Approaches to equipment selection in a small SSK and the alternatives

Abstract — For submarine designers in countries with ambitions of achieving an indigenous submarine design capability, the challenges of major equipment selection can have a significant impact on the actual design and its associated costs.

Major equipment specifically designed for submarine applications will in most cases come from overseas providers and often from limited, established supply chains. This provides many problems for designers trying to meet their bespoke requirements and achieving the goal of having a truly indigenous design.

Using COTS/MOTS equipment can introduce several risks into the submarine design programme, including issues with global licensing and export security controls which can affect a country's ability to procure the right equipment for their needs. This has the knock on effect that the equipment integrated into the submarine introduces potential deficiencies against requirements not just for the equipment itself but for the platform in terms of size, weight, capability, redundancy and safety.

These risks are further compounded once the submarine is in-service as the source of COTS/MOTS major equipment has a direct impact on the ability of a country to undertake through life maintenance without reliance on external providers; this introduces the challenge of balancing availability against the need for a capable and safe platform.

The designer is left with two options: accept these deficiencies and the associated risks or choose an alternative approach. Using the lessons learned from the BMT WYVERN concept, this paper will explore the risks and challenges of major equipment selection and procurement in a small SSK. It will identify the potential options and discuss the considerations that need to be made when assessing them, thereby providing submarine nations who have the aspiration for an indigenous design capability with an approach for assessing the risks between the different approaches.

1 INTRODUCTION

1.1 Context

New SSK submarine programmes are emerging throughout the world as existing operating nations look to upgrade aging fleets, and other countries look to add a submarine capability to their defence portfolio. Whilst many programmes are going to be fulfilled from the export market there is also a growing desire for nations to embark on indigenous designs which fulfil their own submarine needs, coupled with the potential to break into the export market.

The Spanish S-80 and the Thai Mini Submarine are examples of indigenous designs, while the Japanese Soryu Class programme is one example of a platform that serves the national needs and offers export potentials.

When considering the design of SSKs, the challenges that designers face can be daunting, Binns [1] describes several key challenges that need to be overcome to create highly capable and affordable submarines. He argues, high capability can be defined in part by the platform endurance and range with faster top speeds and longer submerged performance being the hallmarks of a more capable platform. Consideration of communications and interoperability as part of a network of assets, together with the need for hosting off board systems and embarked military forces are also key challenges and requirements that need to be traded whilst also striving to minimise costs.

When considering how to meet those requirements and overcome the associated challenges, the impact that different approaches to equipment selection can have on the design of platforms can be substantial, especially when high performance and affordability are key drivers that appear to be at odds with each other.

In order to minimise costs there are many areas that should be explored, including the use of modular builds, open architectures, proven technologies and the use of more Commercial off the Shelf (COTS) and Military off the Shelf (MOTS) equipment.

1.2 COTS and MOTS

The use of COTS/MOTS equipment to meet user requirements has become commonplace as a method of increasing affordability in submarine design of both SSK and SSN/SSBN submarines.

Standardisation of components taken from COTS solutions such as pumps, valves and compressors have the potential to simplify supply chains by bringing in commonality across many systems, offering mature technologies proven in other industries, easing the upgrade process as new generations of equipment become available, and introducing the potential to minimise the cost of procurement and management of these assets through bulk buy and common contracts.

A COTS/MOTS approach to equipment selection can also be used as a way of removing risk from the design phase, if a requirement can be met by an off the shelf solution, part of the development and commissioning costs associated with the equipment is captured by the supplier. This can also contribute to more efficient through life support with established support networks.

Commercial technology progressions, that keep up with safety and environmental compliances and track technology trends, tend to develop faster in the commercial sector as there are usually far more commercial applications and therefore more suppliers developing products. However, when it comes to major submarine equipment such as power generation and storage, main propulsion motors, combat systems and Air Independent Propulsion (AIP), the decision to use COTS or MOTS to meet the requirements of the designer and operator may not always be as clear.

Certainly for combat systems, the use of COTS equipment and software to make big leaps in technology and capability through continual upgrade has become the norm [2] [3]. The selection of COTS equipment allows for the introduction of better processing and sensor capability via a continuous upgrade pathway for newer, better, and more capable equipment over the life of the platforms. This allows aging fleets to continue to compete with nations procuring newer, high capability platforms.

When considering the lifecycle of other major equipment, upgrades do not happen at the same rate or see the same level of performance increase as you might expect from a combat systems upgrade. Compromising on design requirements for a COTS/MOTS solution may mean sub-optimal performance for the entirety of the platform life.

A diesel generator, for example, may undergo upgrade of parts through life and possibly a mid-life refurbishment without any translation into higher power, better performance, increased efficiency or reduced battery charging times. In most cases major equipment such as the diesel generator or main propulsion motor are fitted at build for the lifetime of the platform, without provision for planned through life upgrade or update.

Allowance for removal and replacement of major equipment is generally not considered necessary in a submarine design. Therefore the ability of operators to undertake wholesale equipment upgrade is limited without significant impact on the platform.

Considering these points, the use of COTS/MOTS major equipment does not necessarily realise all of the inherent benefits of this procurement approach, and in some cases may introduce risks and design compromises that will need to be reconciled.

2 WYVERN SSK LESSONS LEARNED

The BMT Wyvern concept is based around a philosophy of creating a small, capable, and affordable platform taking a simplistic approach to design; minimising redundancy and maximising the use of COTS and MOTS equipment. Figure 1 displays the BMT Wyvern concept and Table 4 displays the baseline key characteristics.

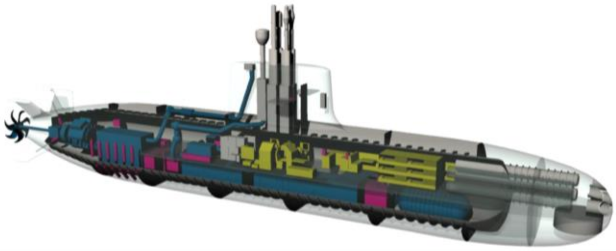

Fig. 1. BMT Wyvern SSK Concept

Table. 1. BMT Wyvern SSK Concept Baseline Characteristics

GENERAL PARTICULARS	
Surfaced Displacement	720 tonnes
Submerged Displacement	863 tonnes
Reserve of Buoyancy	20%
Length Overall	46 meters
Beam	4.5 meters
Diving Depth	210 meters
RANGE & ENDURANCE	
Crew	15 plus capacity to surge to 21 crew
Endurance	20 Days (4 Days Stirling AIP)
Maximum Speed	18 Knots
Range (Snorting)	3000 nautical miles

With no end customer defined for this platform it only has a generic requirement set, thereby maintaining flexibility to sovereign nations. To demonstrate the capability and to achieve the baseline characteristics of maximum speed and endurance, the major equipment selection was taken from off the shelf solutions fitting in with the COTS/MOTS approach.

Each major equipment selection decision had an effect on the design of the Wyvern platform, challenging designers to achieve a balanced design. The impact of these equipment selection choices on the design of a small SSK is far greater due to the potential impact of equipment size and weight on the overall balance of the platform design, and can mean taking up valuable space that could otherwise be used for additional ancillary equipment.

2.1 Diesel Generator

The diesel generator specified for Wyvern is a single MTU4000 1300kW diesel engine paired with a Pillar NTB 60 series DC Generator. This particular diesel generator set was the only one available in the current market that could be used to meet the power generation requirement of the platform. Whilst MTU have significant pedigree in the submarine market, making the decision relatively low risk, for this platform design the choice of only one item to fulfil the requirements also reduces the flexibility of the designer.

Platform design allowances for weight and space are fixed from the outset with the size of the diesel generator in relation to the available internal volume putting limits on the arrangement of the platform.

The use of a single diesel generator also means that there is no redundancy for the main source of power generation. This places a significantly higher burden on the reliability of the equipment to provide continued power generation for the life of the platform.

To provide some operational safety and partial redundancy, use of an additional smaller emergency generator was considered in the design, but was not taken forwards due to availability of space and maturity of the available diesel engines. Therefore the Stirling AIP engine would be the means of providing backup to the power generation should any problems with the diesel engine occur.

Whilst minimising redundancy was a goal of the Wyvern concept design it potentially adds significant risk. In the event of power generation failure, submarine missions would effectively cease until a fix could be applied. Given the maximum snorting range of the platform, maintaining this capability could be considered of paramount importance.

2.2 Main Motor

The Wyvern main motor is a 1700kW Siemens "Permasyn" permanent magnet motor. This type of motor is a popular choice amongst submarine designers with the 1700kW version being the smallest motor in the "Permasyn" range.

Whilst the motor physically fits into the available space envelope, it is more powerful than required. The motor easily accommodates the maximum sprint speed of 18 knots; however this maximum speed will likely only be required on limited occasions, to meet the operational need.

The current Concept of Operations (CONOPs) for the platform identify that in normal operations, whilst in theatre and on patrol, the submarine would be expected to operate at speeds well below sprint speed (~4-5 knots submerged) and would therefore mean that the motor could be running at an inefficient operating point.

This over specification against the requirements led the design team to specify an experimental concept cruise motor. This smaller motor would provide propulsive power for the platform at slow speed on patrol whilst enabling the sprint speed to be met by the main propulsion motor.

The introduction of the cruise motor adds additional spatial demands, weight, and complexity into the design. As the cruise motor would probably be a bespoke design, it means that the savings and benefits from selecting an off the shelf design for the main motor start to become less significant.

2.3 Air Independent Propulsion (AIP)

Submerged power generation in the Wyvern concept design is provided by an AIP system consisting of two Stirling Engines supported by a Liquid Oxygen (LOX) tank to provide up to 4 days submerged. The Stirling AIP is marketed by SAAB (previously Kochums) and whilst this technology is a proven design that has been used and demonstrated at sea in Swedish submarines, currently the only other known user of the Stirling AIP system is Japan on the Soryu Class. An arrangement exists between SAAB and Kawasaki Heavy Industries (KHI) that allows KHI to assemble the AIP units using parts provided by SAAB [4].

In order to use this technology on a new build submarine design, a similar agreement may be required or an agreement made directly with SAAB to provide the units and integrate them into the design. Whilst the implications of commercial agreements were not explored fully during the project, this could have an impact on the choice of technology used to meet the submerged requirement of the platform as intellectual property or commercial constraints can limit the extent to which manufacturers allow their equipment to be integrated with other equipment.

2.4 Wyvern Summary

Whilst the Wyvern concept provided several challenges for the designers and the selected design solutions allowed for a small and capable SSK, the platform can be tailored to suit the specific requirements of a sovereign nation during requirements trading and some of the underlying design choices can be re-visited.

One aspect identified in all three major equipment cases was the seemingly limited number of suppliers of major submarine equipment.

A review of SSK diesel engine suppliers identified that the most widely used variants are supplied by MTU and Pielstick, with Pielstick also being used to supply the French SSN/SSBN fleet.

Some of the other identified manufacturers including Caterpillar (USA), Kawasaki (Japan), Hedemora (Australia), Paxman Velenta (UK), Grandi Motori Triest (Italy), Elektrosila and Kolomensky Zavod (Russia) are not currently known to export diesel engines for submarines. Consequently the potential supplier pool is limited, restricting the choice for submarine designers.

Whilst MTU and Pielstick provide proven designs with established pedigree, there is a potential that some engine variants within their current range do not meet the requirements of the design and could potentially deliver a sub-optimal platform.

Similarly, of the Main Motor manufacturers identified, Siemens and Jeumont Schneider are the largest suppliers of electric submarine propulsion motors, supplying most of today's SSK export submarines.

A number of different AIP technologies have been produced or are undergoing active development programmes, but there are relatively few fully mature options available to submarine designers without carrying development risks. This has driven the Wyvern design to adopt a Stirling AIP baseline.

3 ALTERNATIVE APPROACHES

The design challenges explored from the Wyvern concept study can in part be attributed to the choice to use off the shelf solutions for major equipment selection. Whilst this approach was made to work, other potential approaches could have been considered.

Typically there are four approaches to major equipment selection that could be used when deciding on how best to meet platform requirements; these are identified in Table 2.

Table. 2. Approaches to major equipment selection

APPROACH	DESCRIPTION
COTS/MOTS	Use an existing item to fulfil a requirement.
Tailored COTS/MOTS in domain	Work with existing submarine equipment suppliers to tailor a solution, making modifications to existing product range.
Tailored COTS/MOTS outside domain	Work with parties in other domains to provide a new product based on existing industry equipment.
Fully Bespoke Solution	Develop new equipment solutions, potentially novel.

It could be argued that as the approach moves away from a pure COTS/MOTS solution, there are an ever increasing number of risks that are introduced and need to be considered. These will not just be design risks but also commercial as well.

3.1 Tailored Solutions

As discussed, the decision to use a COTS main motor for the Wyvern concept study served to reduce the risk in one area, but transferred or potentially created risk in other areas. The introduction of a cruise motor means additional development time and increased system integration burden. In this specific case a change in requirement, i.e. lowering the sprint speed may have opened up more options for the designers to investigate including other off the shelf solutions. However, if this was not a tradeable requirement, to continue with the COTS approach would not have satisfied the requirement.

Approaching a supplier to develop a tailored solution may have resulted in a motor that met the requirements and also removed the need for a cruise motor. This would in essence be a direct trade, more time and money would be required to develop the motor but time and money would be saved by not having to develop the cruise motor. Understanding the requirements and the ability to trade and compromise would be key to deciding on an approach.

Although it is recognised that most submarine designs opt for COTS/MOTS solutions that have already been proven in domain or have versions which have been tailored, there are examples of other approaches being considered.

When considering diesel engines, specific examples of countries opting for a different approach to major equipment selection include Japan through Kawasaki Heavy Industries. The diesel engines used in the Soryu Class are modern variants of diesel engines originally produced under license from an established MAN diesel in the 1960’s [5]. They have been through a number of design iterations in Japan’s submarine classes and, alongside the apparent level of investment in the development of Lithium Ion battery technologies [6]; they are also developing higher power diesel generators to reduce charging times. This is a specific example where the submarine requirements are driving the chosen approach to equipment selection.

The Australian Collins Class is another example of an alternative approach; here a decision was taken to satisfy power generation requirements with a solution tailored from another industry. In this case the Collins Class project undertook to modify a Hedemora 12 cylinder diesel engine used in locomotive transport. This later became an 18 cylinder design due to the need to get more power out of the three diesel engines arranged side by side in the platform.

The problems that the project experienced and the performance issues that the diesel engines still appear to have to this day, may be attributed to execution rather than the approach. The failure to consider all of the implications of developing a diesel engine, not just on the platform design but the wider organisation, was evidenced at a number of points in the programme. At the time the diesel engine was being selected, Hedemora was in the process of being sold, consequently support to the submarine designers was limited [7]. Build over-flowed into the in-service phase, meaning that the operators had a new engine, for which they had no operating experience and minimal manufacturer support, which led to extended down-time and the need for subsequent modification work to resolve any residual integration issues.

There are a lot of lessons that can be learned from the Collins Class programme and the failure to consider all of the implications of the procurement decision clearly contributed to the problems during diesel engine development resulting in significant time and cost impact. However, if the execution issues are overlooked, the broader approach to major equipment selection taken on the Collins programme had the potential to satisfy a specific power generation requirement with the provision of additional redundancy. If the project had taken the time to consider all of the implications, including the wider lines of development, the approach had merits which may not have been achieved using a COTS approach.

Buckingham and Mann [8] consider a similar prospect in their paper when comparing the use of two larger diesels with up to four smaller modern diesel engines. They provide a method of assessment to compare between the two cases, exploring the challenges of developing diesels for submarine applications including issues with back pressure, low inlet pressure and the need to ensure that the diesel can work in both open and snorting conditions in saltwater.

When considering this approach for the Wyvern concept having two smaller engines providing the full power requirement could have the potential to offer a level of redundancy that currently doesn’t exist for the diesel generator (although it should be noted that the AIP solution could in theory provide an alternative back up). Having two smaller diesels also has the potential to create flexibility in the design, freeing up designers to think more creatively about arrangement and integration.

3.2 Bespoke Approaches

Fully bespoke approaches to major equipment selection tend to come with the highest risk and cost implications due to their limited appeal in the wider marketplace and lack of potential customers. For example, a fully bespoke solution that replaces the traditional source of power generation by taking advantage of advancements in fuel cell technology is still long way from the required technology maturity needed for submarine applications.

Whilst fuel cell technology for AIP is maturing, overall power output remains low and most of the advancements in the megawatt level have been in Solid Oxide Fuel Cells (SOFC) for stationary power systems and have to be combined with Gas Turbine technology to achieve the necessary megawatt level power [9] [10].

Smaller SOFC power generation capabilities are available and companies such as Bloom Energy are marketing SOFC based "Energy Servers" in the region of 200kW – 250kW range [11]. However, this technology is not widely in development or being invested in for mobile applications such as ships and submarines with fuel sources being focused around natural gas supply. A typical "energy server" is shown in Figure 2.

Fig. 1. Bloom Energy Server [12]

Significant development would be required for a solution such as this and the risks of low technology maturity, cost and time impact on the overall programme, platform integration and through life support is both very apparent and difficult to mitigate. Whilst in this specific example the consideration of bespoke or novel technology to meet power generation requirements is possibly not the answer, creating a novel or fully bespoke solution should not be discounted.

In the current submarine market, AIP solutions include Proton Exchange Membrane (PEM) fuel cells with various fuelling options (Hydrides, Diesel Reformers) and Stirling Engines. Both fuel cells and Stirling engines provide proven technologies for consideration in a small SSK. A study conducted by BMT into alternatives to AIP during the Wyvern concept concluded that the use of Stirling Engines was appropriate for the design, but that fuel cell alternatives were available and could have provided suitable alternative. However, it was identified that all of the solutions would likely come with supply and licensing considerations which have the potential to make COTS and even tailored solutions potentially problematic.

The Japanese Soryu Class currently uses the Stirling AIP which, as mentioned, is achieved through a supply and assembly deal. If fuel cells utilising metal hydrides were preferred as an option, then discussion with TKMS would be required as they are believed to be the only current supplier of metal hydrides for submarine use. Both these examples put a limit on the sovereign nation and in an indigenous submarine design the choice of AIP becomes a difficult one if it is important to maintain independence or if a fully integrated design is needed.

Choosing a fully bespoke approach in this instance may then not be a bad option. If licensing and supply deals mean the project is reliant on an overseas supplier for support for the life of the platform, then this may negatively affect availability, and therefore developing a technology may be more appealing.

As with tailored solutions, there are examples of countries developing bespoke solutions in order to meet their own capability and/or export aspirations.

As previously discussed, the Japanese Soryu Class uses the four Stirling engines, but the latest platform, JS Shuriyu, is believed to be trialling Lithium Ion battery technology alongside the Stirling AIP, with the likelihood that on the final two platforms in the class Stirling engines will be replaced altogether with an all Lithium Ion battery solution.

Whilst it is believed that this approach has been taken to further Japan's submarine export ambitions, it has taken considerable time and money in development on the battery and the support systems to get to the positon they are in today. This development of technology will however mean the reliance on a 3rd party to provide parts and support is significantly reduced.

The Spanish S-80 AIP, which was originally going to be developed in partnership with France, was taken back in country as their quest for longer range and higher capability presented difficulties that could not be overcome jointly. The Spanish S-80 project went on to develop their own bio-ethanol AIP plant [13] in an attempt to fully satisfy their platform requirements.

The design has seen delays and technical issues, which may mean that the first two platforms are launched without the AIP capability in the first instance.

In this case differing views on capability or compromising requirements drove the project towards a bespoke solution to the submerged endurance requirement. Although the decision to maintain a focus on capability has contributed significantly to platform delays initially, when the AIP solution is eventually retrofitted, the result should be an extremely capable platform.

3.3 Summary

For all of the approaches considered there will be an inevitable trade of project risk against platform performance and there are several considerations and implications that need to be taken into account when choosing the right approach for a submarine design.

4 CHOOSING AN APPROACH

The discussion so far has identified four potential approaches to equipment selection. When considering each approach, the question remains how to choose the right one for a particular project and the answer will not be the same for each item of major equipment.

It is also not necessarily the case that each approach should only be considered if the previous is not suitable, the list in table 2 should not be considered to be linear and indeed, each has its own potential merits and drawbacks. Ultimately the choice has to be reconciled with the programme's risk appetite and before choosing a procurement strategy there are a number of considerations to explore that may help identify the most suitable approach to be taken.

4.1 Requirements

Understanding the requirements is a key factor in deciding on an approach to the selection of major equipment. It may be that an off the shelf item can be found that fully meets all of the requirements perfectly. However, in the majority of cases this will not be likely.

The implications of not meeting requirements need to be fully understood and an assessment of requirement priority needs to be undertaken, i.e. which are fixed and which are considered tradeable. This should include understanding the interactions between requirements and the affect it has on overall platform performance as any decision has the potential to cascade changes throughout the design.

4.2 Affordability

Designing affordable submarines and driving down Unit Purchase Costs (UPC) is a significant driver for many submarine nations.

It is recognised that technology development costs money, not only in research, development and testing activities, but also through life since reliability of new products in the submarine environment will remain relatively unknown until they can be tested in operation and a performance history established.

Considering the opposing argument, development costs are also normally only required for the first in class, typically the later platforms in the class will not have to bear the cost and other efficiency savings may be realised that offset some of the earlier development costs.

The implications of each approach need to be identified early in the programme and the effect on project budgets explored. If not managed correctly, these have the potential to spiral quickly if the development of major equipment is delayed or a required performance is not achieved.

4.3 Time

Submarine design and build programmes are often many years long. SSK design and build programmes are much shorter than SSN or SSBN programmes, which can take 10-20 years to complete, but there is still a significant time investment.

All of the equipment selection approaches have a time risk involved with them. COTS/MOTS will have manufacturing lead times. Although in this context COTS/MOTS are taken to mean already available, the reality is that many of the major equipment items are made to order. The equipment lead time and the ability of suppliers to work to the project timescales is an important selection consideration.

Development of new technology or any tailoring of equipment will also need to take place alongside the design of the platform and may inevitably mean that the submarine design and build programme is longer than might be expected resulting in platform delays, or as in the case of the S-80 AIP a delayed platform that may be launched without full capability available.

This serves to illustrate just how much effect delays to major equipment selection can have on the design and build programme.

4.4 Safety

All of the major areas of major equipment discussed have an effect on safety of the platforms and the personnel on them. The ability to operate and maintain equipment in a safe manner is important, and as the approach to major equipment selection moves away from COTS/MOTS (with proven submarine track records), the need to ensure that the choices remain safe is paramount, especially when considering novel or unproven technologies that use different materials and operational characteristics.

4.5 Wider Capability Management

The selection of major equipment in any submarine design has an obvious effect on many aspects of a design but it also has an effect on the wider aspects of defence capability management.

Defence Lines of Development (DLODs) is the UK capability management concept covering Training Equipment, Personnel, Information, Doctrine, Organisation, Infrastructure and Logistics (TEPIDOIL) and whilst there are several different capability management models in use by other nations, the end goal and key levers are broadly similar in concept. All of these aspects need to be considered when making design decisions.

Arguably a COTS/MOTS approach to major equipment selection aligns better with the DLODs as the existing technology is a known quantity and support solutions from manufacturers will likely be available as part of a service package. Submarine replacement programmes usually also benefit more from this as there is a tendency to use legacy submarine equipment in replacement programmes. This will be familiar to both the organisations and the operators.

As the approach moves further away from a COTS solution there will be a need for further additional investment to ensure that tailored or bespoke solutions are operable and supportable, with the appropriate organisational and logistic infrastructure in place. This will be critical in ensuring that any major equipment has the right through life support.

4.6 Design Team and Industry Capability

For any of the approaches to be successful, supply base and domain knowledge will be significant to the success of any of the approaches.

It has already been discussed that the supplier base for submarine major equipment from COTS/MOTS supply is limited to a handful of suppliers and for countries new to the submarine market, the likelihood of having a suitable indigenous supplier base will be low meaning that overseas supply is required.

If a designer needs to tailor a more bespoke solution, either due to a capability decision, non-availability of products or fixed requirements, using options from other industries to fulfil submarine duties may be necessary. However, this will require both scrutiny of the indigenous industrial base and an assessment of the ability of the industry base to support not just the development of products but the through life support requirements. This is just as important a consideration in approach selection as the basic capability issues in ensuring that some of the pitfalls experienced by other submarine projects can be avoided.

5 CONCLUSION

The benefits of using COTS/MOTS to drive down initial purchase costs and through life costs offer real opportunities for a submarine design and build, driving in commonality and simplifying on board systems as shown with the Wyvern concept design.

However, some major equipment doesn’t always benefit from off the shelf solutions since the impact on the overall platform performance and requirements can be significant.

The decision on whether to use COTS/MOTS solutions for major equipment or to tailor a solution will be dependent on the level of risk and the measure of performance that the submarine design project as a whole is willing to tolerate, and this paper has presented a number of considerations that must be made during the decision making process.

Whichever approach is taken to major equipment selection, it needs to be made in the early stages of the design cycle and embedded within a procurement strategy with any subsequent changes likely to add time and cost to the programme and will likely result in a sub-optimal design solution.

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