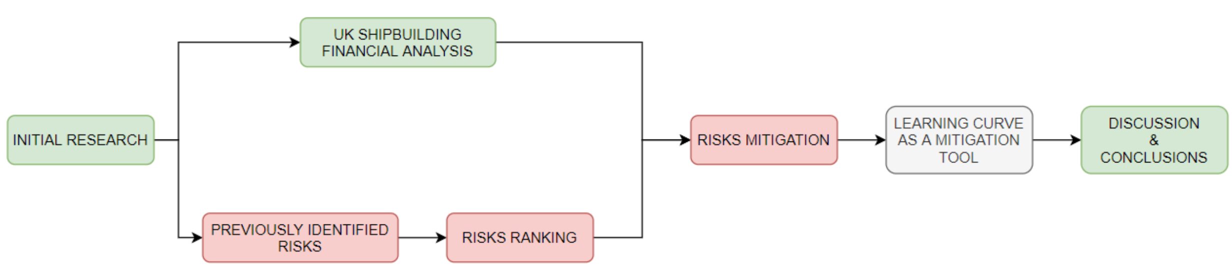

Figure 9. Methodology Summary

4. Financial Analysis of UK Shipbuilding Companies

A form of financial analysis was performed on 6 UK companies that have been historically related to Naval Shipbuilding, namely: BAES, BABCOCK, A&P, Cammell Laird, Ferguson Marine, Harland & Wolf and BMT. All of them have within their core business Shipbuilding and/or Ship repair/maintenance, except for BMT, whose expertise is related to ship design and process efficiency.

Enterprises participating of major supply chains were not considered (e.g., Rolls Royce, Thales, etc.), mainly due to their reliance on several business lines for their survival that are unrelated to shipbuilding and because of project's time constraints.

In the absence of a common measure of valuation for every company, an approximation of their relative sizes can be obtained from comparing their average sales last 5 years, which can be observed in Figure 10.

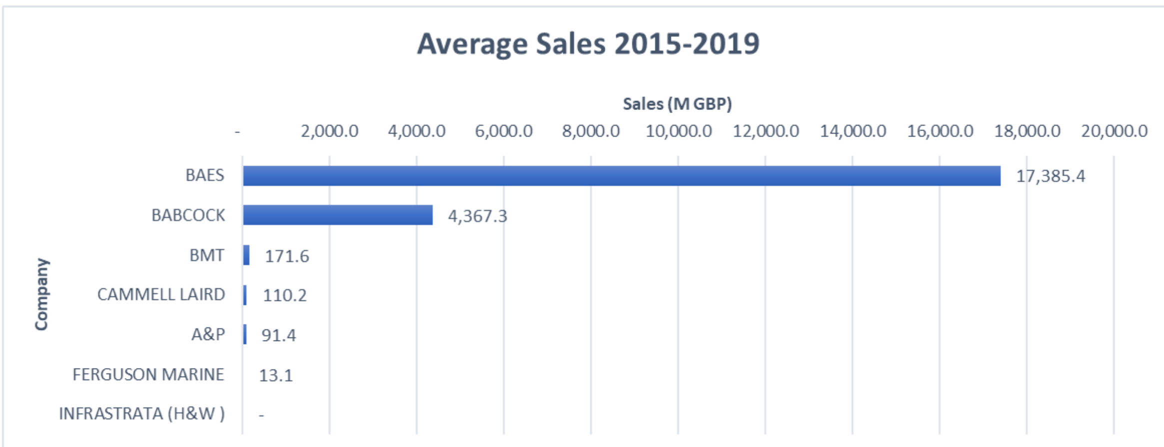

Figure 10. Average Sales 2015-2019 of UK Shipbuilding related companies

Two slightly different methods are used to assess each company's financial performance, depending whether their ownership structure defines them as Publicly Listed Companies or Private.

One interesting aspect is that, unlike the rest, the two dominant companies, BAES and BABCOCK, have ongoing TBA (Term of Business Agreement) signed with the MoD, a type of contract where MoD commits to provide a demand that can at least cover the fixed cost of some facilities, or otherwise reimburse the companies for the unused capacity.

In case of BAES, the TBA was signed in 2009 covering a 15-year period for a minimum annual demand of 230 M GBP, divided in Shipbuilding and Support segments. This is one of the reasons why, on given scenarios, MoD has contracted building of moderate complexity vessels, as OPV´s, to a company that is specialized in providing more complex, and hence costly, naval platforms.

4.1 Publicly listed companies

For publicly traded companies' analysis a brief description of their income sources is performed. In a second step, their share price, company valuation and market Capitalization evolution is revised in a period comprising years 2015-2019.

All company's shares analysed by this method are traded at the London Stock Exchange. Share price performance is compared to FTSE100, to establish a common base of evaluation, despite this BAES is the only company that qualifies as one of its constituents.

4.1.1 BAES

BAES is the largest provider of Naval Shipbuilding Services in the UK. It has over 33,800 employees in the country, and it is organized into five major domains, namely Air, Maritime, Land and Cyber. Shipbuilding business is comprised in the Maritime Segment, and its relative significance when compared to other segments from 2015-2019 can be appreciated in Figure 11.

It has an extensive portfolio of projects worldwide; among its most significant customers are the US, UK, Saudi Arabia, and Australia. These markets relative contribution to the company's revenue can be observed in Figure 12.

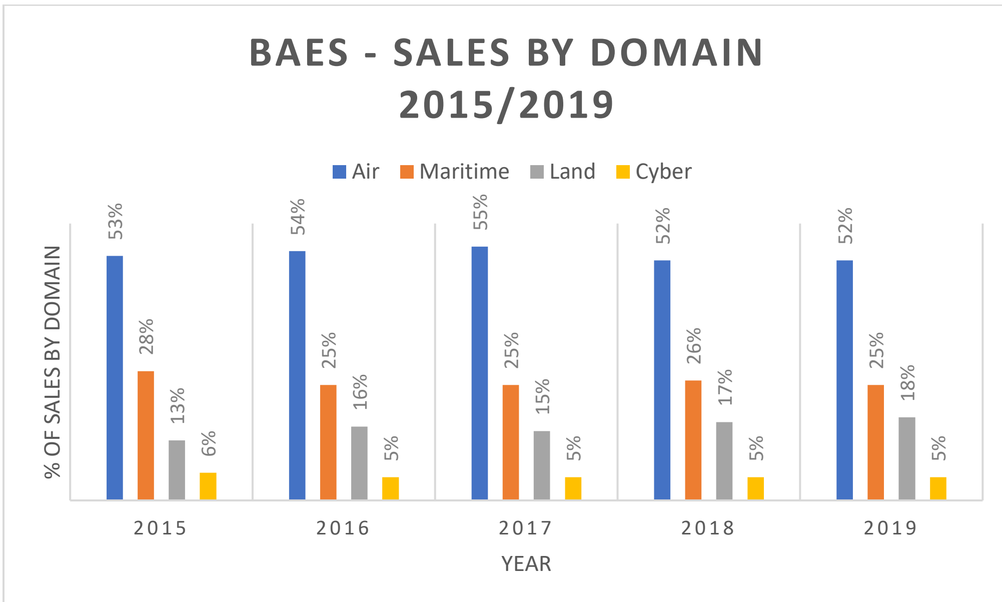

Figure 11. BAES, sales by domain

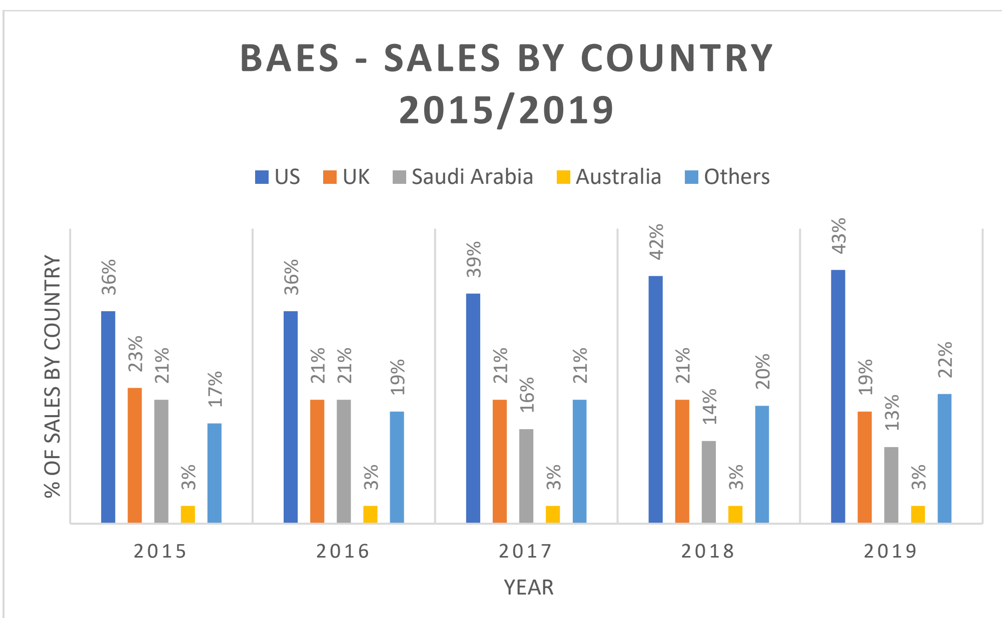

Figure 12. BAES, sales by country

Evolution of the company's share price and its comparison with last 5-year FTSE100 index is as in Figure 13. It can be observed that BAES share price performance has consistently outranked FTSE100, with peaks of outstanding performance as in July 2018, when it was announced that it had won the bid for the procurement of the new Australian Hunter Class Frigate, based in T26.

BAES Valuation and Market Cap have evolved as in Figure 14. Valuation and Market Cap have averaged 18,459 and 17,128 Bn GBP in the period, representing an increase of 17.2% and 14.5% respectively.

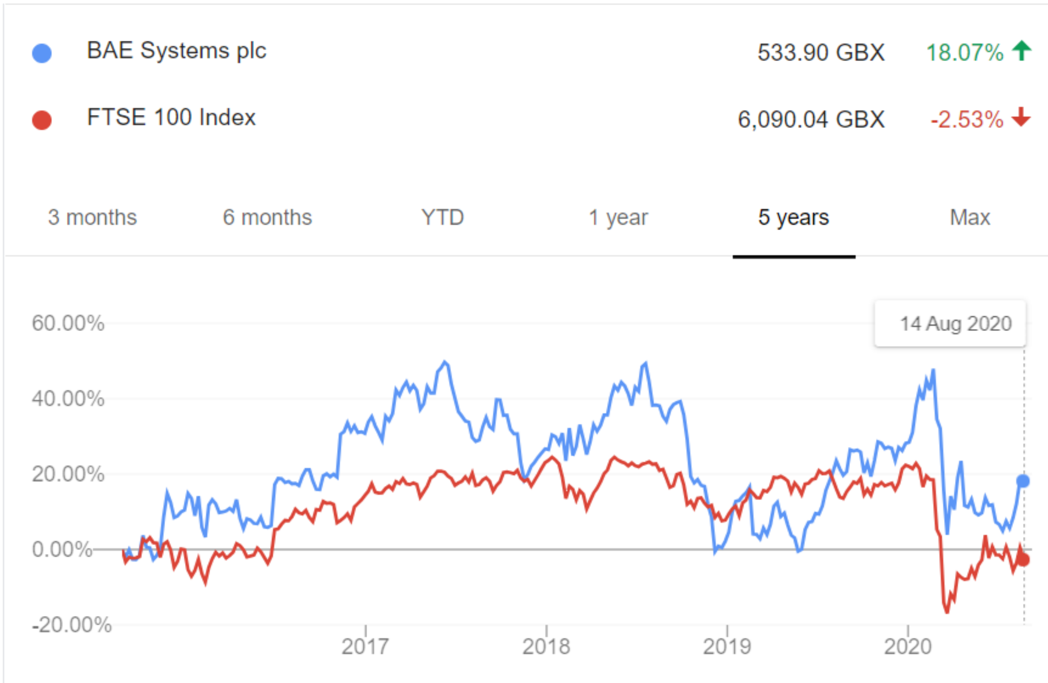

Figure 13. BAES share price v/s FTSE 100 (source: google finance)

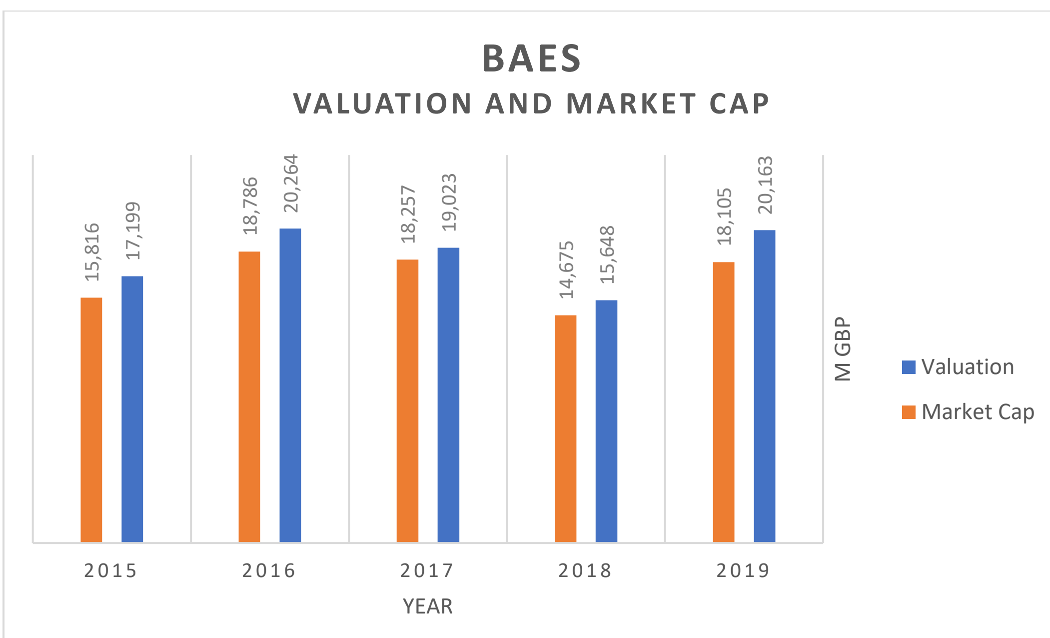

Figure 14. BAES Valuation and Market Cap

4.1.2 BABCOCK

BABCOCK is the second largest provider of Naval Shipbuilding Services in the UK. It has over 35,000 employees, and it is organized into four major domains, namely Marine, Land, Aviation and Nuclear. Shipbuilding business is comprised in the Marine Segment, and its relative significance when compared to other segments from 2015-2019 can be appreciated in Figure 15. It is interesting to notice that Marine domain has consistently lost relevance in the firm's sales to increases in Aviation and Nuclear sectors.

In BABCOCK's case, a vast majority of its income is provided by its UK operations, as can be observed in Figure 16. It is worth noticing that home country operations have decreased its significance in the last 5 years.

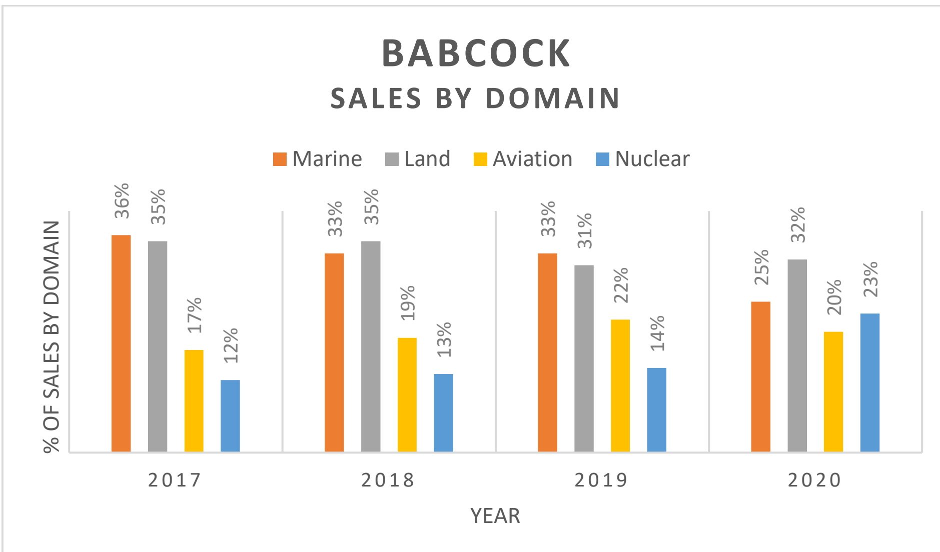

Figure 15. BABCOCK, sales by domain

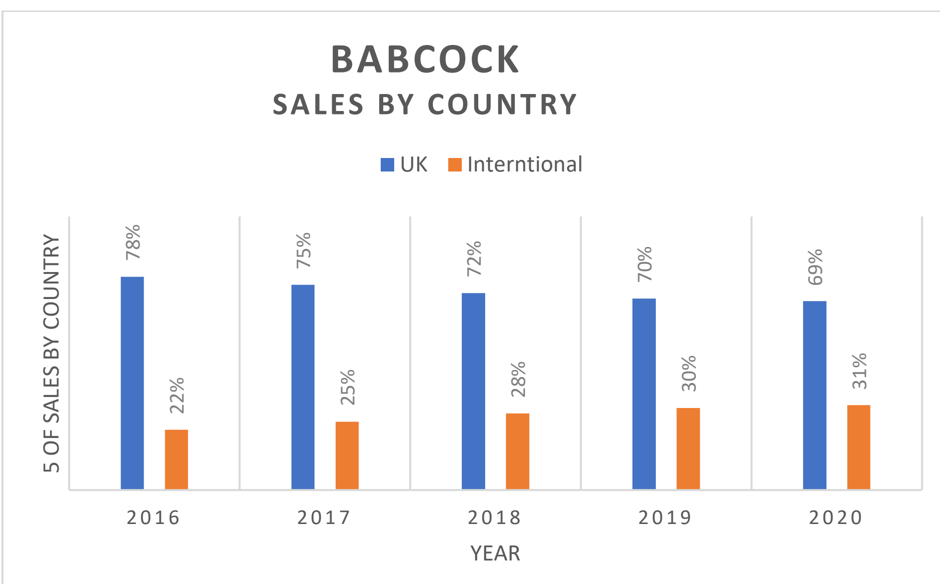

Figure 16. BABCOCK, sales by country

Evolution of the company's share price and its comparison to last 5-year FTSE100 index is as in Figure 17. It can be observed that BABCOCK share price has consistently underperformed FTSE100 behaviour, with a tendency that seems to be continuously drifting away and below the index. One minor exception could be placed in September 2019, when it was announced that the company had won T31e bidding process. However, at the same time, after 4 years of stable earnings, the company reported in 2020 losses for 164.9 M GBP, putting an early end to the improving trend.

Company's valuation and market cap have decreased accordingly to the low performance share price, as can be observed in Figure 18.

Figure 17. BABCOCK share price v/s FTSE 100 (source: google finance)

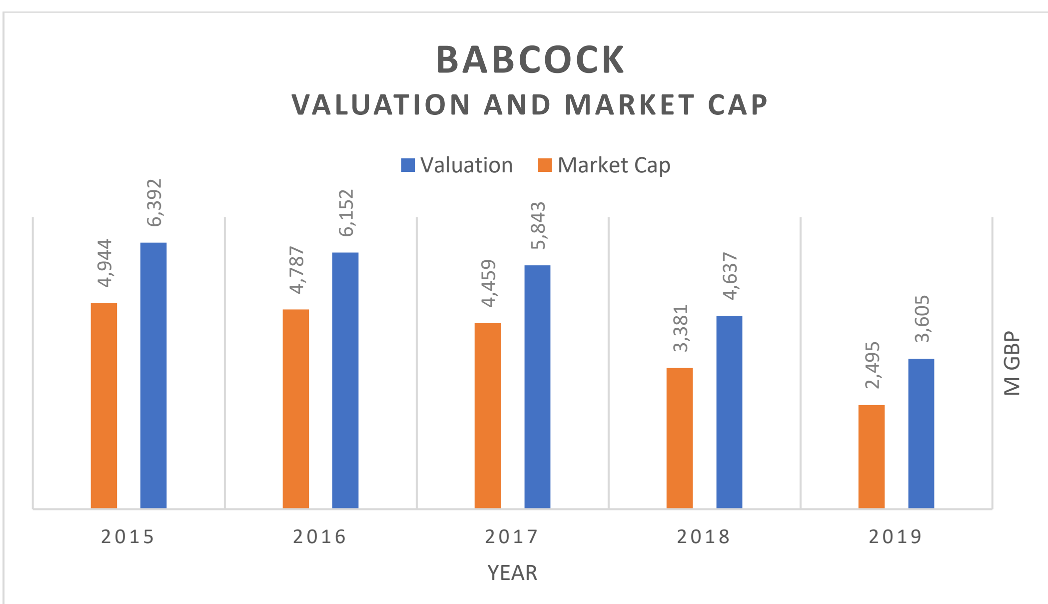

Figure 18. BABCOCK Valuation and Market Cap

4.1.3 INFRASTRATA (FORMER HARLAND & WOLF)

London based renewable energy InfraStrata took over Harland & Wolff in December 2019 at a cost of 5.5 M GBP (INFRASTRATA PLC, 2019), following a strategy to secure in-house industrial facilities to build components for manufacturing parts for renewable energy devices at lowest cost possible.

This happened after the shipyard, that had already been working in Renewable Energy related tasks for some years, declared losses for over 6.0 M GBP on year 2016 (Irish News, 2017), which caused the company to be put into administration.

In another audacious move, the company acquired former Babcock Installations at Appledore, North Devon, in August 2020, by 7.0 M GBP (Neate, 2020). Obtaining this asset only reinforces the company's intentions towards continuing to provide services in the areas of Ship Repair, Ship Conversion and Offshore Industries, using Belfast installations for large vessels (length over 300 [m]) and Appledore for smaller platforms (less than 120 [m]).

Performance of InfraStrata share against FTSE100 in last 5 years can be observed in Figure 19. The company has not been able to keep up with the index performance; however, it is still interesting to notice how the share gained value late 2018, due to the expectations raised by Harland & Wolff's acquisition; however, by mid-2019 it had already lost most of the earned price. A similar behaviour can be appreciated on second half 2020, where effects of Appledore´s purchase over share price can be slightly appreciated.

This phenomenon can also be observed on the companies' Valuation and Market Cap in last 5 years, in Figure 20. At this point, it is unclear if long term Valuation will continue to raise as in period comprising 2018-2019, since current share price of 40.0 GBP/share suggests that investors might not be fully convinced about company's potential yet.

Nevertheless, short time valuation has raised to nearly 16.0 M GBP after purchasing former Babcock´s North Devon installations.

Figure 19. INFRASTRATA share price v/s FTSE 100 (source: google finance)

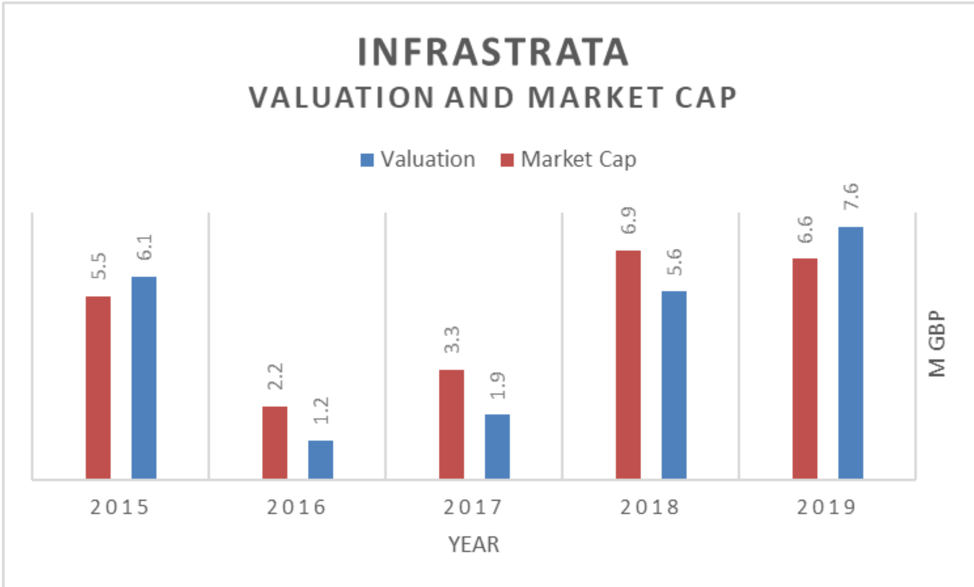

Figure 20. INFRASTRATA Valuation and Market Cap

Share price performance of the three analysed PLC's in the last 5-year period against FTSE100 is as in in Figure 21. BAES has outperformed the index by over 17.0%, whilst BABCOCK and InfraStrata have both underperformed by over 70.0%.

Figure 21. PLC share price v/s FTSE 100, 5-year period (source: Thomson Reuters)

4.2 Private Companies

Private companies' status is evaluated constructing a table with key financial ratios, using the information provided on their annual reports.

Key financial ratios have been determined by those determined as essential by Hulme & Drew (Hulme & Drew, 2020). They comprise three categories, namely: Profitability, Gearing, Liquidity and Efficiency.

4.2.1 BMT

Unlike other companies analysed, all of them directly involved in Shipbuilding/Ship repair, BMT is a company that focuses on vessel design and process efficiency; officially born in 1985, from the fusion of British Ship Research Association and the National Maritime Institute, it has been involved in nearly every UK naval shipbuilding project since WWII. It currently provides work to over 1,000 employees worldwide.

Its ratios can be observed in Figure 22, Figure 23 and Figure 24. All of them are positive and stable, with which confidence in the future of the company. It is especially worth to notice that despite a significant drop in GM from 2017 to 2018, profit before tax is still strong and growing.

Declining ROCE should indicate that there is space for the company's assets to provide more earnings.

Unfortunately, 2019 annual report is still not available, precluding the inclusion of what otherwise would have been a very interesting year to analyse.

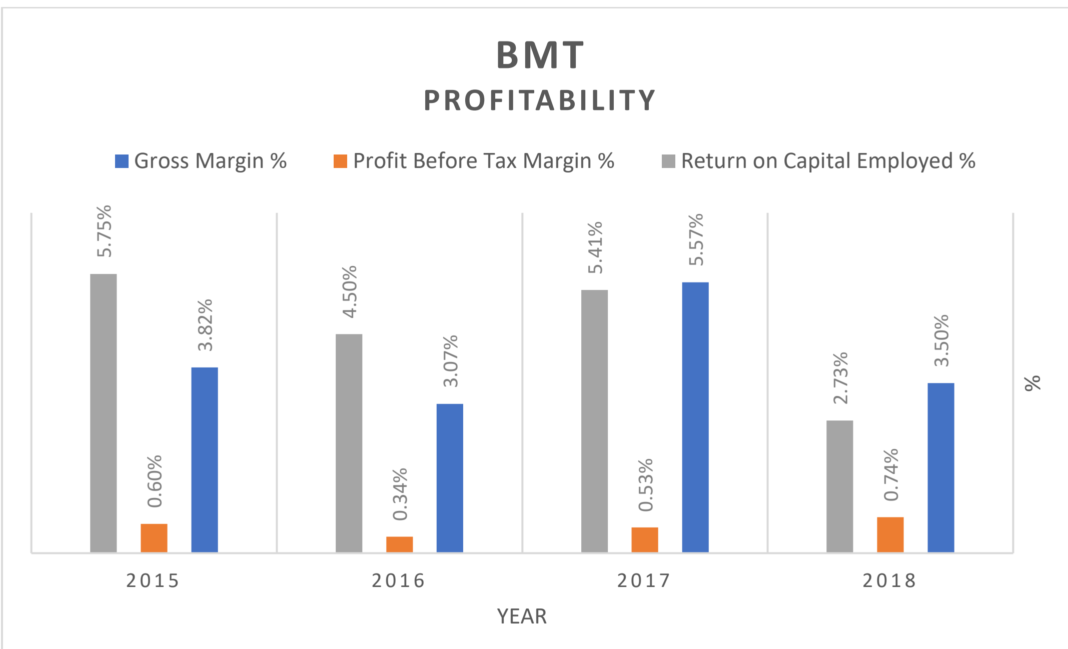

Figure 22. BMT Profitability ratios

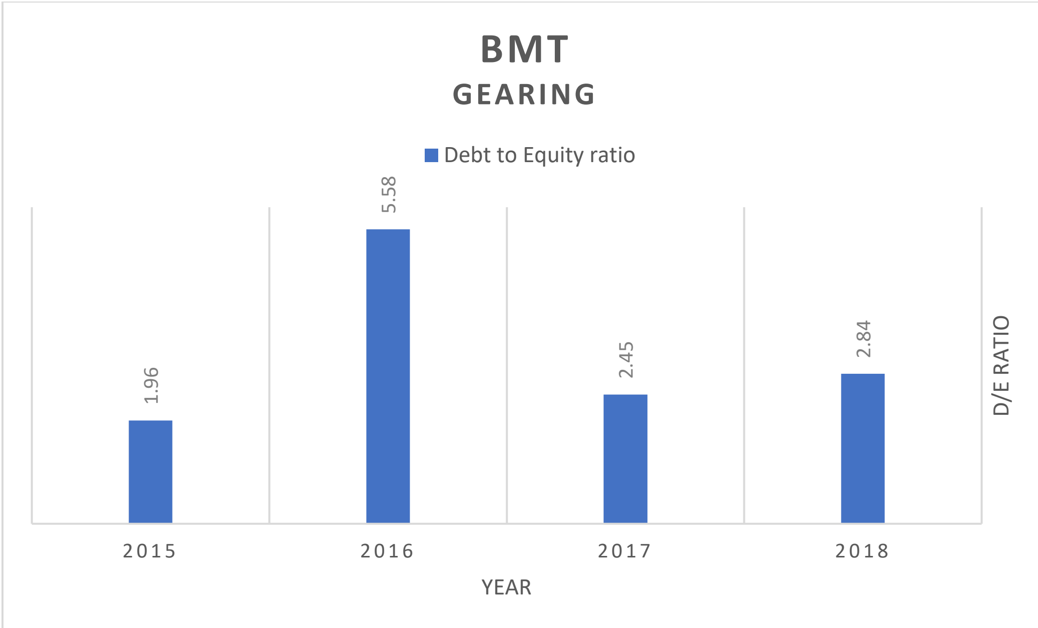

Figure 23. BMT Gearing ratios

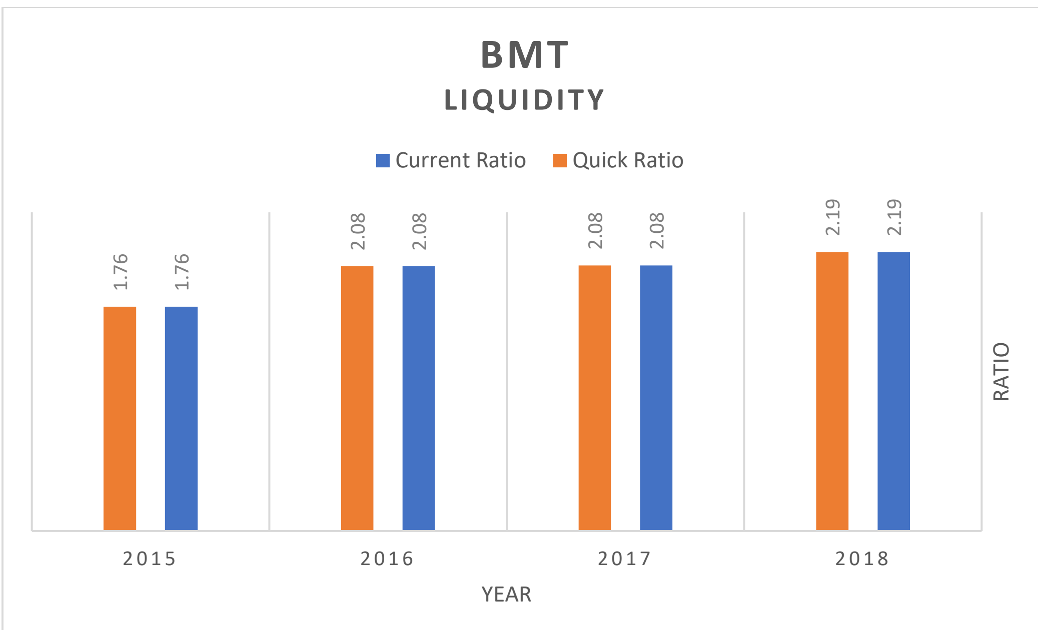

Figure 24. BMT Liquidity ratios

4.2.2 CAMMELL LAIRD

Company's origins trace back to 1860, and its headquarters are located at Birkenhead, Merseyside. After installations were closed in 1993, they reopened in 1997 after being purchased by A&P, company that sold these facilities in 2007 to North Western Ship Repairers & Shipbuilders.

Company's ratios can be observed in Figure 25, Figure 26 and Figure 27. It is sufficiently clear how the company's performance sharply dropped from 2018 to 2019 in every aspect, because of what has been explained as over costs incurred due to "design, production and supply chain issues" in the building of RSS Sir David Attenborough (Cammell Laird, 2019), which will be further discussed on following chapters.

It is concerning that not only company's profit has been greatly affected, but also gearing and liquidity to the great extent. This last parameter has dropped to a value under 1, casting doubts about its short and midterm solvency.

The company teamed up with BAES in the bid for T31e frigate program; however, BABCOCK team was awarded the contract, and therefore, it is unlikely that the company will be able to secure any income as a subcontractor related to this project.

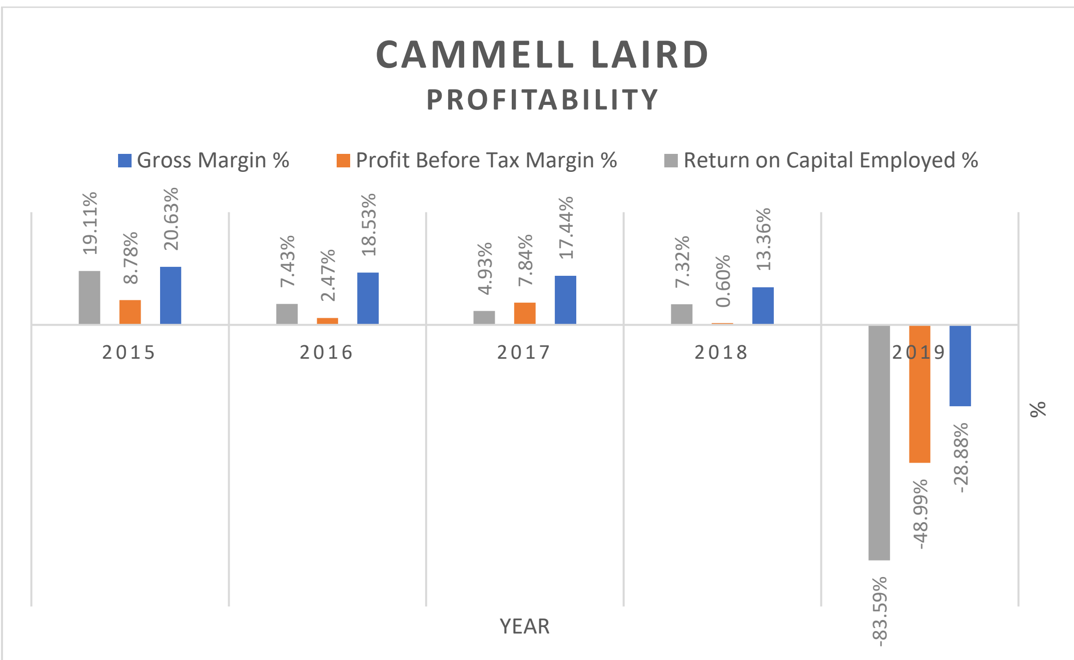

Figure 25. Cammell Laird, Profitability ratios

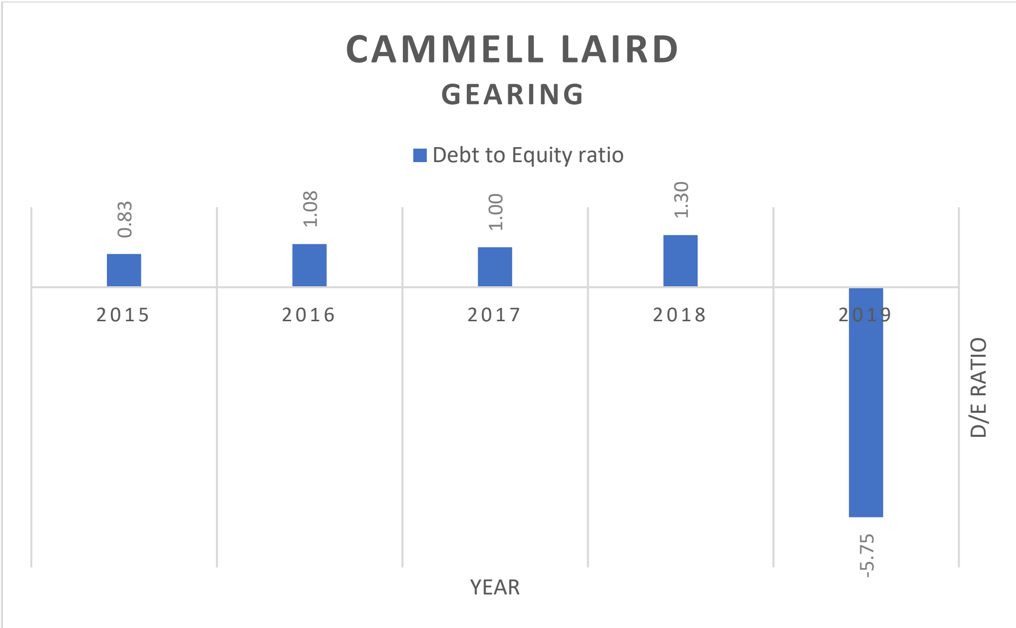

Figure 26. Cammell Laird, Gearing ratios

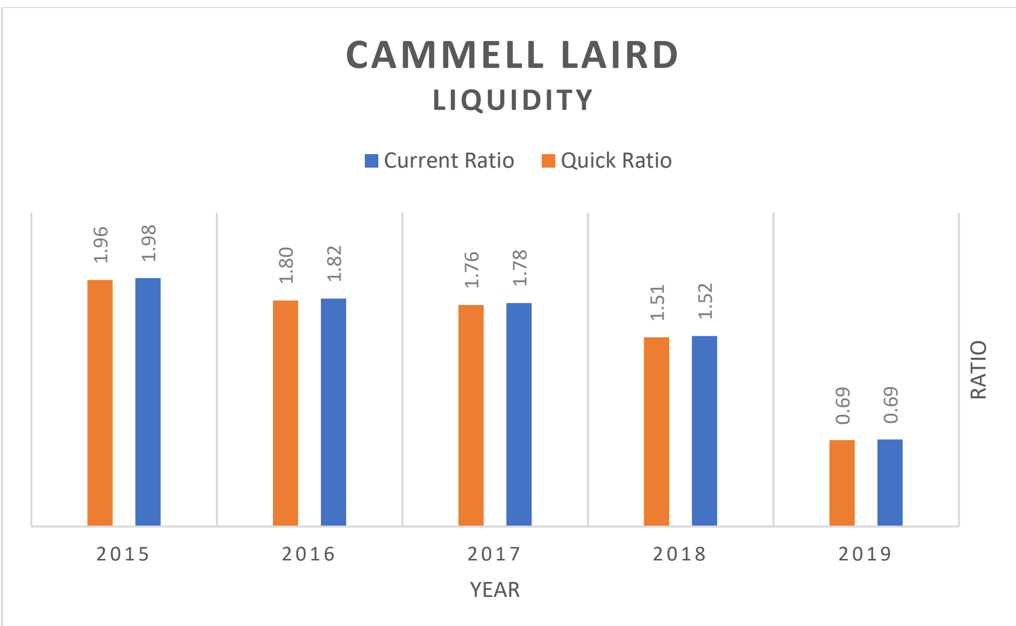

Figure 27. Cammell Laird Liquidity ratios

4.2.3 A&P

The company was founded in 1971 and operates three sites, namely Tyne, Tees, and Falmouth, where core activities are ship repair and marine engineering, being able to attend ships operating in South West and North East of England.

Company's ratios can be observed in Figure 28, Figure 29 and Figure 30. The operational balance achieved by the company is remarkable, allowing it to sort an especially challenging 2017, when it reported losses before taxation of 0.1 M GBP, due to a late start on projects relevant for the company and business volatility (A&P Group, 2019).

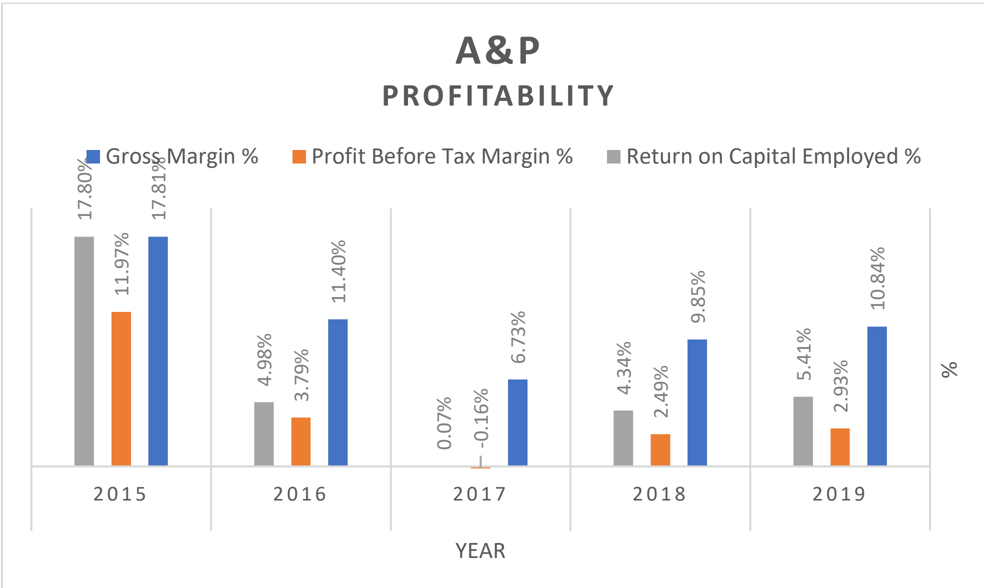

Figure 28. A&P Profitability ratios

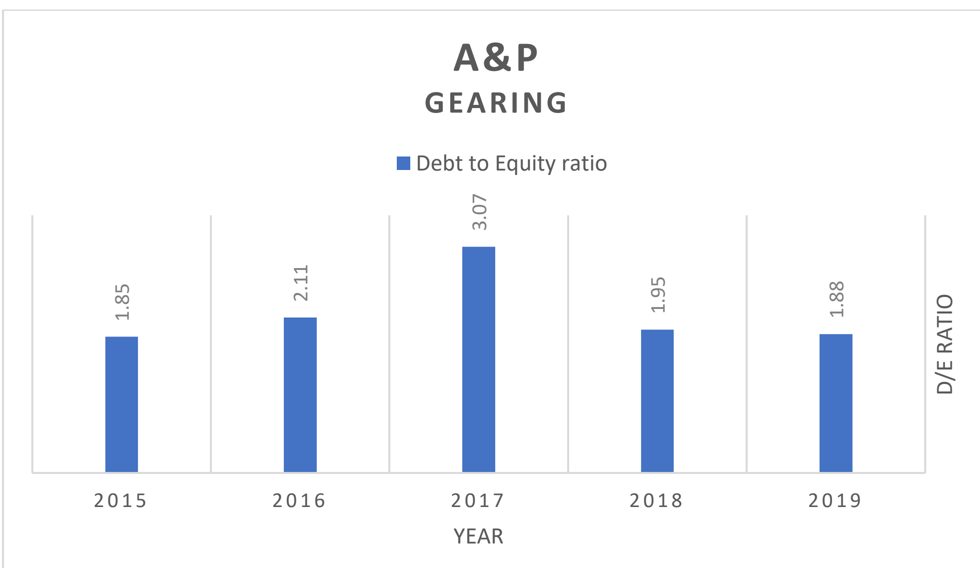

Figure 29. A&P Gearing ratios

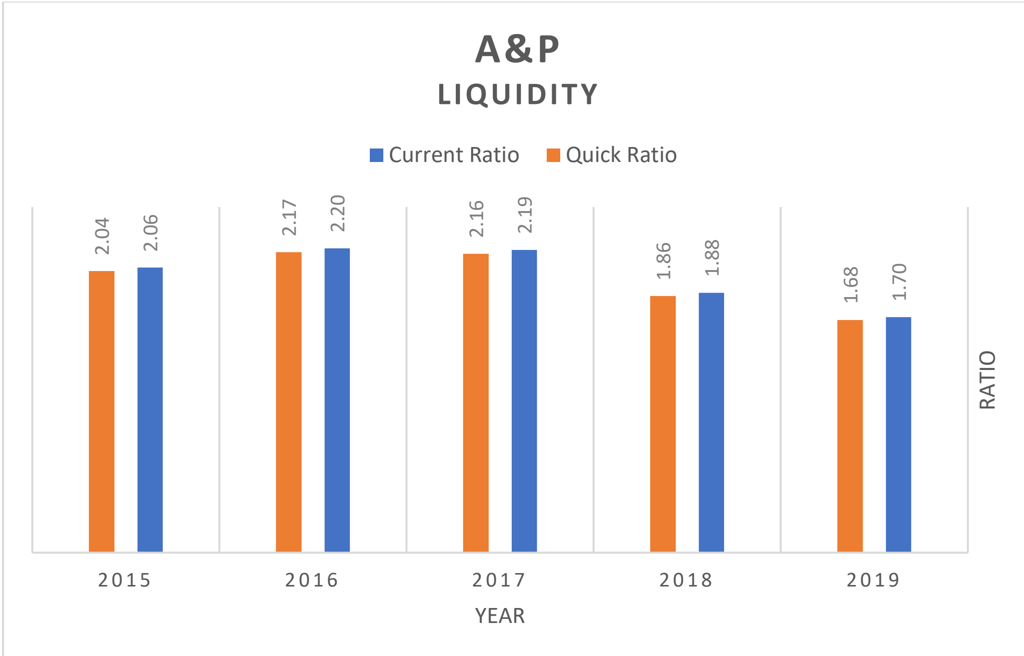

Figure 30. A&P Liquidity ratios

4.2.4 FERGUSON MARINE

Ferguson Marine is a company traditionally specialized in Shipbuilding and Ship repair activities, located in Port Glasgow. Only profitability ratios can be calculated for years 2015 and 2016, since no later financial information is available up to date.

The company signed a contract in October 2015 with Caledonian Maritime Assets Ltd, for building hulls 801/802. Project´s performance was heavily affected by over costs, causing losses of over 45 M GBP in 2016 exercise, which can be appreciated in that year's profitability's ratios.

The company was nationalized by the Scottish government in August 2019.

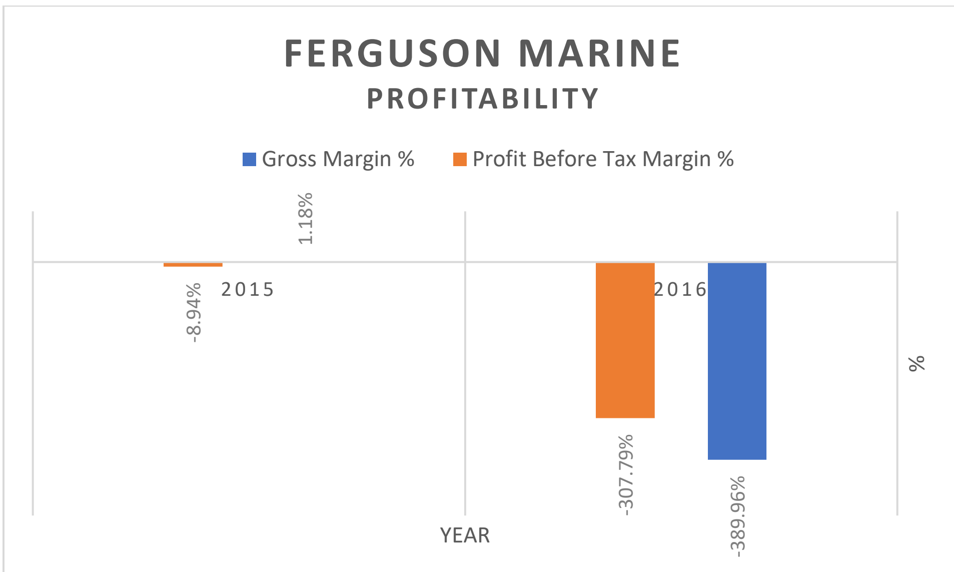

Figure 31. Ferguson Marine Profitability Ratios, 2015-2016

4.3 Benchmarking between UK enterprises

In this section, analysed companies are compared using their calculated ratios in all three categories, namely profitability, gearing and liquidity.

4.3.1 Profitability

From a profit perspective, the industry average for the gross margin percentage in the last 5 years is 19.24%. As can be observed in Figure 32, BAES has a significantly higher GM than all the other enterprises; however, this can be attributed to several factors, among the more important ones the fact that most of its income comes from operations outside the UK and its lower dependence on the maritime sector (see Figure 12 and Figure 11).

Despite this difference, profit before tax and return on capital employed are quite similar among all companies, with an average of 2.61% and 5.07% respectively (see Figure 33 and Figure 34).

In all graphics, financial detriment faced by Cammell Laird, declared in its 2019 annual report, can be clearly observed. As previously explained, this poor performance has been declared to be a consequence of over costs on the building of RSS Sir David Attenborough (Cammell Laird, 2019).

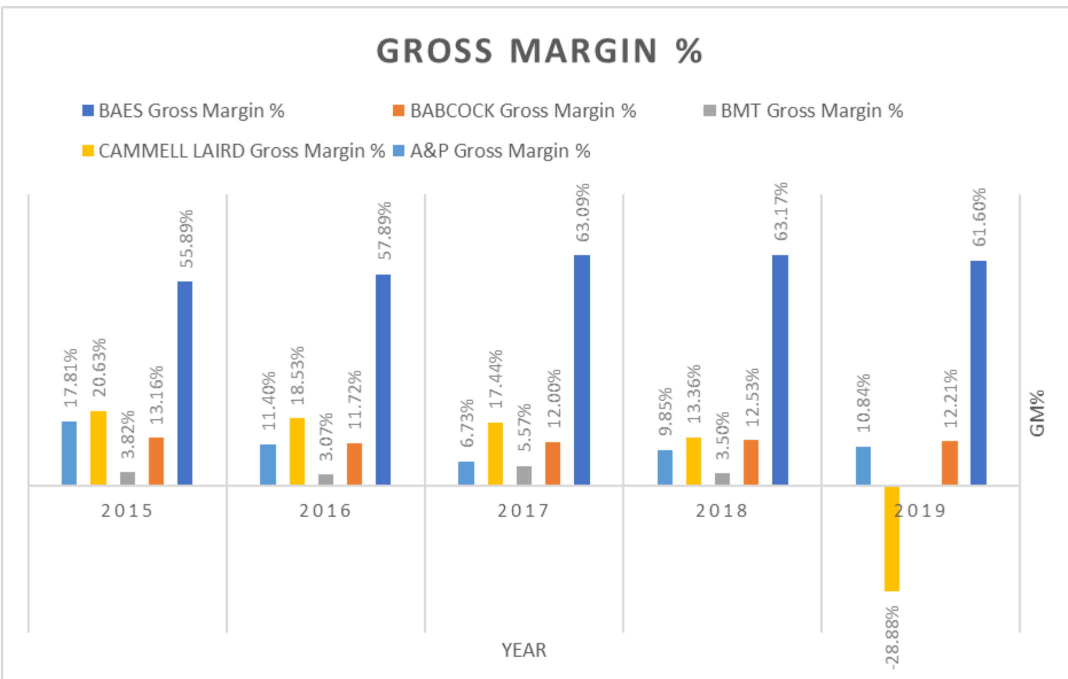

Figure 32. Gross Margin Percentage, UK Companies

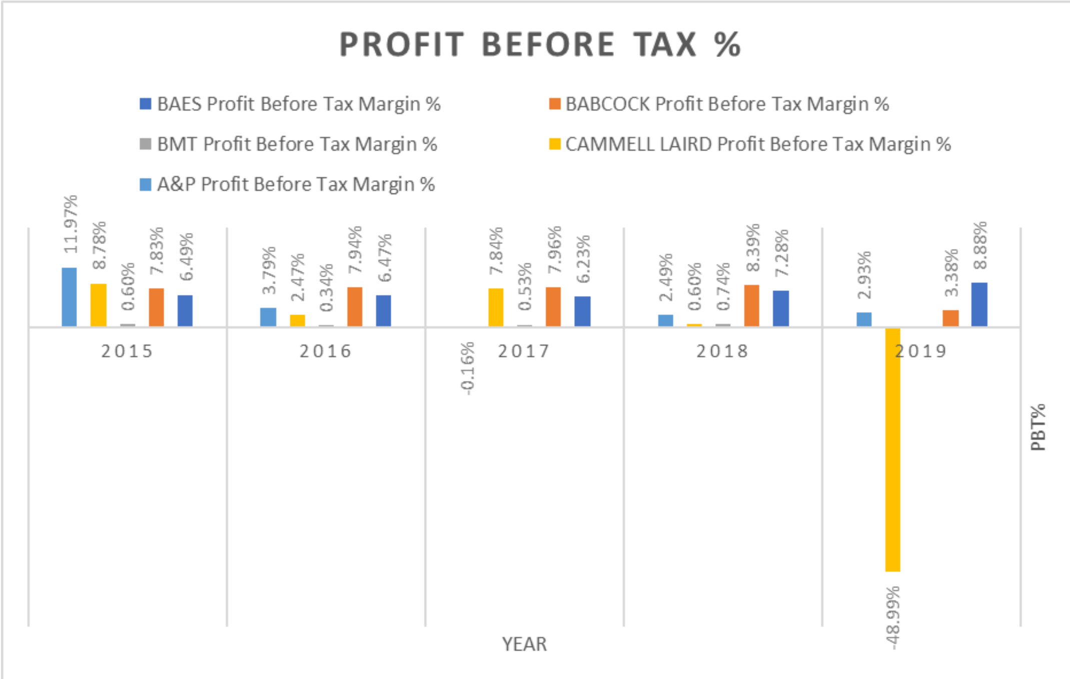

Figure 33. Profit Before Tax Percentage, UK Companies

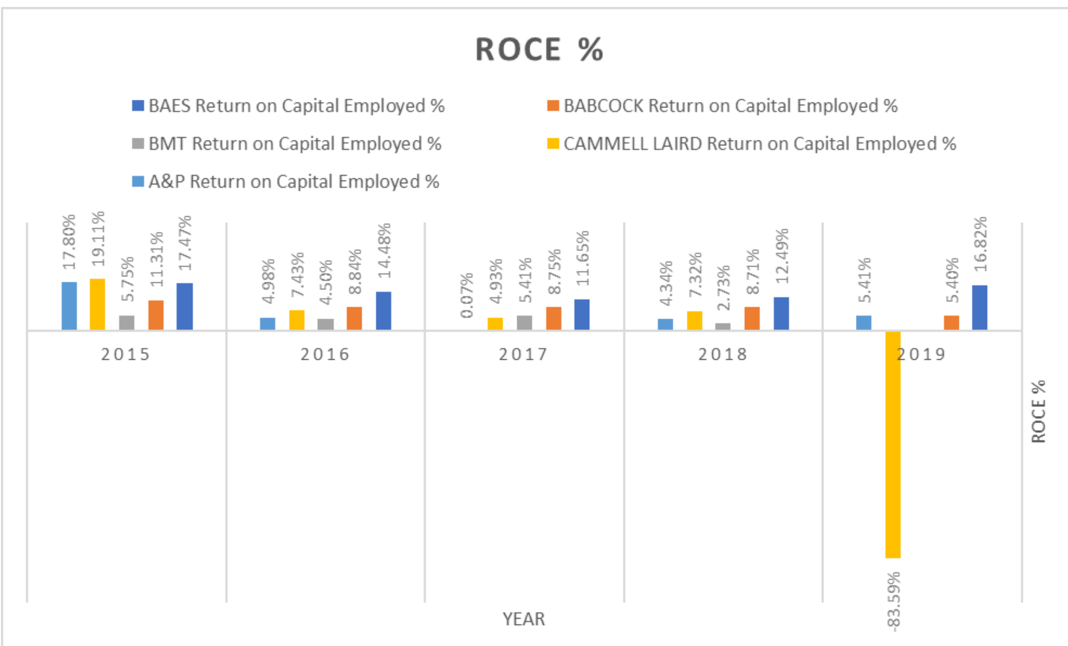

Figure 34. Return Over Capital Employed, UK Companies

4.3.2 Gearing

Debt to Equity ratio average for analysed companies is 1.34. Regarding this index, it is interesting how smaller companies, as BMT and A&P tend to have a stronger gearing than larger size ones, as BAES and BABCOCK, both with values well below one, as can be observed in Figure 35.

Among probable causes, there is that companies of a lower value might be awarded less credit than its counterparts, that can work on a highly leveraged scheme, boosting their profit by using external cash to finance their operations. However, this modus operandi leaves them in a more uncomfortable position for addressing challenges as those imposed by external crises, as COVID 19 circumstances.

Once again, the weak position of Cammell Laird can be evidenced when compared to its peers.

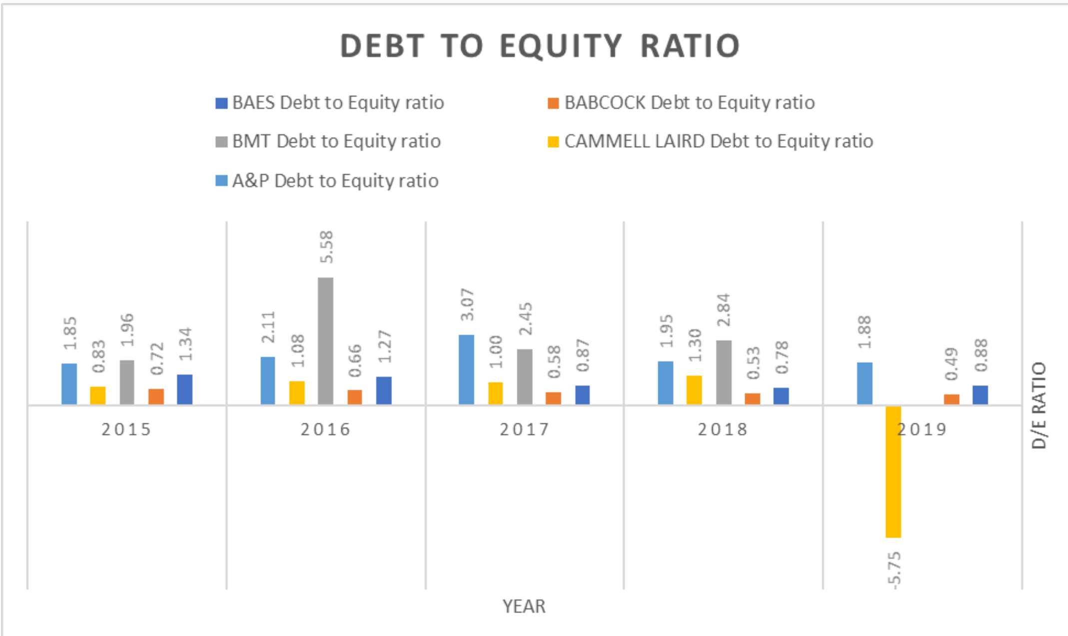

Figure 35. Debt to Equity ratio, UK Companies

4.3.3 Liquidity

Current ratio and Quick ratio averages are 1.50 and 1.45 respectively, meaning that most companies have been in a safe position to cover their short-term debt in case of adversity. A&P and BMT ratios here are well above average for every year, making these mid-sized companies stable even in the most uncertain scenarios.

One good aspect is that current ratios and quick ratios are very close to one another, meaning that there is no overpricing of companies' stocks.

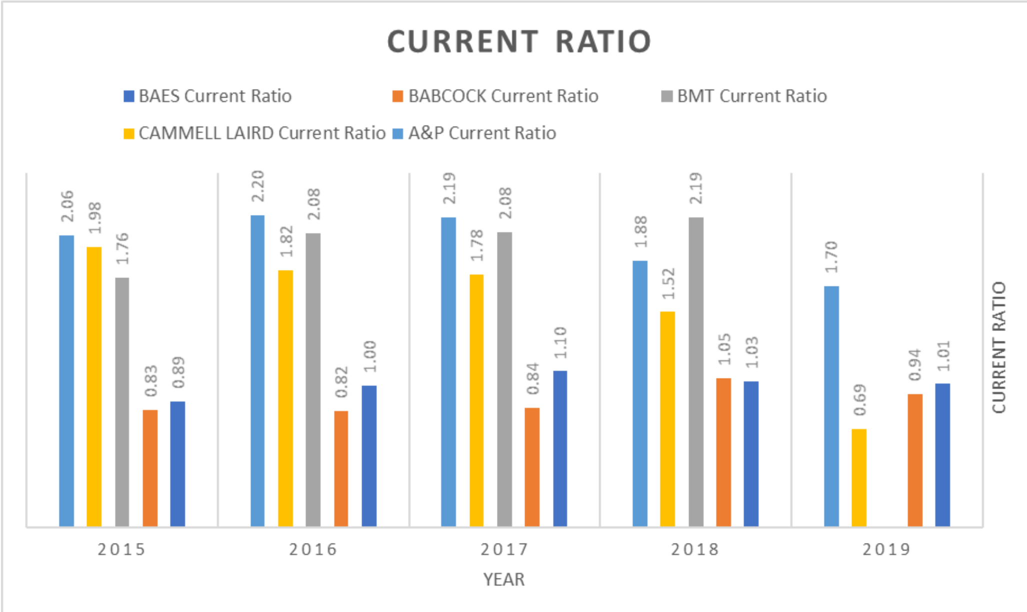

Figure 36. Current ratio, UK Companies

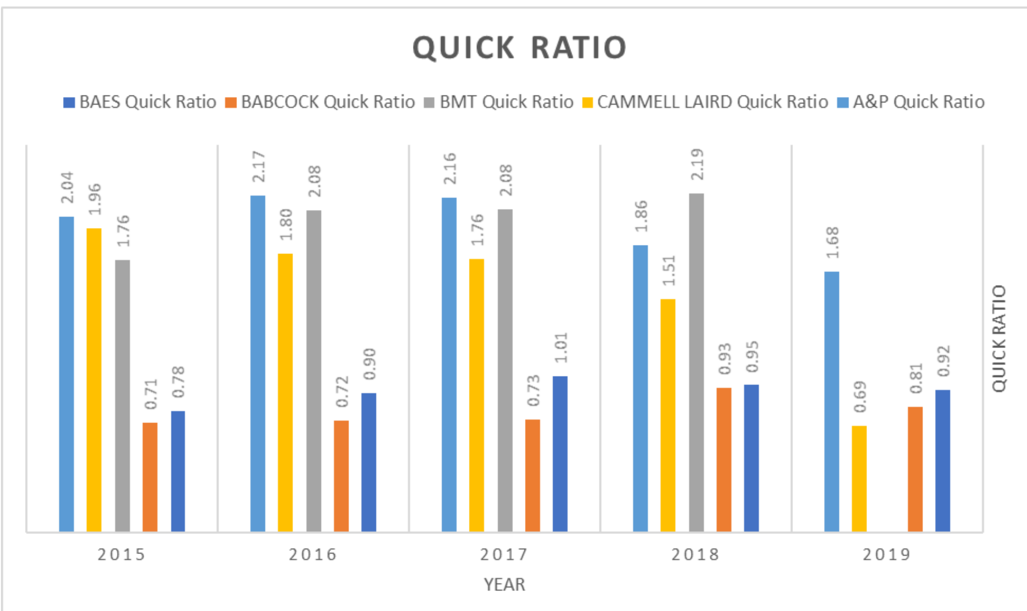

Figure 37. Quick ratio, UK Companies

4.4 Conclusions and Remarks

Based on the comparison of ratios, it can be stated that, from a financial perspective, only two companies are improving their performance, namely BAES and A&P. A&P's case looks particularly interesting, since it is a mid-size enterprise that has managed to consistently produce a positive slope on profit before margin percentage (see Figure 28), which might be in part attributed to its diverse portfolio, relying not only on defence projects, but also on civilian ones.

BMT's financial status can be described as a stable operational balance, with consistent ratios over analysed period.

Finally, Babcock, Cammell Laird, Infrastrata and Ferguson Marine performance has shown to be declining, due to different reasons. To the author's opinion, in Babcock´s case it is especially interesting to notice how share price slightly increased when news announced that the company was the winning bidder for T31e project, only to start its declining movement once again few months later.

This could be a sign that public still has reasonable doubts about future performance, despite the company's securing a contract worth half of its valuation.

From other perspective, in the absence of more accurate information, it is possible to compare UK's profit before tax margins from 2015-2019, calculated in this study (see Figure 33), with EBITDA margins of European shipyards reported on OECD's 2017 report (OECD, 2017).

Neglecting the slight period misalignment, it can be noticed that Profit before tax average for UK companies of 2.16%, should be placed in an area between OECD´s average and lower quartile (OECD, 2017).

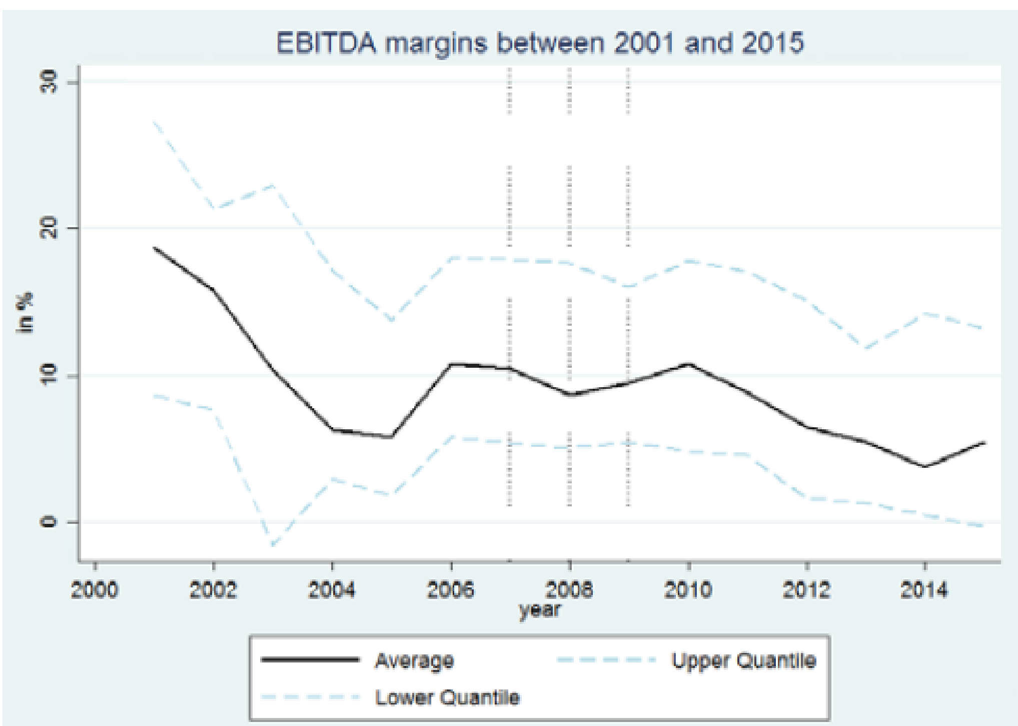

Figure 38. EBITDA margin for Shipbuilding companies from 2001-2015

5. Risks Associated to Naval Shipbuilding Projects

Project theory describes the risk process management process as the interaction of four iterative stages, namely Identification, Assessment, Response Planning and Track and Control, as observed in Figure 39 (Nicholas & Steyn, 2017).

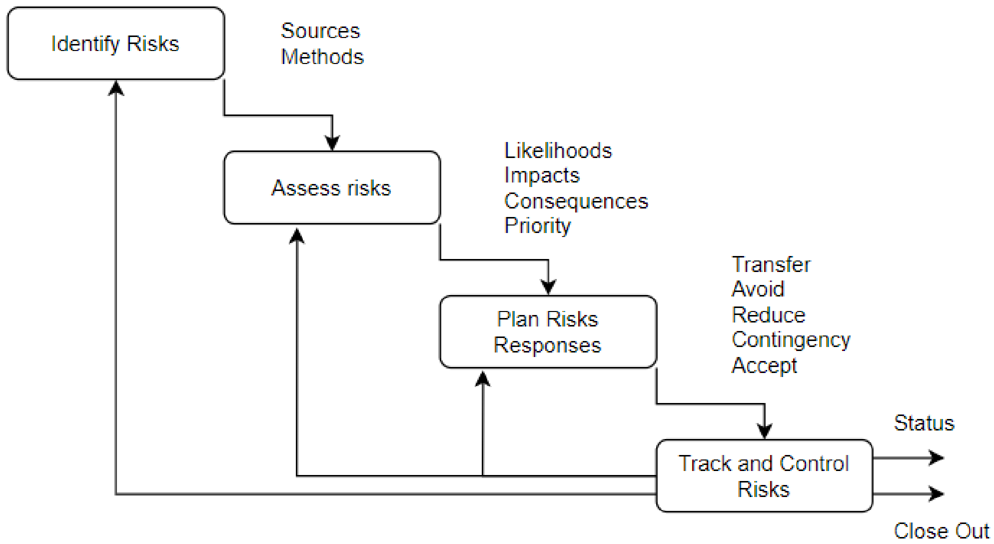

Figure 39. Risk management elements and process (Nicholas & Steyn, 2017)

This procedure is a common practice in shipbuilding related companies; however, little research has been done to have a more general perspective in UK Naval Shipbuilding field, not restricted to a single project or a single company, but accounting for a broader scope of experiences.

Therefore, research performed by expert teams on foreign industries was used to identify the most relevant sources of risk that could be applicable to UK's reality.

A US Defence generated paper was selected to detect risks presents in Naval Ship Design stage, since the US Navy is undoubtedly among naval powers with largest fleets, where design innovation has an important role, as can be witnessed in the development of programs that can be deemed as highly technically challenging, as DDG-1000 and LCS.

A study based on South Korean companies was preferred as the leading document to estimate the risks associated to the overall shipbuilding enterprise, since it is by a significant margin the most important western shipbuilding country, averaging the delivery of 32.87 M CGT per year in the period comprising 2010-2015, equivalent to 29.3% of world's production (Shih-Liang & Yi-Hung Yeh, 2020).

Both investigations were key to design a survey that allowed to gather the opinions of practitioners belonging to 22 organizations, from several backgrounds and areas of expertise.

5.1 Naval Ship Design

Defence System Management College has developed through the years numerous procedures to assess Risk Management in Acquisition Projects managed by the Department of Defence of the US (DSMC, 2001).

It has a primary definition of 13 areas of Risk, as in Figure 40.

Based on that definition, Brown and Mierzwicki published an investigation to assess on risk management, specifically aimed to the Design of Complex Naval Ships (Brown & Mierzwicki, 2004).

Among other tasks, they elaborated on the specific risks concerning each of the previously defined categories, giving origin to a Structure for the process consistent of 43 risks. The complete list is provided in Appendix A

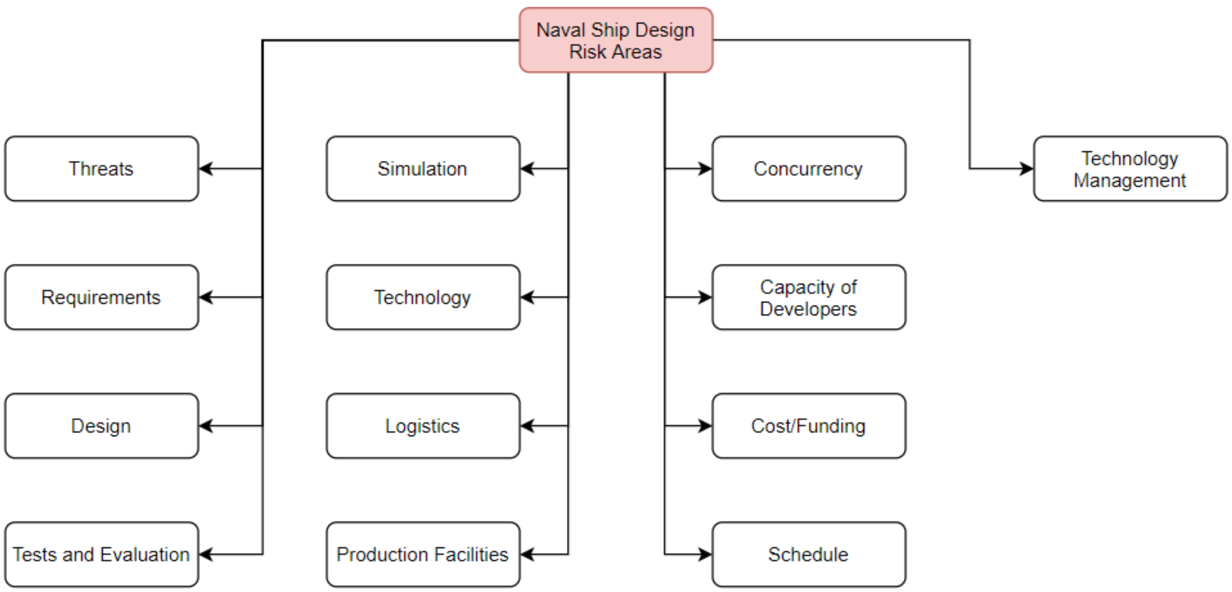

Figure 40. Naval Ship Design Risk Areas

5.2 Shipbuilding Enterprise

Lee, Park and Shin (Lee, et al., 2009) developed a model to manage risks on large engineering projects in year 2009, based in Korean Shipbuilding Enterprise. In one of the steps, the team identified the most relevant risks associated to the Design and Construction Process, by interviewing several key players in Korean Industry.

This process led to the identification of 26 risks, divided into 8 Risk Areas, as in Figure 41 The complete list of risks identified by Lee, Park and Shin is provided in Appendix A..

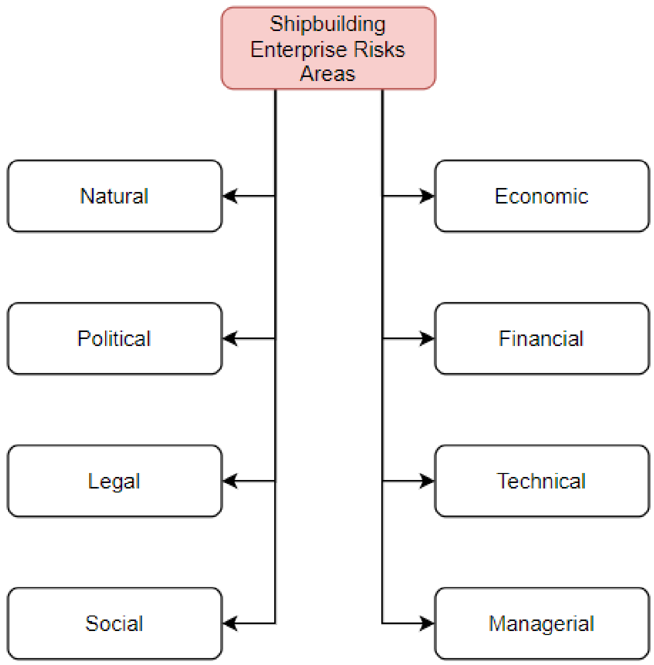

Figure 41. Shipbuilding Enterprise Risk Areas

5.3 Survey Design

To establish the relevance of identified risks identified by literature, a survey was designed, comprising the two areas identified on previous paragraphs. Risks that are not within the scope of the undertaken student program were not included (i.e., natural risks, as earthquakes, or social risks, as riots), a measure that aided the reduction of the survey's length, making it more attractive to the public.

This process generated a Risk Classification Scheme as in Figure 42, where numbers in brackets are the number of risks being addressed in each category.

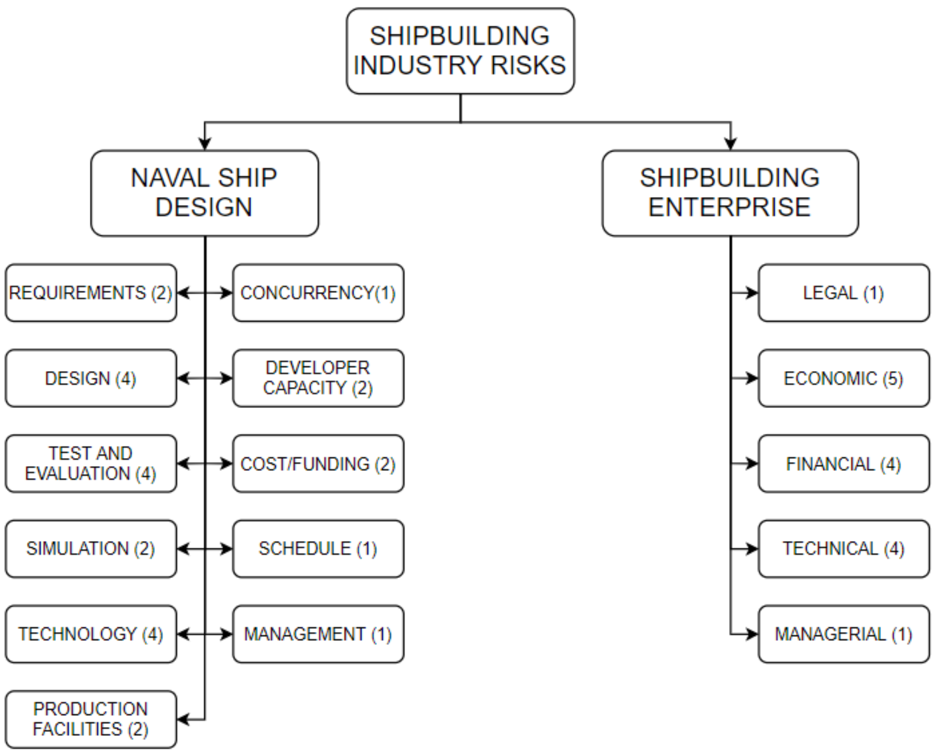

Figure 42. Risk Areas for Survey

6. Identification of Relevant Risks

Before addressing the data provided by the survey, it is worth to comment on its estimated statistical significance.

In this regard, the only quantitative comparation that can be mentioned is that, in total, 126 answers were received, a number that almost triples the 45 participants on Lee, Park and Shin's referenced investigation. No comparison can be done with Brown and Mierzwicki, since the risks they addressed were not taken from interviews, but from US defence standard procedures.

From a different perspective, it can also be mentioned that professionals from over 20 national and international companies contributed with their answers, from corporations such as BAES, Babcock, BMT, ASMAR, OMT, and many others.

In the author's opinion, this diversity contributes to enhance the quality of the answers, since a broad spectre of professional backgrounds, production methods and organizational practices are addressed.

Other aspects such as nationality, role in their respective organization and area of expertise are commented in 6.1; normalized answers are provided in 6.2.

6.1 Characterization of the respondents

Distribution of participants per country is as in Figure 43. Within category "Other" there are representatives of locations as diverse as New Zealand, Ecuador, Finland, France, Germany, India, Italy, Nigeria, Norway, Pakistan, Philippines, Portugal, Qatar, and Turkey.

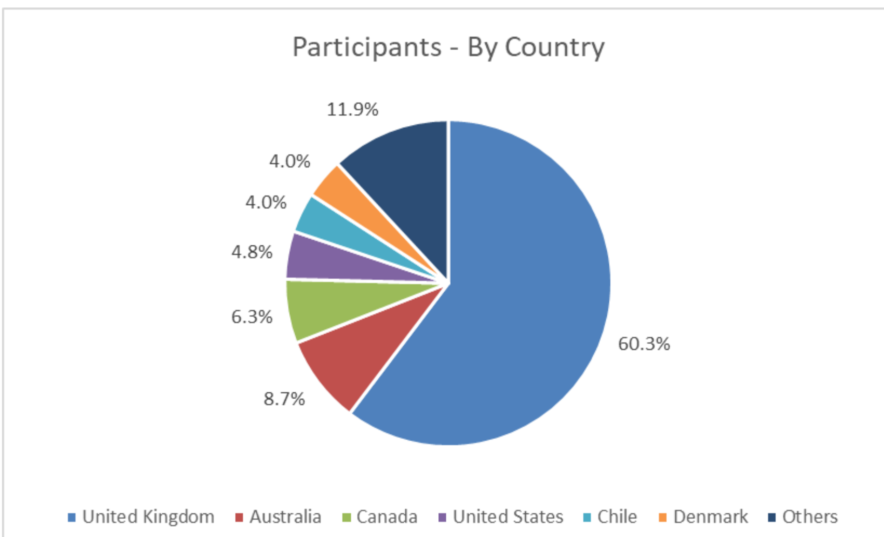

Figure 43. Participants by country

When asked about which part of the life cycle of a Ship participants are involved in, more than 80% of the respondents are comprised within 3 areas: Ship Design (32.1%), Ship Building (26.3%), and In-Service Support (24.7%). This is deemed as a good combination since several shipyards, and especially those most vulnerable, need to rely in a combination of Ship Building and Ship Repair activities.

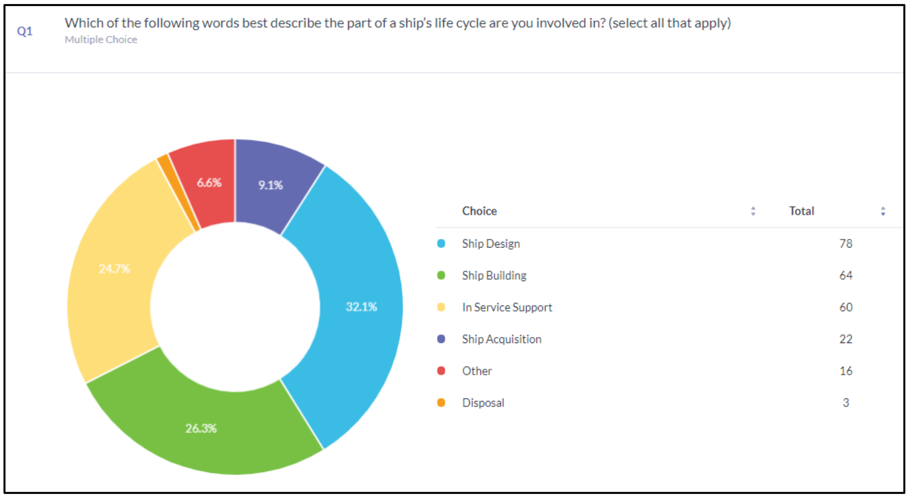

Figure 44. Participants by life cycle within Shipbuilding enterprise

Regarding participant's field of work, close to 80% are characterized within 5 major fields, namely: Ship Production and Manufacturing (26.3%), Consultancy (22.1%), Ship Refit and Repair (16.7%), Research (9.6%) and Equipment Suppliers (5.0%).

It is also worth noticing that only 6 participants report to perform Administration or Finance duties. This may influence the low relevance given to Financial and Economic Risks that will be discussed on further paragraphs.

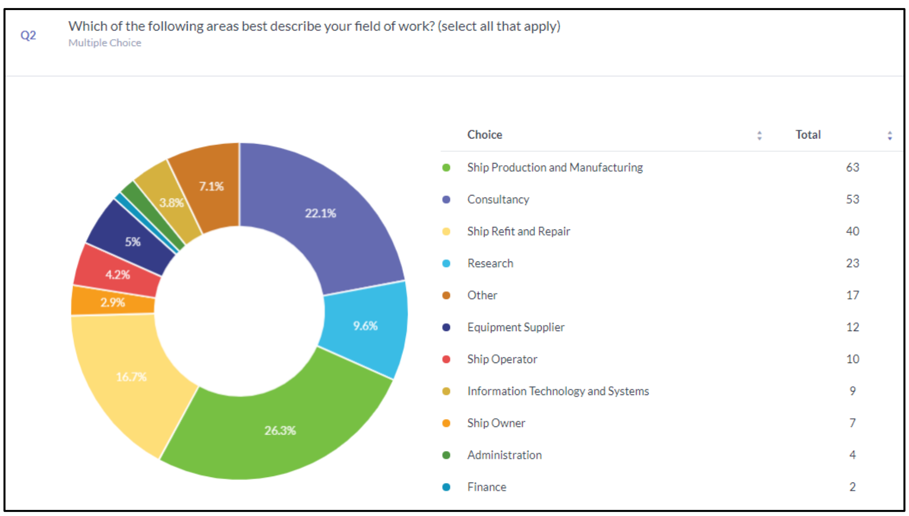

Figure 45. Participants by field of work

There is a wide spread of roles within participants organizations; over 80% are within 6 categories, namely: Engineers (22.8%), Head of Departments (13.4%), Managers (13.4%), Technical Specialists (11.8%), Directors (11.0%), and Project Managers (8.7%).

This combination is again deemed to provide a good set of different approaches to the posssed questions.

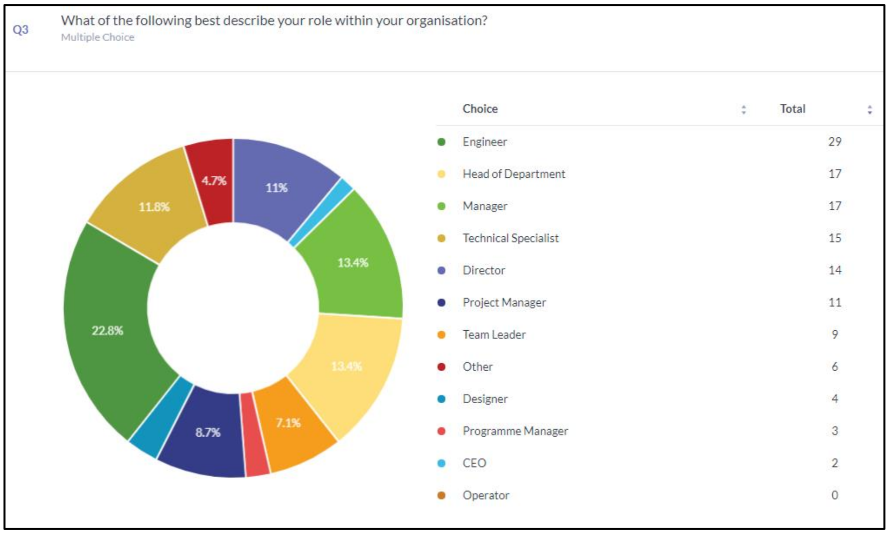

Figure 46. Participants by role within the organization

When asked about the type of Ship participant's experience relates to, every defined category is deemed as significant, being dominated by Naval Ships (42.5%), and followed by Special Purpose Ships like Submarines, Polar, Ro-Ro, Ro-Pax and Fishing Vessels, (15.1%), Passenger Ships (9.9%), Offshore Ships (9.5%), Tankers (8.7%), Container Ships (7.5%), and Bulk Carriers (6.7%).

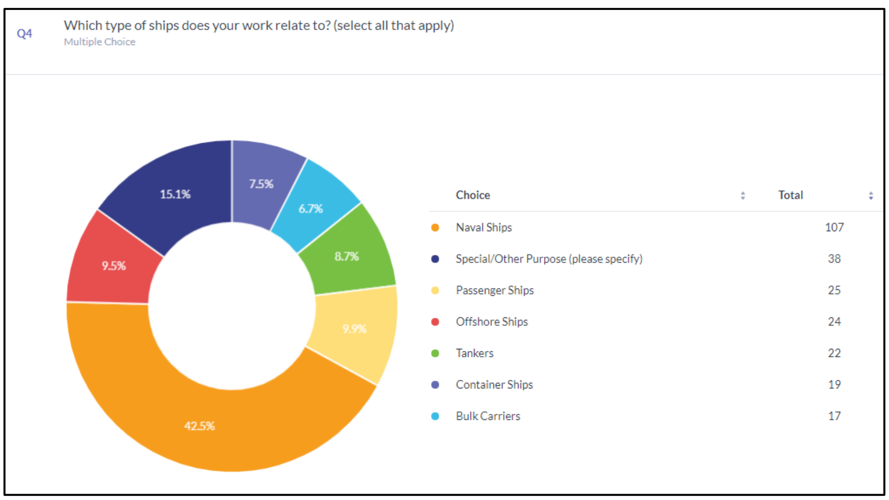

Figure 47. Participants by area of expertise

6.2 Interpretation of Results

Answers to survey's question average scores have been normalized to gain understanding of the statistical behaviour of the sample, resulting in a curve as observed in Figure 48.

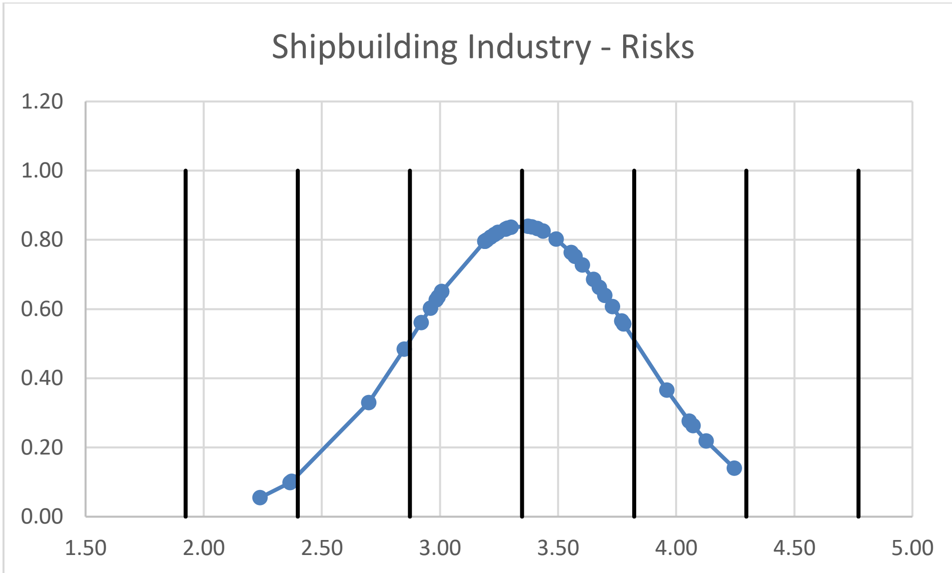

Figure 48. Normal Distribution for Risks in Shipbuilding Survey

Highest and lowest rated risks are as in Table 10 and Table 11 respectively. To qualify in one of them, individual's risk average needs to be more than one standard deviation below/above overall mean.

Table 10. Highest relevance risks

Mean	SD	Question/Risk
3.96	0.37	Q13 - COST/FUNDING: (Realistic cost objectives not established early)
4.06	0.28	Q5 - REQUIREMENTS: (Operational requirements are not properly established or vaguely stated)
4.07	0.26	Q5 - REQUIREMENTS: (Requirements are not stable)
4.13	0.22	Q20 - MANAGERIAL: (Budget is exceeded and does not go according to plan)
4.25	0.14	Q19 - TECHNICAL: (Changes in design)

Table 11. Lowest relevance risks

Mean	SD	Question/Risk
2.24	0.05	Q17 - ECONOMIC: (Unexpected significant changes in taxes)
2.37	0.10	Q18 - FINANCIAL: (Changes in company's credit ratings)
2.37	0.10	Q17 - ECONOMIC: (Unexpected changes in inflation)
2.70	0.33	Q18 - FINANCIAL: (Refund guarantee, operating costs, and other difficulties in capital funding)
2.85	0.48	Q17 - ECONOMIC: (Unexpected significant changes in exchange rates)

At this stage, some interesting facts can be highlighted, such as:

- Risk Identification done by selected literature appears to be consistent with the experience of participants in current study, since no risk is regarded as neglectable by a significant portion of the answers; lowest average obtained is 2.24 for "unexpected changes in taxes".
- There are clear separations in between three zones, classified as low, average, and high relevance.

- All risks regarded with the lowest means are within Economic and Financial areas. This is believed to have two possible origins:
    - The number of participants from Financial area is extremely low when compared to the number of them involved in technical areas (see Figure 45).
    - A sense that economic and financial risks are covered by insurance or similar products.

Hence, from this perspective, some of the risks deemed as most relevant are analysed in Chapters 7 and 8.

7. Risk Mitigation, Financial Perspective

Two areas of risks will be dealt with within this part of the study, related to the early calculation of a realistic project/program cost and the stability of the driving operational requirements. These risks do not necessarily address financial risks, but risks that have a significant incidence in a company´s financial performance.

7.1 Realistic costs not established early

The main recommendation here seems to be to adhere to the most conservative process regarding cost estimation and contract times, leading to the signature of a lower risk contract.

Following the orderly path of going from a complete and class approved basic design, to a fully finished detailed design, leading to an acceptable accuracy cost estimation, that will be reflected on contract terms appears to still be the only viable solution to this clear and present risk, that has endangered the life of several shipbuilding enterprises, being run by capable and experienced management teams.

The instauration of this measure as a company policy has been the driver for Chilean Shipyards ASMAR increased financial performance over the last decade, as expressed by its Corporative Business Manager.

In years 2008-2012 the shipyard built several projects that, due to a combination of inaccurate cost estimation and unfavourable contract terms resulted in direct losses of up to 35%; however, introduction of a conservative (and therefore, lengthy) cost estimation process has caused improvements able to secure the state-owned company’s financial viability, as can be observed in Figure 49, through an increasing direct contribution margin of its shipbuilding business branch.

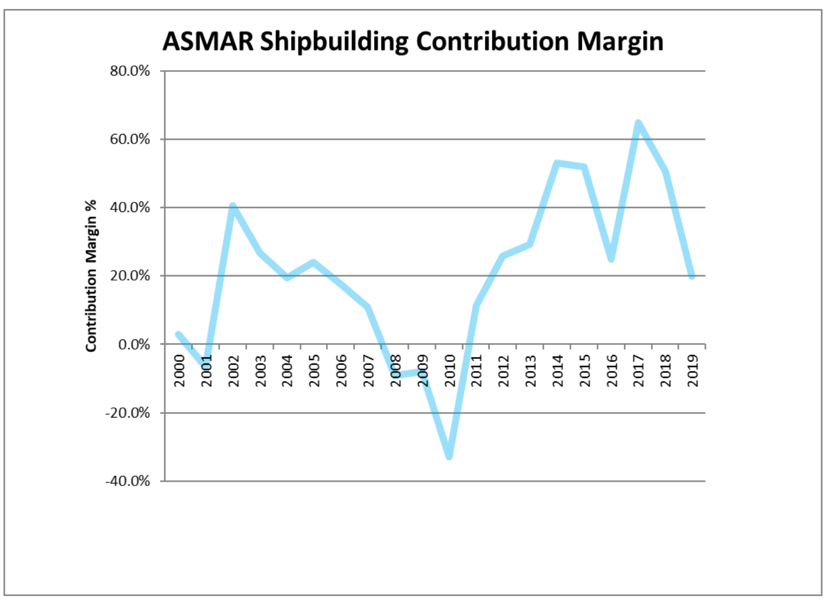

Figure 49. ASMAR Shipbuilding business Contribution Margin, 2005-2019

The relevance of this orderly fashioned process is greater as the project that is to be incurred in is one where the company has little previous experience, and/or in Shipyards facing financial detriment, and/or when their business comprises both shipbuilding and ship repair/maintenance areas.

In this last aspect, it is worth mentioning that the mixture of cultures within an organization seems to shape the response of management teams, being one of the causes of the significantly different cash flow that applies to shipbuilding when compared to in-service support and maintenance/repair business.

In Shipbuilding enterprise, a contractor will use customers payments as the source of work capital. There are substantial amounts of cash transferred on few and well-defined milestones, system that produces an extremely attractive cash conversion cycle, where the contractor has customers capital before doing any expenditure.

As opposed, in Ship maintenance, the contractor normally uses its own capital to pay for personnel and materials, receiving customer's payment only after finishing the task, scheme that implies that the customer gets a short-term credit at zero rate. This is possible due to the lower amounts of cash that are normally involved in this category.

These different behaviours can be summarized as in Table 12

Table 12. Cash Flow Characteristics: Shipbuilding v/s Ship Repair

Parameter	Shipbuilding	Repair – In Service Support
Cash Origin	Customer	Shipyard
Cash Magnitude	Significant	Minor
Cash Conversion Cycle	Benefits the Shipyard	Benefits the Customer
Margins	Very Low (less than 10%)	High (around 50%)

Consequently, from the author's perspective, shipyards incurring in financial hardships are tempted to accept shipbuilding contracts affording great disadvantages well known beforehand by experienced managers, only to allow cash inflow to keep their business running. However, this practice leads almost inevitably to a further financial detriment, since the very low profit after tax average margin of 2.6% for shipbuilding companies (see 4.3.1) makes it extremely difficult to endure mid-term consequences.

This might be the case why Cammell Laird and Ferguson Marine embarked themselves in projects RSS Sir David Attenborough and Hulls 801/802 respectively at extremely low prices, causing the first company to be on an extremely uncomfortable financial position whilst the second had to be nationalized after being put into administration.

To avoid or minimize the social problems and unrest derived from Shipyard's closures (see 2.1), and achieve a balance that can preserve a company's health and provision of labour, it is estimated that a different type of contract could be used on a prototype program, drifting away from the traditional fixed price contract.

Fixed priced contracts are of recognized poor performance on high risk projects (Nicholas & Steyn, 2017), and regarding naval ship construction, they are not deemed to be the only alternative, since these type of platform acquisition is not normally submitted to international bidding processes, that would make their use peremptory.

Fixed priced contracts are normally preferred by Sponsors (e.g., governments), because they give steady figures on future required cashflows, and transfer risks to the contractors; however, the risk asymmetry they impose, i.e., the contractor carries an unproportioned share of the project's risk, in addition to the business´s inherent low margins, often result in major disruptions to all those involved.

Instead, a Fixed Priced contract with Redetermination is suggested. In this form, a base cost is agreed, and escalation provisions for diverse uncertain items, such as potential increases in materials price or labour rates can be specified.

In an advanced form, these provisions could be tied to more complex variables, as uncertainty levels on requirements, number of platforms to be built, development of systems and other, that in turn could be submitted to scheduled revisions by a third party.

Of course, this form of contract is not perfect, and one of its deficiencies is that it is prone to introduce inefficiencies in contractor's side. However, it is the authors opinion that a sensible approach to this type of contract from both parts would report sizeable benefits.

7.2 Operational Requirements not Stable / not properly established or vaguely stated

Untimely changes in requirements is a risk that has been addressed on literature before. However, it is still one of the main sources of concern for shipbuilding practitioners. This issue is can be linked to what Sir John's Parker denominated an "insufficient focus on controlling 'preferential' engineering costs and in understanding costs associated with incorporating key naval standards" (Parker, 2016).

However, on a deeper level, it could also be related to the extremely long span of an average naval shipbuilding project, that produces that the threat that a naval ship was designed against is very often much different to that expected when it enters service.

Some of the mitigation measures against this risk are:

- Keeping customization at lowest acceptable levels, giving preference to commercial equipment where possible, a measure that has already been described as part of the procurement strategy for T31e (Ministry of Defense, 2017).

- The early freezing of new requirements that can cause late changes in design, with a clear and conservative procedure for any changes requested after the contract signature, that allows proper evaluation of impact in terms of schedule and costs.

Despite low customization and early freezing of contracts being enforced, Shipbuilders should also address their own limitations regarding lack of flexibility, since in some specific scenarios the customer might be willing to accept delays and higher costs as trades for a more capable platform.

8. Risk Mitigation, Engineering Perspective

Two areas of risks will be dealt with within this part of the study, related to exceeding budget, and unwanted/unrequested changes in design, due to design/production errors.

8.1 Budget is exceeded and does not go according to plan

As will be discussed at the final part of this study, budget being exceeded, and therefore, not going according to plan, is from an author's perspective a consequence of an identified or unidentified risk becoming present rather than a risk on its own merit.

Nevertheless, as a mitigation measure for this issue, the positive effect of the learning curve in labour costs in naval programs can be evaluated. Its potential effects have been preliminary outlined on previous investigations (Centre for Operational Research and Analysis, 2017).

To acknowledge its true potential within a program, it is necessary to estimate the impact of labour on the overall cost of a naval shipbuilding project; this has been found accountable for a 32% of overall costs on the case of an average US Surface Combatant (RAND, 2006), only surpassed by equipment acquisition, with a 57%.

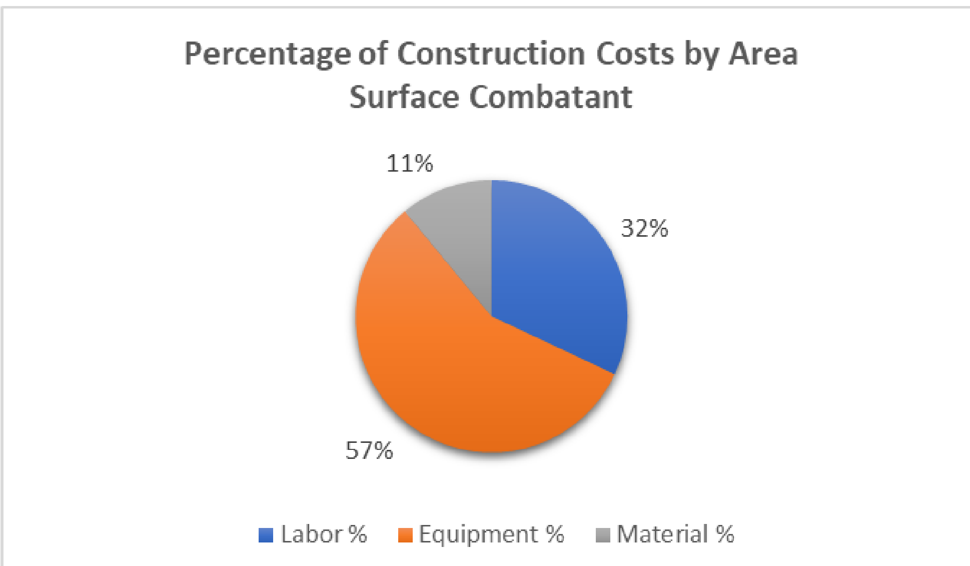

Figure 50. Cost Breakdown for a Surface Combatant by Major Groups

The low number of platforms built within almost every military shipbuilding program is an aspect that prevents the achievement of relevant scale economies when acquiring equipment or materials from suppliers; however, as will be explained on following paragraphs, it does not preclude the positive effect of an enhanced learning process, since due to its modelled behaviour, this exerts a greater impact on the first few hulls rather than on following ones.

The effect of the learning curve can be modelled as in Equation 1 (Thomson, 2015)

$$L_n = L_1 n^{\lambda} \qquad (1)$$

Where L_n is the cost of labour for the n^{th} unit, L_1 is labour cost for 1st unit, n is the unit consecutive number and λ is the learning curve slope. Learning curve slope can be calculated as in Equation 2

$$\lambda = \frac{\log\left({}^{LC}/_{100}\right)}{2} \quad (2)$$

Where LC is the Learning Curve value. A Learning Curve value of 100% means that there is no learning in between consecutive ships, and consequently, labour price stays constant. On the contrary, a lower LC means that a lower cost of labour can be achieved on every consecutive platform.

When plotted for a hypothetical 14 ship program, economies achieved in labour with different learning curve values is as in Figure 51.

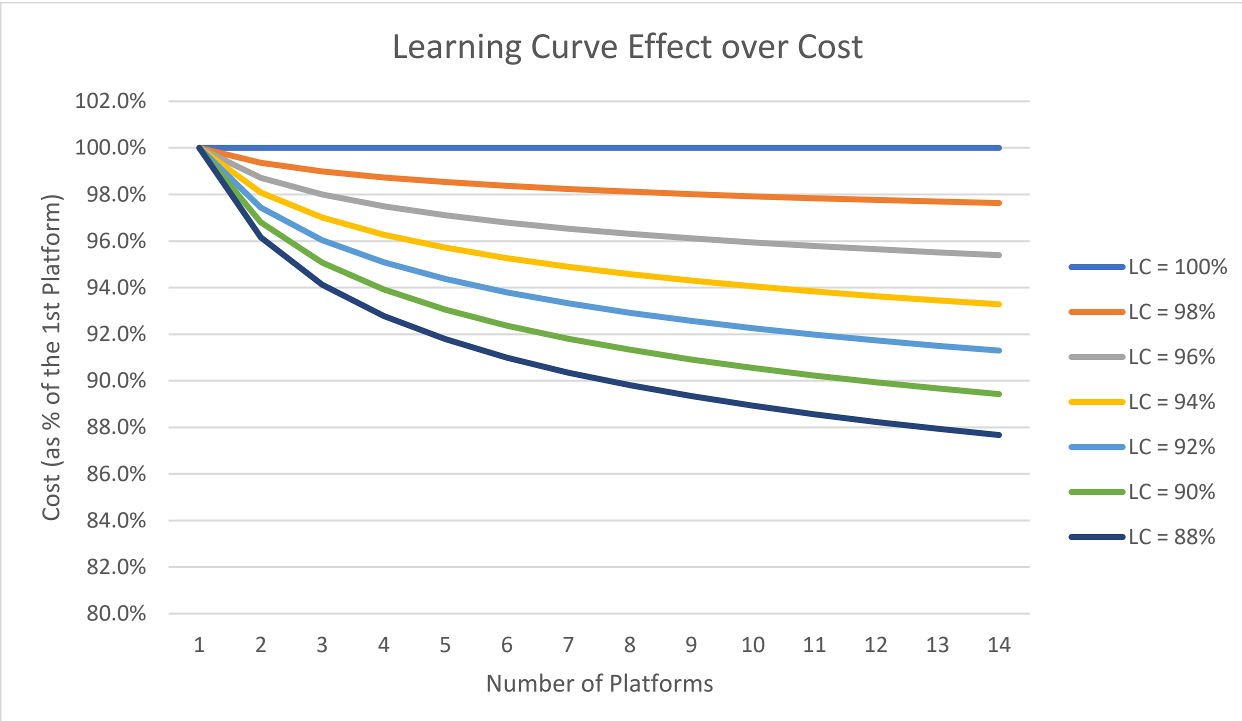

Figure 51. Learning Curve Effect

On the same perspective, there is evidence that only 75% of recently acquired knowledge will remain at the end of one month due to forgetting, in a process accounted for as knowledge depreciation (Kim & Seo, 2009).

Few published theories on how to enhance the learning slope have been found on previous literature. One significant effort is a study intended to isolate conditions that shape the learning curve, based on data provided by the Royal Dutch Mail Service (Wiersma, 2007). This study isolated four ways to influence positively (or negatively) its performance on mature enterprises, summarized in Table 13.

Table 13. Learning Curve Improvement Measures

Variable	Estimated Effect
Temporary Employees	An appropriate number of temporary employees can accelerate the improvement of the learning curve value
Capacity	A lower level of free capacity, expressed as high use of overtime, can slow improvement of the learning curve value
Variation in Tasks	Heterogeneity in tasks can accelerate learning curve improvement
Other Performance Dimensions	Performing peripheral tasks, out of the business core, can slow Learning curve improvement.

First two measures, Temporary employees, and overtime use, are common practices on Shipbuilding Industry. Hence, it is estimated that with current production data, shipyards could eventually estimate how these two parameters have affected their learning curve in the past.

8.2 Changes in Design

This risk refers not to deliberate changes to meet new requirements, but with undesired alterations needed to solve an unseen technical problem, originated on a human or process error.

There is abundant literature regarding the consideration of human factors in Ship Design, as a driver of reducing accidents of an operational platform through the enhancement of crew's performance (i.e., by designing effective man-machine interfaces); as opposed, there are very few studies addressing Human and Organization Errors within Ship Design or Shipbuilding processes, one of the most systematic being that performed by USCG in 1994.

On a first basis, HOE can be divided into those committed by omission and those by of commission. In the marine structures enterprise, past studies have found that the former is predominant, accountable for 80% of design and construction errors (USCG Ship Structure Committee, 1994). On a different classification, errors can be classified by its generating source, namely an individual, an organization, or systems (as software and hardware).

8.2.1 Human (or Individual) Error

Individual, or simply human errors, can be described as actions and inactions performed by an individual that result in lower than acceptable quality. Primary factors that can result in human errors are as in Figure 52, where Mistakes (or cognitive errors) are thought to be the most relevant component, since in the vast majority of cases the user has little acknowledgement of being doing something wrong, and therefore, it takes an experienced outsider to detect such situation (USCG Ship Structure Committee, 1994). Some of the most common and influential causes of human error are inadequate training, and the combination of fatigue and boredom.

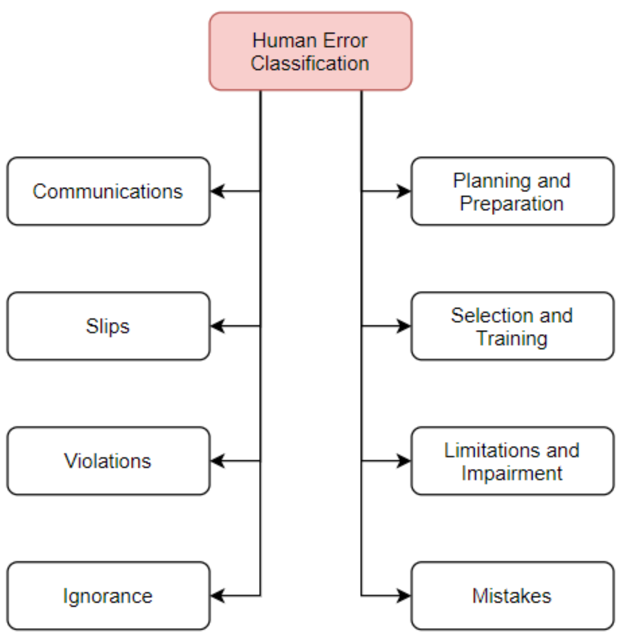

Figure 52. Human Error Classification

8.2.2 Organization Errors

Organization errors can occur as the consequence of the ignorance of a risk or the willingness to accept it on an incorrect appreciation of its potential consequences. This time, culture of the organization has been detected to be one of the most relevant factors, as observed in Figure 53, where, as an example, there might be unrealistic demands for flawless performances, leading to lack of credible feedback or information being transmitted to upper management levels. More often quoted causes for this poor organizational behaviour are Time Pressures, Ineffective monitoring structures and missing or misplaced incentives.

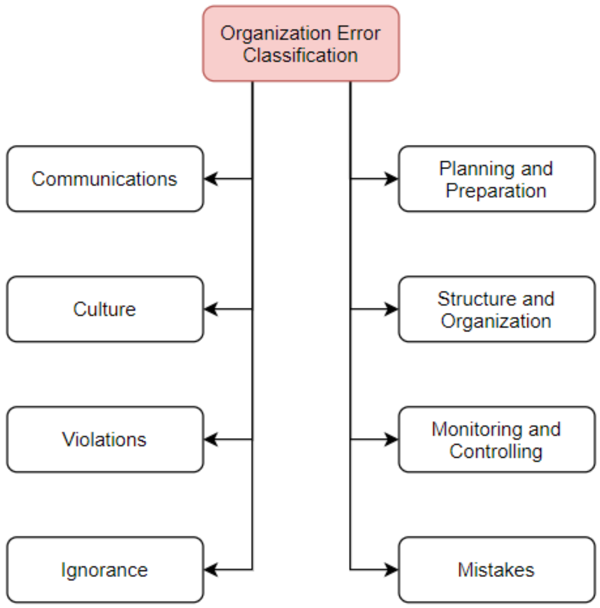

Figure 53. Organization Errors Classification

8.2.3 Systems (or procedure) errors

Individual or organizational errors can be exacerbated by systems or procedures errors. This is especially significant on the design of systems such as ships, circumstance that is only worsened in case of naval platforms, with low volumes of units produced, high levels of (sometimes unproven) technology and systems interaction. These errors classification is as in Figure 54.

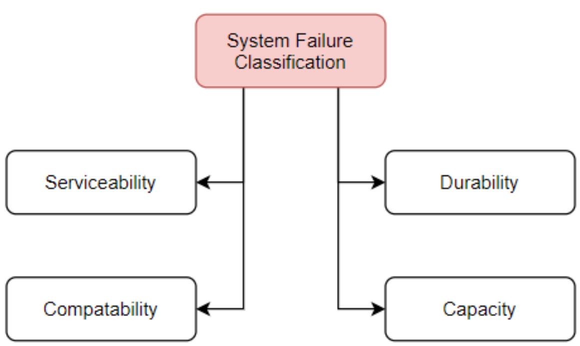

Figure 54. System Errors Classification

8.2.4 Relating error generator sources with consequences severity

Factors such as performing unfamiliar tasks, on hard time constraints and under stressful circumstances have been signalled to be common sources of human errors (Kirwan, 1994).

However, there is an interesting aspect behind this: not every error will have the same negative impact magnitude on the outcome of a given task or project. Furthermore, previous research on marine structures has been able to establish links between an error producing condition and the magnitude of its negative consequences, expressing it as a multiplying effect. The complete list of sources is as in Table 14 (USCG Ship Structure Committee, 1994).

Table 14. Error Producing Condition and Multiplying Effects

Error producing condition	Multiplier
Unfamiliarity	17
Time Shortage	11
Low Signal To noise ratio	10
Feature over-ride allowed	9
Spatial / Functional incompatibility	8
Design model mismatch	8
Irreversible action	8
Information overload	6
Technique unlearning	6
Knowledge Transfer	5.5
Performance ambiguity	5
Misperception of risk	4
Poor feedback	4
Inexperience	3
Communication filtering	3
Inadequate checking	3
Objectives conflict	3
Limited diversity	2.5
Educational mismatch	2
Dangerous incentives	2
Lack of excercise	1.8
Unreliable instruments	1.6
Absolute judgements required	1.6
Unclear allocation of functions	1.6
Lack of progress tracking	1.4
Limited physical capabilities	1.4
Emotional stress	1.3
Sleep cycle disruption	1.2

Normalizing this data through standard statistical procedures, it can be inferred (see Figure 55) that only four sources are above one standard deviation, and therefore, they can be deemed as the most relevant to address.

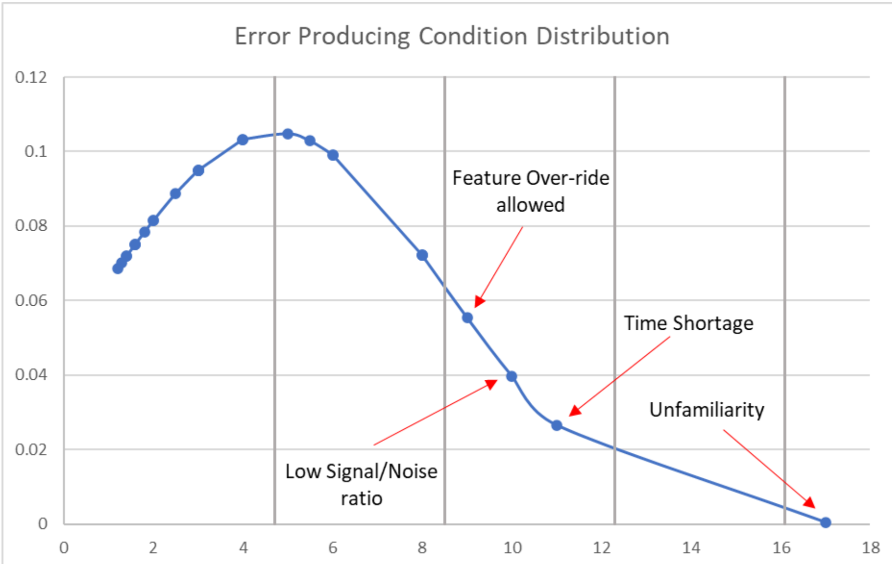

Figure 55. Error Producing Condition Distribution

Based on this, tasks that are unfamiliar, performed under time constraints and with low signal to noise ratio (i.e., lack of clarity to transmit the core aspects of an idea) are not only more prone to cause error, but also to be the responsible for the more disruptive ones.

One modern approach to HOE risk mitigation for complex systems was suggested by former MoD Technical Director and former Babcock's Submarine Technical Director, Mr. Howard Mathers.

These theories propose that a culture that looks at past errors in order to prevent them from happening again, inherently develop a risk management that is lagging developments, becoming in most cases expensive and ineffective. This standard approach has been denominated Safety I, and it is focussed on "avoiding that things go wrong".

As opposed, a leading risk management should concentrate its efforts on analysing what has gone right and as planned in everyday actions rather than on what went wrong on certain specific occasions, deemed as failures (Hollnagel, 2013). This alternative approach has been named Safety II, and its ultimate objective is to "ensure that things go right".

Hence, Safety I and Safety II are different in two fundamental aspects: the former tries to lower the unacceptable outcomes, assuming that complex systems are well understood, and their changes are tractable. The latter aims to enhance the acceptable outcomes, and its assumptions are the exact opposite, i.e., complex systems are not necessarily completely understood, and therefore, they are intractable.

In a practical way, the differences can be thought as: in a process with a 5% error possibility, a very high rate according to any standard, Safety I approach will look and analyse at 5 out of 100 events; on the contrary, Safety II will focus on the significantly larger 95 of them.

A summary of their difference can be observed in Table 15.

Table 15. Differences between Safety I and Safety II approaches

	Approach	
Parameter	Safety I	Safety II
Definition of Safety	That as few things as possible go wrong	That as many things as possible go right
Safety Management principle	Reactive, responds when something happens	Proactive, try to anticipate developments and events
Explanation of accidents	Accidents are caused by failures and malfunctions	Things basically happen in the same way, regardless of the outcome
View of the Human Factor	Liability	Resource

9. Learning Curve: An estimation of its effects on Current Naval Shipbuilding Projects

To estimate the potential impact of the learning curve on current UK Naval Shipbuilding programs, a model of potential savings that can be achieved in undergoing UK naval shipbuilding programs is implemented. Four scenarios are modelled, from the combination of a 14 and 40 ship program with each type of ship under construction, namely T26 and T31e. Schematic of the model is as in Figure 56.

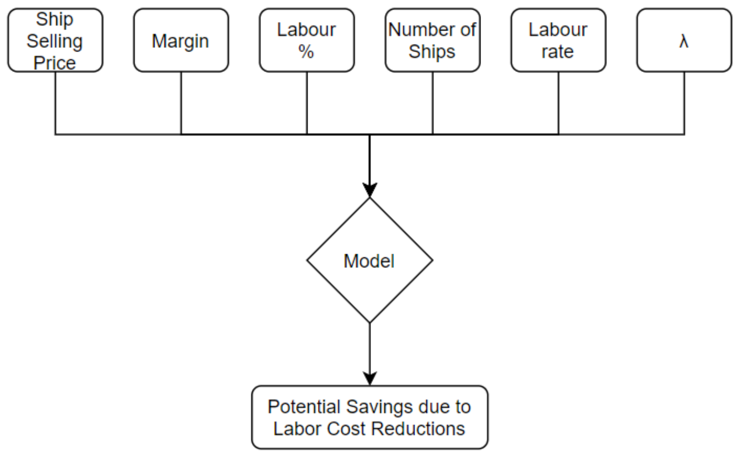

Figure 56. Learning Curve Model Scheme

Model inputs are summarized in Table 16. 1st ship estimated price is gathered from publicly available information, whilst net profit margin is obtained from BAE/BABCOCK PLC's 2014-2019 respective averages (source: Thomson Reuters Eikon).

Labour as percentage of the ship's cost is as shown in Figure 50. Number of ships, slope of learning curve and man/hour rate are estimated based on previous programs and potential sells, RAND estimations of achievable learning curve values and publicly available information, respectively.

1st ship price and net profit margin are not necessarily of a high degree of accuracy, since the first is estimate from open sources due to commercial confidentiality, whilst the second is distorted by other business segments in BAES/BABCOCK. Nevertheless, the aim of the exercise is to outline the potential magnitude of the learning curve effect.

Table 16. Learning Curve Effect - Model Inputs

	Program	
Input	T26	T31e
1st Ship Sale price [M GBP]	1,000,000,000	400,000,000
Net Profit Margin [%]	6.0 %	6.5 %
Labour as % of total cost [%]	32	32
Total number of Ships within the program	3-14 / 3-40	3-14 / 3-40
λ, slope of learning curve	88%-100%	88%-100%
Man/hour rate [GBP]	22	22

Considering the Labour Cost defined as in Equation 1, n^{th} ship cost can be expressed as in Equation 3

$$C_n = C_1 - L_1 + L_n \quad (3)$$

And savings of the n^th ship respect to the previous platform can be estimated as in Equation 4

$$S_n = C_{n-1} - C_n \quad (4)$$

Hence, program savings for *n* ships can be calculated a in Equation 5

$$Program\ Savings = \sum_{i=1}^{n} S_i \quad (5)$$

Using previous equations, and an arrangement of stepped number of platforms and learning curve values gives origin to 76 possible combinations for 14 ship programs and 266 combinations for 40 ship programs Due to space constraints, only 14 ship programs results are shown in this section; nevertheless, complete tables are provided on Appendix C.

Calculated potential savings for 14-ship programs, based on the enhancement of learning curve slopes and increased number of platforms, are as in Table 17 and Table 18. Lines in green represent the currently secured contracts for each type of Ship.

Table 17. Estimated Savings for an up to 14-ship T31e Program

	Learning Curve Factor						
Number of Ships	100%	98%	96%	94%	92%	90%	88%
3	-	6.2	12.3	18.4	24.4	30.4	36.3
4	-	10.9	21.7	32.3	42.8	53.1	63.3
5	-	16.4	32.5	48.3	63.8	79.1	94.0
6	-	22.5	44.5	66.0	87.0	107.6	127.7
7	-	29.1	57.4	85.1	112.0	138.3	163.8
8	-	36.1	71.2	105.4	138.5	170.7	201.9
9	-	43.5	85.8	126.7	166.3	204.7	241.8
10	-	51.3	100.9	148.9	195.3	240.0	283.2
11	-	59.4	116.7	172.0	225.3	276.6	326.0
12	-	67.7	133.0	195.8	256.2	314.2	370.0
13	-	76.4	149.8	220.3	287.9	352.9	415.1
14	-	85.2	167.0	245.4	320.5	392.4	461.2

Table 18. Estimated Savings for an up to 14-ship T26 Program

	Learning Curve Factor						
Number of Ships	100%	98%	96%	94%	92%	90%	88%
3	-	15.5	30.9	46.1	61.3	76.3	91.3
4	-	27.4	54.5	81.2	107.5	133.5	159.1
5	-	41.2	81.7	121.4	160.5	198.8	236.4
6	-	56.5	111.8	165.9	218.8	270.5	321.0
7	-	73.1	144.4	213.8	281.6	347.5	411.7
8	-	90.8	179.0	264.8	348.1	429.0	507.5
9	-	109.4	215.5	318.4	418.0	514.4	607.8
10	-	129.0	253.7	374.3	490.8	603.3	711.8
11	-	149.3	293.3	432.2	566.1	695.1	819.3
12	-	170.3	334.3	492.1	643.9	789.8	929.9
13	-	191.9	376.4	553.6	723.7	886.9	1,043.3
14	-	214.2	419.7	616.8	805.5	986.3	1,159.2

Practical Implications

Hence, in today's scenario, BABCOCK savings on T31e program due to the learning curve factor enhancement could be as high as 94.0 M GBP, with an LCF of 88%. Attaining a similar LCF, BAES could save up to 91.3 M GBP on its T26 program.

A learning curve factor below 80.0% is, in practical terms, very difficult to reach, since automated processes introduced in the last few decades have flattened the curve's improvement capability. Previous investigations have shown that realistic LCF accounting for the level of automation of a given facility is as in Table 19 (Smith, 2008).

Table 19. Achievable Learning Curve Factors

Automated/Manual Labour Ratio	Achievable LCF
3/1	80%
1/1	85%
1/3	90%

Hence, one interesting reflection is that the more automated installations are, the least economy can be achieved through learning curve effect.

To gain a more intuitive perception of the relative influence of improvement in learning curve factor and number of platforms, discrete results can be translated onto a continuous surface. Only 14-ship programs are shown in this section.

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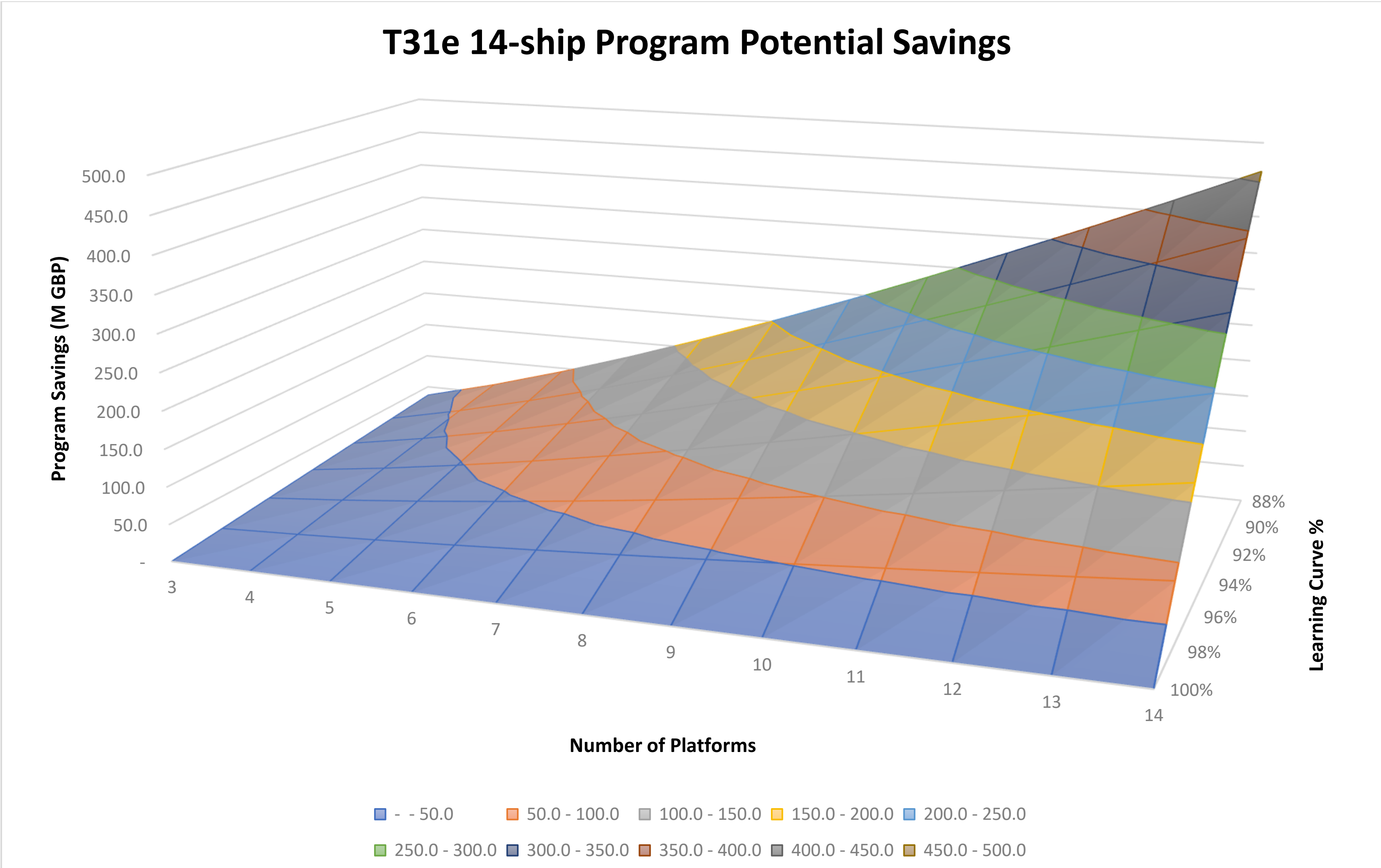


Figure 57. T31e 14-Ship Program Potential Savings

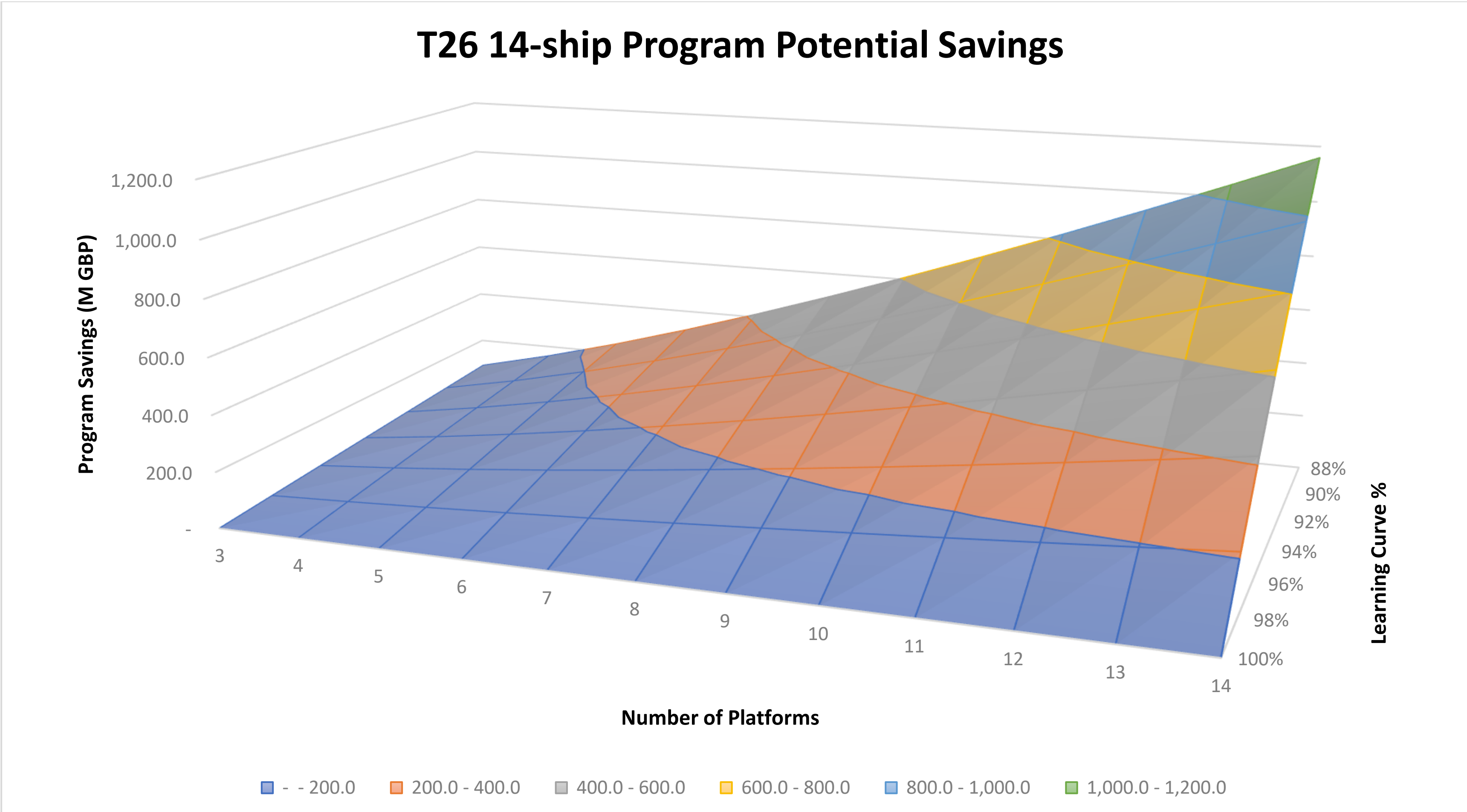


Figure 58. T26 14-Ship Program Potential Savings

10. Discussion and Conclusions

The most relevant conclusion of the study is that naval shipbuilding's enterprise status demands a close to perfection performance from management, design and production teams on an unprecedented scale, due to a unique combination of low margins, an inherently risky enterprise, high cost uncertainties, and low number of platforms to be built in the vast majority of programs.

Any error in cost estimations or design features can have devastating effects over a shipbuilding's company future. The high value of a standard shipbuilding contract makes small and mid-size companies especially vulnerable to high impact risks.

Relevant risks identified by this study and suggested matching mitigation measures are as in Figure 59, where learning curve effect is deemed as especially relevant for keeping naval projects within planned budget and schedule, due to its ability to reduce significantly labour times and associated costs. As an extra benefit, it has shown to exert its greater magnitude on the first few platforms, a feature of especial relevance for low number programs.

Finally, increasing learning curve factor has shown to be, at least theoretically, a more effective way to enhance industry's viability than increasing the number of platforms of a given naval program.

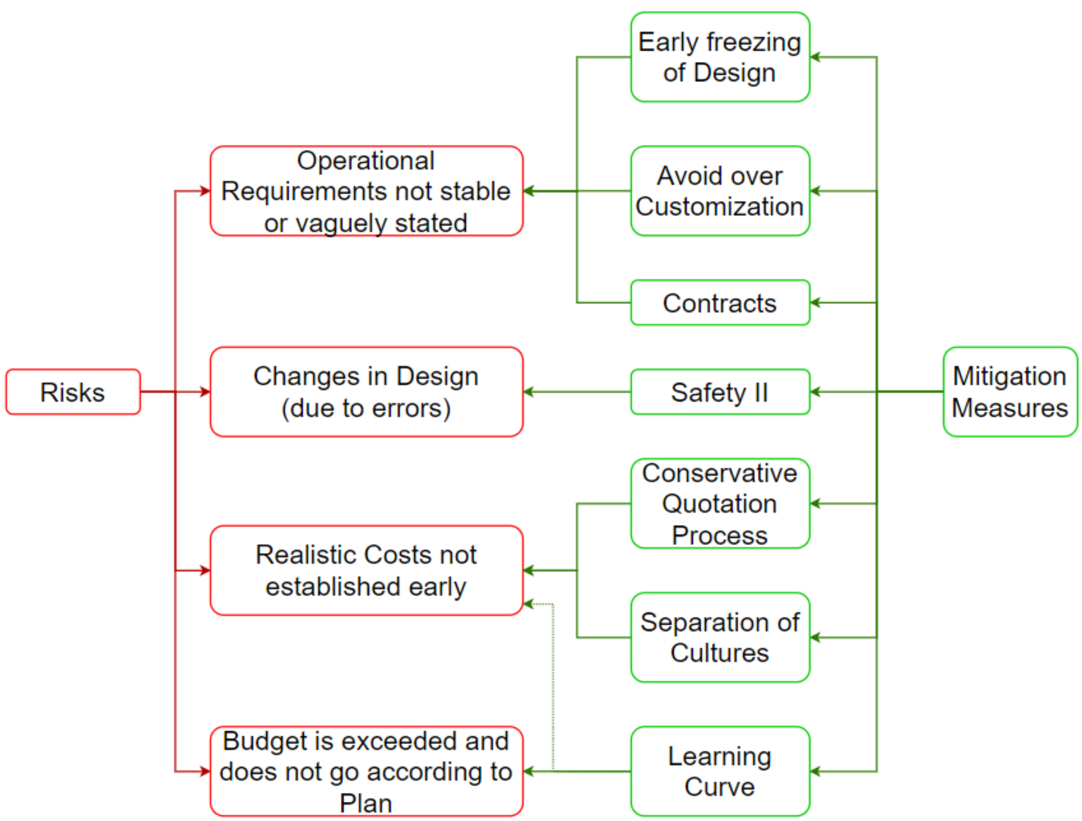


Figure 59. Risk and Mitigation measures summary

Some discussion points deemed as relevant are:

a. There seems to be some grey area even in high standard studies about where to draw a line of what can be defined as a risk and what can be classified as a consequence of that risk occurring. This is evident when, revising relevant literature, schedule and budget deviations are addressed as risks. To the author's opinion, deviating from schedules or budgets is undoubtedly a consequence of a risk becoming present, and their inclusion among the list of identified risks diminishes the quality of the processes that follow.

b. It is the author's opinion that TBA scheme gives little room for innovation, and it should be avoided to use its resources for building low to moderate complexity naval platforms, such as OPVs', that could provide a stable pipeline of orders for shipbuilding companies that are more vulnerable due to their lower magnitude and scope of business.

c. If it is essential to keep the abovementioned scheme, it is the author's opinion that a greater benefit could be achieved by investing the funds in R&D activities, that could in turn give some guidance on what future trends are expected to be, discharging these costs from a particular program.

d. It is worth revising some of the conclusions that Sir John Parker's Independent report revealed that gave shape to the National Shipbuilding Strategy. Cammell Laird was praised for its competitiveness in NSS for winning an International Competition in the bid for RSS Sir David Attenborough; however, several failures within the process, not attributable to a single source, have significantly damaged the company's financials, risking from the author's perspective its mid-term viability. Winning a contract seems to be not enough of a good reason for being too optimistic.

e. Automation role within mid-size naval shipbuilding companies could be revised, due to learning curve factor effects as explained on 9. While it is obvious that great economies and efficiencies can be achieved through automation, investment in costly edge technology for building just a few platforms might not provide the best financial balance. This is even more relevant if no future contracts are secured, which is normally the case for naval shipbuilders.

f. An overwhelming majority of experts' mention "old problems" as the major sources of risks for Naval Shipbuilding Industry, such as cost estimation and planning/programming issues. Furthermore, only one respondent mentioned transferring digital design into production among his/her priorities within their answers. Hence, it could be argued that technical modernization is important, but to a lesser extent than what could be expected.

g. For a shipyard to be viable and sustainable, as essential as its technical expertise is its capability to generate a type of contract that can minimize the inherent asymmetry of risk assumed when committed to build a new type of vessel. A change in the type of contract could report more sustainability to the Shipbuilding enterprise, especially when contracts are signed with Government organizations, such as MoD, in programs that are not required to go through an international bidding process. In this regard, it is the author's opinion that periodical contract revisions by third independent parties should report great benefits.

h. Choosing T31e as the platform to deliver on the NSS seems to be in the right way to keep naval shipbuilding on track. The fact that OMT's original design is operating successfully on IVER HUITFIELD class, in service at the Danish Navy, should greatly reduce costs uncertainty and therefore, risks.

Regarding the completion of the project's objectives, most of them were fully achieved, namely:

a. Summarizing pre-National Shipbuilding Strategy status
b. Review Past Projects
c. Identify and rank risks inherent to the Industry
d. Evaluating Financial health of UK Shipbuilding companies

One objective was only partially achieved, regarding the comparison of UK naval shipbuilding industry programs with foreign competitors, since exceptional COVID 19 circumstances conspired against the need of doing on-site research and interviews; however, is the author's opinion that this effect has been partially compensated by the inclusion of a broad number of national and international experts and companies within several parts of the study.

In the same direction, an effort to build a model of the learning curve effect was put in place for current UK Naval Programs, providing data on aspects that were not considered in the project's original plans.

11. Further Work

Some of the areas that could be addressed to better understand how to improve the delivery of naval shipbuilding programs are:

a. To determine historical net margins for the broad UK Naval Shipbuilding enterprise, detached from other companies´ source of revenue. This exercise might provide some very interesting results, probably reinforcing the conclusion that margins are too low and incompatible with the business inherent risks. This task should also allow to benchmark UK naval shipbuilding alone with shipbuilding companies elsewhere performance.

b. To establish the learning rate slope improvement that has been achieved by recent history UK naval programs. In this regard, plotting labour cost reductions in T23 and T45 programs should provide highly valuable information, due to the significant number of platforms built in each one of them.

c. To investigate practical measures to improve learning curve performance, applicable to naval ship design and shipbuilding context. A reasonable starting point would be to investigate the effect of the rate of temporary employees on productivity KPI’s.

d. To investigate innovative contract forms to be used in Ship Design and Shipbuilding environment that help to reduce the risk asymmetry between customers and contractors.

12. References

A&P Group, 2019. *A&P Annual Reports 2015-2019.* s.l.:s.n.

APPG Shipbuilding and Ship Repair, 2020. *Inquiry into the National Shipbuilding Strategy.* s.l.:s.n.

Araluce, G., 2020. *Diario El Español.* [Online]
Available at: https://www.elespanol.com/espana/20180118/submarino-no-flotaba-dispara-millones-gasto-armada/277973300_0.html
[Accessed 09 10 2020].

BABCOCK PLC, 2020. *Annual Reports 2015-2020.* s.l.:s.n.

BAE Systems, 2019. *Annual Reports 2015-2019.* s.l.:s.n.

Brooke-Holland, L., 2016. *The Royal Navy's new frigates and the National Shipbuilding Strategy.* s.l.:s.n.

Brown, A. & Mierzwicki, T., 2004. Risk Metric for Multi-Objective Design of Naval Ships. *Naval Engineers Journal,* 116(2), pp. 55-71.

Cammell Laird, 2019. *Annual Reports 2015-2019.* s.l.:s.n.

Carrasco Santos, A., 2020. ¿Quo Vadis, FLOSUB?. *Revista General de Marina,* 1(1), pp. 99-104.

Centre for Operational Research and Analysis, 2017. Cost risk analysis and learning curve in the military shipbuilding sector. *International Journal of Data Analysis Techniques and Strategies,* 9(4), pp. 300-313.

Chutter, A., 2018. *UK hires team to stop destroyers from breaking down at sea.* [Online]
Available at: https://www.defensenews.com/naval/2018/03/21/uk-hires-team-to-stop-destroyers-from-breaking-down-at-sea/
[Accessed 21 08 2020].

Departament for Business, Energy & Industrial Strategy, 2017. *How to measure the prosperity impacts of UK Shipbuilding.* s.l.:s.n.

DSMC, 2001. *Risk Management Guide for DoD Acquisition.* Virginia: s.n.

GMB Union, 2018. *Turning the Tide; Rebuilding the UK's Defence Shipbuilding Industry and the Fleet Solid SUpport order.* s.l.:s.n.

Hollinger, P., 2019. *Financial Times.* [Online]
Available at: https://www.ft.com/content/39c16806-0019-11ea-b7bc-f3fa4e77dd47
[Accessed 16 06 2020].

Hollnagel, E., 2013. A tale of two safeties. *Nuclear Safety and Simulation,* 4(1), pp. 1-9.

Hulme, S. & Drew, C., 2020. *Entrepreneurial Finance.* 1st ed. London: s.n.

INFRASTRATA PLC, 2019. *Annual Report.* s.l.:s.n.

Irish News, 2017. *The Irish News.* [Online]
Available at: http://www.irishnews.com/business/2017/07/21/news/harland-wolff-reports-big-loss-in-

unacceptable-year--1089566/
[Accessed 17 08 2020].

Iwankowicz, R. R. & Rosochacki, W., 2014. Clustering risk assessment method for shipbuilding industry. *Industrial Management and Data Systems,* 114(9), pp. 1499-1518.

Kim, I. & Seo, H. L., 2009. Depreciation and transfer of knowledge: an empirical exploration of a shipbuilding process. *International Journal of Production Research,* 47(7), pp. 1857-1876.

Kirwan, B., 1994. *A guide to practical Human Reliability Assessment.* s.l.:s.n.

Konovessis, D., Cai, W. & Vassalos, D., 2013. Development of Bayesian Network Models for. *Journal of Marine Science and Application,* 12(1), pp. 140-151.

Lee, E., Park, Y. & Shin, J. G., 2009. Large engineering project risk management using a Bayesian belief network. *Expert Systems with Applications,* 36(1), pp. 5880-5887.

Levering, R., Ligthart, R., Noorderhaven, N. & Oerlemans, L., 2013. Continuity and change in interorganizational project practices: The Dutch shipbuilding industry, 1950–2010. *International Journal of Project Management,* Volume 31, pp. 735-747.

Mickeviciene, R., 2011. Global Shipbuilding Competition: Trends and Challenges for Europe, The Economic Geography of Globalization. *InTech,* 1(1), pp. 201-222.

Ministry of Defence, 2017. *Request for Information to Support Type 31e Market Testing.* s.l.:s.n.

Ministry of Defense, 2017. *National Shipbuilding Strategy: The Future of Naval Shipbuilding in the UK.* s.l.:s.n.

Neate, R., 2020. *The Guardian.* [Online]
Available at: https://www.theguardian.com/business/2020/aug/25/appledore-shipyard-in-devon-to-reopen-after-7m-infrastrata-buyout
[Accessed 11 09 2020].

Nicholas, J. M. & Steyn, H., 2017. *Project Management for Engineering, Business and Technology.* 5 ed. s.l.:Routledge.

Nicholls, D., 2020. *Has the Royal Navy enough Ships?.* [Online]
Available at: https://www.telegraph.co.uk/news/defence/has-royal-navy-enough-ships/
[Accessed 21 08 2020].

OECD, 2017. *IMBALANCES IN THE SHIPBUILDING INDUSTRY AND ASSESSMENT OF POLICY RESPONSES.* s.l.:s.n.

Parker, S. J., 2016. *An Independent Report to inform the UK National Shipbuilding Strategy.* s.l.:s.n.

Parker, S. J., 2017. *Review of the Implementation of the National Shipbuilding Strategy.* s.l.:s.n.

Pugliese, D., 2020. *The Chronicle Herald.* [Online]
Available at: https://www.thechronicleherald.ca/news/canada/pbo-to-examine-60-billion-price-tag-of-new-warships-and-compare-to-other-less-expensive-foreign-programs-482874/
[Accessed 10 09 2020].

RAND Corporation, 2014. *Keeping Major Naval Ship Aquisition on Course.* Australia: s.n.

RAND Corporation, 2015. *Australia's Naval Shipbuilding Enterprise: Preparing for the 21st Century.* Santa Monica: s.n.

RAND Europe, 2005. *The United Kingdom's Naval Shipbuilding Industrial Base: The Next Fifteen Years.* s.l.:s.n.

RAND, 2006. *Why Has the Cost of Navy Ships Risen? A Macroscopic Examination of the Trends in U.S. Naval Ship Costs Over the Past Several Decades.* Santa Mónica: s.n.

Shih-Liang, C. & Yi-Hung Yeh, Y., 2020. Comparing the productivity of major shipyards in China, South Korea, and Japan – an application of a metafrontier framework. *Maritime Business Review,* 5(2), pp. 193-210.

Smith, M. B., 2008. *Updating MIT's Cost Estimation Model for Shipbuilding.* s.l.:s.n.

Thomson, M., 2015. *The 2015 RAND report on Australian naval shipbuilding.* s.l.:s.n.

UK Parliament, 2016. *Restoring the Fleet: Naval Procurement and the National Shipbuilding Strategy Contents.* s.l.:s.n.

USCG Ship Structure Committee, 1994. *The Role of Human Error in Design, Construction and Reliability of Marine Structures.* s.l.:s.n.

Wiersma, E., 2007. Conditions That Shape the Learning Curve: Factors That Increase the Ability and Opportunity to Learn. *Management Science,* 53(12), pp. 1903-1915.

Appendix A

Previously Identified Risks

Table 20. Significant Risks and Risk Areas in Naval Ship Design

ID	Risk Area	Significant Risks
1	Threat	Uncertainty in threat accuracy.
2	Threat	Sensitivity of design and technology to threat.
3	Threat	Vulnerability of system to threat and threat countermeasures.
4	Threat	Vulnerability of program to intelligence penetration.
5	Requirements	Operational requirements not properly established or vaguely stated.
6	Requirements	Requirements are not stable.
7	Design	Status of system development.
8	Design	Requirement for increased skills.
9	Design	Reliance on immature technology or "exotic" materials to achieve performance.
10	Design	Status of software design, coding, and testing.
11	Test & Evaluation	Test planning not initiated early in program (Phase 0).
12	Test & Evaluation	Testing does not address the ultimate operating environment.
13	Test & Evaluation	Test procedures do not address all major performance and suitability specifications.
14	Test & Evaluation	Test facilities not available to accomplish specific tests, especially system-level tests.
15	Test & Evaluation	Insufficient time to test thoroughly.
16	Simulation	M&S are not verified, validated, or accredited for the intended purpose.
17	Simulation	Program lacks proper tools and modelling and simulation capability to assess alternatives.
18	Technology	Success depends on unproved technology for success.
19	Technology	Success depends on achieving advances in state-of-the-art technology.
20	Technology	Technology has not been demonstrated in required operating environment.
21	Technology	Technology relies on complex hardware, software, or integration design.
22	Logistics	Inadequate supportability late in development or after fielding.
23	Logistics	Life-cycle costs not accurate because of poor logistics supportability analyses.
24	Production/Facilities	Production not sufficiently considered during design.
25	Production/Facilities	Inadequate planning for long lead items and vendor support.
26	Production/Facilities	Production processes not proven.
27	Production/Facilities	Prime contractors do not have adequate plans for managing subcontractors.
28	Production/Facilities	Sufficient facilities are not readily available for cost-effective production.
29	Production/Facilities	Contract offers no incentive to modernize facilities or reduce cost.
30	Concurrency	Immature or unproven technologies will not be adequately developed before production.
31	Concurrency	Concurrency established without clear understanding of risks.
32	Capability of Developer	Developer has limited experience in specific type of development.
33	Capability of Developer	Contractor has poor track record relative to costs and schedule.
34	Capability of Developer	Contractor has experienced loss of key personnel.
35	Capability of Developer	Prime contractor relies excessively on subcontractors for major development efforts.
36	Capability of Developer	Contractor requires significant capitalization to meet program requirements.
37	Technology Cost/Funding	Realistic cost objectives not established early.
38	Technology Cost/Funding	Excessive life-cycle costs due to inadequate treatment of support requirements.

39	Technology Cost/Funding	Funding profile is not stable from budget cycle to budget cycle.
40	Schedule	Schedule does not reflect realistic acquisition planning.
41	Schedule	Resources are not available to meet schedule.
42	Technology Management	Proper mix (experience, skills) of people not assigned to PMO or to contractor team.
43	Technology Management	Effective risk assessments not performed or results not understood and acted on.

Table 21. Significant Risks and Risk Areas in Shipbuilding Enterprise

ID	Risk Area	Significant Risks
1	Natural	Typhoon, flood, earthquake, and other uncontrollable event
2	Political	Regulations against shipbuilders' interests, tightened or amended
3	Legal	Classification's rules change and influence shipbuilders
4	Social	Incendiary fire or burglaries occurs, riots
5	Economic	Difficulty in the supply of raw materials
6	Economic	Labour cost rise
7	Economic	Difficulty in meeting labour demands for production
8	Economic	Shortages in design manpower
9	Economic	Difficulty in supplying production equipment
10	Economic	Unexpected changes in inflation
11	Economic	Unexpected significant changes in taxes
12	Economic	Unexpected significant changes in exchange rates
13	Financial	Unexpected significant changes in interest rates
14	Financial	Changes in company's credit ratings
15	Financial	Refund guarantee, operating costs, and other difficulties in capital funding
16	Financial	Unexpected difficulties in cash flow
17	Technical	Changes in design
18	Technical	Introduction of new technologies incur new risks
19	Technical	Failures in production equipment occur
20	Technical	Instances arise where the specifications of the shipbuilding contract cannot be met
21	Managerial	Productivity does not improve
22	Managerial	Problems in quality management arise
23	Managerial	Problems arise due to strike in headquarters
24	Managerial	Problems arise due to strike in subcontractors
25	Managerial	Time schedule is exceeded and does not go according to plan
26	Managerial	Budget is exceeded and does not go according to plan

Appendix B

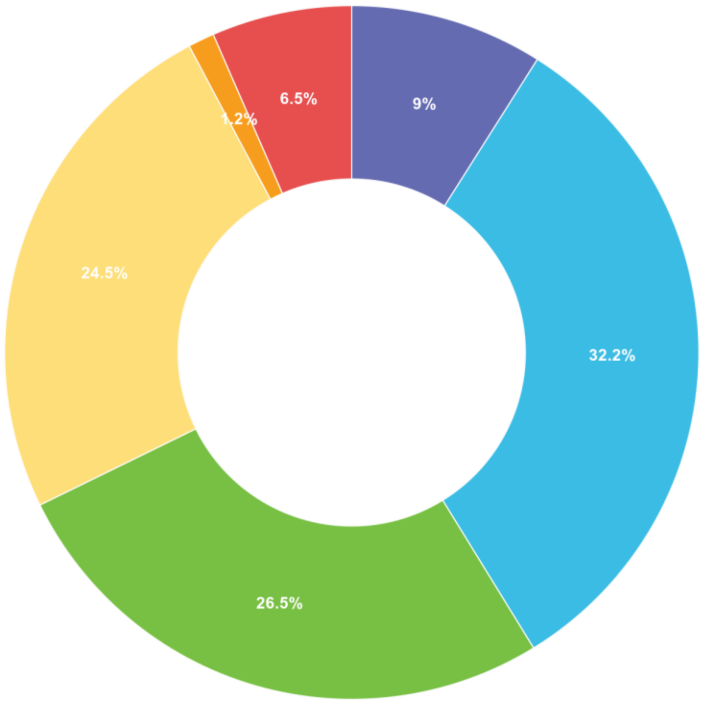
Survey questions and basic results

Shipbuilding Enterprise Challenges

I am conducting a study addressing "Challenges of Translating Ship Designs into Production" and seeking inputs on risk perception in Shipbuilding Projects from experts across the Industry. The survey should take about 9 minutes and is anonymous. However, if you are happy to be contacted directly about your answers, please provide an email address below (not compulsory).

Q1 Which of the following words best describe the part of a ship's life cycle are you involved in? (select all that apply)

Multiple Choice

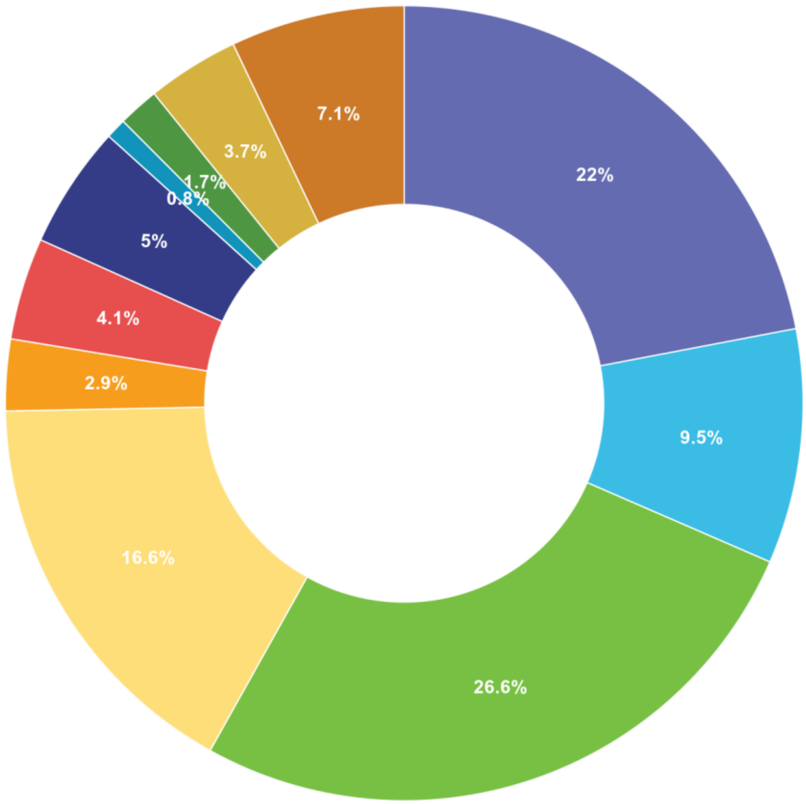


Responses 128 **Answered** 128 **Unanswered** 0

Choice	Totals
Ship Acquisition	22
Ship Design	79
Ship Building	65
In Service Support	60
Disposal	3
Other	16

Q2 Which of the following areas best describe your field of work? (select all that apply)

Multiple Choice



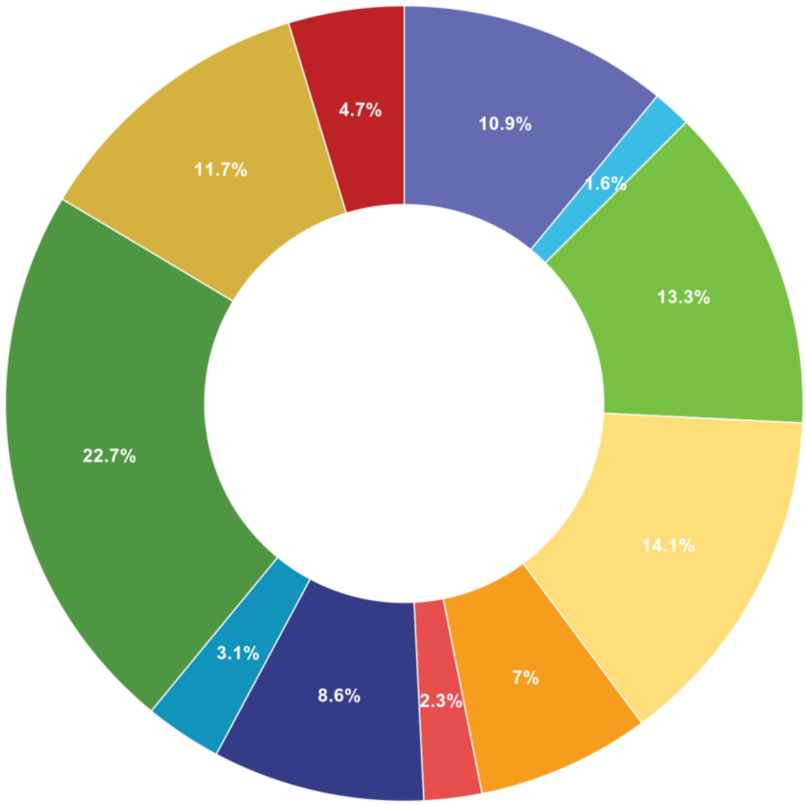
Responses 128 **Answered** 128 **Unanswered** 0

Choice	Totals
Consultancy	53
Research	23
Ship Production and Manufacturing	64
Ship Refit and Repair	40
Ship Owner	7

Choice	Totals
Ship Operator	10
Equipment Supplier	12
Finance	2
Administration	4
Information Technology and Systems	9
Other	17

Q3 What of the following best describe your role within your organisation?

Multiple Choice



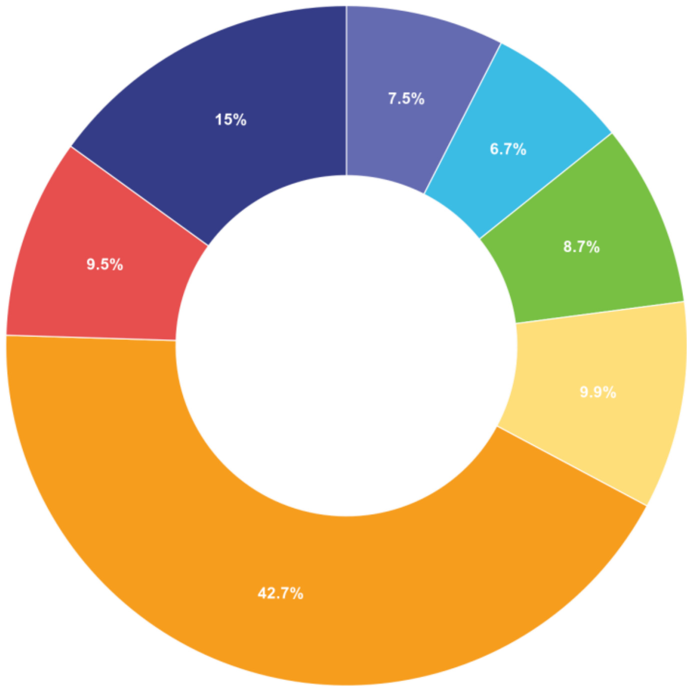
Responses 128 **Answered** 128 **Unanswered** 0

Choice	Totals
Director	14
CEO	2
Manager	17
Head of Department	18
Team Leader	9

Choice	Totals
Programme Manager	3
Project Manager	11
Designer	4
Engineer	29
Technical Specialist	15
Operator	0
Other	6

Q4 Which type of ships does your work relate to? (select all that apply)

Multiple Choice

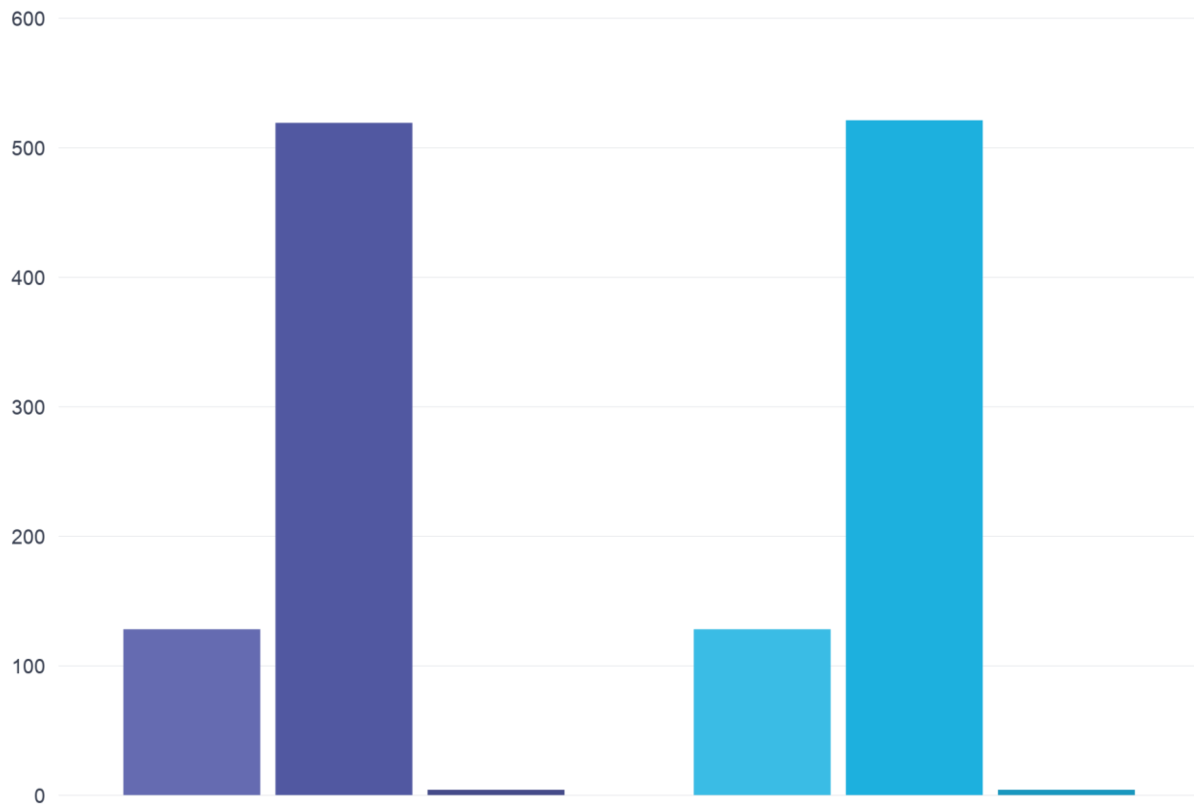


Responses 128 **Answered** 128 **Unanswered** 0

Choice	Totals
Container Ships	19
Bulk Carriers	17
Tankers	22
Passenger Ships	25
Naval Ships	108
Offshore Ships	24
Special/Other Purpose (please specify)	38

Q5 Questions 5 to 15 address risks previously identified by Brown and Mierzwicki (Brown and Mierzwicki, 2004) in the process of Naval Ship Design. On the basis of your experience, please rate these risks from Low to High, based on the combination of their probability of occurrence and their consequence to the success of a project in terms of delivering on schedule, within budget and expected capabilities. REQUIREMENTS:

Scoring

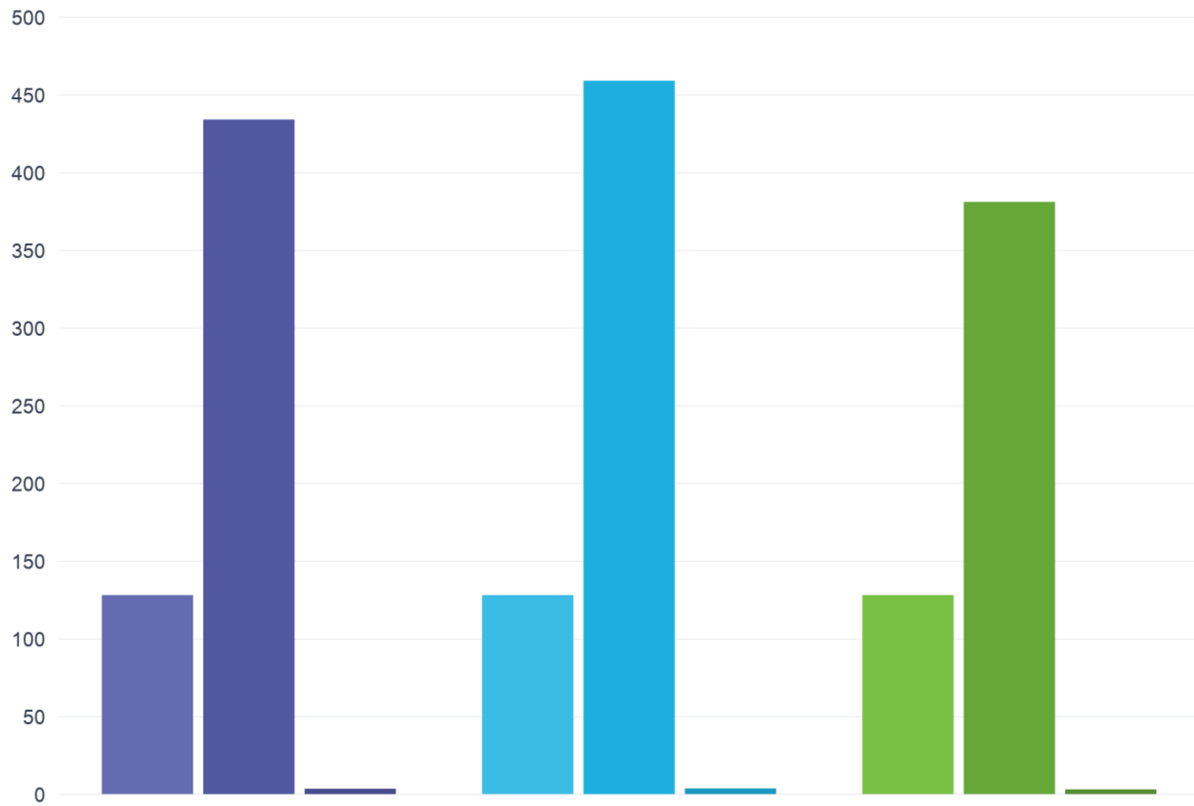


Responses 128 **Answered** 128 **Unanswered** 0

Choice	Score	Average
Operational requirements are not properly established or vaguely stated	519	4.05
Requirements are not stable	521	4.07

Q6 DESIGN:

Scoring

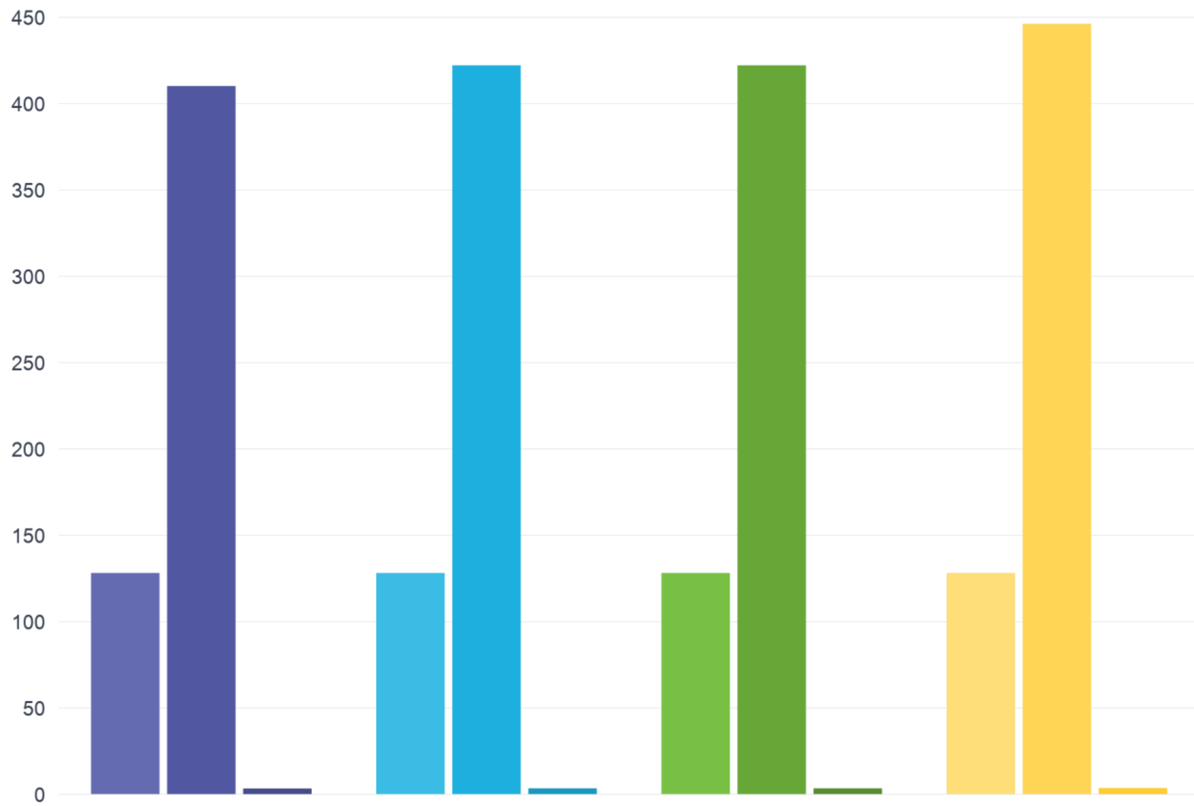


Responses 128 **Answered** 128 **Unanswered** 0

Choice	Score	Average
System development is at low technological readiness	434	3.39
Insufficient skilled personnel available	459	3.59
Reliance on immature technology (e.g., “exotic” materials) to achieve performance	381	2.98

Q7 TEST and EVALUATION:

Scoring

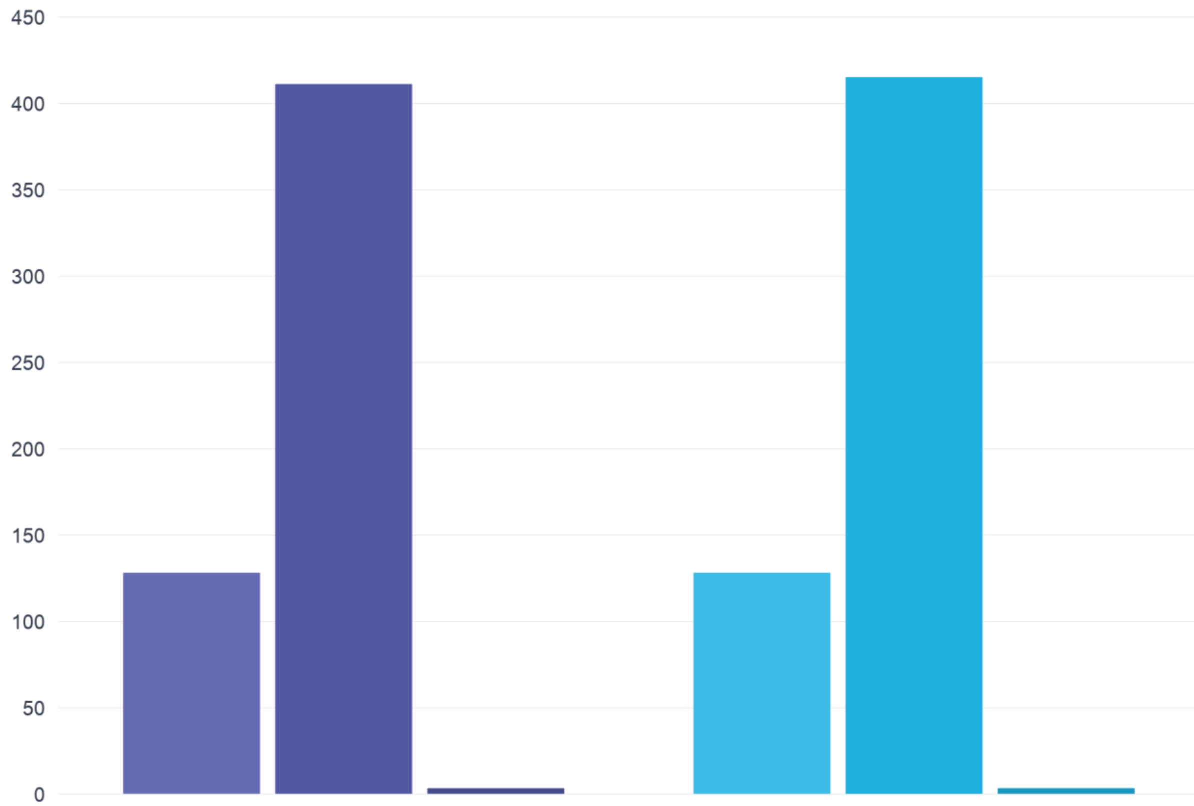


Responses 128 **Answered** 128 **Unanswered** 0

Choice	Score	Average
Testing does not address the ultimate operating environment	410	3.2
Test procedures do not address all major performance and suitability specifications	422	3.3
Test facilities not available to accomplish specific tests, especially system-level tests	422	3.3
Insufficient time to test thoroughly	446	3.48

Q8 SIMULATION:

Scoring

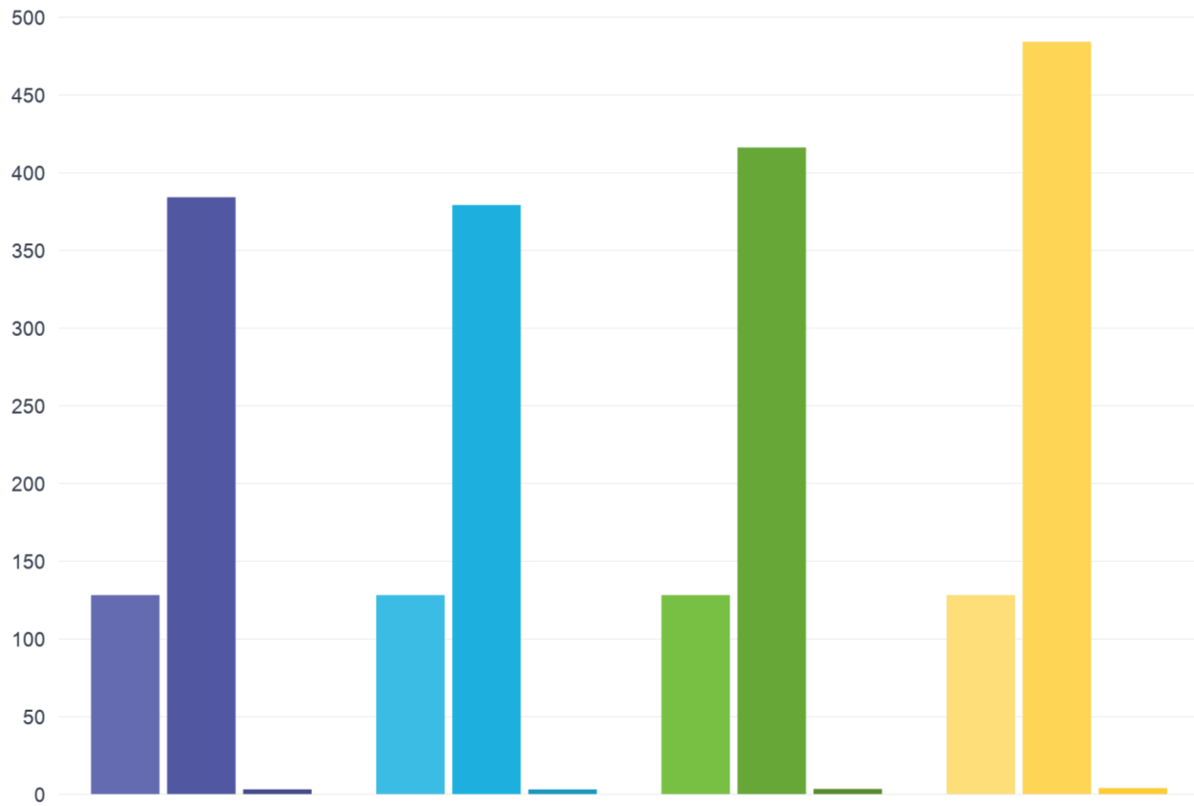


Responses 128 **Answered** 128 **Unanswered** 0

Choice	Score	Average
Modelling and/or Simulations are not verified, validated, or accredited for the intended purpose	411	3.21
Program lacks proper tools and modelling and simulation capability to assess alternatives	415	3.24

Q9 TECHNOLOGY:

Scoring

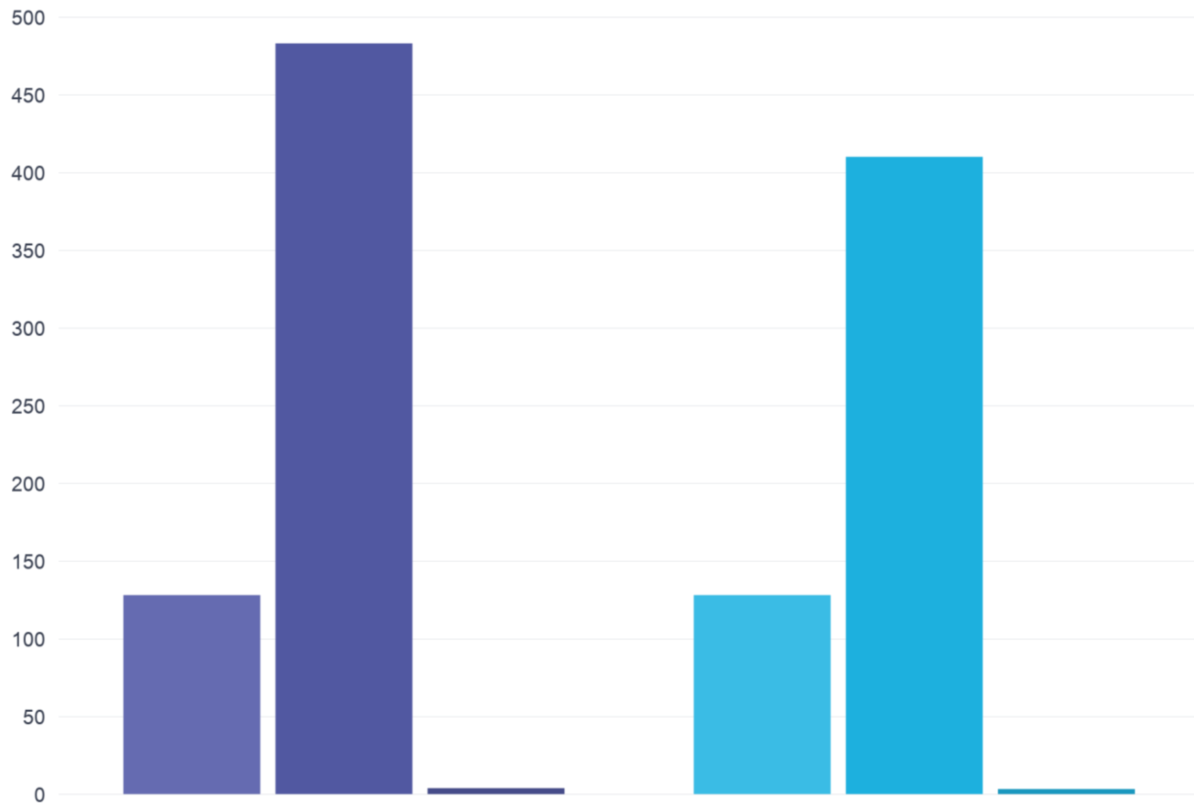


Responses 128 **Answered** 128 **Unanswered** 0

Choice	Score	Average
Success depends on unproved technology	384	3
Success depends on achieving advances in state-of-the-art technology	379	2.96
Technology has not been demonstrated in required operating environment	416	3.25
Technology relies on complex hardware, software, or integration design	484	3.78

Q10 PRODUCTION FACILITIES:

Scoring

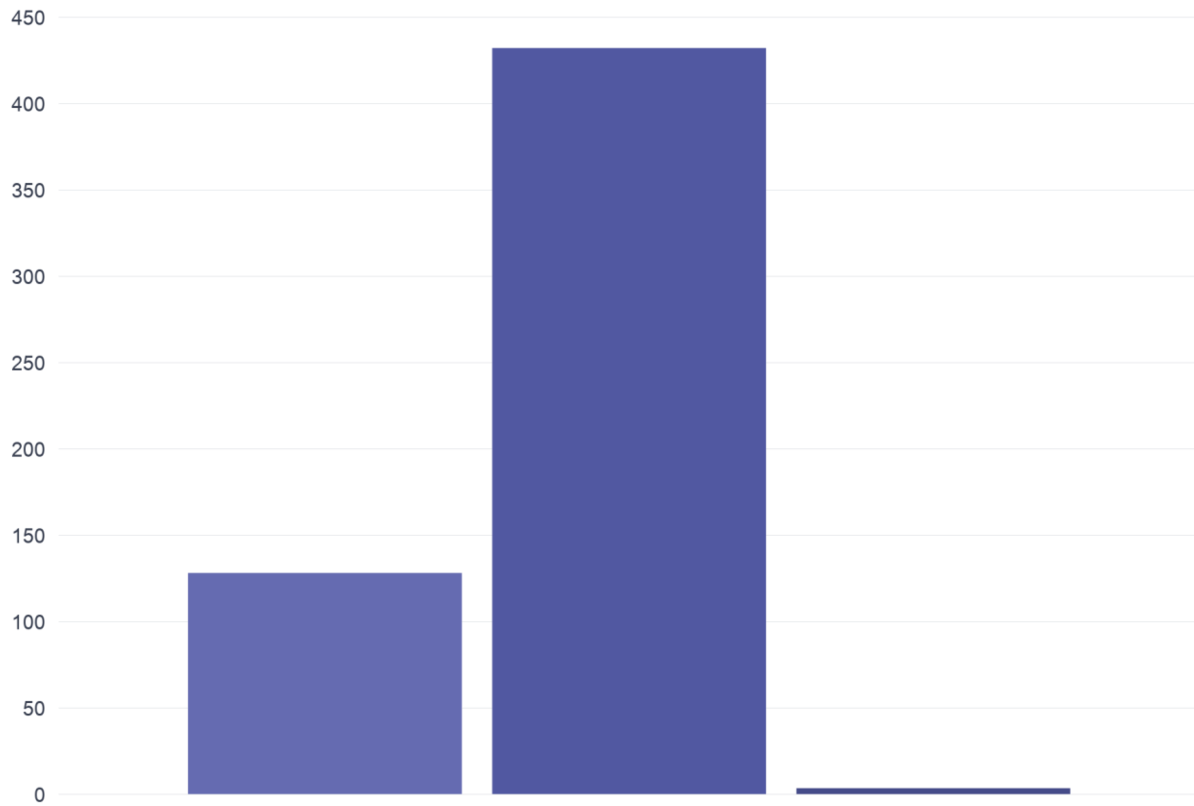


Responses 128 **Answered** 128 **Unanswered** 0

Choice	Score	Average
Production methods not sufficiently considered during design	483	3.77
Production processes not proven	410	3.2

Q11 CONCURRENCY:

Scoring

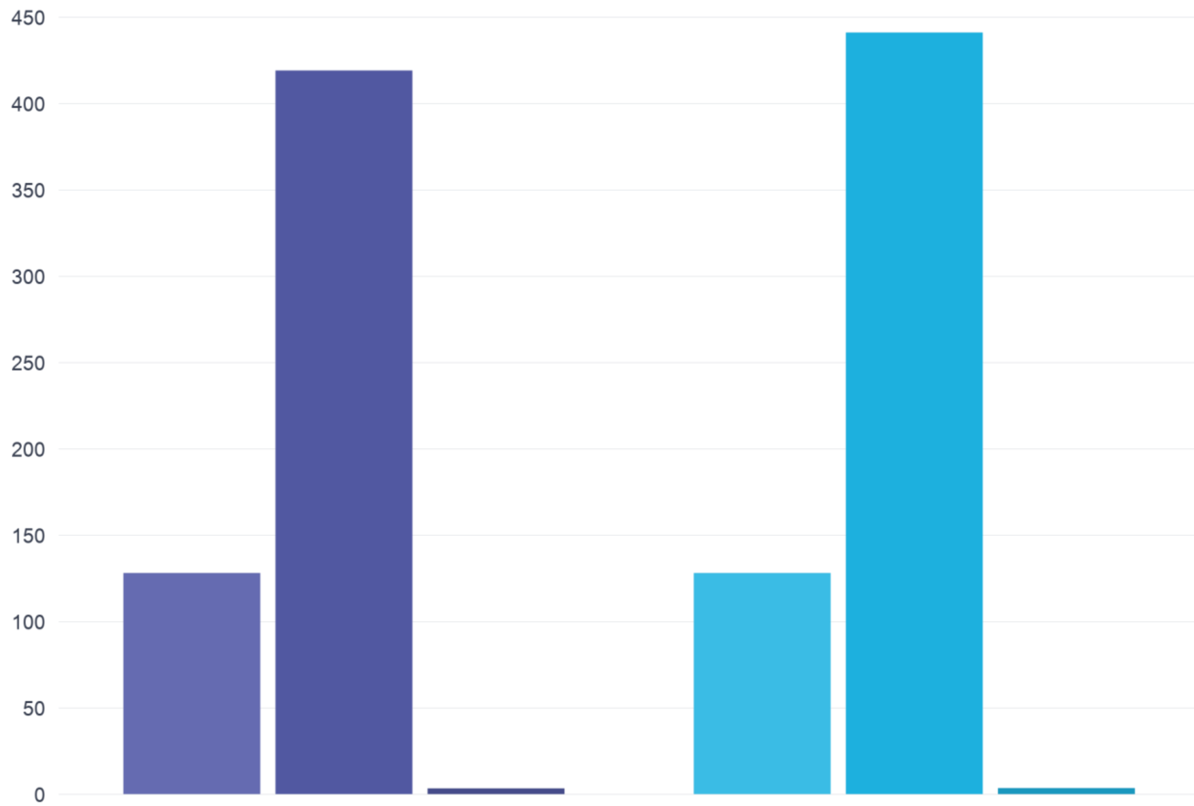


Responses 128 **Answered** 128 **Unanswered** 0

Choice	Score	Average
Immature or unproven technologies will not be adequately developed before production	432	3.38

Q12 CONTRACTOR'S CAPABILITY:

Scoring

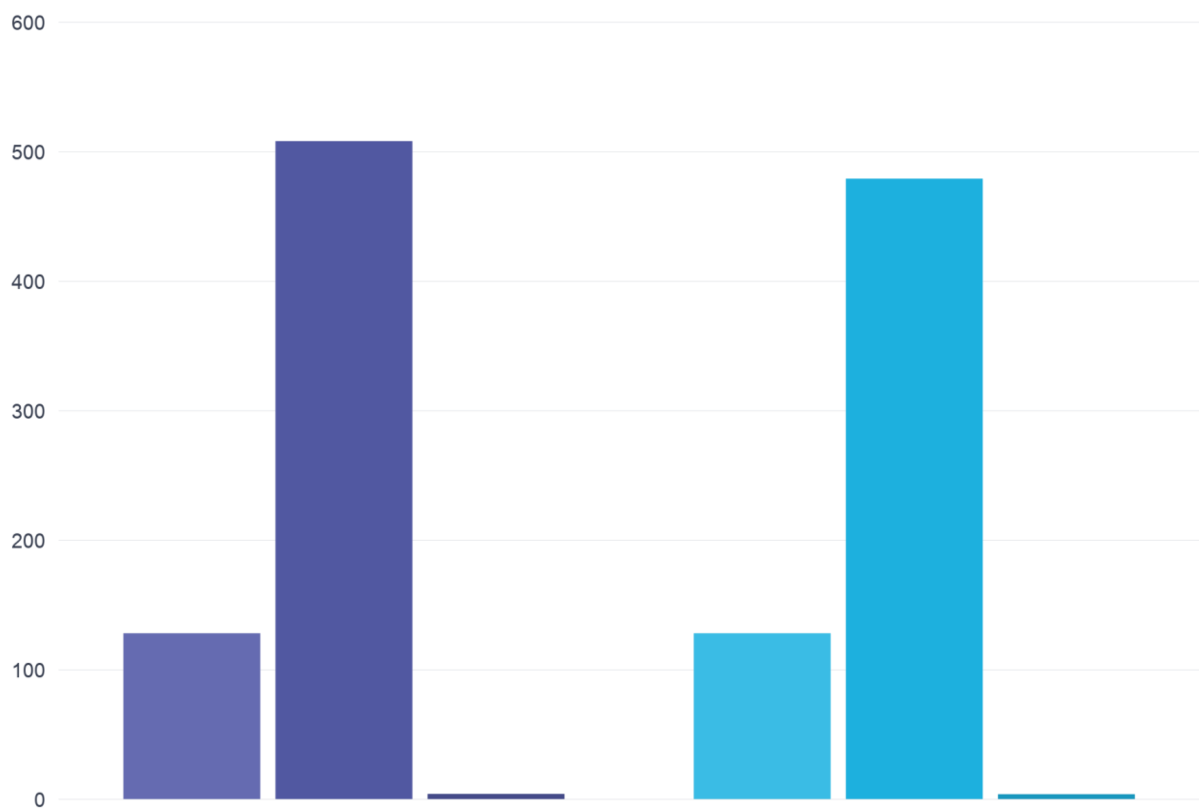


Responses 128 **Answered** 128 **Unanswered** 0

	Choice	Score	Average
●	Contractor has limited experience in specific type of ship	419	3.27
●	Contractor requires significant capitalization to meet program requirements	441	3.45

Q13 COST/FUNDING:

Scoring

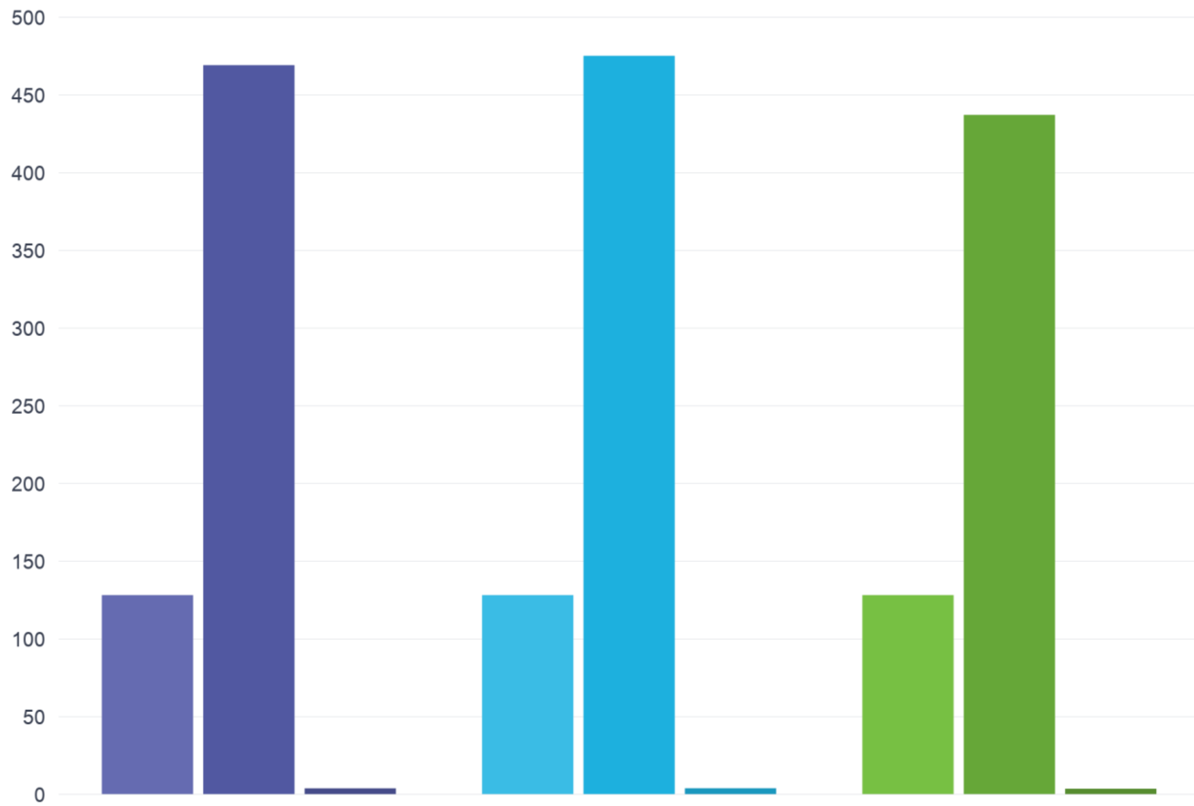


Responses 128 **Answered** 128 **Unanswered** 0

Choice	Score	Average
Realistic cost objectives not established early	508	3.97
Funding profile is not stable from budget cycle to budget cycle	479	3.74

Q14 SCHEDULE:

Scoring

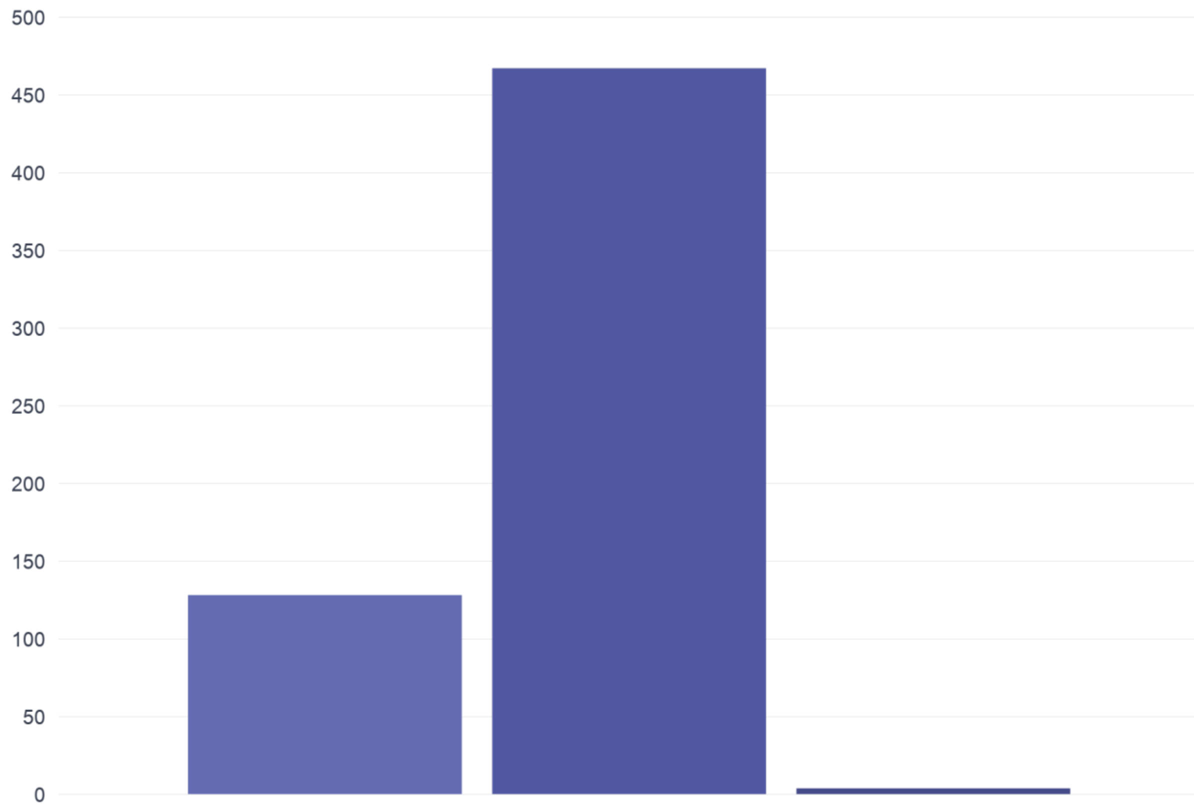


Responses 128 **Answered** 128 **Unanswered** 0

Choice	Score	Average
Financial Resources are not available to meet project's schedule	469	3.66
Human Resources are not available to meet project's schedule	475	3.71
Material Resources are not available to meet project's schedule	437	3.41

Q15 MANAGEMENT:

Scoring

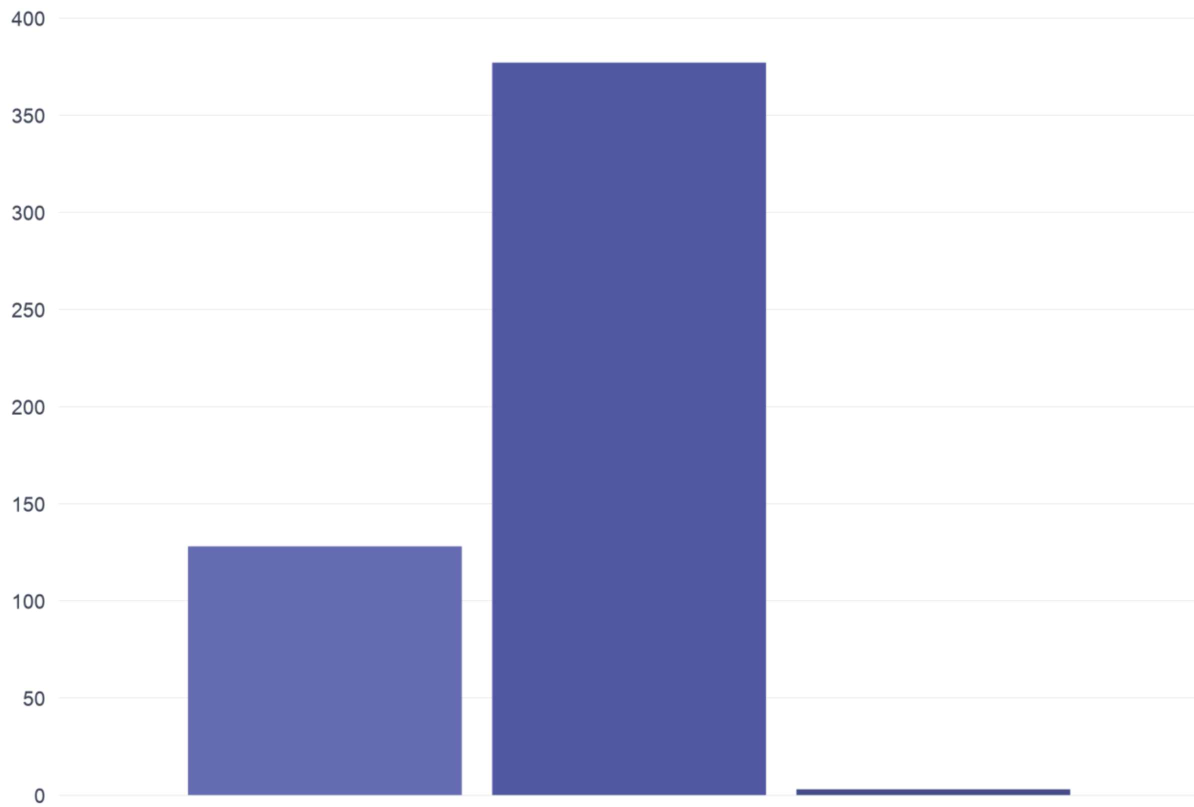


Responses 128 **Answered** 128 **Unanswered** 0

	Choice	Score	Average
●	Effective risk assessments not performed or results not understood and acted on	467	3.65

Q16 Questions 16 to 20 address risks previously identified by Lee, Park and Zhin (Lee, Park and Zhin, 2009) in the overall process of Shipbuilding. On the basis of your experience, please rate these risks from Low to High, based on the combination of their probability of occurrence and their consequence to the success of a project in terms of delivering on schedule, within budget and expected capabilities. LEGAL:

Scoring

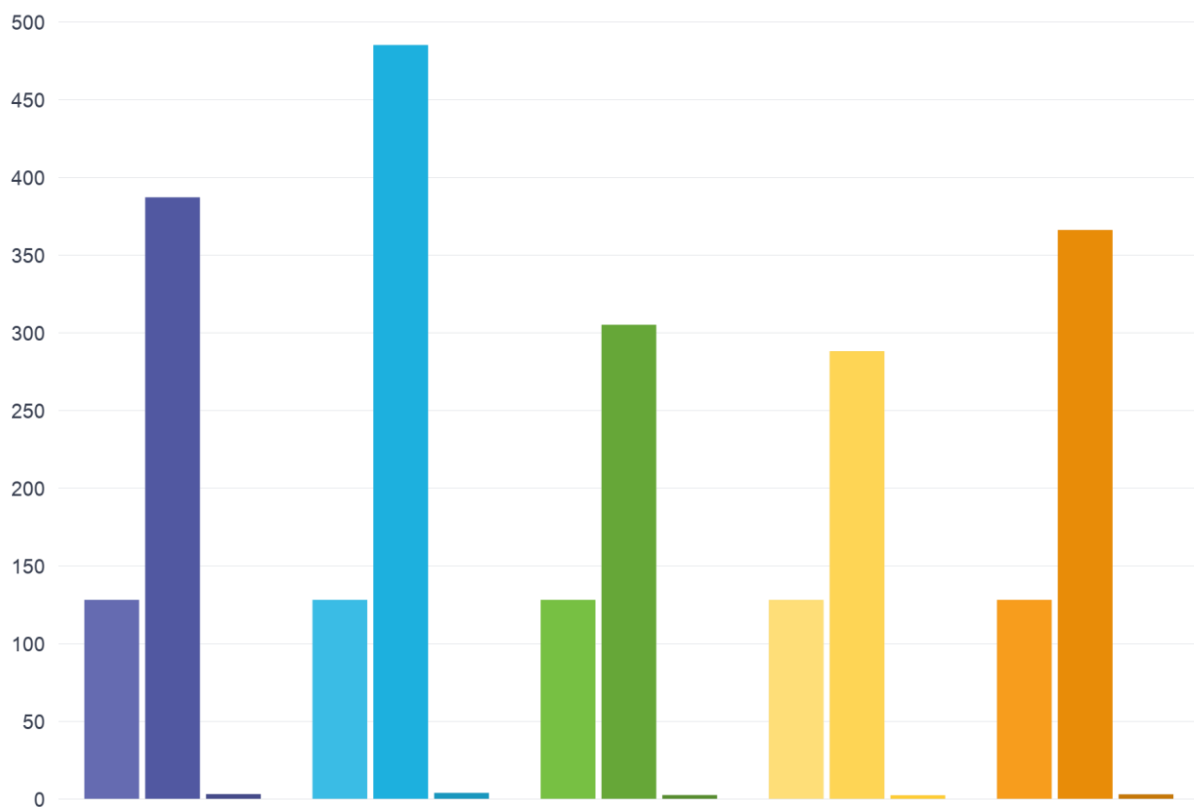


Responses 128 **Answered** 128 **Unanswered** 0

Choice	Score	Average
● Legislation and/or Regulations change and influence shipbuilders	377	2.95

Q17 ECONOMIC:

Scoring

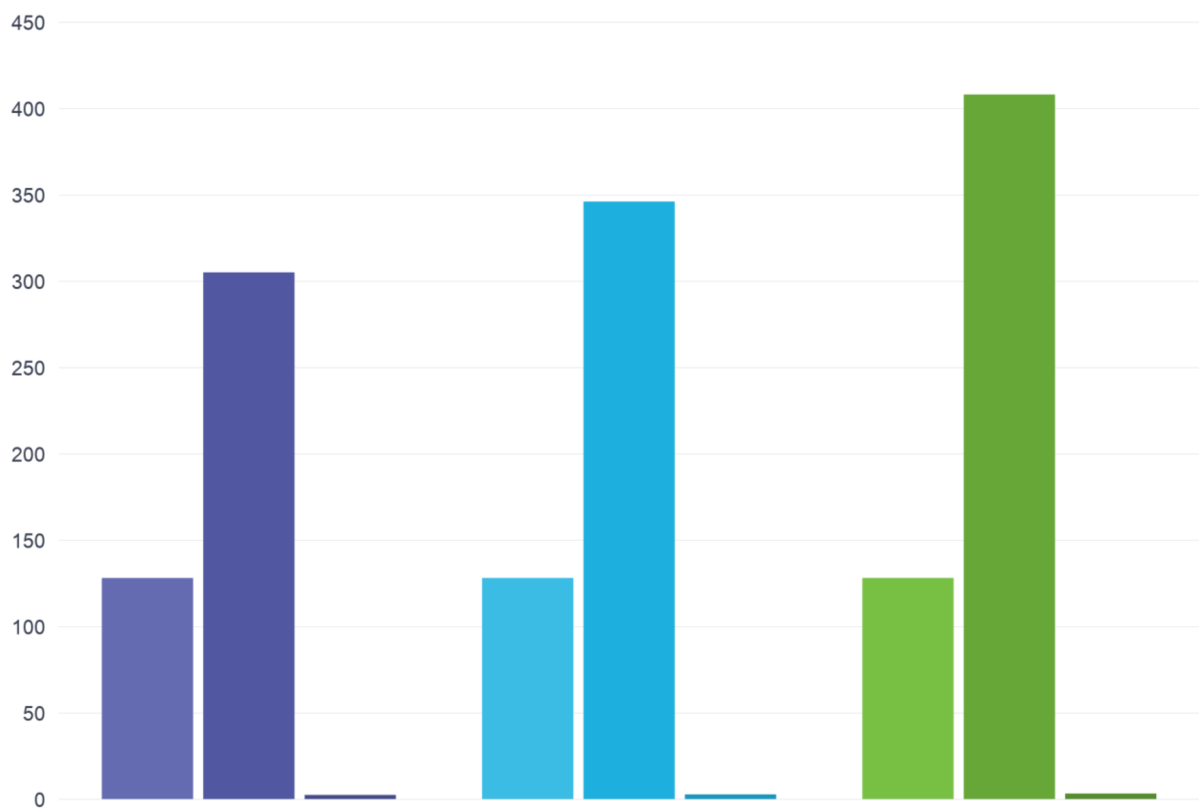


Responses 128 **Answered** 128 **Unanswered** 0

Choice	Score	Average
Labour cost rise	387	3.02
Shortages in design manpower	485	3.79
Unexpected changes in inflation	305	2.38
Unexpected significant changes in taxes	288	2.25
Unexpected significant changes in exchange rates	366	2.86

Q18 FINANCIAL:

Scoring

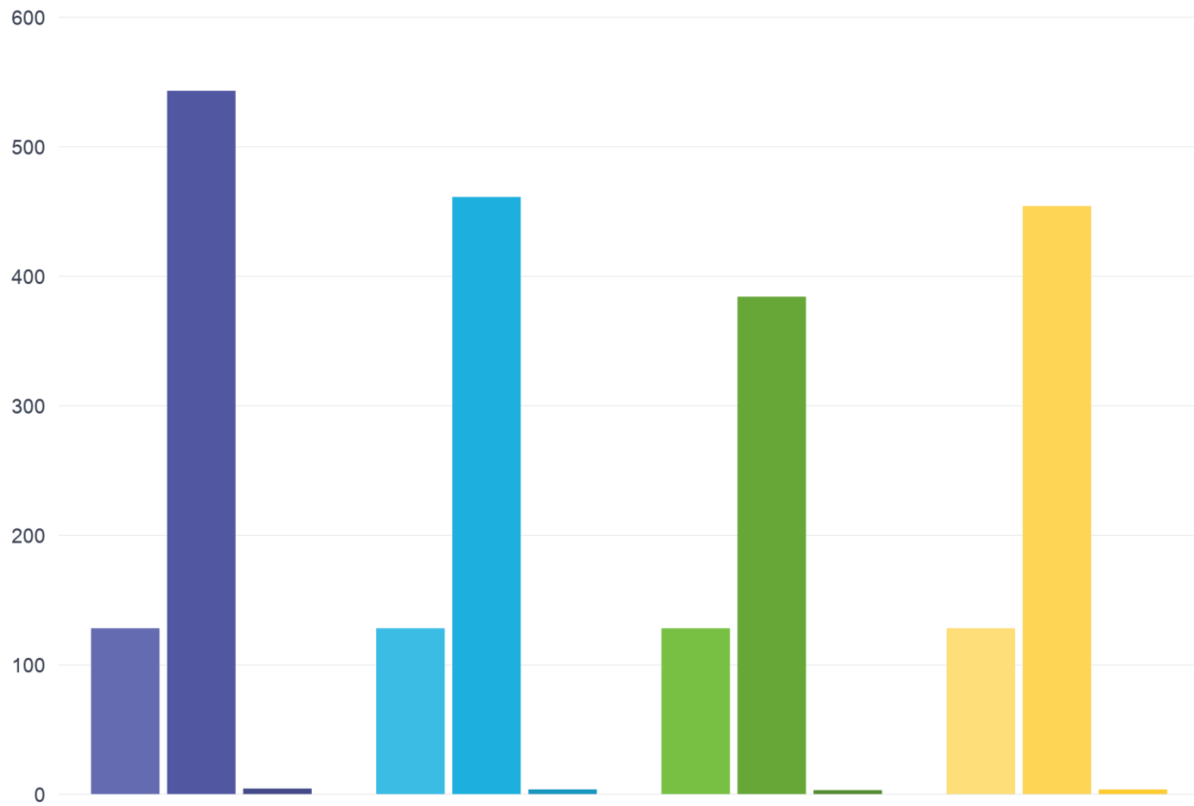


Responses 128 **Answered** 128 **Unanswered** 0

	Choice	Score	Average
●	Changes in company's credit ratings	305	2.38
●	Refund guarantee, operating costs, and other difficulties in capital funding	346	2.7
●	Unexpected difficulties in cash flow	408	3.19

Q19 TECHNICAL:

Scoring

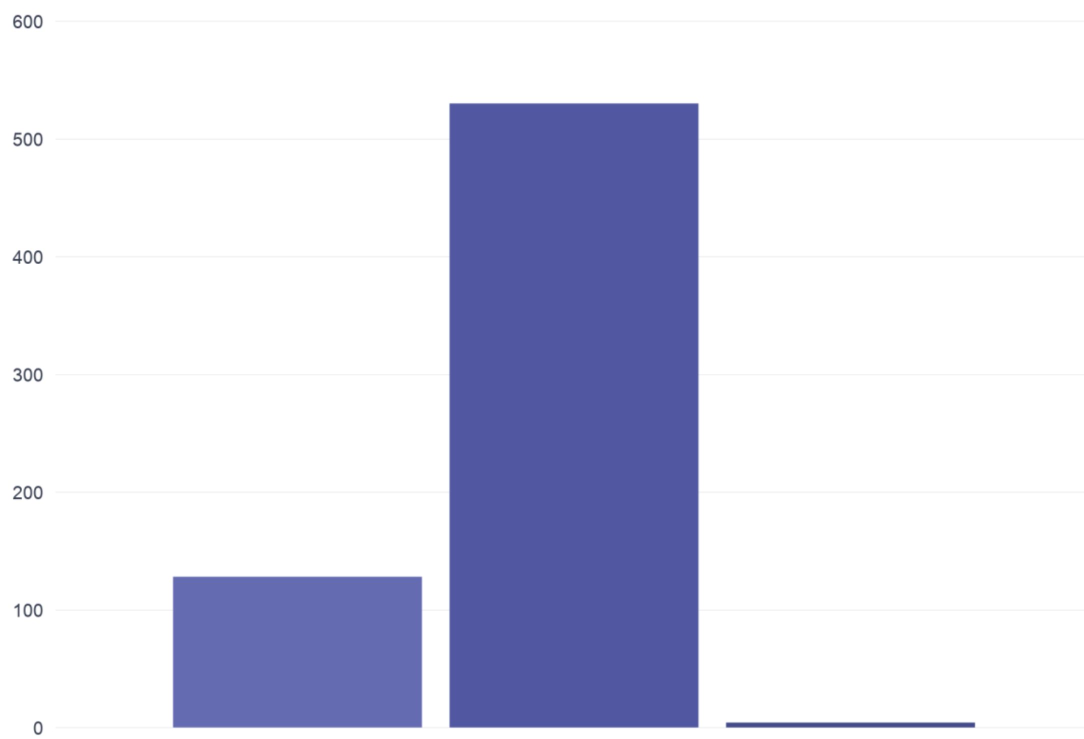


Responses 128 **Answered** 128 **Unanswered** 0

Choice	Score	Average
Changes in design	543	4.24
Introduction of new technologies incur new risks	461	3.6
Failures in production equipment occur	384	3
Instances arise where the specifications of the shipbuilding contract cannot be met	454	3.55

Q20 MANAGERIAL:

Scoring



Responses 128 **Answered** 128 **Unanswered** 0

Choice	Score	Average
● Budget is exceeded and does not go according to plan	530	4.14

Q21 Finally, please share any thoughts you may have on the subject of challenges and risks faced by Ship Designs being translated into Production

Essay

Responses 128 **Answered** 71 **Unanswered** 57

Appendix C

Learning Curve Model and Tables

Table 22. T31e 40-ship program potential savings

	Learning Curve Factor						
Number of Ships	100%	98%	96%	94%	92%	90%	88%
3	-	6.2	12.3	18.4	24.4	30.4	36.3
4	-	10.9	21.7	32.3	42.8	53.1	63.3
5	-	16.4	32.5	48.3	63.8	79.1	94.0
6	-	22.5	44.5	66.0	87.0	107.6	127.7
7	-	29.1	57.4	85.1	112.0	138.3	163.8
8	-	36.1	71.2	105.4	138.5	170.7	201.9
9	-	43.5	85.8	126.7	166.3	204.7	241.8
10	-	51.3	100.9	148.9	195.3	240.0	283.2
11	-	59.4	116.7	172.0	225.3	276.6	326.0
12	-	67.7	133.0	195.8	256.2	314.2	370.0
13	-	76.4	149.8	220.3	287.9	352.9	415.1
14	-	85.2	167.0	245.4	320.5	392.4	461.2
15	-	94.3	184.6	271.1	353.8	432.8	508.3
16	-	103.6	202.7	297.3	387.7	474.0	556.2
17	-	113.1	221.1	324.1	422.3	515.8	604.9
18	-	122.8	239.8	351.3	457.4	558.4	654.3
19	-	132.6	258.8	379.0	493.1	601.6	704.5
20	-	142.6	278.2	407.0	529.3	645.3	755.3
21	-	152.8	297.9	435.5	566.0	689.7	806.7
22	-	163.1	317.8	464.4	603.2	734.5	858.7
23	-	173.5	338.0	493.6	640.8	779.9	911.3
24	-	184.1	358.4	523.2	678.8	825.8	964.3
25	-	194.8	379.0	553.0	717.3	872.1	1,017.9
26	-	205.7	399.9	583.3	756.1	918.8	1,072.0
27	-	216.6	421.1	613.8	795.2	966.0	1,126.5
28	-	227.7	442.4	644.5	834.8	1,013.5	1,181.4
29	-	238.9	463.9	675.6	874.6	1,061.5	1,236.8
30	-	250.2	485.6	707.0	914.8	1,109.8	1,292.6
31	-	261.6	507.5	738.6	955.3	1,158.5	1,348.7
32	-	273.1	529.6	770.4	996.1	1,207.5	1,405.2
33	-	284.7	551.9	802.5	1,037.2	1,256.8	1,462.1
34	-	296.4	574.4	834.8	1,078.6	1,306.5	1,519.3
35	-	308.2	597.0	867.4	1,120.2	1,356.4	1,576.9
36	-	320.0	619.7	900.1	1,162.1	1,406.7	1,634.8
37	-	332.0	642.7	933.1	1,204.3	1,457.3	1,693.0
38	-	344.0	665.7	966.3	1,246.7	1,508.1	1,751.4
39	-	356.2	689.0	999.7	1,289.4	1,559.2	1,810.2
40	-	368.4	712.3	1,033.2	1,332.3	1,610.6	1,869.3

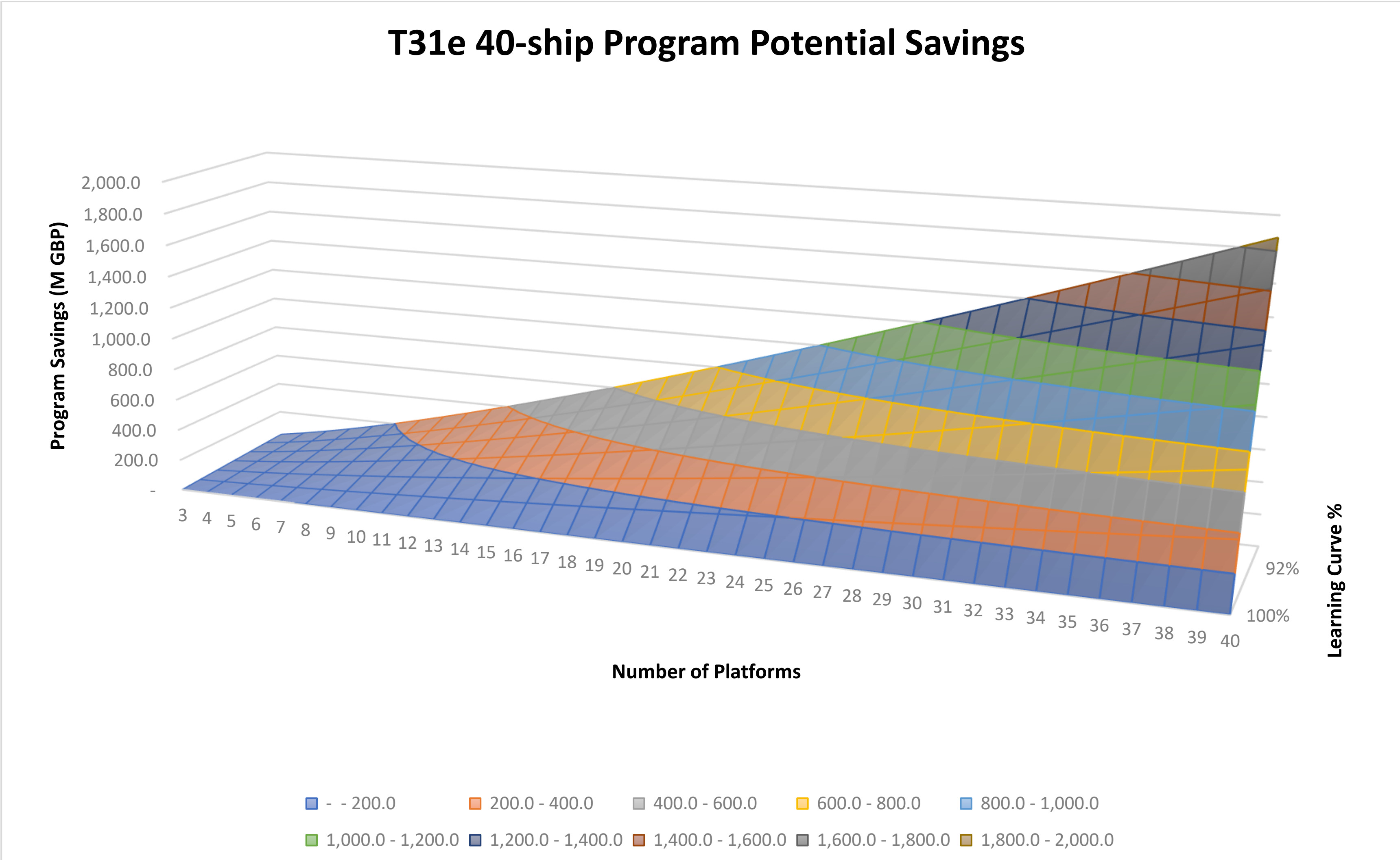


Figure 60. T31e 40-ship program potential savings

Table 23. T26 40-ship program potential savings

	Learning Curve Factor						
Number of Ships	100%	98%	96%	94%	92%	90%	88%
3	-	15.5	30.9	46.1	61.3	76.3	91.3
4	-	27.4	54.5	81.2	107.5	133.5	159.1
5	-	41.2	81.7	121.4	160.5	198.8	236.4
6	-	56.5	111.8	165.9	218.8	270.5	321.0
7	-	73.1	144.4	213.8	281.6	347.5	411.7
8	-	90.8	179.0	264.8	348.1	429.0	507.5
9	-	109.4	215.5	318.4	418.0	514.4	607.8
10	-	129.0	253.7	374.3	490.8	603.3	711.8
11	-	149.3	293.3	432.2	566.1	695.1	819.3
12	-	170.3	334.3	492.1	643.9	789.8	929.9
13	-	191.9	376.4	553.6	723.7	886.9	1,043.3
14	-	214.2	419.7	616.8	805.5	986.3	1,159.2
15	-	237.0	464.1	681.4	889.2	1,087.8	1,277.5
16	-	260.4	509.4	747.3	974.5	1,191.2	1,397.9
17	-	284.2	555.6	814.5	1,061.3	1,296.5	1,520.3
18	-	308.5	602.7	882.9	1,149.7	1,403.4	1,644.6
19	-	333.3	650.6	952.5	1,239.4	1,512.0	1,770.6
20	-	358.4	699.2	1,023.0	1,330.4	1,622.0	1,898.3
21	-	384.0	748.6	1,094.6	1,422.7	1,733.4	2,027.5
22	-	409.9	798.7	1,167.2	1,516.1	1,846.2	2,158.2
23	-	436.2	849.4	1,240.6	1,610.6	1,960.2	2,290.3
24	-	462.8	900.7	1,314.9	1,706.2	2,075.5	2,423.7
25	-	489.7	952.7	1,390.0	1,802.7	2,191.9	2,558.4
26	-	517.0	1,005.2	1,465.9	1,900.3	2,309.3	2,694.3
27	-	544.5	1,058.3	1,542.6	1,998.7	2,427.9	2,831.3
28	-	572.3	1,111.9	1,620.0	2,098.1	2,547.4	2,969.4
29	-	600.5	1,166.0	1,698.1	2,198.2	2,667.9	3,108.5
30	-	628.9	1,220.6	1,776.8	2,299.2	2,789.4	3,248.7
31	-	657.5	1,275.7	1,856.3	2,401.0	2,911.7	3,389.8
32	-	686.4	1,331.2	1,936.3	2,503.6	3,034.9	3,531.9
33	-	715.5	1,387.2	2,016.9	2,606.9	3,158.9	3,674.8
34	-	744.9	1,443.6	2,098.2	2,710.9	3,283.7	3,818.6
35	-	774.5	1,500.4	2,180.0	2,815.5	3,409.3	3,963.3
36	-	804.4	1,557.6	2,262.3	2,920.9	3,535.6	4,108.8
37	-	834.4	1,615.3	2,345.2	3,026.8	3,662.6	4,255.0
38	-	864.7	1,673.3	2,428.6	3,133.5	3,790.4	4,402.0
39	-	895.1	1,731.7	2,512.5	3,240.7	3,918.8	4,549.8
40	-	925.8	1,790.4	2,596.9	3,348.5	4,048.0	4,698.2

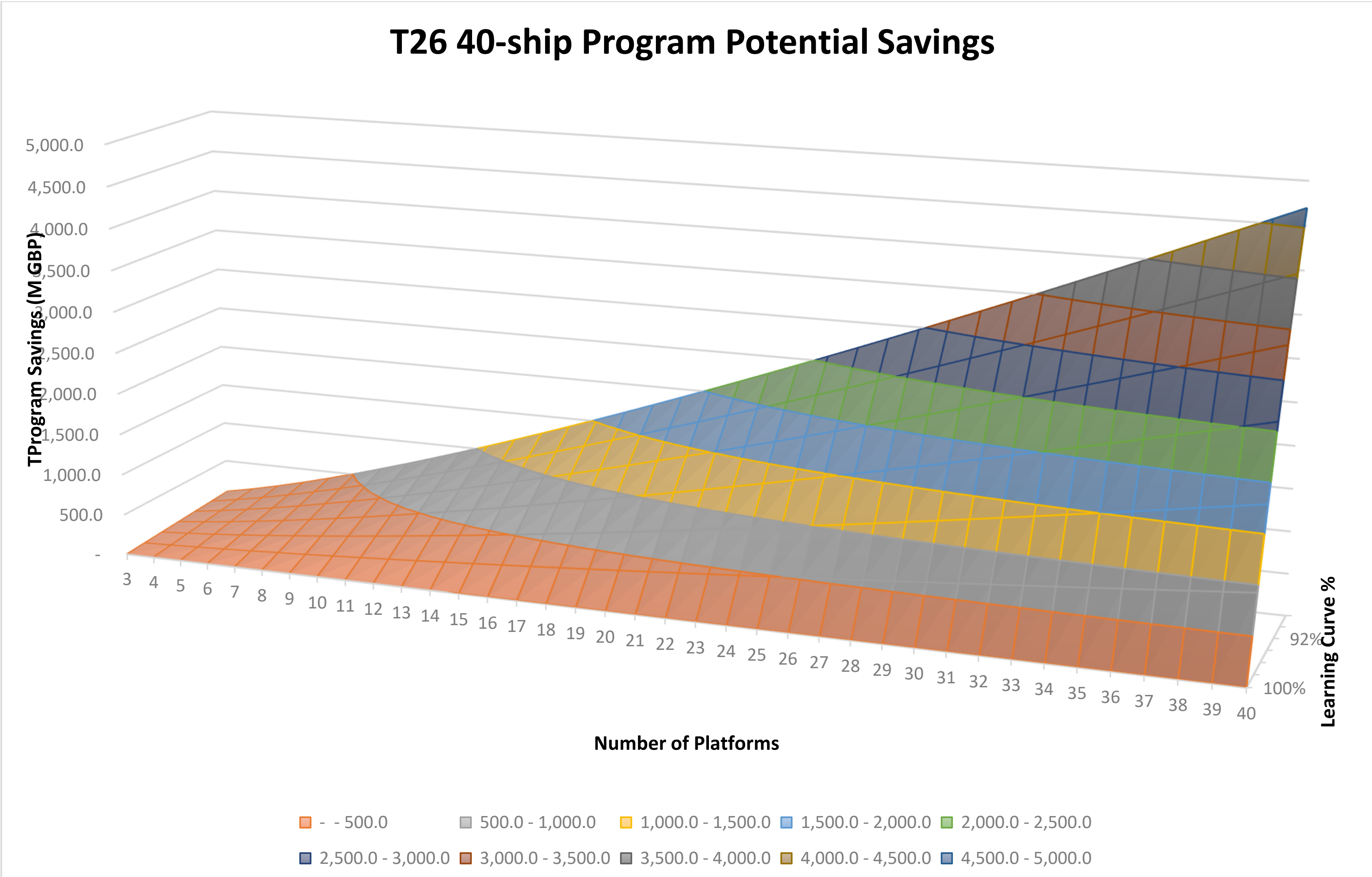


Figure 61. T26 40-ship program potential savings