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Department of Marine Technology

M.Sc.THESIS

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Abstract:

The need to explore designs and arrangement configurations that will enhance operational flexibility and sustainability of the DSVs, without jeopardizing their operational efficiency and lifecycle costs (LCC) was crucial in the present study because of the uncertainties inherent in the mapping of the purpose built DSVs for long duration contracts and anticipated depletion in future offshore development projects across the globe. Three design concepts that focused on arrangement of the mission equipment of the DSVs were proposed and developed using system based design approach and design standards for North Seas operation. The designs were evaluated towards five key performance indicators using the Analytic Hierarchy Process. The study found that a DSV with top side modular design for SAT diving system would be flexible and sustainable to operate, while maintaining efficiency and reduced LCC compared to designs that have either their ROV equipment and air diving system or only ROV equipment in standard container modules. The assumptions made about downtime cost influenced this conclusion. However, sensitivity analysis confirms that in the absence of downtime cost, the design concepts which had either ROV equipment and air diving system or only ROV equipment in standard container modules were cost efficient compared to the one with top side modular design for SAT diving system. The targeted markets for the design concepts were the North Sea and Offshore West Africa, and the designs have the capability to operate in both markets.

Keyword:

DSV, design concept, flexibility, sustainability, diving system, etc

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Master Thesis in Marine Systems Design
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"Conceptual Design of Purpose Built Diving Support Vessel"
Spring 2010

Background

Over the years, diving support vessels have been designed without integration of main mission equipment. Rather, the deck arrangement was optimized towards work area and equipment storage requirements. Currently, we see a change in design philosophy that involves incorporation of almost all the mission equipment permanently onboard. This is already evident in high spec DSV designs. At the same time, the design of these vessels is becoming increasingly complex due to its multi-role nature which makes it possible to operate in the following markets; DSV/ROV/Supply, DSV/ROV/Construction, DSV/Construction/Accommodation, etc.

Having the mission equipment onboard makes it possible to overcome the need to mobilize and demobilize for equipment when executing one or more contracts, and thereby reducing both the cost and the lifecycle emission footprint of the DSV. The disadvantages are that the cargo carrying capacity and deck space are reduced while operating in supply market, that some equipment might become redundant but still contribute to light weight and costs, and that the opportunity to deploy equipment on the spot market could be affected.

As a consequence of decreasing offshore field development projects across the globe, a reduction in offshore construction work is foreseeable in near future. At the same time enormous subsea facilities would provide opportunity for inspection, repair and maintenance work, and offshore production platforms would also require supply support. The high spec DSV can be sustained with a fixed contract otherwise it may not be profitable. The DSVs designed for harsh environment of the North Seas may not be competitive in a typical West African environment which is benign in nature; hence the need for a more flexible design for both regions.

Overall aim and focus

The overall aim and focus of the work is to propose, develop and evaluate alternative design concepts and corresponding arrangement solutions for a DSV that will meet future

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The overall aim and focus of the work is to propose, develop and evaluate alternative design concepts and corresponding arrangement solutions for a DSV that will meet future requirements for sustainable and flexible operations both in the North Sea and West African markets.

Scope and main activities

The candidate should presumably cover the following main points:

1. *Provide an overview of historical and likely future trends in development of diving support vessels*
2. *Describe a case includes the main mission, payload and operational profile of the DSV*
3. *Develop a set of possible design concepts*
4. *Evaluate the proposed design concepts towards main performance indicators, including sustainability, flexibility and operational efficiency.*
5. *Discuss, conclude.*

Modus operandi

At NTNU, Professor Stein Ove Erikstad will be the responsible advisor.

The work shall follow the guidelines given by NTNU for the MSc Project work

Stein Ove Erikstad
Professor/Responsible Advisor

PREFACE

The Master Thesis has been done as one of the requirements for the award of M.Sc degree in Marine Technology, Marine Systems Design option at the department of Marine Technology, Norwegian University of Science and Technology. The subject of the Thesis is “Conceptual Design of Purpose-Built Diving Support Vessel” The task was defined in collaboration with my advisor, Prof. Stein Ove Erikstad and the work was completed under his supervision. The Thesis is a combination of ship design and operational experience gained while working as a Planning Engineer with Tethys Plantgeria Ltd; a diving and marine contracting firm in Nigeria.

The present work explores alternative designs and arrangement solutions for a DSV that would meet future requirements for flexible and sustainable operations in two main regions, the North Seas and offshore West Africa. First, an overview of historical and likely future trends in the development of the DSV is presented. The study progressed with case description of a DSV in service including its mission, payload and operational profile. Thereafter, three design concepts were proposed and developed. The evaluation of the designs was done using five key performance indicators (KPIs), and the result of the evaluation shows that integrating a modular design in top side SAT diving system is one of the ways to improve operational flexibility and make the Purpose-Built DSV more sustainable.

I am privileged to study in this great institution of learning which ranks amongst the world’s best centres for university education. The opportunity provided by the institution for me to study as an exchange student at Delft University of Technology in the Netherlands is highly appreciated, and the knowledge gained from the Masters Programme is invaluable. I wish to express my gratitude to Prof. Erikstad for finding time to give guidance on this M.Sc Thesis. I owe thanks to all who have tutored me in the present phase of my career for the knowledge bequeathed to me. To all who have encouraged me by words of advice, financial support and prayers, I want to say thank you. May the Almighty God who provided the means to embark on this study, be exalted forever.

Ikenyiri, Udo Okwuchukwu
Trondheim, 14th of June 2010

NOMENCLATURE:

Abbreviations

AHP	Analytic Hierarchy Process
CAPEX	Capital Expenditure
DDC	Deck Decompression Chamber
DP	Dynamic Positioning
DSV	Diving Support Vessel
DWT	Deadweight
IMR	Inspection, Maintenance and Repair
KPI	Key Performance Indicators
LARS	Launching and Recovery System
LCC	Lifecycle Costs
LWT	Lightweight
NPV	Net Present Value
OPEX	Operating Expenditure
ROV	Remote Operated Vehicle
SAT	Saturation
WOW	Waiting on Weather

Symbols

B	Beam [m]
BM	Distance from centre of buoyancy to the metacentre [m]
C_B	Block Coefficient [-]
C_M	Midship Area Coefficient [-]
C_P	Prismatic Coefficient [-]
C_W	Waterplane Area Coefficient [-]
D	Depth [m]
Fn	Froude Number [-]
GM	Metacentric Height [m]
GM_T	Transverse Metacentric Height [m]
Hs	Significant Wave Height [m]
KB	Distance from keel to centre of buoyancy [m]
KG	Distance from keel to centre of gravity [m]
Kn	Knots
Loa	Length Overall [m]
Lpp	Length Between Perpendiculars [m]
P	Power [kW]
p_f	Fuel Price [$]
sfc	Specific Fuel Consumption [g/kW-hr]
T	Draft [m]
V_d	Design Speed [knots]
V_s	Sailing Speed [knots]
ρ	Density [kg/m^3]

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1.0 INTRODUCTION

1.1 Historical Developments of DSVs

At the advent of offshore oil and gas exploration, diving activities were carried out from drilling platforms such as drill barge, jack-up barge, semi-submersible, and drill ship which are illustrated in Figure 1. The dive systems were packaged in modules and transported from onshore locations to the platforms in readiness of diving operation to support oil and gas exploration and production.

Figure 1 Drilling platforms

A typical drill ship as shown in Figure 2 had a dedicated moonpool for diving bell, deck space for decompression chamber and diving gas quads. The frequency of diving related

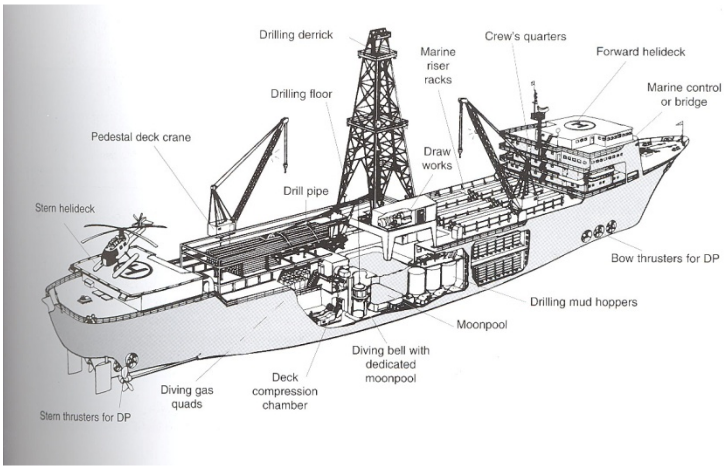


Figure 2 Drillship indicating diving equipment
(Source: Professional diver's handbook, 2005)

work was high especially, during exploration drilling and was often reduced soon after the operators enter production phase. Under this circumstance, the operators were reluctant to concede a substantial portion of deck space for diving systems. As a panacea to the deck space problem, semi-submersible barges like "Uncle John" and vessels from other trades were used for the purpose of diving support. Although the semi-submersible barges provided the required deck space, cargo handling capability and stable platform for diving support, they were expensive to operate, had poor manoeuvrability and could not move around the platform easily to support operations; and this could be attributed to their need for ballasting and de-ballasting operations during such movements.

Table 1 Early Medium of Diving Operations

	Vessel Properties	
Strilhav – Fishing vessel	**Length Overall**	56.59m
	**Breadth**	9m
	Deadweight	1000tons
	Deck Space	
	Cargo Handling	5 ton crane
	Moon Pool	none
Built: 1963,Converted to	**Propulsion System**	
DSV: 1982	**Installed Power**	736kW
Stril Tender – Off Trawler	**Length Overall**	47.17m
	**Breadth**	8.4m
	Deadweight	500tons
	Deck Space	160m^2
	Cargo Handling	1 x12 ton & 1 x 28 ton crane
	Moon pool	none
Built: 1965,Converted to	**Propulsion System**	1 Azimuth & 1 Stern thrusters
DSV: 1983	**Installed Power**	883kW
MSV Regalia	**Length Overall**	95m
	**Breadth**	91.5m
	Displacement	21030ton
	Deck Space	
	Cargo Handling	1x400 ton & 1x100 ton crane
	Moon pool	none
	Propulsion System	6 Azimuth thrusters
Built: 1985 – Semi-	**Installed Power**	18326kW
submersible	**Diving System**	2x3 men bells
		2x6 & 1x4 chambers

Fleming (1982) remarks that the converted tonnage compromised "good marine and diving practice" This was because they were underpowered, had no heave compensation system and their cargo handling capability was insufficient. A critical look at the properties of the first two vessels (fishing vessel and offshore trawler) in Table 1 which are examples of converted tonnage, confirms that their installed power, deck space, crane capacity, and propulsion systems were not adequate to support diving operations. Whereas, the converted tonnage were cost effective alternative to the semi-submersibles, it is possible that their inability to keep position in extreme environmental conditions, did obstruct diving activities and restricted it to a seasonal operation; due to the absence of stabilization and heave compensation systems in these vessels, the incidence of roll, pitch and heave motions could be severe when compared to the third vessel in Table 1which is a semi-submersible (MSV Regalia), lifting and lowering of equipment during seabed operation could be seriously hindered, giving rise to the need for a "purpose built DSV" to cope with the environmental challenges and fulfil operator's specifications.

Table 2 DSV properties

Ship Data	Seven Atlantic	Acergy Havila	Seven Pelican	Acergy Harrier	Acergy Osprey	Gulmar Falcon
Built	**2010**	**2010**	**1985**	**1985**	**1985**	**1975**
CAPEX ($)	200 000 000	181 187 000				11 293 094
DWT (ton)	11885	7 250	2043	2350	3104	1636
GT (ton)	17496	9 500	4763	4782	6254	2645
Length Overall (m)	144.79	120	94.1	83.4	101.7	80.93
Length (BP) (m)	128.96	107.4	84.17	73	90.02	73.97
Breadth Moulded (m)	26	23	18	19.5	21.62	16.01
Draught (m)	8	8.25	6.56	5.75	5.5	4.376
Depth (m)	12	10	9	8.63	10.7	7.12
Service Speed (knots)	13.6	12	12	12.5	12	12
Max Speed (knots)		17				15
Consumption (tons/day)				12	16	
Total Power: Mcr kW	20160	12648	12012	8405	7728	6060

Between the late 60's and early 70's, plans were hatched to launch dedicated DSVs for North Sea operations and the Gulf of Mexico. According to Steven (1979), the DSV came into the market around 1975 with saturation diving complex, moon pool, DP systems, stabilization, heavy lift capabilities and accommodation space for about 40 people. Towards the late 70's, we had two types of purpose built DSVs in the market; these were the mono-hull and semi-submersible DSVs. From Table 2 and appendix 1, we note that the pioneer design of purpose built DSVs were “Seaway Falcon” now known as “Gulnar Falcon” and “Uncle John”. They were mono-hull and semi-submersible types of DSV respectively. “Gulnar Falcon” came into the market in 1975 while “Uncle John” was built in 1977. Fleming (1982) did a cost comparison of both the mono-hull and semi-submersible DSVs and remarked that the lifting capability of the semi-submersible gave it some leverage over the mono-hull DSV despite its high operating costs. More recently, “purpose built DSVs” have been designed towards addressing the shortcomings of both the converted tonnage and the semi-submersible diving support vessels. The capability of the “purpose built DSVs” has improved tremendously such that its performance has surpassed both the station keeping and lifting capability of the then semi-submersible diving support vessel. The entrance into the market of the high efficient “purpose built DSVs” may have threatened the economic viability of the semi-submersibles diving support vessels and they suddenly disappeared from the market. The DSVs in today’s market have further increased in scope and size. We see increase in the size of moonpools to enable deployment of ROVs, some DSVs also have separate moonpool for lowering installation packages. Breadth has increased significantly to address the problem of beam seas, in the pasts service speed had been within 12 knots but speed ranges of 13-17knots are in existence today and deck space has further increased to carry more loads. With oil and gas exploration becoming more and more challenging in rough and deep seas, DSVs have been designed to cope with the ensuing environmental demands.

The design of the “purpose built DSVs” is becoming increasingly complex. Lately, we see a change in design philosophy of the DSVs; almost all the mission equipment is integrated in their designs and accommodation support is included for hotel complements of up to 150 persons, which come with increase in construction costs. The level of sophistication in “Seven Atlantic” shown in Figure 3, calls for concern about the multi-role status of this state-of-the-art DSV and the volume of activities that would make it profitable over its lifetime, considering the huge acquisition costs of about Two Hundred Million Dollars ($200million). The major concerns about this design are that some equipment might become redundant but still contribute to light weight of the DSV, the opportunity to deploy equipment on the spot market could be hindered, and cargo carrying capacity and deck space might be affected while operating in supply market. The factors highlighted above, question the operational flexibility and sustainability of the state-of-the-art DSV.

Figure 3 Seven Atlantic, a state-of-the-art DSV

Morrissey and Stone (1997) identified long duration diving contracts as the driver of the "purpose built DSVs" and further stated that such DSVs would be useful and cost effective in an atmosphere of increased exploration and exploitation of offshore fields. This implies that more discoveries of offshore oil and gas reservoirs would create the market for construction and installation of offshore structures and subsea facilities; inspection and maintenance of existing facilities and upcoming ones would also remain a continuous process and by these deductions, the use of a DSV or the like in the offshore industry is inevitable. Although fixed contracts and operator's specifications remain the ultimate driver of the "state-of-the-art DSV" design, it would be necessary to look at the design from the view point of decreasing offshore exploration and exploitation of oil and gas. In which case, its sustainability could be jeopardized since there will be hardly any offshore field development project that will have the same characteristics like the one it was designed for.

Three decades ago, Robin Rattray then Marketing Director of offshore marine was sceptical about the viability of the purpose built DSVs and referred to it as a "highly risky business" (Offshore, 1979). This assertion was based on the dwindling DSVs market in the late 70's which made offshore marine to shun investment in purpose built DSVs because they required enormous capital outlay. The 21st century investors are of a different view and do not mind the risk that was envisaged 30 years ago. Can fixed contracts be the sole economic driver of this technology? Fleming (1982) compared the cost effectiveness of the mono-hull DSV with that of a semi-submersible DSV and stated that the cost advantage of the mono-hull over semi submersible was significant and that uncertainty surrounds the lifespan of the semi-submersible. This conclusion came from the high operating costs and the multi-role nature of the semi-submersible DSV which is also similar to the present design of the highly sophisticated DSVs present in today's market. There is therefore the need to make the design of the DSVs more flexible to enhance their sustainability.

1.2 North Sea DSVs Market and Operation

The moment offshore exploration drilling platforms were deployed to the North Seas; the services of divers and diving equipment were needed to support drilling activities (Rosengren, 1986). The early days of diving operations in the North Seas was characterised by the use of vessels which were converted from other trades; majority of the conversions took place in the 70's and early 80's such that barges, ore carrier, supply vessels, car ferry, pipe carriers, tankers and trawlers were converted to serve the purpose of diving support vessel (appendix 1). The 70's also witnessed the coming on stream of purpose built diving support vessels with dynamic positioning capability; a survey of the North Sea diving support vessels (offshore; March 1979) shows that the number of vessels converted from other trades surpassed purpose built DSVs. The reason for the huge influx into the provision of diving support services other than the original missions of these vessels may not be unconnected with the oil boom of the 1970,s and the fact that the industry was in a shortage of offshore support vessels.

However, Noroil (1978) states that the owners of the purpose built DSVs were motivated by the desire of operators to have more sophisticated vessels capable of maintaining position in rough weather irrespective of the capital intensive nature of this venture. The case of the converted tonnage was different; rather than being motivated by operators, owners of converted tonnage enticed operators by offering cheaper rates and shorter time window in making the vessels available instead of waiting for years to accomplish new built project. The North Sea DSV market was highly competitive and made provisions for the existence of two classes of vessels to operate but Noroil (1978) remarks that the converted tonnage were used mainly for short term projects while the purpose built DSVs were focussed on long term and more complex projects. With the availability of numerous diving companies operating in the North Sea environment, the competiveness of the North Sea DSV market is sustained not by having substandard vessels as DSVs but through regulations which have engendered investment in adequately equipped DSVs. The DSVs of today and the diving systems have been designed to meet strict class rules bordering on operational safety.

The North Sea offshore oil and gas fields are concentrated within the UK and Norwegian sectors. As at today, out of the 79 major offshore oil and gas fields in the North Sea, the distribution in Figure 4 shows that UK sector has 54% while Norwegian sector accounts for 33%. According to Hovland (2007), the DSV market in the North Sea needs a constant provision of about 9 DSVs while the global market requires between 30 to 35 DSVs with saturation system.

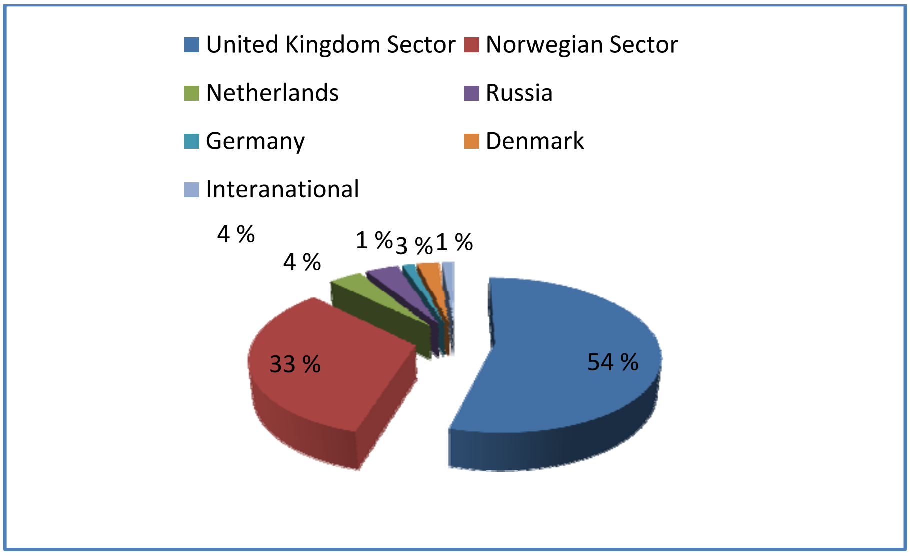


Figure 4 Distribution of North Sea Offshore Fields
(Pie-chart is based on information obtained from http://www.offshore-technology.com)

North Sea market holds great potentials for utilization of DSVs based on the existing subsea infrastructures and ongoing offshore development projects. As the search for oil and gas goes into deeper seas, the challenges of exploration and production will be great and more efficient support vessels will be needed to cope with the envisaged challenges. It is on this premise that experienced North Sea Diving Companies like Acergy, Subsea Seven; Technip etc are investing on highly efficient DSVs as part of their fleet renewal scheme. The improvement in operational efficiency makes it possible for the new generation of DSVs to operate more than 90% of the time in high sea state. More discussions on the operability are presented in section 3.3

1.3 West African Market and Operation (Nigeria)

DSVs have been used to support offshore field development projects in West Africa and the market is expanding yearly as more offshore fields are explored and the existing subsea infrastructures require inspection, maintenance and repair. Presently, there are 29 major deep sea oil and gas fields in West Africa and majority of these fields are in Nigeria and Angola. Figure 5 shows that Nigeria and Angola dominate the market with ownership of 41% and

38% of the offshore oil and gas fields respectively. Acergy (2010) agrees that West African offshore market is becoming increasingly stronger because new offshore field development projects are on the way and would require construction and installation works for subsea facilities which include but are not limited to production and injection flow lines, umbilicals, risers; export lines, subsea trees, well heads and manifolds. As operators brace up for the challenges of prospecting for oil and gas in a continuous dynamic marine environment, the important fact is that exploration and production activities in the expanding Nigerian offshore fields and other West African countries, where there are no existing subsea infrastructures will require efficient offshore support vessels to sustain operations and DSV is one of them.

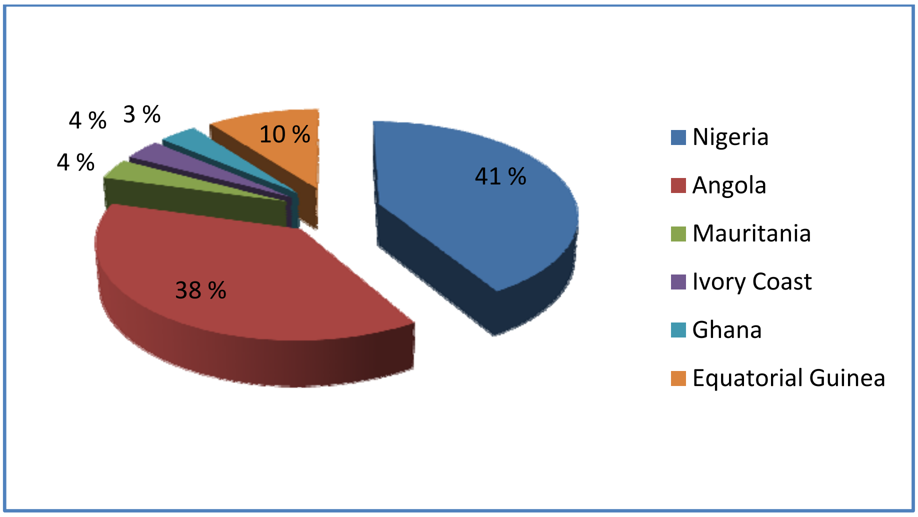


Figure 5 Percentage distributions of West Africa deep offshore fields
(Pie-chart is based on information obtained from http://www.offshore-technology.com)

There are enormous opportunities for the utilization of diving support vessels and the like in the Nigerian offshore industry, which is one of the market environments considered in this work. Oil exploration started in Nigeria in 1937 and commercial quantity was discovered in 1956 at Oloibiri in the onshore Niger Delta area of Nigeria (NNPC, 2010). Since then, oil exploration and production has gradually moved from land and swamp to deep offshore in water depth of up to 2500m. In further quest for oil and gas, the Nigerian National Petroleum Corporation (NNPC) in conjunction with major oil exploration companies aspire to expand the exploration frontiers beyond water depth of 2500m in order to increase the country's oil and gas reserve "blue print".

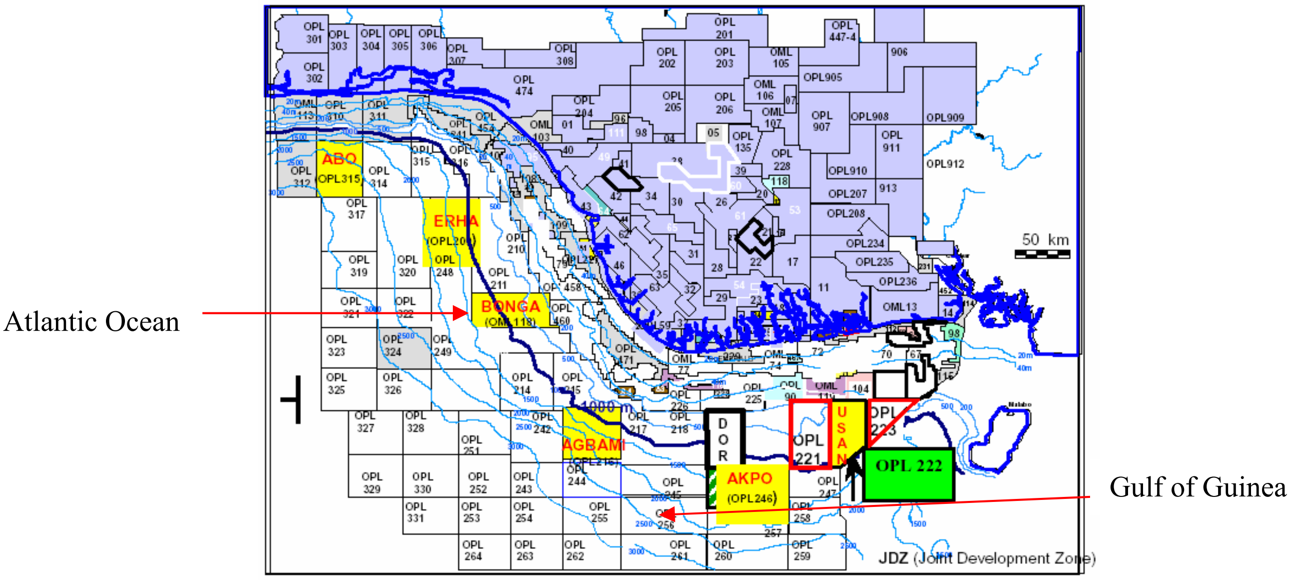


Figure 6 Extract from concession map of Nigeria showing offshore fields in Niger Delta
(Source: Nigerian Ministry of Petroleum Resources)

All offshore fields in Nigeria are in the Niger Delta region and stretch towards the Atlantic Ocean and Gulf of Guinea where Nigeria has a joint development zone (JDZ) with Sao-Tome and Principe. The present deep offshore oil and gas fields, which either are in operation or underway, are the areas marked yellow in Figure 6. The areas marked white are oil blocks that have been allocated for exploration under a production sharing contract while the blocks marked blue are offshore fields within inland at water depths up to 200m. Huge investments have already been committed in underwater and floating marine systems, to harness crude oil and natural gas. Pipelines run in shallow and some deep waters, anodes are installed to prolong the life span of floating and underwater structures, risers are used to transport the crude oil and gas produced to storage facilities, well heads are installed on the seabed, subsea umbilical runs several kilometres, and calm buoy and offloading systems are used to transfer the crude oil produced to an export tanker. These facilities require periodic inspection to ascertain their integrity; maintenance/repairs are carried out in some cases after inspection.

Unlike the North Sea environment that requires sophisticated DSVs to cope with environmental challenges and strict regulations; the West African environment is calm and diving operations in some cases are carried out by means of AHTS and standard supply vessels with the equipment packaged in container modules similar to early developments in the North Sea. The current practice will change with new field development projects extending into the Atlantic Ocean where environmental challenges will increase; more specialized DSVs functioning in combination of roles would be needed to support offshore operations hence the need for a possible DSV design solutions for this environment. Knowledge gained by operators in some complex offshore field development projects in the North Seas has been transferred to similar projects in Angola and some of the deepwater projects in Nigeria like the Bonga and the Usan field development projects. Therefore, a DSV capable of alternating between North Sea and West Africa environments would enable foreign diving companies to consider the spot markets opportunities available in the West African region. With Nigerian government persistence on 60% local contents portion in oil and gas related projects in Nigeria, indigenous diving companies can go into partnership with their foreign counterparts in areas of technical cooperation on DSVs usage for SAT diving operation.

1.4 Future Trends in Development of DSVs

Early development of the DSV was a learning experience because owners had no knowledge about what the likely future developments of offshore infrastructures and subsea installations would be; thus, they focused on a very compact design that could perform their envisaged tasks in diving operations. After the learning phase, there came the era of combination of roles for the DSV to widen its capabilities. If we compare the properties of the 1975 DSV design in Table 2 with those of the succeeding years up to the present (2010), we see that deck and accommodation spaces have exceeded twice the 1975 DSV design, installed power has increased tremendously because of provisions for redundancy and the size as well as cargo carrying capacity have also increased. The aim is to make the DSV more efficient but it comes with increasing construction and operation costs and these require operators to pay more.

To have an understanding of what the likely future trend in development of DSVs would be; it will be important to compare the development of both the semi-submersible and the mono-hull DSV technologies. Using the S-Curve model in Figure 7 to illustrate these developments, we see that the semi-submersible DSV technology came to maturity at about the time mono-hull technology was experiencing a breakthrough. The history of the semi-submersible DSVs informs that they were expensive to build, had complex operational profile and were deployed mostly for specialized and complex operations where the capability of the mono-hull DSVs could not be guaranteed. Thereafter, capability of the mono-hull DSVs improved tremendously such that the semi-submersibles were no more cost effective to be kept in service.

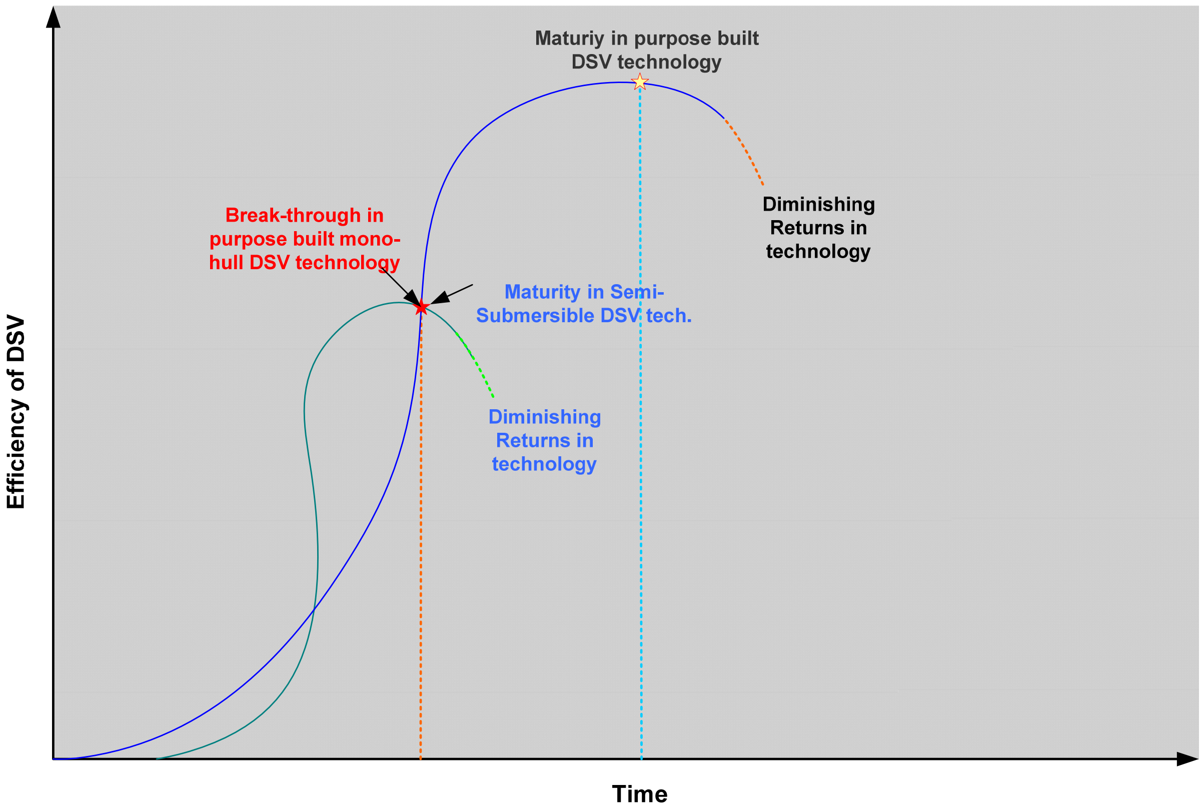


Figure 7 S-Curve model of DSV Development

Similarly, the state of the art DSVs are said to be for specialized operations which are synonymous with the trend of the semi-submersibles DSVs. They require huge capital investment and operational costs because of their capabilities, size, mission and payload. Unlike the era of the semi-submersible DSVs where there was a shift in technology to improve the capability of purpose built mono-hull DSVs, class regulations have further impacted on the design of the purpose built DSVs. There is now a requirement for improvement in technology mandating all vessels designed to carry more than 600m3 of fuel oil to have their fuel oil tanks protected by double hull in line with IMO regulation 12A and one of the new built state-of-the-art DSVs "Acergy Havila" has a double hull construction. The DSVs seem to be attaining technological maturity in the near future; studies have shown (Hovland 2007 and Acergy 2009) that increasing the operability of the DSVs above 6m Hs would not yield further gains in the operational window of the vessel although, the owners of the expensive state-of-the-art DSV claim it has operability of 6m. There may not be any major shift in technology; rather, the size and scope of the mission of the purpose built DSV will be configured to become more cost effective amongst its family.

Looking into the future, Hovland and Gudmestad (2006) developed the trimaran DSV concept and outlined four notable characteristics of the design which include low vessel motion, fuel economy, large deck space and high loading capacity. However, this concept seems to take us back to the era of the semi-submersible DSV design, which also had the above mentioned features except fuel economy. The trimaran DSV concept may suffer a major set back regarding manoeuvrability, which was also the shortcoming of the semi-submersible DSV design. However Hovland and Gudmestad (2006) concede that despite the advantages of the trimaran DSV concept, the possibility of "hidden difficulties" in the technology may not be ruled out. It may be difficult to say with certainty what the future trend in DSV development will be because the capabilities of ship designers cannot be under estimated but designs that are cost efficient and offer operational flexibility will be sustained.

The future will likely witness modularity in DSV design to produce a flexible DSV. This concept has already been implemented in the design of frigates and logistic support ships as against having a multifunctional logistic support ship with little being achieved. The present work will among other things x-rays the concept of modularity in the design of the top side SAT diving system and the use of standard container modules for some mission equipment.

2.0 CASE DESCRIPTION

The case description in this study is a diving and construction support ship known as "Acergy Osprey" which is shown in Figure 8. It was built in 1985 and it is a "100m class DSV and construction support ship" It is one of the early designs of DSVs that has stood the test of time in terms of operational performance and could be seen as a platform that provides good learning experience for the owners to improve on efficiency of future DSVs. Having operated this vessel for about 25 years, Acergy (2006) states that the Osprey has "impressive station keeping and high stability" which have enabled it to undertake construction and IRM works over the years in extreme environmental conditions.

Figure 8 Acergy Osprey

2.1 Main Mission

Acergy Osprey is designed to provide diving support for subsea constructions, installations, inspection, maintenance and repairs. The services that are linked to the above mission are: diving, ROV, accommodation support, offshore supply, and survey services. Acergy Osprey is currently operating within the UK sector of the North Sea and the Baltic and has been active in the IRM and construction market. IRM and installation of subsea facilities can be done using divers for water depths up to 250m but North Sea regulations stipulates a maximum depth of 180m for the Norwegian sector while ROVs are utilized in greater water depths. Figure 9 provides a description of the main mission of Acergy Osprey and in the sections that follow; these missions will be discussed with emphasis on the tasks that are related to each mission.

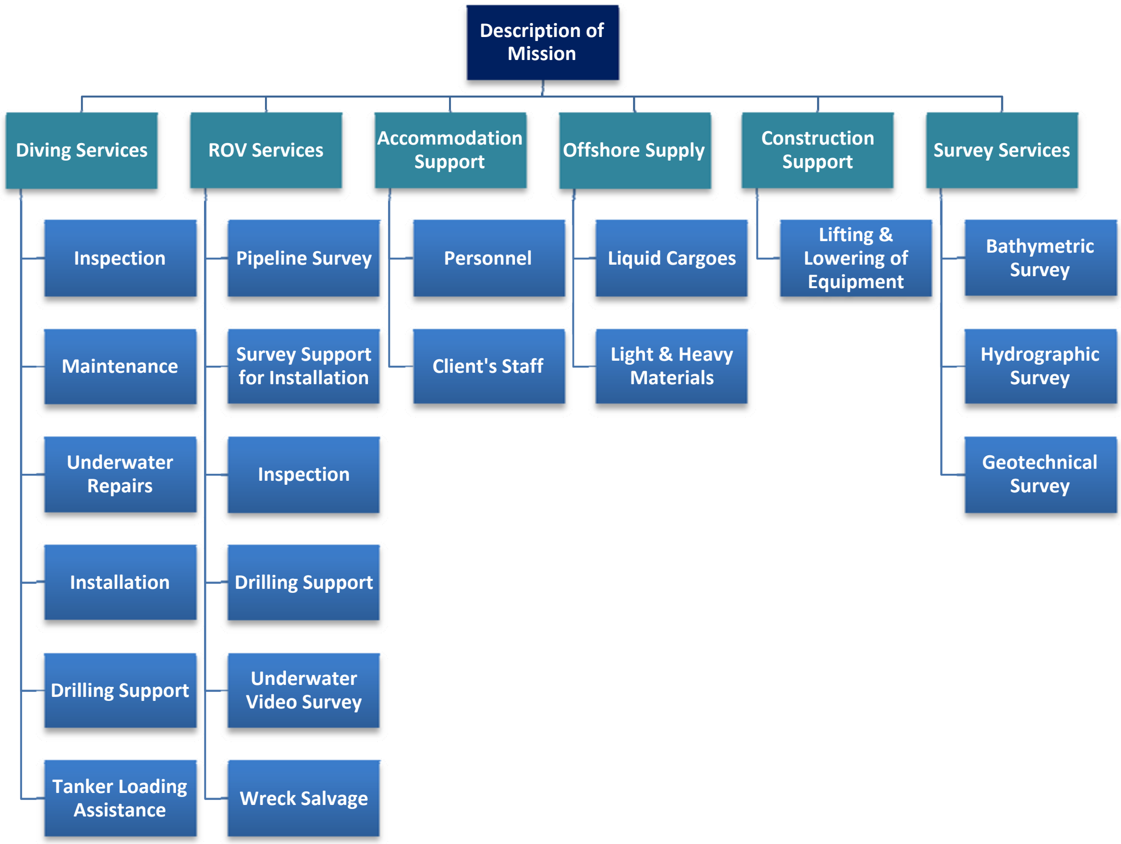


Figure 9 Services that can be performed using Acergy Osprey

2.1.1 Diving and ROV Services

IRM of subsea facilities which are part of the main missions of Acergy Osprey, can be done using divers and ROV in the case of diverless operations. The DSV maintains position using its DP systems for either divers or ROVs to perform inspection aimed at determining the integrity of submerged parts of oil and gas production platforms, calm buoys and offloading systems, pipelines, manifolds, subsea trees, buoyancy tanks, mooring systems to mention a few. Inspection of subsea facilities is a routine operation and is mainly by means of non-destructive testing techniques (NDT) such as close visual inspection, magnetic particle inspection, ultrasonic inspection, cathodic potential measurement and underwater video recording; examples of inspection images involving divers are furnished in Figure 10. For subsea facilities that spread across several kilometres, Inspection and observation class ROVs are deployed from a DSV to do the same work that would have been done by divers. Visual inspection is often the primary inspection technique which is done before any other inspection method is further applied to check for fatigue cracks, anode corrosion, metal thickness, and any other variable needed to determine the status of a subsea facility.

Figure 10 Divers carrying out inspection on pipelines and chain leg of a CALM buoy
(Source: Tethys Plantgeria Ltd, Nigeria)

After the inspection of subsea facilities is accomplished, inspection data and photograph images are assessed by experts to compare the data and photograph images obtained with the bench mark values and images, where disparity exists then maintenance or repairs would be carried out to effect corrections. A sensitive offshore facility like Calm Buoy and offloading system (Figure 11) which is used to transfer crude oil cargo into a shuttle tanker in relatively calm offshore environment like West Africa requires weekly, monthly, quarterly and six-monthly inspection to ensure its availability. The above mentioned activities and tanker loading assistance are done by divers using DSVs as platforms.

Figure 11 Calm buoy and offloading system
(Source: Tethys Plantgeria Ltd, Nigeria)

One of the major milestones achieved by Acergy Osprey in the area of installation is the subsea hot tap operation for the attachment of piping valve assembly which was needed for the tie in of gas export lines at Ettrick field in the UK sector of the North Sea. Hot tap operations could be challenging because the fluid flowing through the pipeline is not shut-in rather a trade off is considered between the cost of suitable hot tap machine and contingencies, and the revenue lost as a result of downtime. In this case, hot tap machine using diver and ROV together with Acergy Osprey as diving support vessel was considered more economical since the revenue lost during the nine days that this operation lasted exceeded the cost of the operation.

Figure 12 Acergy Osprey mobilizing for Ettrick field operation
(Source: Cassie and Harrison, 2009)

Installation tasks using saturation diving operation is a challenging task and the DSV must be in position to support the divers. Acergy Osprey has a good operability and caters for about 18 persons in saturation diving. Large numbers of divers are required for SAT operations; a typical example is in anode installation on subsea facilities which takes a lot of days to accomplish depending on the size of the facility and long tie back projects. Also Acergy Osprey can provide drilling support using ROV systems to help in shut-off and turn on of valves, carryout underwater cutting, perform hydro-blasting for cleaning up debris, locate pipelines and perform route fix up.

2.1.2 Accommodation Support

Acergy Osprey has an accommodation space for 120 persons including crews. During a major construction project and in the case of emergency response, it could provide accommodation support services, which yield revenue to the owners. However, there has been sufficient saturation diving work for Acergy Osprey in IRM and construction markets and the accommodation support has been mainly for personnel carrying out saturation diving operation; for instance a major underwater construction work would require a team of 8 divers in about 12 sets for saturation diving but when the vessel is not engaged in saturation diving, most of the accommodation space will be vacant.

2.1.3 Offshore Supply

Most offshore installations and construction works go with supply of the items to be installed and the deck space of Acergy Osprey provide many opportunities for platform supply services for light and heavy materials, and drilling support to evacuate drilling mud and waste oil from offshore platforms. The cargo tanks can also be used to supply liquid cargo to exploration and drilling platforms.

2.1.4 Construction Support

Lifting and lowering of equipment during seabed operation requires good cargo handling system and Acergy Osprey can support construction work even in severe weather conditions. Construction support for installation of jackets, spool piece, flow lines, umbilical and revamping of anodes on platforms are challenging tasks. According to Acergy (2006), Acergy Osprey was equipped with a 150-ton heave compensated crane in 2002, which has improved its construction capability. Also the deck space of Acergy Osprey is sufficient to provide construction support.

2.1.5 Survey Services

Acergy Osprey is equipped with survey systems that aid data acquisition for survey tasks such as hydrographical survey, bathymetric survey, and pipeline survey. Hydrographical survey includes but not limited to seabed and site survey. It helps to determine the seabed profile and locate accumulation of debris within a determined circumference of a platform or subsea infrastructure, which may obstruct navigation and smooth operation of the facility. Bathymetric survey is usually carried out by divers or ROV to determine the configuration of flexible subsea installations like the subsea hose used in a calm buoy. In the case of using ROV in deep sea installations, the survey suite can be used to process the data acquired.

2.2 Estimate of Payload

The payload is the revenue yielding function of the ship, which is used to achieve the intended mission defined for a vessel. The main payload of Acergy Osprey includes deck space, cranes, survey systems, saturation diving system and bell ancillary equipment. The biggest weights amongst the payload are contributed by the SAT diving system, diving bell ancillary equipment and crane.

2.2.1 Saturation Diving System

A SAT diving system is a complex system that is formed by the integration of several subsystems such as deck decompression chambers, moonpools, diving bell, launching and recovery system, gas transfer compressor, chamber gas reclaim, diver gas reclaim, hot water and portable water units, hyperbaric external regeneration system (HERS), hyperbaric lifeboat and gas storage unit. The entire system is controlled through the bell control panel and saturation diving control console. Figure 13 is a layout of an inbuilt saturation diving system showing the integration of the subsystems into a single system.

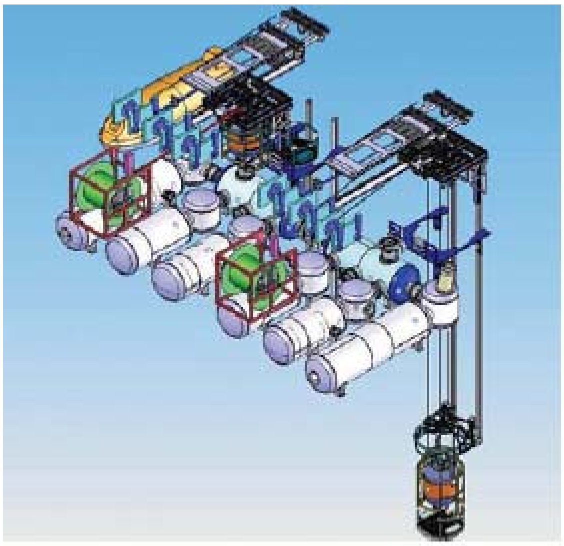


Figure 13 Layout of inbuilt SAT diving system
(Source: Technip 2009)

Acergy Osprey has an inbuilt SAT diving system, which is designed for a maximum of 18 persons. Also, the system has two wet bells of 3-person capacity which are deployed through two different moonpools. Although, details of the weight of SAT diving system that is installed onboard are not provided in the technical data sheet of the vessel, estimates that reflect the SAT diving system capacity of Acergy Osprey have been determined from similar specifications given by Drass Galeazzi Underwater Technology and LexMar Engineering Pte who are DNV and IMCA certified manufacturers of diving systems and furnished in Table 3 to be about 307.7 tons. Diving operational stability in rough seas is achieved through the heave compensation systems of the inbuilt SAT diving system. Also the integration of the SAT diving system in the design of the vessel reduces the number of days required for mobilization and demobilization from a subsea operation when compared to using an all modularized system which will require more man-hours to crane on and off the modules from the DSV, in readiness for a different mission that does not involve SAT diving, for instance a construction support and supply service that will require a large portion of deck space. However, the main shortcoming of the inbuilt SAT diving system is that the payload remains in the DSV throughout its lifetime and cannot be utilized on the spot market. Second, refurbishment of the DDC may require dismantling of the entire SAT system, which means that more time will be spent in dry dock.

Table 3 Estimate of weight of 18 man SAT diving system

Item	System	Unit	Dimension L(mm) x W(mm) x H(mm)	Weight [ton]
1	Diving bell control console	1	3800 x 1310 x 2315	1
2	Chamber saturation control panel	1	5400 x 4700 x 2300	1.5
3	3 man Diving bell	2	Ø2750mm x 3520mm	19.3
4	Diving bell cursor	2		2.24
5	Bell onboard charging panel	1	605 x 390 2050	0.1
6	Gas pressure reduction panel	1	3785 x 560 x 2190	0.7
7	6 man DDC complex	3	9420 x 2704 x 2756	78
8	Gas transfer compressor	2	1900 x 1100 x 1434	1.8
9	Chamber + diver gas reclaim	1	3500 x 1200 x 1656	2.2
11	Hot water + portable water unit	3	1215 x 1000 x 924	0.7
12	HERS	4	2470 x 1370 x 2050	10
14	Self Propelled Hyperbaric Lifeboat	1	10500 x 3300	16.7
15	Emergency support module for SPHL	1	3048 x 2430 x 2430	2.1
21	Gas storage skid of 8 tubes	4	12050 x 1540 x 2900	**118**
	Total			**254.3**
	Ancillary Equipment			
15	Guide wire and shock absorber	2		1.9
16	Bell wire shock absorber	2		1
17	Bell winch	2		18.15
18	Anchor weight	2		4.825
19	Guide wire winches	2		9.41
20	Hyraulic power pack	3		10.5
22	Umbilical winch	2		7.59
	Subtotal			**53.4**
	Total Weight of Saturation Diving System + ancillary equipment			**307.7**

Source: Drass Galeazzi Underwater Technology & LexMar Engineering Pte Ltd

2.2.1.1 Deck Decompression Chamber

The DDC is part of the Saturation diving system and it serves double roles of "living chamber and decompression chamber" it is fitted with basic facilities such as communication system, breathing system, fire fighting system, bunks, toilet and bath room, medical lock, lighting system etc. to support the life of the divers who temporary inhabit it. Acergy Osprey has an 18-man DDC which is used to support the divers who carry out deep-sea construction, installation, inspection, repairs and maintenance work. The DDC has different configurations but the 18-man DDC could be in a layout of 3 by 6-man or 2 by 6-man and 2 by 3-man depending on the available space on board. The weight of the 6-man DDC in Figure 15 is approximately 26 tons and Acergy Osprey is assumed to have three of it.

Figure 14 External and internal of a 6-man DDC with outfits
Source: Drass Galeazzi Underwater Technology

2.2.1.2 Bell Diving System

The bell diving system conveys the divers under pressure to the depth where the subsea tasks are to be carried out and it is equipped with the following gadgets:

- *Closed Circuit Breathing System (CCBS)*
- *Environmental control*
- *Communications and video monitoring equipment*
- *Hydraulic systems for bottom door*
- *Emergency Beacon/Transponder*
- *On-board gas for Emergency Life Support*
- *On-board battery to power the essential components during emergency*

Two bell diving systems designed for 3 men and weighing about 9.2 tons each are installed onboard Acergy Osprey, an example of this type of bell is provided in Figure 15 which is a typical design for underwater constructions, installations and IRM. Two divers will carry out the subsea tasks while one remains as the “tender diver” to them; for a huge subsea project, many teams of 8 divers are needed for saturation diving. The two bells may not be used at the same time but the essence is to provide redundancy in the deployment of divers for subsea tasks.

Figure 15 a 3-man diving bell
Source: Drass Galeazzi Underwater Technology

2.2.1.3 Self Propelled Hyperbaric Lifeboat

SPHL is considered to be a suitable installation for inbuilt SAT diving systems where there are no space constraints onboard, but where the later does exist, then hyperbaric rescue chamber would be the most preferable option. The SHPL for an 18 man SAT diving system and four crew members weighs about 16.7 tons; the recommended endurance for a SHPL is a minimum of 72 hours.

Figure 16 a self propelled hyperbaric lifeboat
Source: Drass Galeazzi Underwater Technology

2.2.1.4 Storage bottles

Gas storage capacity for 18-man SAT diving system of Acergy Osprey is 18000 cubic metres (Acergy, 2006). The standard capacity of each of the gas storage bottles is 576 normal cubic metres and 32 bottles are needed. If we assume, that the storage bottles are mounted on a skid of 8 bottles, it will result to a total weight of 29.5 tons. Based on the above, an estimated amount of four skid mounted storage bottles weighing 118 tons is onboard Acergy Osprey.

Figure 17 skid mounted gas storage bottles
Source: Drass Galeazzi Underwater Technology

The skid mounted gas storage bottles remain the largest weight component of the SAT diving system and it is usually installed below the main deck to keep the centre of gravity as low as possible.

2.2.1.5 Hyperbaric External Regeneration System

The HERS is also known as environmental control unit (ECU) and the main functions are to regulate the temperature, humidity and level of CO_2 gas in the DDC. These are achieved by circulating and re-processing the gas in the DDC when the divers are at depth on breathing gas media like mixed gas or natural air. It is estimated that three HERS with a weight of 2.5 tons will be needed and there is also a requirement for redundancy in the system bringing the total number of HERS for 18-man SAT diving system to 4.

Figure 18 a typical HERS installed on board
Source: Drass Galeazzi Underwater Technology

2.2.1.6 Ancillary Equipment of Bell Diving System

The ancillary equipment is used mainly for the deployment of bell diving system and umbilical through the moonpools. The estimated weight of seven major ancillary equipment of bell diving system in Acergy Osprey as shown in Table 4 is about 53.4 tons and this represent 17.3% of the SAT diving payload.

Table 4 Ancillary equipment

Items	Ancillary Equipment		units	Weight [ton]
1	**Guide wire shock absorber:** It reduces the loads, stress and fatigue on the bell handling system and the ship structure where the bell handling system is mounted.		2	1.9
2	**Bell wire shock absorber:** Its functions are the same with that of guide wire shock absorber. The overall purpose is to ensure that diving operation goes on in severe sea state without the effect of vessel motion affecting the bell system.		2	1
3	**Bell winch:** It performs the function of lowering and lifting of the bell diving system which the LARS of a modular system would have done.		2	18.15
4	**Anchor weight:** It carries the guide wire at working depth to stabilize the bell position, provides smooth entry and exit of divers from the bell and functions as a platform for maintenance of the diving bell		2	4.825
5	**Guide wire winches:** It is used to deploy and recover the two parallel cables which guide the diving bell.		2	9.41
6	**Hyraulic power pack:** It powers the bell handling system		3	10.5
7	**Umbilical winch:** It is used to deploy and recover the umbilical housing electrical and communication wires, and oxygen supply cables.		2	7.59
Total				**53.4**

Source: Drass Galeazzi Underwater Technology & LexMar Engineering Pte Ltd

2.2.2 Cargo Handling System

There are two cranes installed onboard Acergy Osprey with a total capacity of 190 tons. The biggest of the twos is a 150 ton heave compensated crane that is capable of supporting lowering and lifting operation in higher seastates. The purpose of installing the heave compensated crane is to extend the "weather window" of the DSV for offshore operations.

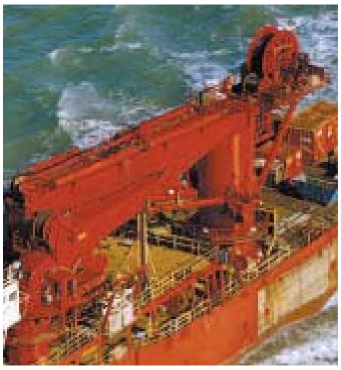


Figure 19 150 tons heave compensated crane onboard Acergy Osprey

2.2.3 Survey Systems

The survey systems onboard Acergy Osprey includes Navipac survey computer, DGPS. Hipap 500, Hipap 300, seapath 200 and Gyro. These systems are suitable for carrying out a wide range of surveys such as hydrographical survey, seabed mapping, platform survey, pipeline survey, installation survey etc. The weight of the survey systems is quite small and space equivalent of about 20-foot container footprint can accommodate these systems.

2.3 Operational Profile of Acergy Osprey

Operational profile defines the activities a vessel is performing at any particular moment in its operational history over a given period of time. Figure 20 shows that Acergy Osprey spends 75% of its annual operational time on DP which covers times spent waiting on weather (WOW) and on position working. Another chunk of the time about 12% is spent on transit from one job location to another and resupply. The time spent on mob/demob is 7% and it is a bit moderate and depends on the number of mob/demob for a particular period while dry dock and maintenance account for 6% of its operational profile. In the present conceptual design, a possible operational profile will be assumed for the respective designs.

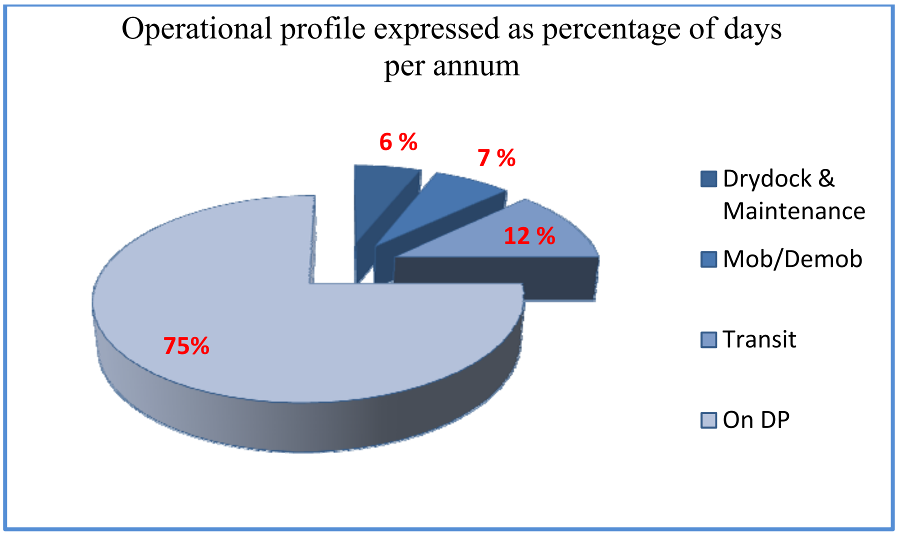


Figure 20 Operational Profile of Acergy Osprey
(Source: Hovland 2007 & e-mail communication with Hovland 2010)

3.0 DESIGN

3.1 Design Concepts

The cardinal objective of this thesis is to propose, develop and evaluate alternative design concepts and corresponding arrangement solutions for a DSV that will meet future requirements for sustainable and flexible operations, both in the North Sea and West African markets. To achieve the above stated objective, three design concepts are proposed with the features that would be inherent in the designs outlined in Table 5.

Diving operation in North Seas is highly regulated especially in the Norwegian Sea, and the Norwegian Petroleum Directorate forbids DSVs with DP system other than class-3 from operating in Norwegian sector of the North Seas (Hovland 2007). The North Sea operators are comfortable with this regulation and desire to have a DSV with an increase in operational window, which comes with high acquisition cost due to a number of factors, which include but not limited to the size of the vessel, stabilization system and system redundancy. In this circumstance, the concepts are developed in accordance with requirements for DP class-3 system (DYNPOS AUTRO) and NORSOK U-100 standard.

Table 5 Features of the design concepts

Features	Concept A	Concept B	Concept C
Accommodation	120 Persons	120 Persons	120 Persons
Propulsion System	Diesel Electric	Diesel Electric	Diesel Electric
24-man SAT Diving System	Modularized-top side	Inbuilt	Inbuilt
Air Diving System	Inbuilt	Container Module	Inbuilt
ROV Control/Survey System	Inbuilt	Container Module	Container Module
Deck Space	>1000m^2	>1000m^2	>1000m^2
Deck Cargo Capacity	3000tons	3000tons	3000tons
Helideck Class	HELDK SH	HELDK SH	HELDK SH
DP System	DYNPOS-AUTRO	DYNPOS-AUTRO	DYNPOS-AUTRO
Cargo Handling System	250 tons	250tons	250tons

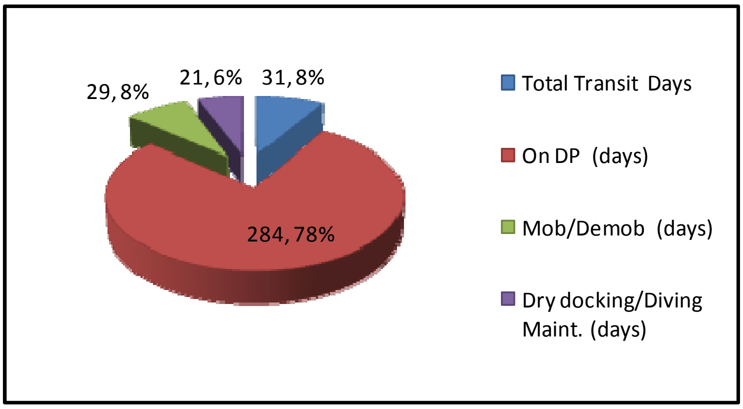
The common features of the three concepts are accommodation, propulsion system, deck cargo capacity, helideck, DP system and cargo handling system. The main dimension will also be the same for the three concepts. The aforementioned properties have been kept constant to avoid unhealthy deviation from the central theme of this thesis, which is focussed on design and arrangement solutions for the main mission equipment of the DSV to enhance, flexible and sustainable operations. Thus, the weight and size of main mission equipment have been ascertained and provided in Appendix II, to know what systems can remain fixed in the DSV and those that could be kept in the contractor's tool kit ashore without jeopardizing operations.

3.2 Operational Profile

An operational profile is assumed for the present designs based on the operational profiles of existing DSVs and furnished in Table 6. However, the designs are assumed to sustain operation for 50 days before resupply. It is important to remark that the operational profile of a DSV may not be constant throughout its lifetime. Therefore, the design concepts proposed should have the capacity to adapt to a different operational profile while in service. In assuming an operational profile for the DSV, 50% margin has been added to the transit time to account for year round movement from one work location to another within an oil field and manoeuvrings in port. To reflect the importance of this study, it will be good to consider a situation where the operational profile changes as a result of reduced work load and the DSV wants to switch role. What concept will be ideal for this situation? The acquisition costs of the DSV is enormous to keep it redundant over a long period of time, therefore the arrangement of the diving systems should be optimized for flexibility in its mission and easy adaptation to sets of operational profiles since the later may not be constant throughout the lifetime of the DSV.

Table 6 Assumed annual operational profile

Vessel Speed (knots)	12
Range (nm)	500
Endurance (days)	50
Round Trip Time (hrs)	83.3
Sailing Days per leg	3.5
No of Trips per annum	6.0
Actual Transit Duration (days)	20.8
50% Margin on Transit (days)	10.4
Total Transit Days	31
On DP (days)	284
Mob/Demob (days)	29
Dry docking/Diving Maint. (days)	21
Total Operation Days	365



3.3 Environment

Environmental factors have lots of influence on offshore operations. As a result of this, ships and ship shaped structures are designed to withstand the prevailing environmental conditions in the intended area of operation. The present design is meant for the North Sea and offshore West Africa, which are characterised by high sea state and benign environment respectively.

Table 7 Sea state with a return period of 100 yr and 3-hour duration, 1 hr mean wind speed with return period of 100 yr and surface current with a return period of 10 yr for the North Seas and West Africa

	Sea State			1 hr Mean Wind Speed		Surface Current	
Norwegian Sea	Hs	=	16.5m	37	m/s	0.9	m/s
	Tp	=	17.0 - 19.0 s				
Northern North Sea (Troll field)	Hs	=	15m	40.5	m/s	1.5	m/s
	Tp	=	15.5 -17.5 s				
North Sea (Greater Ekofisk area)	Hs	=	14.0m	34	m/s	0.55	m/s
	Tp	=	15.0 - 17.0 s				
West Africa							
Nigeria (swell)	Hs	=	3.6m	16	m/s	1.1	m/s
	Tp	=	15.9s				
Nigeria (squalls)	Hs	=	2.7m				
	Tp	=	7.6s				
Gabon (wind generated)	Hs	=	2.0m	16.6	m/s	0.91	m/s
	Tp	=	7.0 s				
Gabon (swell)	Hs	=	3.7m				
	Tp	=	15.5 s				
Ivory Coast (swell)	Hs	=	6.0 m	29.5	m/s	0.9	m/s
	Tp	=	13.0 s				
Angola (swell)	Hs	=	4.1 m	21.8	m/s	1.85	m/s
	Tp	=	16.0 s				

(Source: DNV 2004)

Although the operability of DSVs in the North Seas has improved tremendously, significant amount of time is spent waiting on weather due to extreme environmental conditions. There is also variation in seastates across the North Sea environment; each location has a distinct sea state at any particular time of the year. Taking a looking at Figure 21, we see that more operational time is gained at the Visund field in northern North Seas when the operational sea state of a vessel is increased up to 5m Hs but much is not gained in stretching the operability above 6m Hs. If we liken this scenario to other parts of the North Seas with similar environmental conditions, we could assume that it is possible to operate 90% of the time in a sea state of 5m Hs. According to Hovland (2007), operators' desires are for vessels than can operate within this threshold and they are willing to pay for the significant costs that go with it. However, other limitations that cut across bell operation, working on deck and lifting operation make it difficult to operate above 5m Hs. Therefore, most DSVs and offshore construction vessels are designed to support operation up to 5m Hs. However, the West African region, apart from Ivory Coast which has a sea state of 6m Hs in one out of hundred in a year, maintains a sea state which is below the bench mark design value for a DSV operating in the North Seas. This implies that any DSV capable of operating in the North Sea can operate year round in offshore West Africa.

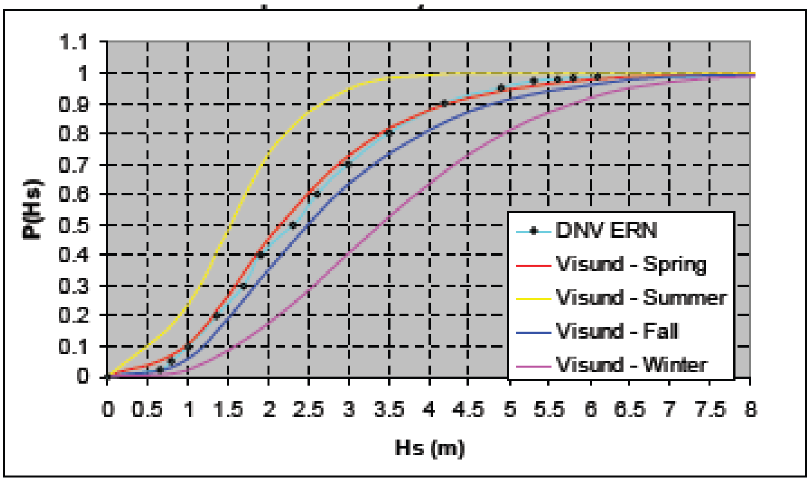


Figure 21 Operability curves for visund field in comparison with DNV ERN
(Source: Acergy 2009)

3.4 Rules and Regulations

It is vital to carry out the present design and arrangement of diving systems in line with rules and regulations governing the operation of special purpose vessels like DSVs in the harsh environment of the North Seas, and on the fact that any vessel capable of operating in the North Seas will be highly efficient when deployed to less hostile West African offshore environment.

3.4.1 Diving systems

The diving systems on board the DSV and the layout shall conform to technical requirements of NORSOK Standard for Manned Underwater Operation U-100 (2008) and UK department of energy air range diving support vessel guidance (1991). Both standards highlight the importance of good ergonomics in the design, layout and arrangement of diving systems. Technical redundancy in the bell system, ECU, gas supply units, power supply unit, and communication systems of the SAT diving system are also emphasized and they have been considered in defining the system requirements for the SAT diving system in the respective design concepts. Two important excerpts from the technical requirements in NORSOK U-100 that deals with space allocation in the design concepts are:

(a) *Chamber complex size, architecture, lighting and lay-out shall support and optimise all the functions planned to take place in the chambers for the maximum number of occupants. It shall be possible to bring personnel, equipment and provisions into and out of the chamber complex.*

(b) *Inner height of the chambers shall be no less than 200 cm over the deck plates (measured in the middle of the chamber)*

3.4.2 Accommodation Standard

There has been serious concern about comfort of diving personnel in recent time; various class regulations and standard (DNV, NORSOK, and IMCA etc) are already in place to ensure the comfort and safety of the divers. The designs are based on DNV comfort class and the UK department of energy air range diving support vessel requirements (1991) which have made provisions for the highest level of comfort for diving personnel and ensures that indoor climate of the DSV which affect the health of those onboard complies with defined environmental standards.

3.4.3 Helideck

The helicopter deck is dimensioned according to NORSOK C-004 and DNV-OS-E401 standards for Sikorsky S61N helicopter decks. This implies that any other helicopter which capacity is less than that of Sikorsky S61N can safely land and take-off from the helideck. The following design criterion then applies in determination of the helideck size.

Minimum helideck size forward on ships:

$D_H = 1.0D + 0.25D$ (NORSOK C-004)

Where: D is the maximum external dimension of the helicopter with both rotors rotating defined by DNV-OS-E401 to be 22.2m and maximum weight of about 9.3tons for Sikorsky S61N. The position of the helideck will be in the view of the captain and will be raised to a height of about 3m above the forecastle deck to create good air gap that will cushion aerodynamic turbulence effect.

3.4.4 Cargo tanks

The following MARPOL regulations are implemented in the design:

1. All fuel oil tanks with capacity greater than 600m^3 shall have a double hull construction.

2. The capacity of individual fuel oil tank shall not be greater than 2,500 m^3.
3. Slop tanks shall be 2% of cargo capacity for vessels with segregated ballast tanks.
4. Accommodation, service space and control room shall not be located close to Fuel oil tanks unless they are spaced at least 7m away from the cargo tanks

3.5 Design Constraints

The most important constraint with respect to vessel's dimension, which is to be considered in the present work, is the length of the DSV. Ubisch (1981) examined the wave spectra from the North Sea and confirmed that a length of about 100m would have a good operability. Recently, Hovland (2007) established a relationship between vessel's length and percentage of operational time in the North Sea, which is represented in Figure 23.

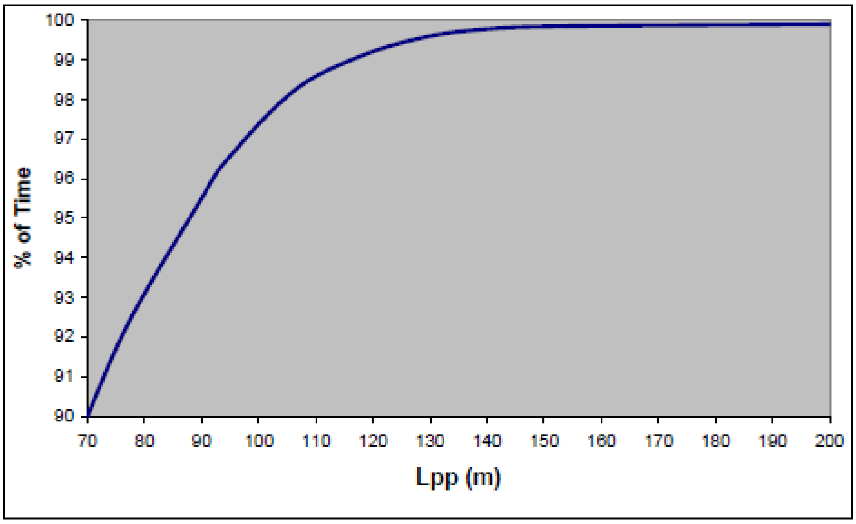


Figure 22 Vessel length Vs percentage of operational time in the North Sea
(Source: Hovland 2007)

Although Figure 22 is independent of wave action, it takes into consideration of the effect of vessel motions on diving bell operation. The significance of Figure 22 is that minimum vessel length, that can support diving operation in high sea state, can be selected as a first approximation during conceptual design phase. Operability of about 97% can be achieved for North Sea environment with a vessel length of 95m; higher operability can also be achieved as the vessel's length increases but it may not be economical to have a vessel whose length between perpendiculars is greater than 120m. This is because beyond 120m, the operability of the vessel becomes almost constant. Therefore, the boundary fixed for the present designs is 95m<=Lpp<=120m.

3.6 Design Methods

System based ship design approach developed by Levander (2004) has been used in this work for preliminary estimate of areas, volumes and weight groups needed to fulfil the functions of the DSV. Although, there is no documented approach for system based design of DSVs the later could be likened to a capacity carrier; hence methods developed for such cases where the payload and volume determine the size of the ship were relevant in developing a framework for the system requirements of the DSV. The initial size of the DSV has been determined by comparing the estimated gross tonnage with statistical data from reference vessels sourced from fairplay online data base, while power estimate was based on deadweight, design speed and data of installed power of reference vessels. The weights of likely diving systems and ship equipment to be installed onboard the DSVs have been sourced from the websites of diving and ship equipment manufacturers. The ship hull was modelled with the software "Marsurf" using an existing hull as a starting point; this was necessary for a parametric transformation to obtain mid-ship area coefficient for the designs and waterlines for geometric estimates of hull and deckhouses. The general arrangement drawings were then produced with Auto-CAD version 2010. Some Key Performance Indicators were developed for the evaluation of the design concepts using Analytic Hierarchy Process (AHP).

3.7 DSV Design Process

The system based ship design process begins with the mission description of the vessel and the mission defined for Acergy Osprey in Figure 20 is assumed for the three design concepts in Table 5. Having itemized the features of the designs, the next phase is to produce a bigger picture of the systems required to perform the functions of the DSVs. Thereafter, areas and volumes needed in the DSV to accommodate the various systems are estimated, followed by selection of main dimensions and hull form using statistical data derived from a pool of successful designs. Geometric estimates of areas and volumes in the hull and deckhouses are done and compared with system-based requirements; preliminary estimate of stability is also carried out to ascertain conformity with design criteria. The design concepts are represented by their general arrangements and discussed in details. The designs are evaluated using key performance indicators (KPIs) and sensitivity analysis is carried out to examine the robustness of the design concepts to changes in assumed variables. The steps in the present designs are shown in Figure 23.

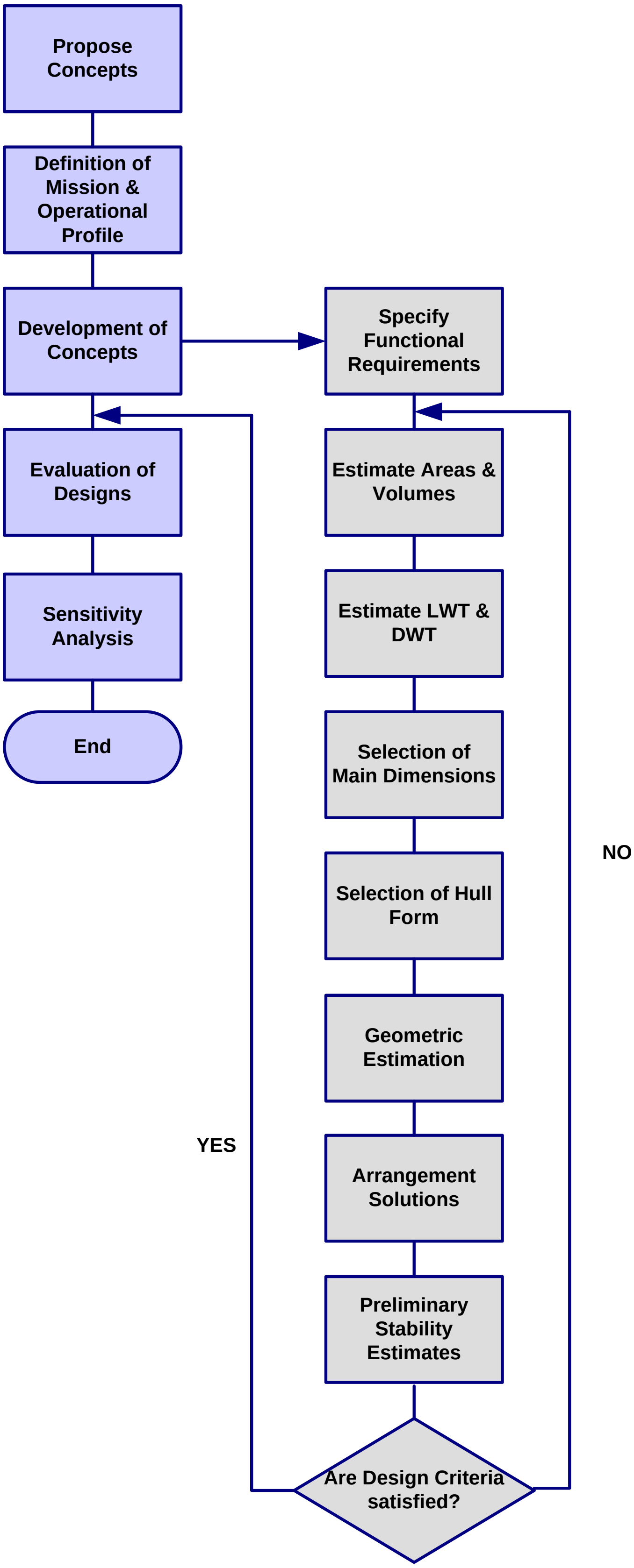


Figure 23 Design Algorithm

3.8 Functional Requirements

The functional requirements for a typical DSV are shown in Figure 24. It reflects the features of the three design concepts. The payload function is different from those of other types of vessels because of the intended mission which is diving and construction support while the ship function is more or less similar to other type of vessels.

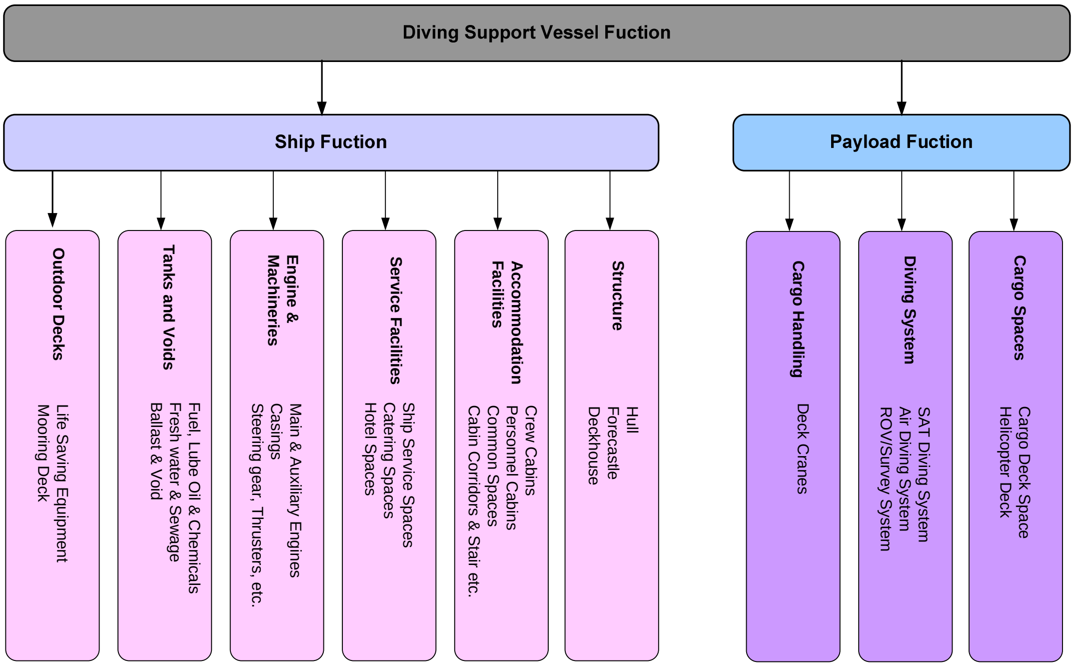


Figure 24 Functional requirements for DSV

3.8.1 Estimates of Areas and Volumes

The areas and volumes for the functional requirements of the DSV have been dimensioned based on available data from other vessels but the space requirements for the payload systems have been determined using the size of the equipment and machinery to be installed onboard with a mark up of 30% to account for panels and ancillary equipment that go together with such machineries. The diving systems, engines and machineries require a lot of enclosed space onboard the DSV due to redundancy in the systems. The summary of space requirements for the three concepts is furnished in Table 8 below while the details are provided in Appendix III.

Table 8 Summary of system requirements

SYSTEM DESIGN SUMMARY	Concept A		Concept B		Concept C	
SPACE ALLOCATION	**Area [m2]**	**Volume [m3]**	**Area [m2]**	**Volume [m3]**	**Area [m2]**	**Volume [m3]**
Cargo Deck Space	1102		1262		1200	
Helideck	773		773		773	
Total Deck Spaces	**1875**		**2036**		**1973**	
Accommodation Spaces	1089	3048	1089	3048	1089	3048
Personnel Common Spaces	633	1773	633	1773	633	1773
Ship Service	769	2365	769	2365	769	2365
Catering Spaces	234	655	234	655	234	655
Hotel Spaces	43	440	43	440	43	440
Total Furnished Spaces	**2768**	**8282**	**2768**	**8282**	**2768**	**8282**
Technical Spaces in the Accommodation/Offices	271	954	271	943	271	949
Total Interior Spaces	**3039**	**9236**	**3039**	**9225**	**3039**	**9231**
Diving Systems	1489	6156	1368	5731	1433	5889
Engine & Machineries Room	1269	8901	1269	8901	1269	8901
Personnel & Emergency Stairways	76	302	76	302	76	302
Total Technical Spaces	**2758**	**15360**	**2637**	**14935**	**2702**	**15093**
Tanks		**7759**		**7759**		**7759**
System Area [m2]		**10440**		**10480**		**10463**
Gross Volume [m3]		**32354**		**31919**		**32081**
Gross Tonnage [Tons]		**10111**		**9975**		**10025**

The differences in space requirements are in deck space and technical spaces due to variations in arrangement of the diving systems. Concept A requires more technical spaces than the other two concepts since it has a modular design for top side SAT diving system which is integrated in the design but flexible.

3.8.2 Weights

Data on weights of equipment and machineries are not readily available but an estimate of weights has been made using the data of likely equipment to be installed onboard obtained from "Tethys Plantgeria Ltd" a diving and marine construction company and manufacturers' websites. The knowledge about weights and size of some diving equipment and machineries has also played a major role in determining the overall weight of the diving systems, which are provided in Appendix II. The helideck and structure is made of aluminium material, which is lighter than steel and has gained prominence in construction of offshore helidecks; the estimate provided by Aluminium Offshore in their website was used in this study. The remainder of the lightweight were estimated using volumes, areas and installed power together with their assigned coefficients proposed by Levander (2004). The breakdown of the ship's weight and the estimate of the weights are shown in Figure 25 and Table 9 respectively.

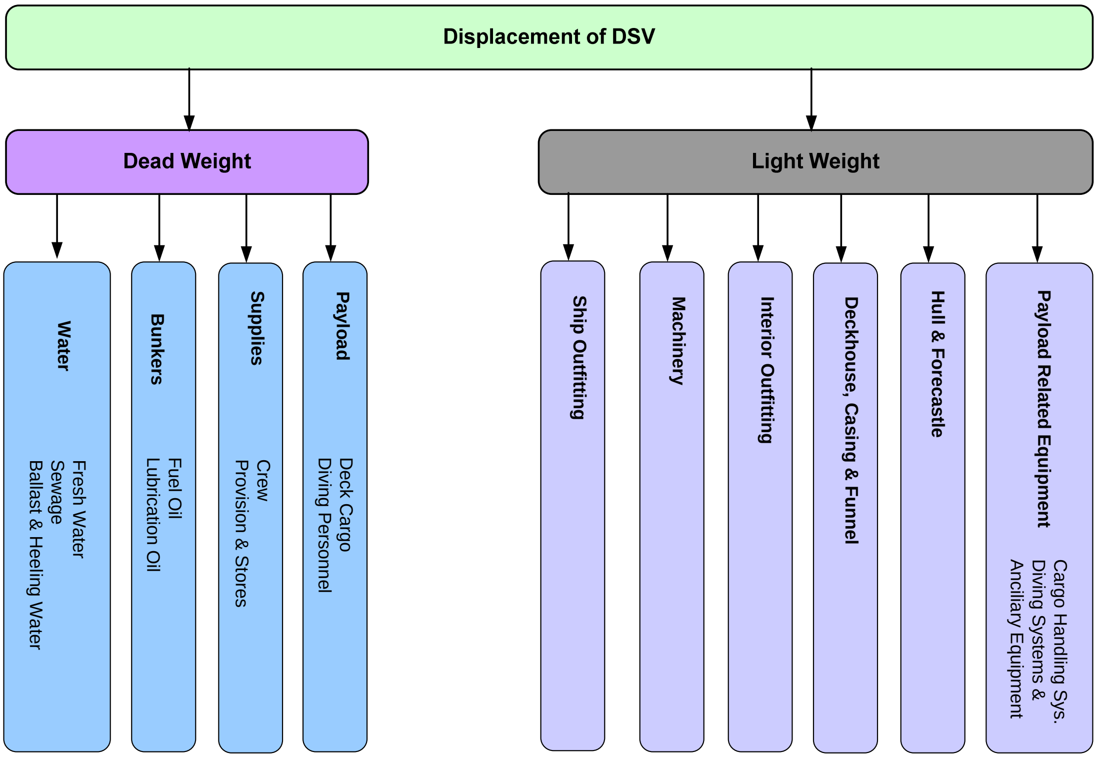


Figure 25 Weight group

Table 9 Estimate of Ship's Weight

WEIGHT ESTIMATION					Concept A	Concept B	Concept C
LIGHT WEIGHT	**Unit**	**Value**		**Coeff ton/unit**	**weight [ton]**	**weight [ton]**	**weight [ton]**
Weight Group:							
Payload related:							
Deck Cranes	No	1	unit	250.00	250.00	250.00	250.00
	No	0	unit	50.00	0.00	0.00	0.00
Helideck & Structure	No	1	unit	44.50	44.50	44.50	44.50
Hatches	Aggregate			30.00	30.00	30.00	30.00
SAT Diving System	Aggregate	1	unit	466.66	466.66	466.66	466.66
Air Diving System	Aggregate	1	unit	50.00	50.00	-	50.00
ROV System	Aggregate	1	unit	52.00	52.00	-	-
Hull and Forcastle	Hull Vol	21947	m3	0.08	1755.76	1721.44	1732.48
Deckhouse, Casing & Funnel	S-Structure Vol	10407	m3	0.05	520.35	520.05	524.85
Interior Outfitting	Area	3039.063	m2	0.20	607.81	607.81	607.81
Machinery	Pp+Pa	15800	kW	0.06	948.00	948.00	948.00
Ship Outfitting	Gross Volume	32354.07	m3	0.01	258.83	255.35	256.65
Total					4983.91	4843.81	4910.94
Reserve	%	5			249.20	242.19	245.55
LIGHT WEIGHT					**5233.11**	**5086**	**5156.49**
DEAD WEIGHT	**Unit**	**Value**		**Coeff**	**Weight [ton]**	**Weight [ton]**	**Weight [ton]**
Weight Group:							
Deck Cargo	Capacity	3000	ton	1.00	3000.00	3000.00	3000.00
Helicopter	Capacity	0	ton	1.00	0.00	0.00	0.00
Crew & Diving Personnel	Persons	120	pers.	0.10	12.00	12.00	12.00
Provision & Stores	Persons x 6kg/d	120	pers.	0.40	48.00	48.00	48.00
Fuel Oil	Consumption	1618.301	m3	0.89	1440.29	1440.29	1440.29
Lubrication Oil	Consumption	52.92313	m3	0.92	48.69	48.69	48.69
Fresh Water	Consumption	1209.6	m3	1.00	1209.60	1209.60	1209.60
Sewage Sludge	Produced	0	m3	0.72	0.00	0.00	0.00
Ballast Water for Stability	10% Capacity	300	m3	1.03	30.75	30.75	30.75
BW for Anti-heeling & Trimming	50% Capacity	750	m3	1.03	768.75	768.75	768.75
Total					**6558.08**	6558.08	**6558.08**
Miscellaneous	%	5			327.90	327.90	327.90
DEAD WEIGHT					**6886**	**6886**	**6886**
DISPLACEMENT					**12119**	**11972**	**12042**
DWT/DISPL					**0.6**	**0.6**	**0.6**

The deadweight of the three concepts is the same but their lightweight varies because of the differences in the mission equipment to be installed onboard. The variation in light weight will influence cost since ship building cost among other factors is based on lightweight.

3.8.2.1 Estimation of Storage Tubes

To determine the number of storage bottles needed for the saturation diving system, the working depth and the number of diving personnel supported in a single operation need to be considered. A depth of 1000fsw (~300msw) is assumed since most SAT diving systems are manufactured based on 300msw. The following relation from the US Navy diving manual was used to estimate gas usage for 24 hours operations involving three sets of SAT diving teams.

$$ata = \frac{D+33}{33}$$

1 scfm (for one diver at depth) = ata x acfm
Total scfm = scfm x number of divers
scf required = scfm x minutes

Where:
D = depth of diver
ata = atmosphere absolute
acfm = actual cubic feet per minute
scf= standard cubic feet

First the working depth is converted to absolute atmosphere and then to standard cubic feet per minute by multiplying with actual cubic feet per minute equivalent of 1 absolute atmospheric pressure. An estimate of the number of storage tubes that will support 24 divers for 24 hours working period, and that for the chamber gas reclaim unit was then determined to be 49 tubes which will give a total capacity of 28224m^3 excluding safety margins and the weight of the storage tube accounts for 38% of the weight of 24-man SAT diving system. Details of the calculation are provided in Appendix II.

3.9 Parametric Studies

The estimate of main dimensions has been done using statistical data from existing ships. The parameters were obtained by interpolations with the calculated gross tonnage of the DSV. Preliminary estimate of power requirements were also based on statistical data and empirical relations and compared with power requirements of some DSVs in service. The details of the DSV statistics developed from "fairplay" database are furnished in Appendix IV. The slenderness ratio of approximately 5 was obtained for the design concepts and this depicts a displacement hull. Since the same hull is used for the three concepts, their hull form coefficients are almost the same except the block and prismatic coefficients. The variation in light weights is responsible for this deviation but the hull could still be the same since the equipment that is not fixed would from time to time be brought back to the vessel when needed.

The following expressions were used to determine the hull form coefficients:

$$C_B = \frac{\Delta}{\rho_{seawater} \times L_{pp} \times B \times T}$$

$$C_W \approx 0.3 \times C_B^2 \times +0.7$$

$$C_P = \frac{C_B}{C_M}$$

The midship area coefficient was derived from a similar hull which was parametrically transformed in Marsurf to the particulars of the present designs.

Table 10 Main Dimensions and geometric estimate of hull and deckhouses

PARTICULARS				A	B	C
LOA	116	m	**LWL/Vol^1/3:**	4.89	4.91	4.90
LWL	111	m	**LWL/LPP**	1.03	1.03	1.03
LPP	108	m	**L/B**	4.70	4.70	4.70
Breadth	23.0	m	**B/T**	3.29	3.29	3.29
Draught	7	m	**Fn**	0.23	0.23	0.23
Freeboard Deck	12	m	**CB**	0.68	0.67	0.67
Freeboard + Margin	5	m	**CW**	0.84	0.84	0.84
Depth to Upper Deck		m	**CM**	0.98	0.98	0.98
			CP	0.69	0.68	0.69

DECK AREAS AND VOLUMES IN THE HULL						
Deck Name	**Height above BL [m]**	**Deck Height [m]**	**Deck Area [m2]**	**Area Coeff**	**System Area [m2]**	**System Volume [m3]**
Double Bottom	0.00	2		-	-	1814
Tank Top	2	4.5	1974	0.84	1658.16	5863
Tween Deck	6.5	3.5	2622	0.92	2412.24	6791
Main Deck	10	3.5	2668	0.94	2507.92	7377
	13.5					
Total Hull Portion					**6578**	**21845**

AREAS AND VOLUMES IN DECKHOUSES						
Deck Name	**Height above BL [m]**	**Deck Height [m]**	**Deck Area [m2]**	**Area Coeff**	**System Area [m2]**	**System Volume [m3]**
Deck 2 - Main Deck	10.00	3.5	-	-	-	-
Deckhouse 1	13.5	2.8	1610	0.98	1578	3696.56
Deckhouse 2	16.3	2.8	1610	1.02	1642	3786.72
Deckhouse 3	19.1	2.8	1288	1.06	1365	3101.504
Deckhouse 4	21.9	2.8	598	1.08	646	1506.96
Bridge	24.7	2.8	322	1.08	348	811.44
Sky Lobby	27.5	2.8	252	1.1	277	635.04
	30.3					
Total Deckhouses					**5856**	**13538**

Total Hull and Deckhouses	**Geometric Definition**	**12434**	**35383**
	System Based Demand	**10440**	**32334**

The geometric definition of areas and volumes in the hull and deckhouses as shown in Table 10, compare fairly with system based requirements. The following design criteria, which are synonymous with system-based ship design, have been verified to ensure that the functional requirements of the DSV are accommodated in the hull and deckhouses.

$$V_{hull} + V_{deckhouse} \geq \Sigma V_{systemdescription}$$

$$A_{hull} + A_{deckhouse} \geq \Sigma A_{systemdescription}$$

$$\Delta = L_{pp} \times B \times T \times C_B \times \rho_{seawater} \geq LWT + DWT$$

3.9.1 Hull Design

Two hull types (Bulbous bow and X-bow) were appraised for the present design based on the criteria listed in Table 11, both hull types have improved seakeeping behaviour and good propulsion characteristics but X-bow concept has reduced fuel consumptions because it has low added resistance in seaway. Its power requirement in waves is low compared to bulbous bow. The hull volume forward and operation in ice are also better for X-bow. However, bulbous bow is more cost efficient and has ample deck area forward for the installation of helideck and structure within the view of the Master. A trade-off between these criteria was made and because the helideck need to be within the sight of the Master in the present design, bulbous bow was selected.

Table 11 Evaluation of hull technology

Criteria	Bulbous bow	X-Bow
Seakeeping	better	better
Resistance in seaway	high	low
Deck Area Forward	better	poor
Hull Volume Forward	good	better
Cost Efficiency	better	good
Operation in ice	good	better
Power Requirement in waves	high	low
Propulsion Characteristics	good	good

Figure 26 3-D model of the hull with bulbous bow

3.10 Detailed Concept Description

The key issues on design of the present generation of purpose built DSVs are sustainability and operational flexibility. The concepts development is focused on integrating flexibility in the arrangement solutions of the mission equipment of the DSV to make it more sustainable. Three design concepts that have equal system characteristics but different arrangement solutions were proposed and developed. The reason for making the system characteristics the same is to avoid unnecessary repetition of the design process but to focus on arrangement solutions. The concept of modularity, which has become the current fashion in modern technology, is considered as one of the feasible arrangement solutions for the top side SAT diving system. It is also possible to package some of the mission equipment in container modules rather than integrating them in the design of the DSV. These arrangement solutions are viewed to be more sustainable than keeping the mission equipment fixed. The main mission equipment includes SAT diving system, air diving system and ROV system. For the three concepts weight sensitive parts of the SAT diving system like the gas storage tubes, hyperbaric chambers and the environmental control units have been kept beneath the main deck to reduce the topside weight and lower the centre of gravity of the DSV.

3.10.1 Concept A

This concept involves integration of the air diving and ROV systems in the design of the DSV while modularizing the top side SAT diving system, the essence of making the top side SAT diving system flexible is to gain deck space; about 45% of the original deck space could be gained when the modular section is removed. The modular portion of the diving system must conform to the requirements of DNV comfort class; this implies that the comfort of the diving personnel must be ensured while implementing the concept of modularity in part or whole of the diving system. Another motivation for this concept is that the Royal Danish Navy has successfully developed a standard flex concept for their combat ships making them to function in several roles instead of building a dedicated combat ship which will end up achieving little. Those behind the flex concept saw the need to minimise costs in replacement of certain categories of warships (torpedo boats, patrol boats and minesweepers) as a result of budget constraints, and today the flex concept is a reality and has extended to large combat ships like the Command and Support units of the ABSALON-Class. The role dedicated equipment forms the flexible part of the vessel and are packaged in standard container modules which is shown in Figure 27.

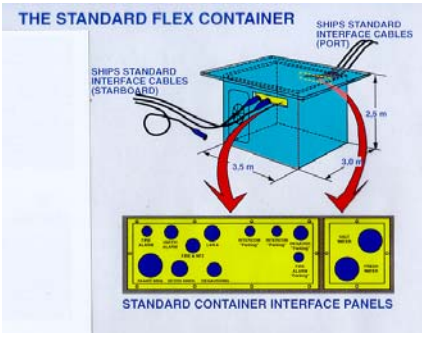


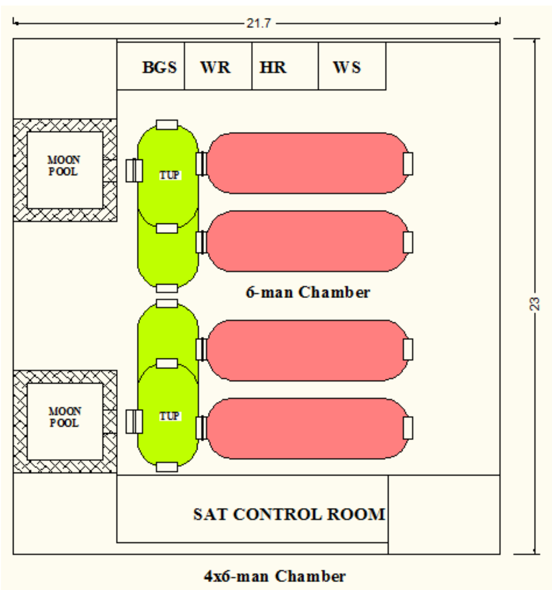
Figure 27 Arrangement of standard flex container
(Source: Royal Danish Navy 2010)

Similarly the knowledge gained in the design of the flexible combat ships could be replicated in the design of the multipurpose DSVs specifically in the top side SAT diving system and some of the mission equipment. To achieve a flex concept for multipurpose DSVs, we need a design where the top side mission equipment will be mainly light weight items; creating flexible top side modular systems of mainly SAT diving control and ancillary equipment is possible because “Drass Galeazzi Underwater Technology” has the expertise in design and construction of modular SAT diving systems.

Currently, SAT diving is dominating in offshore operations but when there will be decline in SAT diving activities as oil and gas production go into deeper seas, it would be necessary to take out the top side SAT diving systems to create deck space for diverless interventions and supply services. A lot could be done with large deck space, for instance sea fasting of spool can be done on deck and lowered to the seabed during diverless operation with ROV system and air diving operation in shallow waters and this will reduce the overall diving bottom time for the remaining underwater tasks. In diverless operation with ROV system, some of the huge subsea umbilicals that are often conveyed to offshore installation sites with other supply vessels due to deck space limitations could be carried onboard. The gain in deck space could be further useful, should there be need to switch to a long time supply services.

3.10.1.1 Selection of Hyperbaric Chamber Layout

A feasible modular topside design for the SAT diving system in concept A requires an arrangement where the hyperbaric chambers will remain under the main deck. This is to reduce the weight and number of modules as well as installation and de-installation time in port. It is possible to configure various chamber arrangements for 24-man SAT diving system which is the biggest in the offshore diving industry. Possible arrangements are 4x3-man and 2x6-man system, 3x6-man and 2x3-man system, 4x6-man system, and 8x3-man system. The main factor influencing configuration of the hyperbaric chamber layout is the space available onboard and the first question diving equipment manufacturers do ask is "what space do you have onboard? Can we see the general arrangement of the vessel?" However, three arrangement options shown in Figures 28, 29 and 30 were evaluated using the rank order centroid (ROC) method, which involves conversion of ranks into ratings or weights. The aim is to choose a hyperbaric chamber arrangement that will be cost effective and support modular arrangement for top side SAT diving system. The criteria for selection are space, cost, weight and complexity; and the layout with the best performance metrics is selected.



Legend:

TUP – Transfer Under Pressure unit

BGS – Breathing Gas System

WR – Washing Room

WS - Workshop

HR – Heating Room

SCM – Saturation Control Module

Figure 28 Option A of chamber arrangement

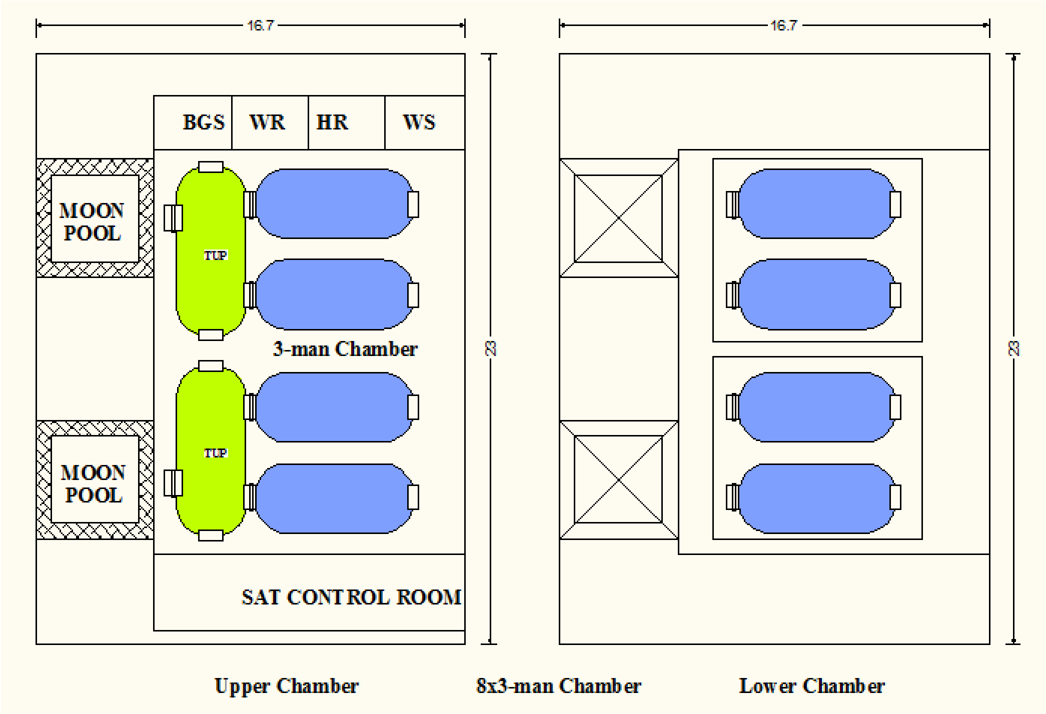


Figure 29 Option B of chamber arrangement

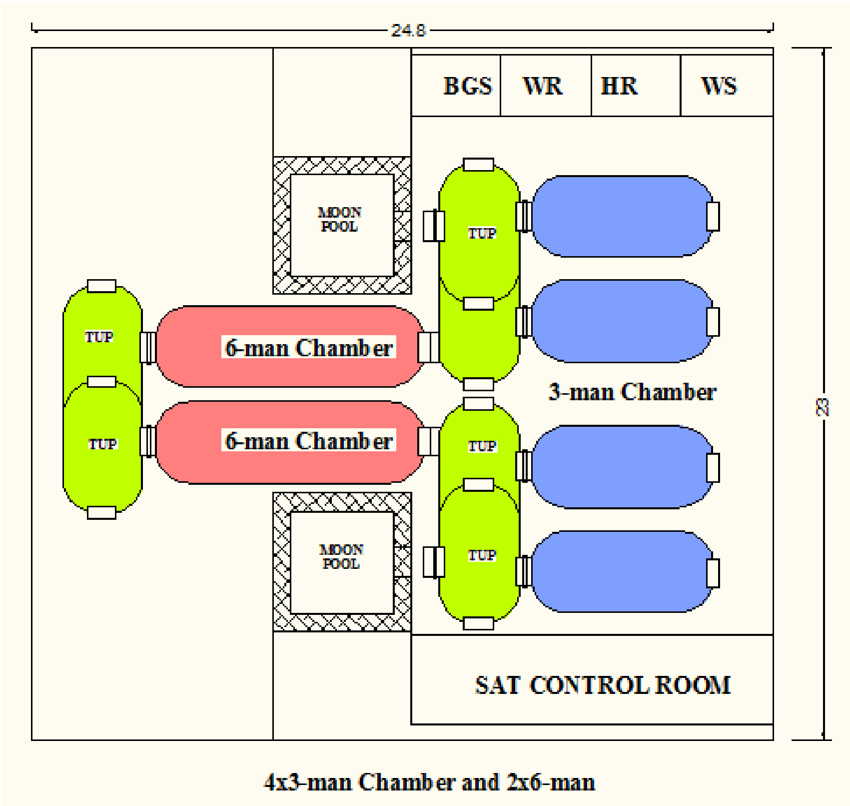


Figure 30 Option C of chamber arrangement

The objective hierarchy is as follows:

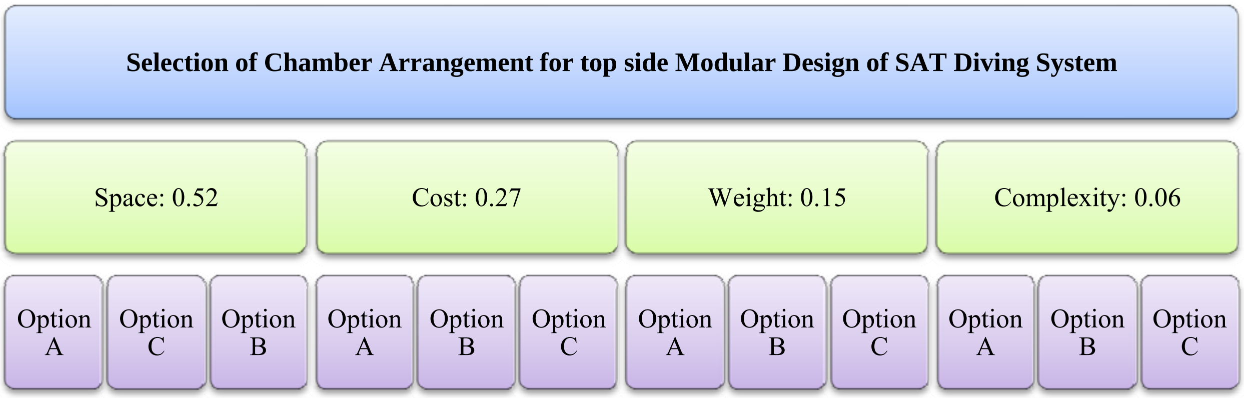


Figure 31 Hierarchy representation of the selection problem

In the objective hierarchy above, space is the most important attribute followed by cost, weight then complexity. We need space on the tween deck to accommodate the hyperbaric chambers; this will help lower the centre of gravity of the DSV and reduce the top side weight that will be modularized but where there is no sufficient space on the tween deck then the system will be separated into upper and lower chambers. The option A of the chamber arrangement occupies less space followed by option C then option B. The cost of the hyperbaric chambers is another important attribute and it depends on the chamber arrangement and the level of system complexity hence, the chamber with less complexity in arrangement solution and less weight is assumed to be cheaper and option A ranks best in that regard followed by option B then option C. In terms of weight and complexity, option A has less weight and it is less complex than options B and C while option B weighs less than option C and it is equally less complex than option C.

Table 12 Evaluation of chamber arrangement

Main Attributes	Relative Weight	
Space	W1	0.52
Cost	W2	0.27
Weight	W3	0.15
Complexity	W4	0.06
Option A, Space	W1	0.61
Option C, Space	W2	0.28
Option B, Space	W3	0.11
Option A, Cost	W1	0.61
Option B, Cost	W2	0.28
Option C, Cost	W3	0.11
Option A, Weight	W1	0.61
Option B, Weight	W2	0.28
Option C, Weight	W3	0.11
Option A, Complexity	W1	0.61
Option B, Complexity	W2	0.28
Option C, Complexity	W3	0.11
Final Evaluation		
Option A	=	**0.61**
Option B	=	**0.19**
Option C	=	**0.20**

The result of the evaluation above shows that option A, with a performance metrics of 61% will be the most suitable arrangement for a top side modular SAT diving system. This chamber arrangement will take off the hyperbaric chambers from the main deck thereby eliminating the need for two layers of chambers offered by option B.

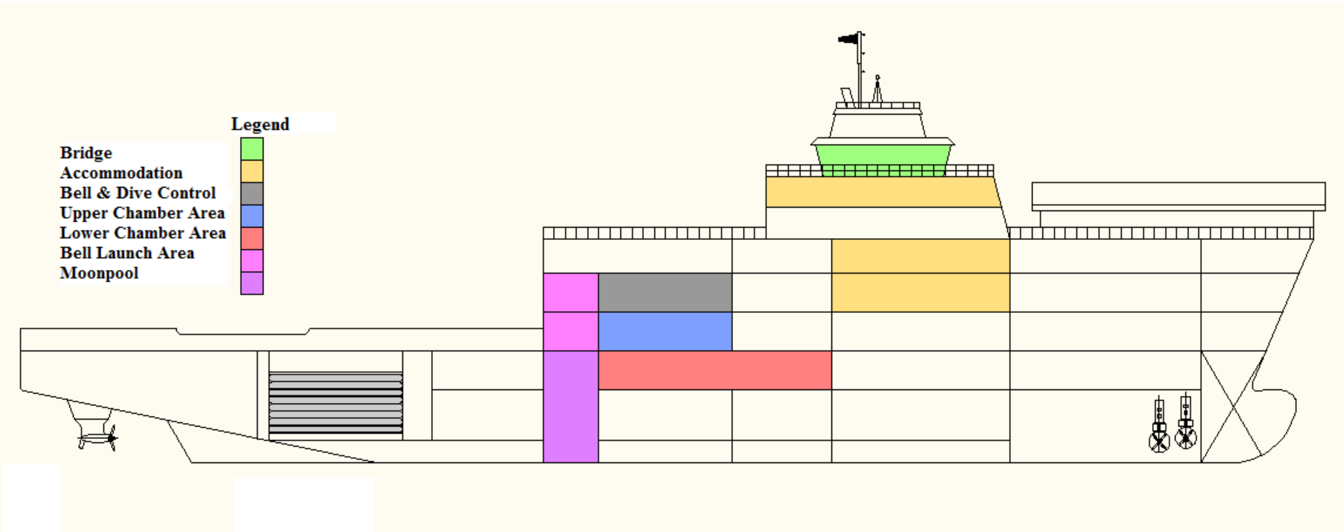


Figure 32 Profile view of concept A

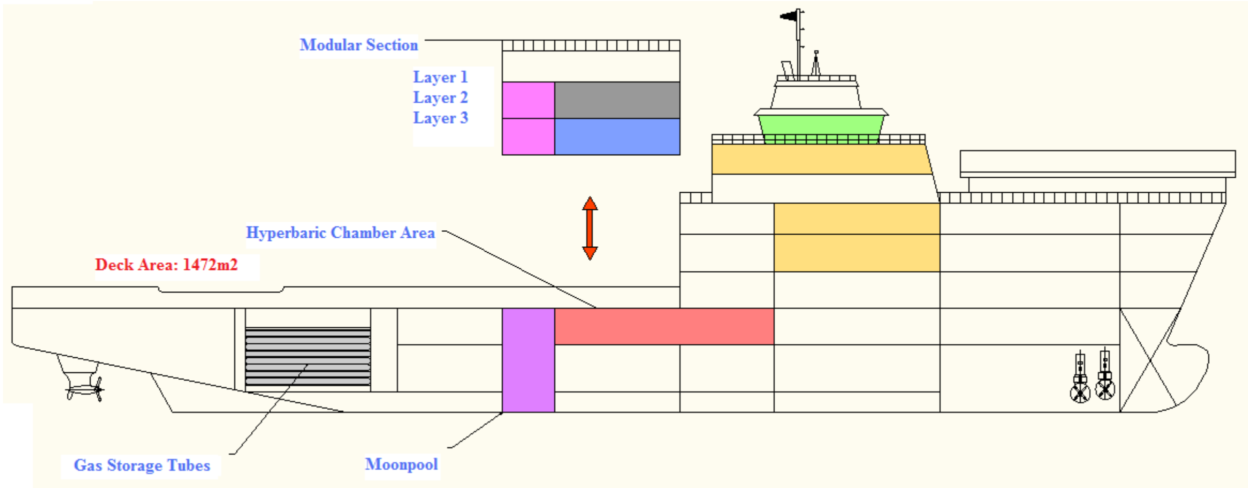


Figure 33 Profile view of concept A showing modular section

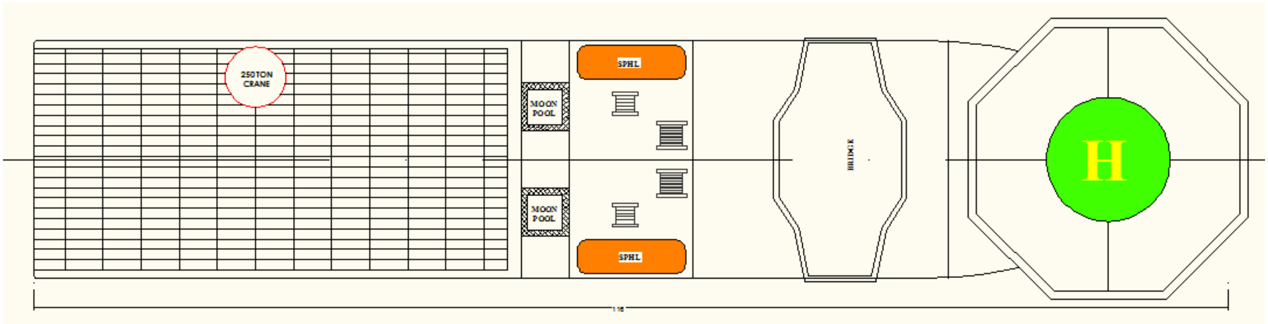
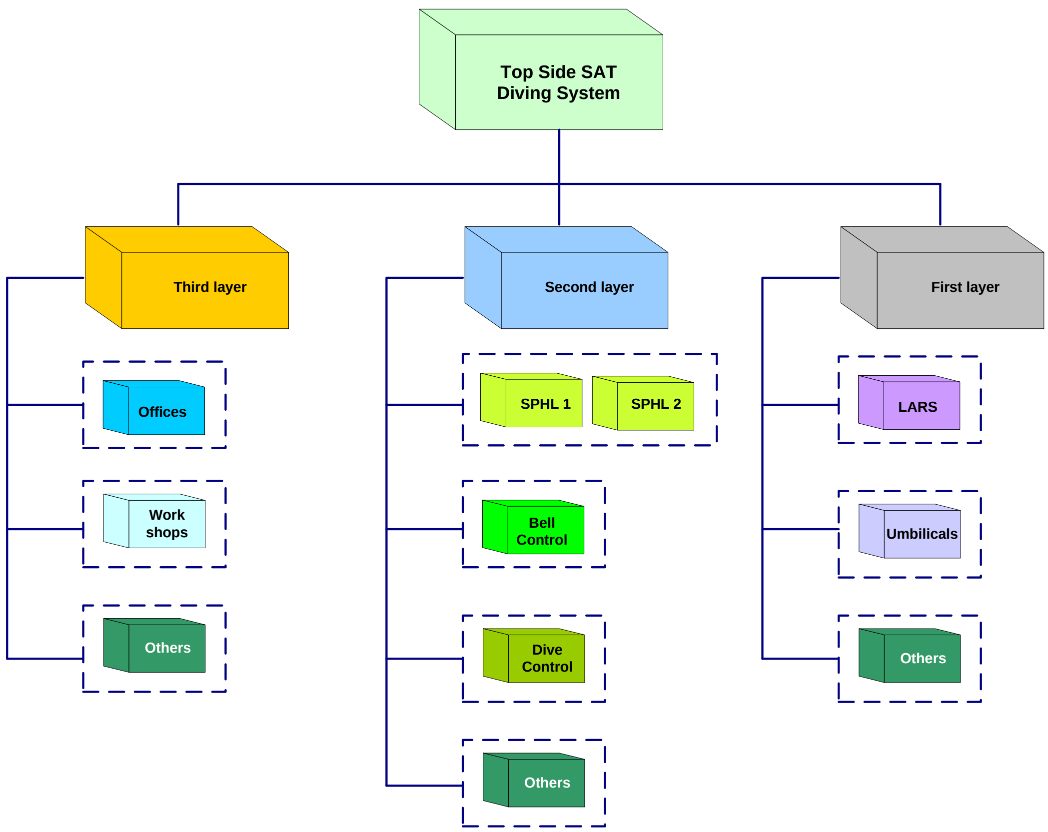


Figure 34 Plan View of Concept A

3.10.1.2 Modular Design

The modularity concept has been widely embraced in engineering design, manufacturing and production. The modular section in Figure 33 is in form of "stack modularity" which could be defined as anthology of modules that are linked to create a unit that represents the sum of the individual modules. This modular section is assumed to have a weight equal to the weight of total container modules required and it is further divided into three layers according to the number of decks affected. On the third layer, we have offices and workshops. The second layer accommodates the SPHLs, bell and dive control modules while the LARS, umbilicals and bell handling drives are contained in the first layer. By manufacturing the top side SAT diving system in standard container modules as shown in Figure 35, it will ease installation and de-installation. The main weight items of this system are SPHLs which weighs 16.5tons each and LARS. The first layer contains launching and recovery system (LARS), umbilical winch, bell handling drive and other support systems. The weight of this layer is about 60 tons.



Legend:

SPHL – Self Propelled Hyperbaric Lifeboat

LARS: Lunching & Recovery System

Figure 35 Modular hierarchy

The deck space covered by the modular design is about 391m^2 including the space for moonpools; this is quite large when fragmented into standard container modules of 10.5m^2 which is currently utilized by the Royal Danish Navy but the modular architecture for the present study is simplified by focusing on the top side mission equipment, workshops and office support as shown in Figure 35. By this arrangement, about 11 standard container modules of 10.5m^2 will be needed for this concept.

3.10.2 Concept B

The ROV and air diving systems are packaged in standard container modules while the SAT diving system is integrated in the design of the DSV. This arrangement provides the opportunity to utilize the ROV and air diving systems in the spot market. As shown in Figure 36, both systems could be launched using the port and starboard sides respectively but moonpool lunching is usually recommended in severe seastates.

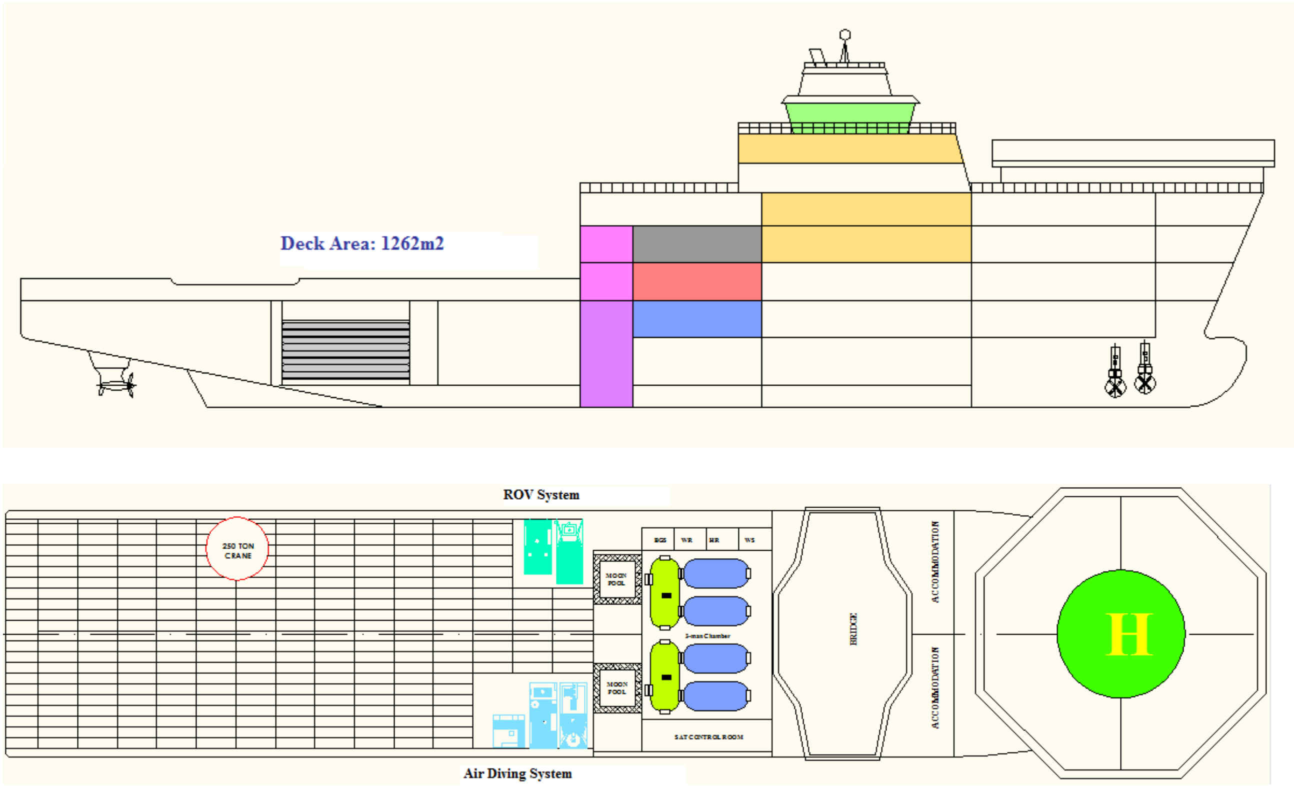


Figure 36 Profile, and combination of main deck and plan views for concept B

The option B of hyperbaric chambers arrangement in section 3.10.1.1 has been adopted for this concept. This is because of insufficient space on the tween deck to accommodate bigger hyperbaric chambers and it may not be economical to have a flexible top side SAT diving system in this concept because of the existence of an upper chamber area.

3.10.3 Concept C

The ROV system, is to be packaged in container modules as shown in Figure 37 while the SAT and air diving systems are integrated in the design of the vessel. Utilization for spot market offer is the main driver of concept C. Also, the ROV system modules offer flexibility in usage since it will remain on contractor's tool pool and are readily available for any DSV that has ROV contract. This eliminates duplication of ROV system within a contractor's tool pool. Fixed ROV system does not offer the above advantages and will be under utilized if the DSV is not operating on driverless mode. Concept C has a similar arrangement with Concept B but the later has more deck space than Concept C.

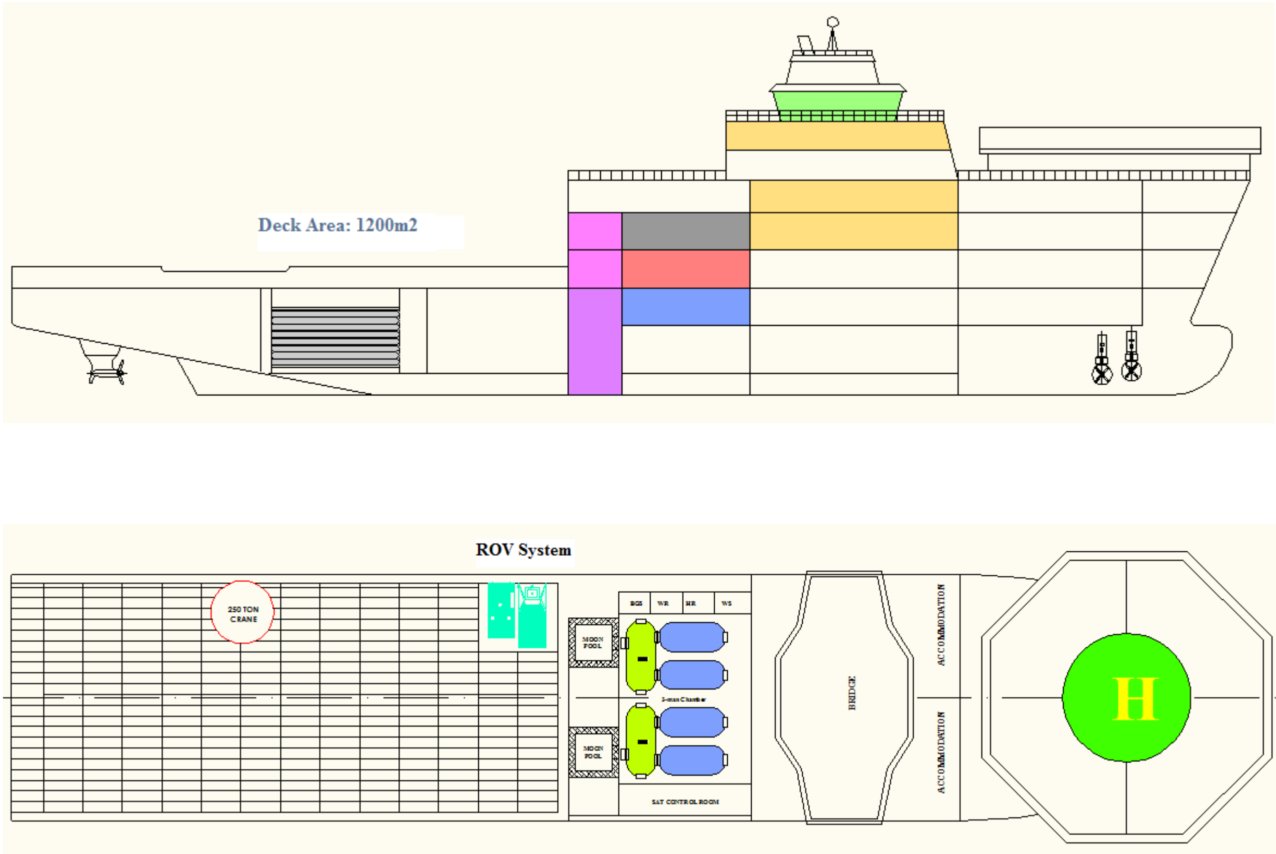


Figure 37 Profile and combination of main deck and plan views for concept C

3.11 Stability Estimation

A detailed stability analysis was not done in this study but a preliminary stability check has been carried out for the intact stability of the respective concepts. The centre of buoyancy above the keel and the metacentric height was estimated for the selected hull form using the following empirical relations obtained from Levander (2004).

$$KB = T \times \left(\frac{5}{6} - \frac{1}{3} \times \frac{C_B}{C_W} \right)$$

$$BM = \frac{I_T}{\nabla} = \left[0.0372 \times (2 \times C_W + 1)^3 \times L \times B^3 / 12 \right] / \nabla$$

$$KM = KB + BM$$

$$GM = KM - KG$$

Table 13 Initial stability

PRELIMINARY STABILITY ESTIMATE			Concept A		Concept B		Concept C	
LIGHT WEIGHT	**weight**	**Centre of gravity**		**Moment**				
Weight Group:	**[ton]**	**KG/D**	**KG [m]**	**[t.m]**	**KG [m]**	**[t.m]**	**KG [m]**	**[t.m]**
Payload related:								
Deck Cranes	250.00	2.20	22.00	5500.00	22.00	5500.00	22.00	5500.00
Additional Crane	0.00	0.00		0.00		0.00		0.00
Helideck & Structure	44.50	2.08	20.80	925.60	20.80	925.60	20.80	925.60
Hatches	30.00	0.34	3.40	102.00	3.40	102.00	3.40	102.00
SAT Diving System	466.66	1.00	10.00	4666.57	10.00	4666.57	10.00	4666.57
Air Diving System	50.00	1.80	18.00	900.00	-	-	18.00	900.00
ROV System	52.00	1.79	17.90	930.80	-	-	-	-
Hull and Forcastle	1755.76	1.28	12.80	22473.73	12.80	22034.43	12.80	22175.74
Deckhouse, Casing & Funnel	520.35	2.21	22.10	11499.74	22.10	11493.11	22.10	11599.19
Interior Outfitting	607.81	1.85	18.50	11244.53	18.50	11244.53	18.50	11244.53
Machinery	948.00	0.34	3.40	3223.20	3.40	3223.20	3.40	3223.20
Ship Outfitting	258.83	1.00	10.00	2588.33	10.00	2553.48	10.00	2566.46
Total	4983.91	1.29	12.85	64054.49	12.75	61742.92	12.81	62903.28
Reserve	249.20	0.75	7.50	1868.97	7.50	1816.43	7.50	1841.60
LIGHT WEIGHT	**5233.11**	**1.26**	**12.60**	**65923.45**	**12.50**	**63559.35**	**12.56**	**64744.89**
DEAD WEIGHT	**weight**	**Centre of gravity**		**Moment**				
Weight Group:	**[ton]**	**KG/D**	**KG [m]**	**[t.m]**	**KG [m]**	**[t.m]**	**KG [m]**	**[t.m]**
Deck Cargo	3000.00	1.20	12.00	36000.00	12.00	36000.00	12.00	36000.00
Helicopter	0.00	0.00		0.00	0.00	0.00	0.00	0.00
Crew & Diving Personnel	12.00	2.21	22.10	265.20	22.10	265.20	22.10	265.20
Provision & Stores	48.00	1.77	17.70	849.60	17.70	849.60	17.70	849.60
Fuel Oil	1440.29	0.46	4.60	6625.32	4.60	6625.32	4.60	6625.32
Lubrication Oil	48.69	0.40	4.00	194.76	4.00	194.76	4.00	194.76
Fresh Water	1209.60	0.46	4.60	5564.16	4.60	5564.16	4.60	5564.16
Sewage Sludge	10.00	0.10	1.00	10.00	1.00	10.00	1.00	10.00
Ballast Water for Stability	25.63	0.10	1.00	25.63	1.00	25.63	1.00	25.63
BW for Anti-heeling & Trimming	1025.00	0.10	1.00	1025.00	1.00	768.75	1.00	1025.00
Total	6809.20	0.74	7.43	50559.67	7.39	50303.42	7.43	50559.67
Miscellaneous	340.46	0.40	4.00	1361.84	4.00	1361.84	4.00	1361.84
DEAD WEIGHT	**7149.66**	**0.73**	**7.26**	**51921.51**	**7.23**	**51665.26**	**7.26**	**51921.51**
LIGHT WEIGHT + DEAD WEIGHT			**9.52**		**9.42**		**9.48**	

Table 14 Summary of stability estimates

Parameter		unit	Design Concepts A	B	C
Centre of gravity	KG	m	9.52	9.42	9.48
Centre of Buoyancy	KB	m	3.94	3.96	3.95
Transverse Metacentre	BM	m	6.65	6.68	6.66
Metacentre above keel	KM	m	10.59	10.64	10.61
Initial Stability	GM_T	m	1.07	1.22	1.13

The initial stability estimate is within acceptable GM limitation (GM_T=1.0) for a diving support vessel and Levander (2004) suggests a GM_T range of 0.3-1.0.

4.0 EVALUATION OF DESIGN CONCEPTS

4.1 Evaluation Method

The evaluation method used in this work is the Analytic Hierarchy Process (AHP). The AHP has been used in many multi-objective decision problems, in engineering design, purchasing, transport systems, selection of suppliers for contract awards etc, to resolve differing objectives in the selection or evaluation process and it involves pairwise comparison of the attributes or performance criteria. The design concepts will be evaluated using the following key performance indicators (KPIs): operational flexibility, costs, sustainability, operational efficiency and cargo volume. These KPIs will be ranked based on the priority matrix in Table 15.

Table 15 Priority Matrix

INTENSITY OF IMPORTANCE	DEFINITION
1	Equal Importance
3	Moderate Importance
5	Strong Importance
7	Very Strong Importance
9	Extreme Importance
Note: Intensities of 2, 4, 6, & 8 can be used to express intermediate values	

4.1 Evaluation Criteria

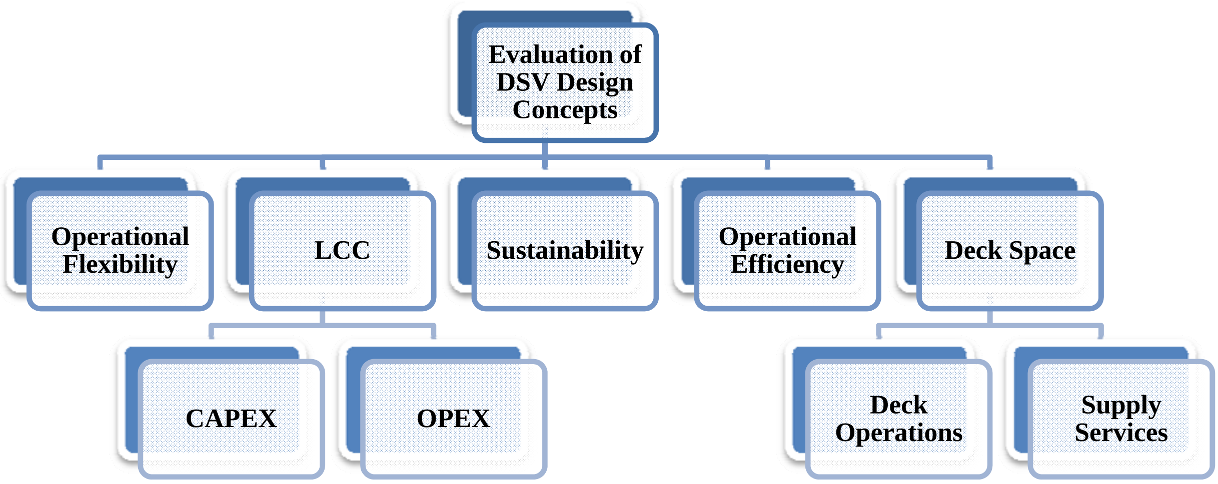


Figure 38 Objective hierarchy for the evaluation of DSV design concepts

In the objective hierarchy above, operational flexibility is imperative because it is the bedrock of the design problem, and compares the degree of flexibility in the respective concepts. Another factor is cost; a design must be cost efficient and initial decisions during conceptual design phase affect operating cost, which has great influence on lifecycle cost. Sustainability is important because of stricter emission regulations in one of the intended areas of operation (North Seas) and it comes with additional costs for emission control systems or emission tax. The way the DSV operates will affect its lifecycle emission footprint; a sustainable operation seeks to reduce the emission footprint of the vessel but frequent calls of the DSV at port and at high speed will increase the emission footprint. Also, any operation that impacts negatively on operating cost cannot be sustainable. Operational efficiency is another vital performance criterion because of the increasing demands by offshore operators to extend operation window by pushing vessel owners to improve on the stages in the operational profile. This comes with additional costs, but remains the essence of building a purpose built DSV. Finally, deck space is of interest for the DSV; even though the design concepts have the same initial cargo carrying capacity, their cargo volume is not the same but a function of deck space.

The highlighted five attributes will then be developed for the evaluation of the three design concepts. It would have been proper to develop a questionnaire for the ranking of the attributes for the respective designs but time constraint in administering it and getting responses from diving contractors was a major constraint. Therefore, I have elucidated the strengths and weaknesses of each design and ranked them accordingly.

4.2.3 Operational Flexibility

Operational flexibility depicts the ability of the various design concepts to switch roles and adapt to a different operational profile other than the customised one. Although, SAT diving is the core mission of the design concepts, they can switch roles to carry out a variety of services either in stand alone or combination of operations as supply and ROV vessels. They can also provide accommodation support. However, concept B which has ROV equipment and air diving system in standard container modules will have a higher degree of flexibility compared to concepts A and C while the duo will have approximately the same degree of flexibility.

4.2.4 Lifecycle Cost

The cost of the purpose-built DSV is in two segments, which are the vessel's costs and the costs of mission equipment. These costs are further divided into capital and operational expenditures as shown in Figure 39. The costs breakdown structure captures each element of the lifecycle cost, excluding dry-dockings and end of life disposal costs. Costs estimation for the purpose-built DSV could be a complex exercise because lots of cost and non-cost variables come into play. However, the core costs elements comprising CAPEX and OPEX of the vessel and that of the mission equipment are estimated in this work. The OPEX for both the vessel and mission equipment are based on the assumed operational profile. A sensitivity analysis will be done later in this chapter to examine the effect of changes in some assumed variables on the design concepts.

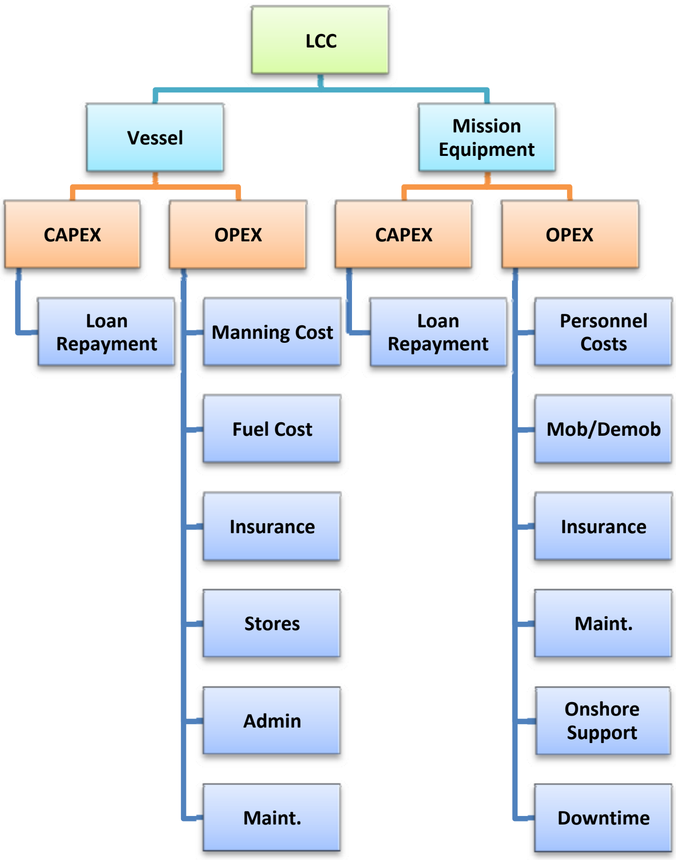


Figure 39 Costs breakdown structure for a purpose built DSV

4.2.4.1 Capital Expenditure (CAPEX) of Vessel

The accurate breakdown of costs estimate of building a ship is difficult to come by because most shipyards find it difficult to divulge costs related information that could make them vulnerable to their competitors. This matter is made worse by the complexities in shipbuilding value chain involving the ship designers, shipyards, equipment manufacturers, suppliers and subcontractors whereby each of the actors in the ship design process may not be able disclose the costs of materials and services they have supplied. In this regards, it becomes difficult to keep accurate records of CAPEX of ship. However, Levander (2004) presents an approach that makes use of system-based description and weight data in the estimation of building cost of a prototype vessel based on shipyard practice. The major shortcoming of this method is that there is no defined procedure to revalidate the cost coefficients to reflect continuous changes in ship building costs. Also, the machinery system may not have taken care of the high level of system redundancy required for a DP-3 vessel and the installation of helideck and heave compensated crane may not have been envisaged. In recognition of the above stated facts, an inflation margin of 70% is added on materials' costs to account for inflations that had occurred since the publication of the compendium in 2004. Also, the CAPEX of the helideck and 250ton heave compensated crane are determined and added to the CAPEX of the vessel. A Norwegian helideck manufacturer, Maritime Product AS provided the costs of helideck and structure while the costs of the heave compensated crane was obtained from maritime journal. The financing of the vessel and the mission equipment is based on loans with 15 years repayment plan.

Table 16 Summary of Vessel's costs for the respective design concepts

		Concept A		Concept B		Concept C	
COST SUMMARY		**Price MNOK**	**Price NOK/kg**	**Price MNOK**	**Price NOK/kg**	**Price MNOK**	**Price NOK/kg**
Design		18.32	3.50	17.80	3.50	18.05	3.50
Labour + Overhead		92.07	17.59	91.28	17.95	91.68	17.78
Material		262.61	50.18	260.97	51.31	261.67	50.75
Subtotal		372.99		370.05		371.40	
Building time financing (interest x time/2)		27.97	5.35	27.75	5.46	27.85	5.40
Total Production Cost		**400.97**	**76.62**	**397.81**	**78.22**	**399.25**	**77.43**
Profit	8%	32.08		31.82		31.94	
Financing, Payment	3%	12.03		11.93		11.98	
Broker fees	1%	4.01		3.98		3.99	
Building Price [MNOK]	**CAPEX of Vessel**	**449.03**	**86**	**445.54**	**88**	**447.16**	**87**
	CAPEX of Helideck	**3.94**		**3.94**		**3.94**	
	CAPEX of Crane	**78.81**		**78.81**		**78.81**	
	Cost	**531.78**		**528.29**		**529.91**	
	Cost/DWT	**77441**	NOK/ton	**76719**	NOK/ton	**76955**	NOK/ton
	Cost/GT	**52629**	NOK/GT	**52964**	NOK/GT	**52858**	NOK/GT
Building Price [M$]	**CAPEX of Vessel**	**75.85**	**14**	**75.26**	**15**	**75.53**	**15**
	CAPEX of Helideck	**0.67**		**0.67**		**0.67**	
	CAPEX of Crane	**13.31**		**13.31**		**13.31**	
	Cost	**89.83**		**89.24**		**89.51**	
	Cost/DWT	**13081**	$/ton	**12959**	$/ton	**12999**	$/ton
	Cost/GT	**8890**	$/GT	**8947**	$/GT	**8929**	$/GT

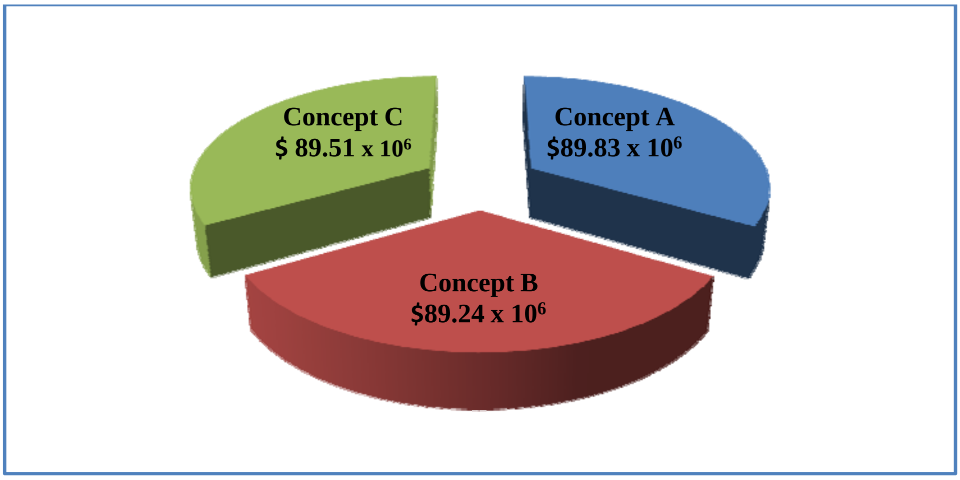


Figure 40 Building price distribution

From the summary of the CAPEX of the respective design concepts in Table 16 and the building price distribution in Figure 40, we observe that the building price of Concept A is greater than that of concepts B and C while concept C is more expensive than concept B. The difference in CAPEX is somewhat significant; by implementing concept B and C rather than concept A we save MNOK3.54 (million$0.6) and 1.92MNOK (million$0.32) respectively. The difference in lightweight, gross volume and internal areas are responsible for the costs variations. The hull steel weight for concept A will reduce in the course of implementation of the modular design for topside SAT diving system but the overall CAPEX for this concept could still be high due to the significant number of standard container modules required, coupled with the additional cost for the design of container interface panels with the DSV. Details of the CAPEX estimation for the vessel are provided in Appendix V and the CAPEX are taken as loan with a repayment plan of 15 years and furnished in Appendix VIII and it will be included in annual operating costs until it is liquidated.

4.2.4.2 Operational Expenditure (OPEX) of Vessel

The OPEX is simply the sum of the individual cost elements required for the daily operation of the DSV, which include manning, fuel, administration, insurance, stores, and maintenance. These costs are taken as a certain percentage of the CAPEX for the three concepts except fuel, and manning costs. The costs of fuel depends on the assumed operation profile while manning cost is obtained from the book "Multipurpose Vessels Market Review and Forecast, 2009" for an offshore support vessel with some margins added to account for the cost of additional personnel required for the catering crew. The insurance, maintenance, stores and supplies and administration costs are taken as: 1%, 1.1%, 1.2% and 0.8% of CAPEX respectively while the fuel cost is based on consumption at three operating modes which include transit, DP and mob/demob (port).

$$F_{act} = F_{Transit} + F_{DP} + F_{\text{Port}} \, [ton]$$

$$F_{act} = P \times \left[\frac{V_s}{V_d}\right]^{\beta} \times sfc \times time + [P \times sfc \times time]_{DP} + [[P \times sfc \times time]_{MCR} + [P \times sfc \times time]_{AUX}]_{port}$$

$$C_{fuel} = F_{act} \times p_{fuel} \left[\frac{\$}{\text{year}}\right]$$

Where:

C_{fuel}: cost of fuel

F_{act}: actual fuel consumption $\left[\frac{tons}{annum}\right]$

P: Power $[kW]$

V_s: sailing speed $[knots]$

V_d: design speed $[knots]$

p_{fuel} : price of fuel $\left[\frac{\$}{\text{ton}}\right]$

$time$: operating days

β: is an exponent taken as 3 for desiel engines

Table 17 Estimate of fuel cost

Operation Profile	Operation (Days)	Required Power [kW]	sfc [kW/kg-h]	Variables	Values
Transit (@ service speed of 12knots	31	5400	180	V_s [knots]	12
DP	284	4800	190	V_d [knots]	15
Mob/Demob (Port)	29	20% MCR + 80% AUX	190, 205	Beta [-]	3
Drydocking/Maintenance	21	Shoreside power supply		Fuel Price [$/ton]	600
Total Operation Days	365		F_{act} =	7074	tons/annum
Fuel Costs			C_{fuel} =	4.2	million $/annum

The fuel and manning costs are assumed to be the same for the designs but in actual operational condition, there would be differences in fuel consumption.

Table 18 Breakdown of vessel's operating cost

OPEX-Vessel	Concept A $/annum	Concept B $/annum	Concept C $/annum
Manning	890600.00	890600.00	890600.00
Stores	1077935.22	1070855.85	1074138.66
Maintenance	988107.29	981617.87	984627.10
Administration	718623.48	713903.90	716092.44
Fuel	4244693.53	4244693.53	4244693.53
Insurance	898279.35	892379.88	895115.55
Total	**8818239**	**8794051**	**8805267**

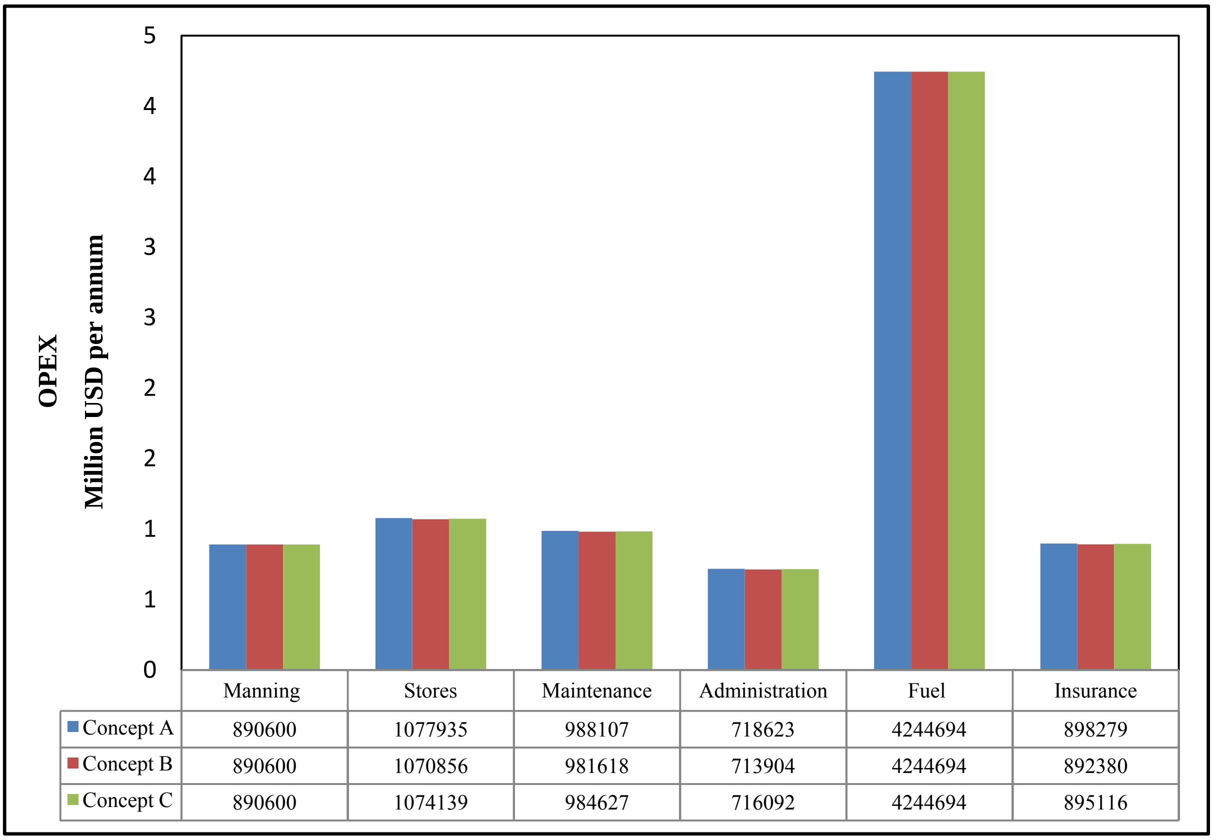


Figure 41 Ideal operating expenditures of the design concepts without mission equipment

Assuming an ideal situation, we see from Table 18 that it will cost more to operate concept A which has a modular top side SAT diving system with ROV and air diving system integrated in the vessel. The cost difference at this stage, is attributed to the influence of the vessel's CAPEX on stores and supplies, maintenance, administration and insurance. From Figure 41, we observe that the greatest operating cost of the vessels is the fuel cost, which is a function of the operational profile, speed and fuel price. This is followed by stores and supplies which take care of lubricating oil, provisions and spare parts. The administration cost is the least and accounts for money spent on surveys, renewal of operational permits and sundry expenses.

4.2.4.3 CAPEX of Mission Equipment

The costs of the diving systems which are the core mission equipment of the DSV are the same for the three concepts but their operating costs will differ greatly. The assistance of one of the world's leading manufacturers of SAT diving systems "Drass Galeazzi Underwater Technology" and a diving company "Tethys Plantgeria Ltd" were sought to obtain the current market value of the diving systems. Details of the capital expenditures of the mission equipment are furnished in Table 19 below.

Table 19 Costs estimate of Mission Equipment

DIVING SYSTEMS	**Qty**	**€**	**Unit Price [$]**	**Total [$] x$10^6$**
24-Man Saturation Diving System	1 set	27400000	36474606.00	36.47
Design & Engineering				
Hyperbaric Chambers				
Bells & Bell Handling System				
Control Panels				
Gas System				
Ancillary Equipment				
Installation & Commissioning				
Hyperbaric Lifeboat	2 sets	6300000	8386497.00	8.39
Additional Equipment	1 set	1100000	1464309.00	1.46
Life Support System				
Set of Critical Spare Parts + 2 yrs Operation				
Integrated Logistic Support Software				
Costs of SAT Diving System				**46.33**
Air Diving System/NDT Equipment	1 set	800000	1064952.00	**1.06**
Plant Equipment	1 set	400000	532476.00	**0.53**
ROV SYSTEM	**Qty**	**£**	**Unit Price [$]**	**Total [$] x$10^6$**
Inspection/Survey Class ROV System	2	128750	197336.41	0.39
Tether Management System (TMS)	1	55105	84459.98	0.08
Lunching & Recovery System (LARS)	1	98000	150205.58	0.15
Armoured main lift umbilical cable	2500	31	47.51	0.12
Anciliary System	Aggregate	226157.53	346633.91	0.35
Work Class ROV/Systems (complete Pkg)	1		2166666.00	2.17
Sub-total				**3.26**
10 % Inflation				**0.33**
20% margin for spare parts				**0.65**
Costs of ROV System				**4.24**
Total Costs of Mission Equipment	**Fifty One Million and Sixty Three Thousand Dollars**			**52.16**

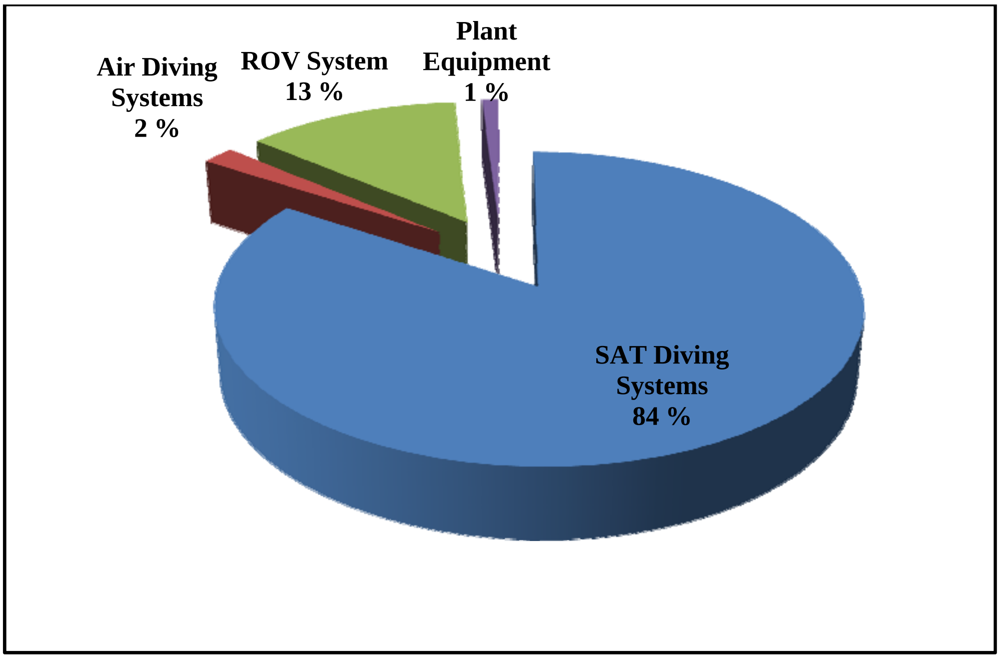


Figure 42 Percentage distribution of Costs of Mission Equipment

The SAT diving system is worth 46.3 million dollars representing 84% of the costs of mission equipment as shown in Figure 42 and it remains the single most expensive payload system of the DSV. This is because the system in this study is designed for 24 divers in saturation and the requirements for split level diving which involves using two diving bells simultaneously while working at different depths and also system redundancy in line with NORSOK U100 contribute to increase in cost of the SAT diving system. The cost would certainly reduce in SAT diving system designed for few divers for instance 6-18man system. The ROV system, comprising one work class and two observation/inspection class ROVs are estimated at 4.24 million dollars representing 13% of the costs of mission equipment while the air diving system and plant equipment which includes welding machines, hydro-blasting equipment, pumping machines etc are the least payload system and account for 2% and 1% of the costs of mission equipment respectively.

4.2.4.4 Non-Vessel OPEX

The non-vessel operating costs of the DSV are huge. They include personnel, mob/demob, insurance, maintenance, onshore support, and downtime costs. There is no direct method of estimating the cost of onshore support, downtime, and mob/demob but since concepts B and C will require their flexible mission equipment to be taken to port and back ashore during each mob/demob period; their mob/demob cost will be greater. Therefore, the estimation of non-vessel OPEX will be based on the following assumptions:

1. The insurance and maintenance costs are 1% and 1.1% of the CAPEX of mission equipment respectively and 15 years repayment plan is adopted for the mission equipment.

2. Concept A will carry the personnel cost of ROV and air diving system during its lifetime.

3. There is an annual fixed cost of USD200000 for mob/demob for personnel and materials for offshore support for the three concepts.

4. The flexible mission equipment of concepts A and B are taken to contractor's onshore base during demob and back to the port at mobilization period.

5. The transport distance by road is 50 kilometres and the cost is $2.0 per ton-km and would be based on the weight of the mission equipment transported.

6. The cost of haulage is cheaper than using a support base for stacking of flexible mission equipment.

7. The absence of any of the mission equipment during unscheduled intervention leads to downtime.

8. There is a downtime cost equivalent to the cost of 20,000 barrels of crude oil per day @ $70 per barrel when the DSV is not on position working and the sailing days per leg (3.5 days) is used as the number of days affected per annum.

9. The number of scheduled mob/demob per annum is taken as 6

The estimate of non-vessel personnel costs was done using cost data from "Oceaneering". The costs of SAT diving operation could be high but it is assumed that all personnel work on contract basis; and that there is no permanent SAT diver, air diver and ROV employees rather personnel are sourced from the labour market and engaged for the predicted effective working period and this is the practice in the industry as at today. Although, the vessels will be on DP for 284 days in a year, it will not be carrying out one kind of service but varieties of services that span 284 days including the time spent waiting on weather (WOW). Therefore, the personnel cost estimation is based on the assumption that effective working period for all personnel is 180 days per annum. This implies that when only SAT diving is going on, there will not be any ROV and air divers onboard and vice versa aside from concept A which carries the personnel cost of both ROV and air diving personnel for the number of days on DP and concept C which will also carry the personnel cost of air diving personnel. For a long duration contract, the personnel cost attracts some discounts but these were not considered in the analysis.

Table 20 SAT diving personnel costs

SAT Diving Personnel	24-hr Team	No of Teams	Day rate ($)	Costs ($/Day)	Costs ($/Annum)
Saturation Superintendent	2	1	2495.00	4990.00	898200
Life Support Supervisor	2	1	2252.00	4504.00	810720
Saturation Technician	2	1	1252.00	2504.00	450720
Life Support Technician	2	1	1188.00	2376.00	427680
Saturation Diver per 24 hr. Day	3	8	3664.00	87936.00	15828480
Diver/Tender	2	1	704.00	1408.00	253440
Tender	2	1	582.00	1164.00	209520
Total				**104882**	**18878760**

Table 21 Air diving and NDT personnel costs

					Concepts A & C	Concept B
Air Diving & NDT Personnel	**No. of Personnel**	**No of Teams**	**Day rate ($)**	**Costs ($/Day)**	**Costs ($/Annum)**	**Costs ($/Annum)**
Superintendent	1	1	2078	2078.00	590152	374040
Non-Diving Supervisor	1	1	1426	1426.00	404984	256680
Diving Supervisor	2	1	1488	2976.00	845184	535680
Diver	4	1	1200	4800.00	1363200	864000
Air Diving Operator	2	1	1434	2868.00	814512	516240
Air Diving Technician	2	1	1434	2868.00	814512	516240
Diver / Tender	2	1	974	1948.00	553232	350640
NDT Inspection Diver	4	1	1175	4700.00	1334800	846000
Underwater Welder / Diver	4	1	1409	5636.00	1600624	1014480
Total				**29300**	**8321200**	**5274000**

Table 22 ROV personnel costs

					Concept A	Concepts B & C
ROV Personnel	**24-hr Team**	**No of Teams**	**Day rate ($)**	**Costs ($/Day)**	**Costs ($/Annum)**	**Costs ($/Annum)**
Superintendent	2	1	2535	5071	1440153	912773
Supervisor	2	1	2383	4767	1353743	858006
Pilot/Technician	2	1	2214	4429	1257733	797155
Total				**14266**	**4051629**	**2567934**

Table 23 Additional personnel costs

Additional Personnel	No. of Personnel		Day rate ($)	Costs ($/Day)	Costs ($/Annum)
Project Manager	1		2303	2303.00	414540
Data Engineer	1		900	900.00	162000
Crane Operator / Rigging Supervisor	2		974	1948.00	350640
Rigger / Labourer	2		704	1408.00	253440
Total				**6559**	**1180620**

Table 24 Summary of Non-Vessel OPEX

Non-Vessel OPEX	Concept A $/annum	Concept B $/annum	Concept C $/annum
SAT Diving Personnel	18878760	18878760	18878760
ROV Personnel	4051629	2567934	2567934
Air Diving & NDT	8321200	5274000	8321200
Additional Personnel	1180620	1180620	1180620
Maintenance	521627	521627	521627
Insurance	573790	573790	573790
Onshore Support	250000	265000	263000
Mob/Demob	200000	261200	231200
Downtime	0	4900000	4900000
Total	**33977626**	**34422930**	**37438130**

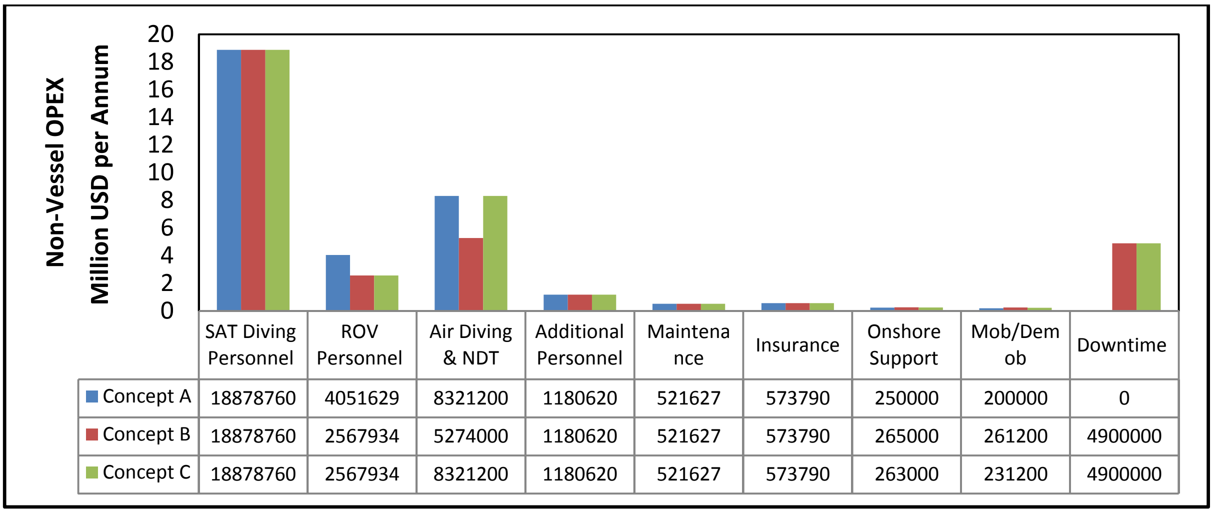


Figure 43 Percentage distribution of non-vessel OPEX

From Table 24 and Figure 43, we see that SAT diving personnel cost is the greatest cost contributor of the non-vessel OPEX and it is assumed to be the same for the design concepts. However, Concept A is assumed to carry the operating costs of the ROV and air diving system, and spot market opportunities are lost on the one hand. On the other hand, concepts B and C provide for spot market opportunities for combination of air diving and ROV systems and only ROV system respectively but have great penalty attached to downtime and emission when the systems are not onboard and a supply vessel is hired to convey them to offshore location. In addition to downtime cost, concept C carries the personnel cost of air diving personnel.

Table 25 Summary of lifecycle cost analysis

	Concept A	Concept B	Concept C
Vessel			
Loan Repayment [$/annum]	9248933	9188190	9216357
OPEX [$/annum]	8818239	8794051	8805267
Sub-Total [$/annum]	**18067171**	**17982241**	**18021624**
Mission Equipment			
Loan Repayment [$/annum]	5370815	5370815	5370815
OPEX [$/annum]	33977626	34422930	37438130
Sub-Total [$/annum]	**39348440**	**39793745**	**42808945**
Total [$/annum]	**57415612**	**57775986**	**60830570**
Expenses for first 15 years [$]	861234177	866639792	912458544
OPEX [Vessel + Mission Equipment]	42795865	43216981	46243398
Expenses for last 15 years [$]	641937968	648254722	693650966
LCC [$]	**1503172144**	**1514894514**	**1606109509**
Discount rate	10%	10%	10%
Lifetime [years]	30	30	30
NPV [$]	**-14 170 275 234**	**-14 280 781 013**	**-15 140 656 970**

From Table 25, we see that concept A has the least negative net present value and the minimum LCC compared to the other two concepts followed by concept B. The assumptions made on downtime cost and extra personnel charge for air diving and ROV systems could have significant impact on the end result but the issue of downtime cost is critical on decisions about design and investment on offshore support systems, and cannot be ignored.

4.2.5 Sustainability

Sustainability in the context of this work deals with lifecycle emission footprint of each design concept and the associated emission costs. More money will be spent on mob & demob for transporting the ROV and air diving systems to and from the port. Looking into the future, the shifting of oil and gas production to deep offshore will increase voyage distance and in such circumstance vessel operators would want to increase speed to reduce the transit time but this will increase emission rate compared to sailing at the service speed or slow steaming. The design concept A with all the mission equipment onboard will sustain operation for a longer time moving from one offshore platform to another and will have reduced emission associated with transit for mob/demob while the emission footprint of concept B will be higher followed by concept C. Although Concept A carries personnel cost of both ROV and air diving system when they are not in use due to uncertainties in operation, the costs of downtime is great on concepts B and C and increases their operating cost hence concept A will be more sustainable based on LCC.

4.2.6 Operational Efficiency

This includes how fast the DSV can be mobilized for an offshore project and demobilized, capability to support offshore operations in extreme environmental condition and attend to emergency situations that could lead to downtime. With respect to the aforementioned facts, efficiency of the DSV is of utmost priority and cannot be compromised for any other KPI. The efficiency in mob/demob operations will differ for the three design concepts; the DSV with all mission equipment onboard can be quickly mobilized and demobilized while those that require the mission equipment to be craned on and off the vessel will spend more time in port. Concept A will have a higher efficiency in mob/demob when there is the need to mobilize the ROV and air diving system for offshore operations and the time to load and align the standard container modules on the deck attracts additional costs. This will be followed by concept C then concept B. In terms of supporting offshore operation in extreme environmental condition the three concepts are assumed to have equal capabilities but in emergency situation when driverless operation need to be carried out in the unpredicted environment of the North Seas and Concepts B and C for want of deck space have been mobilized without the ROV system and on the basis that scheduled operation is just for SAT diving alone then concept A stands out as the best option.

4.2.7 Deck Space

The three concepts have been designed to carry 3000 tons of cargo each but their cargo deck space differs. In SAT diving operation alone, the deck space of concept B will be more than that of concepts A and C while the deck space of concept C will be greater than that of concept A. But in combination of air diving and ROV operation, the deck space of concept A will be the greatest when its flexible part is removed followed by concept B then concept C. Also, in the event of long time supply services concept A will carry more cargo and has advantage of increasing its cargo capacity up to the equivalent of the capacity of top side module of the SAT system. This will be followed by concept B then concept C.

Table 26 Ranking of attributes

Main Evaluation Criteria Analysis					
	Op. Flexibility	**Costs**	**Sustainability**	**Op. Efficiency**	**Deck Space**
Op. Flexibility	1	1	3	0.333333333	3
Costs	1	1	3	0.333333333	5
Sustainability	0.333333333	0.333333333	3	3	0.333333333
Op. Efficiency	3	3	0.333333333	1	2
Deck Space	0.333333333	0.2	3	0.5	1
	5.666666667	**5.533333333**	**12.33333333**	**5.166666667**	**11.33333333**

Attributes	Op. Flexibility	Costs	Sustainability	Op. Efficiency	Deck Space	Average
Op. Flexibility	0.176470588	0.180722892	0.243243243	0.064516129	0.264705882	**0.19**
Costs	0.176470588	0.180722892	0.243243243	0.064516129	0.441176471	**0.22**
Sustainability	0.058823529	0.060240964	0.243243243	0.580645161	0.029411765	**0.19**
Op. Efficiency	0.529411765	0.542168675	0.027027027	0.193548387	0.176470588	**0.29**
Deck Space	0.058823529	0.036144578	0.243243243	0.096774194	0.088235294	**0.10**

The outcome of the ranking for the attributes of the designs in Table 26 shows that operational efficiency has the highest performance metrics of 29%. In spite of the fact that we want to integrate flexibility in the design of the purpose built DSVs, efficiency must not be compromised and this could be the reason why these vessels are very expensive to build.

Table 27 Result of the Evaluation

Design Alternatives	Op. Flexibility	LCC		Sustainability	Op. Efficiency	Deck Space		Total
		CAPEX	OPEX			Deck Ops	Supply Serv.	Weight
Concept A	0.04	0.01	0.11	0.12	0.21	0.02	0.03	**0.54**
Concept B	0.11	0.04	0.05	0.02	0.02	0.02	0.01	**0.27**
Concept C	0.04	0.01	0.01	0.05	0.06	0.01	0.01	**0.18**
				1.00				**1.00**

The evaluation result in Table 27 above shows that concept A has a weight of 54% and could be a better alternative if implemented. Concept B is fairly better than concept C with a weight of 27% while concept C has a weight of 18%. The detailed analysis is in appendix vii.

4.3 Sensitivity Analysis

In the evaluation of the designs in section 4.2, a number of assumptions were made to determine the LCC and NPV, which are the cost decision criteria. It is therefore imperative to consider the uncertainties in some assumed parameters when varied, could affect the outcome of the final solution regarding cost. The main economic variables are downtime, fuel price and discount rates. With respect to the LCC in function of downtime in Figure 44 below, we note that in the absence of downtime and as it increases to about 3 days, concept B will have a lower LCC compared to concepts A and C. Similarly, in just a day's downtime, the LCC of concept C will be less than that of concept A, but as the downtime increases up to 3.3 days, the LCC of concept A begins to decrease more than concept B and much more cost effective than concept C, irrespective of the additional personnel costs for unused number of days of air diving and ROV systems per annum.

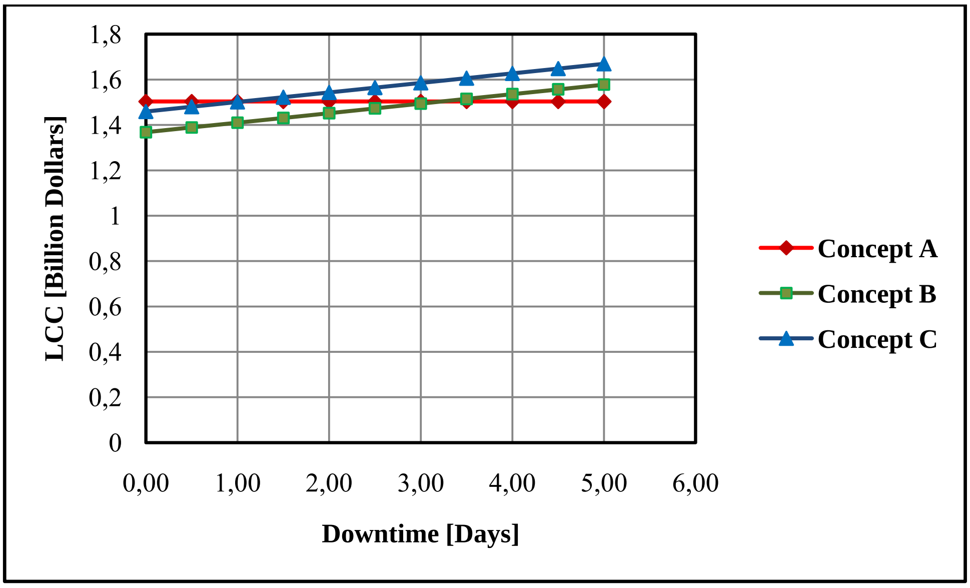


Figure 44 Lifecycle Cost in function of downtime

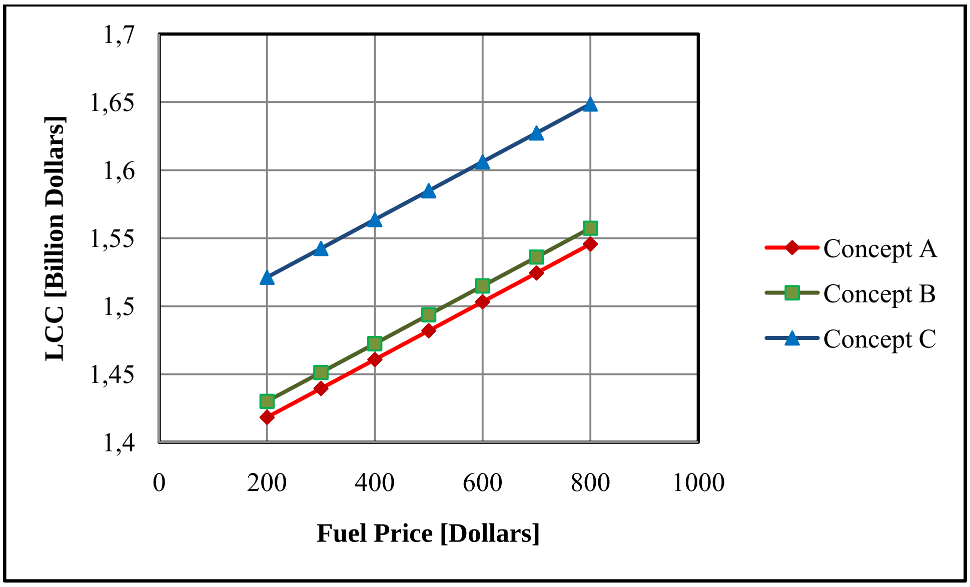


Figure 45 LCC in function of fuel price

Another economic variable that influences the LCC is the fuel price. As shown in Figure 45, LCC will increase for the three concepts as fuel price increases but concept C will be very expensive to operate at both low and high fuel price in comparison with the other two concepts.

The NPV was originally estimated using 10% discount rate but varying the discount rate as shown in Figure 46, indicates that the three concepts compete fairly as the discount rate increases to 20% and beyond in the midst of downtime cost on the one hand. On the other hand, as the discount rate increases in Figure 47 in the absence of downtime cost, the NPV of Concept B is the least negative compared to concepts A and C. In this circumstance, concept B will be more profitable.

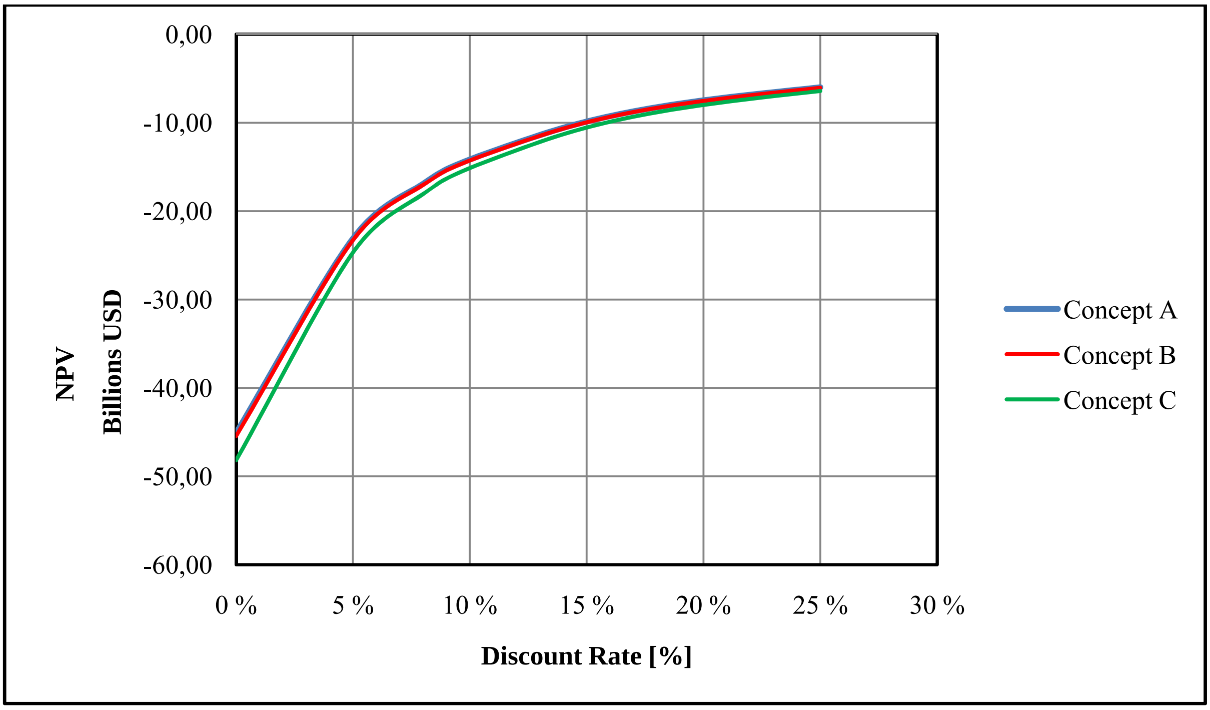


Figure 46 NPV in function of discount rate when downtime cost is in LCC

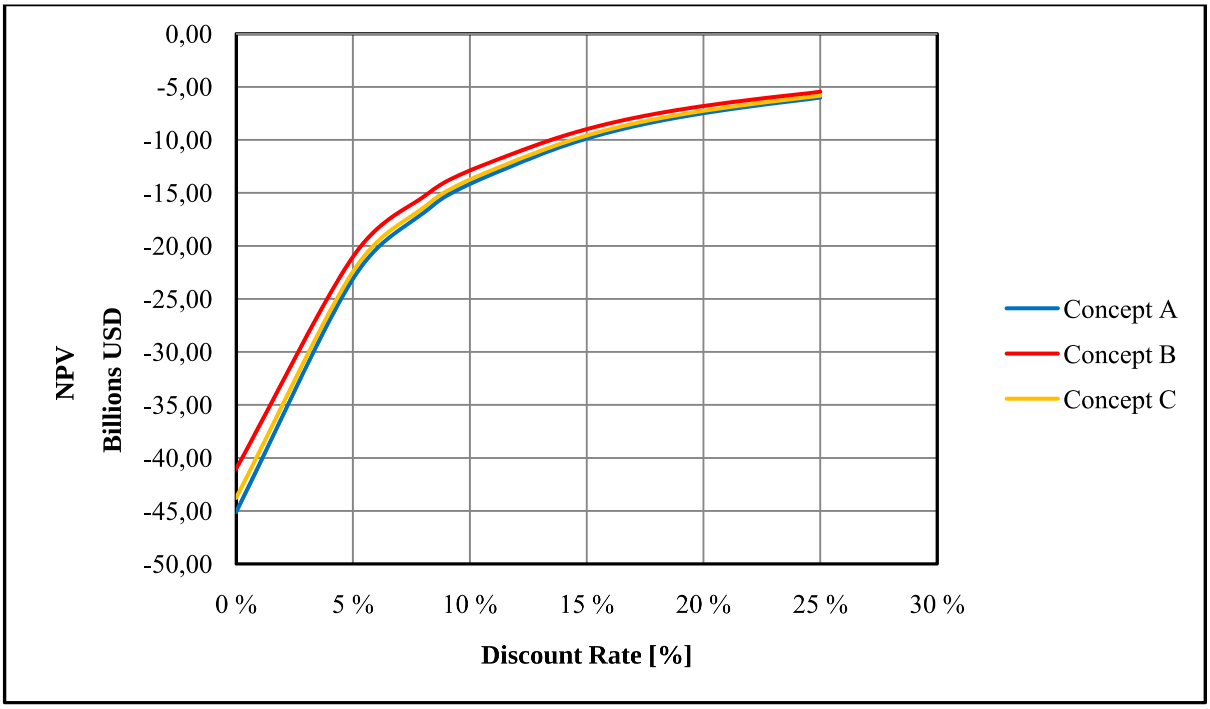


Figure 47 NPV in function of discount rate when there is no downtime cost in LCC

5.0 DISCUSSIONS AND CONCLUSION

5.1 Discussions

Since the emergence of the purpose built DSV in the early 70's, its design has undergone different transformations to meet the needs of the offshore industry. The design has been strengthened by class regulations, standards, operational area and market requirements. The initial problem was that of operational efficiency which deals with but not limited to position keeping in extreme environmental conditions and cargo handling capability. Today, the problem of operational efficiency has been overcome but with huge impact on LCC. This is because in addition to increase in size of the DSV, the position keeping systems and cargo handling capability have been improved at added costs. In the quest for further operational efficiency improvement, the main mission equipment is now integrated in DSV designs making it increasingly complex and this has engendered the problems of flexibility and sustainability.

To resolve these two problems without undermining operational efficiency and LCC, three design concepts (concepts A, B and C) that focused on arrangement of the mission equipment of the DSVs were proposed and developed, using system based design approach, class regulations and design standards for North Seas operations, with the assumption that any DSV capable of operating in the North Seas can conveniently operate in West African region. Five key performance indicators comprising flexibility, operational efficiency, lifecycle cost, sustainability and cargo deck space were developed for the evaluation of the designs. Amongst these criteria, LCC required numerical estimation of capital expenditure for the vessel and the mission equipment as well as their operating expenditures. On the average, the CAPEX estimation for both the DSV and the mission equipment is valued at about one hundred and forty two million dollars ($142 million) with mission equipment taking up 36.7% of the CAPEX. The estimation of the OPEX shows that because of their high day rate, the personnel cost for SAT diving personnel was the greatest costs contributor when operating the DSV in SAT diving mode.

The designs were then evaluated using the analytic hierarchy process based on the five key performance indicators mentioned above. The evaluation result shows that concept A with top side modular design for SAT diving system would be flexible and sustainable to operate while maintaining operational efficiency and reduced LCC compared to concepts B and C that have either ROV equipment and air diving system or only ROV equipment in modules respectively. The assumptions about downtime costs in the absence of any of the mission equipment in unscheduled intervention contributed in boosting the performance metrics of concept A.

However, the three DSV designs have capability to operate in both North Seas and West African markets, but in a typical North Seas market where the cost of downtime could be severe in line with the evaluation, concept A stands out as a better design for this environment while concepts B and C could be used in the markets where the cost of downtime may be marginal. In validating this result, sensitivity analysis was done to consider the impact of changes in the assumed variables on the design and it was established that in the absence of downtime cost, the design concepts which had either ROV equipment and air diving system or only ROV equipment in standard container modules were cost efficient compared to the one with top side modular design for SAT diving system. However, in consideration of other KPIs which could have effect on LCC at the long run, concept A would be preferred to the other designs.

5.2 Conclusion

The current design philosophy that involves integration of the main mission equipment in the design of the DSVs, aims at increasing operational efficiency but it impacts negatively on their lifecycle costs, flexibility and sustainability. A more flexible and sustainable design and arrangement solutions is needed for the future. One of such designs that could make the DSV more flexible and sustainable in operation is to configure the top side SAT diving system in modules. Also, using standard container modules for the ROV and air diving systems rather than integrating them in the design offers operational flexibility and spot hire opportunities. A flexible DSV design will reduce costs and efforts in the case of conversion to another trade in the future. Finally, adopting a design concept for future DSVs requires trade off between the key performance indicators and scenario analysis to access the level of benefits that can be derived by preferring a design to another.

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APPENDICES

Appendix I Early developments in diving support vessels

Diving support/construction units in the North Sea

Owner/Operator	Vessel	Flag	Charter	Diving Capability	Fire-fighting	Dynamic Positioning	Type and date converted or built
Comex/Serra	Sandokan	Pan		1,000 ft			Converted barge (1974)
	Talisman	FR	Shell 135 days from May	1,000 ft		x	Purpose-built ship (1977)
Houlder/Comex	Oregis	UK	(Charter for April 1979 installation of CALM or Buchan Field)	1,500 ft			Converted ore carrier (1975)
	Uncle John	UK	Statfjord group then 150 days with Shell from mid-April	1,000 ft		x	Purpose-built semi-sub (1977)
Northern Offshore	Northern Installer	UK	Elf – 12 months starting early summer	1,000 ft	x		Purpose-built ship (1978)
Odd Berg	Arctic Seal	Nor	Preparing for first season	500 m	x	x	Purpose-built ship (1978)
	Arctic Surveyor	Nor	For Phillips since March 75, now in drydock with contract renewal being negotiated	400 m		x	Purpose-built ship (1974)
OSA/C.G Doris	Kattenturm	Ger	Ten day assignment for Shell Espana repair to SALM	1,000 ft		x	Converted supply vessel (1976)
Samson Ocean Systems	Samson Diver	Nor		1,500 ft			Converted tanker (1976)
Seaforth Maritime	Seaforth Cape	UK	Amoco long-term from Nov.76	1,000 ft			Converted trawler (1976)
	Seaforth Clansman	UK		1,000 ft	x		Purpose built ship (1977)
Star Offshore Services	Star Canopus	UK	Ready for work April 78	300 m	x		Converted pipe carrier (1978)
	Star Pegasus	UK	Conoco – three years from April 1977	100 m	x		Con.platform supply (1977)
	Star Pisces	UK	Hamilton – long-term from February 1977	1,000 ft			Converted trawler (1977)
Stolt-Nielsen	Seaway Eagle	Nor		300 m		x	Con.supply vessel (1976)
	Seaway Falcon	Nor	Phillips long-term to July 1978	500 m	x	x	Purpose-built ship (1974)
	Seaway Hawk	Nor		300 m		x	Convert.supply vessel (1977)
	Seaway Swan	Nor	Operational June 1978	1,500 ft	x	x	Purpose-built semi-sub (1978)
Thalassa	Capalonga	Pan	Shell – 3 years from April 1977	1,000 ft	x	x	Converted car ferry (1973/74)
Wharton Williams	Stena Welder	UK	BNOC – 2 years from Dec. 1977	1,000 ft	x	x	Converted pipe carrier (1977)
Wilhelmsen	Tender Carrier	Nor	Union Oil from April 15 1978	1,000 ft		x	Converted pipe carrier (1977)
	Tender Contest	Nor		1,500 ft		x	Converted pipe carrier (1977)

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Appendix II Functional requirement estimation for diving system

	Saturation Diving System				
Item	**System**	**Unit**	**Dimension L(mm) x W(mm) x H(mm)**	**ton/ unit**	**Weight [ton]**
1	Diving bell control console	2	3800 x 1310 x 2315	1	2
2	Chamber saturation control panel	2	5400 x 4700 x 2300	1.5	3
3	3 man Diving bell	2	Ø2750mm x 3520mm	9.65	19.3
4	Diving bell cursor	2		1.12	2.24
5	Bell onboard charging panel	2	605 x 390 2050	0.1	0.2
6	Gas pressure reduction panel	2	3785 x 560 x 2190	0.7	1.4
7	24 man DDC complex	8	4900 x 2704 x 2756	14.5	116
8	Gas transfer compressor	2	1900 x 1100 x 1434	0.9	1.8
9	Chamber + diver gas reclaim	2	3500 x 1200 x 1656	2.2	4.4
11	Hot water + portable water unit	3	1215 x 1000 x 924	0.24	0.72
12	ECU	11	2470 x 1370 x 2050	2.5	27.5
14	Self Propelled Hyperbaric Lifeboat	2	10500 x 3300	16.7	33.4
15	Emergency support module for SPHL	1	3048 x 2430 x 2430	2.1	2.1
21	Gas storage skid of 8 tubes	6	12050 x 1540 x 2900	29.5	177
	Sub Total				**391.1**
	Ancillary Equipment				
15	Guide wire and shock absorber	2		0.95	1.9
16	Bell wire shock absorber	2		0.5	1
17	Bell winch	2		9.075	18.15
18	Anchor weight	2		2.4125	4.825
19	Guide wire winches	2		4.705	9.41
20	Hyraulic power pack	3		3.5	10.5
22	Umbilical winch	2		3.795	7.59
	Subtotal				**53.4**
	5% reserve				**22.2**
	Total Weight of Saturation Diving System + ancillary equipment				**466.7**

Source: Drass Galeazzi Underwater Technology & LexMar Engineering Pte Ltd

	ROV System				
Item	**System**	**Unit**	**Dimension L(mm) x W(mm) x H(mm)**	**ton/ unit**	**Weight [ton]**
1	Inspection/Obs. Class ROV Sys. + TMS	2		0.61	1.22
2	Work Class ROV	2	3 x 1.85 x 2	4.3	8.6
3	LARS/Umbilical cable	1		28.5	28.5
4	Workshop and Control Systems	1		10.9	10.9
5	TMS for Work Class ROV	1	Ø1.98 x 2.44	2.5	2.5
	Total Weight of ROV System				**52**

Tethys Plantgeria Ltd & Fugro BV

Storage Tube Estimation		
ata	=	D+33/33
D	=	300 m
ata	=	10.24242
1 ata	=	1.4 actual ft^3/min
SCFM	=	14.33939
24 hrs	=	1440 minutes
Gas usage for 1 diver	=	20648.73 ft^3
Gas usage for 24 divers	=	495569.5 ft^3
	=	14032.96 m^3
Assuming equivalent capacity for gas reclaim units	=	28065.93
Capacity of one storage tube	=	576 m^3
No. of storage tubes	=	49
No. of storage skid	=	6

Appendix III Functional space estimation

Deck Space						
Name	**No of Units**	**Length [m]**	**Breadth [m]**	**Height [m]**	**Area [m2]**	**Volume [m3]**
Cargo Deck	1	47.9	23	0	1102	0
Helideck	1	27.8	27.8	0	773	0
Deck Space					**1875**	0

Accommodation Facilities						
Name	**No. of Cabins**	**Length [m]**	**Breadth [m]**	**Height [m]**	**Area [m2]**	**Volume [m3]**
Captain Suite	1	6.2	3.6	2.8	22.3	62.5
Chief Engineer	1	6.2	3.6	2.8	22.3	62.5
Offshore Manager	1	6.2	3.6	2.8	22.3	62.5
Client	2	6.2	3.6	2.8	44.6	125.0
Single Cabins	24	2.5	3.6	2.8	216.0	604.8
Double Cabins	38	4.2	3	2.8	478.8	1340.6
Sub-total					**806.4**	**2257.9**
Cabin Corridors, wall lining	35% of total spaces				282.2	790.3
Accommodation Spaces					**1089**	**3048**

Personnel Common Spaces						
Name	**No of Units**	**Seats**	**m2/seat**	**Height [m]**	**Area [m2]**	**Volume [m3]**
Conference Room	1	30	2.2	2.8	66	184.8
Cinema	1	25	2.2	2.8	55	154
Gymnasium	1			2.8	170	476
Sky Lobby	1			2.8	170	476
Internet Cafe	1	6	3.2	2.8	19.2	53.76
Day Room	1	15	2.2	2.8	33	92.4
Mess (50% of Personnel)	1	60	2	2.8	120	336
Personnel Common Spaces					**633.2**	**1772.96**

Personnel & Emergency Stairways					
Name	**No of Stairs**	**m2/stair**	**D-height [m]**	**Area [m2]**	**Volume [m3]**
Stairs					
bow thruster & Engine rooms	4	3	8	12	96
Diving Operations	4	3	3.8	12	45.6
Emergency exits aft	2	3	3.8	6	22.8
Emergency exits foward	4	11.5	3	46	138
Personnel & Emergency Stairways				**76**	**302.4**

Service Facilities				
Ship Service				
Name	**No of Units**	**Height [m]**	**Area [m2]**	**Volume [m3]**
Wheel House	1	2.8	240	672
Offices				
Project	1	2.8	125	350
Client	2	2.8	24	134.4
Ship	1	2.8	68	190.4
General	1	2.8	52	145.6
Hospital	1	2.8	24	67.2
Helideck Reception	1	2.8	34	95.2
Muster station	2	2.8	34	190.4
Corridors:	30% of total spaces		168.3	519.96
Ship Service Spaces			**769.3**	**2365.16**

Catering Spaces					
Name	**No of Crew**	**m2/Crew**	**Height [m]**	**Area [m2]**	**Volume [m3]**
Galley	120	0.65	2.8	78	218.4
Galley Stores	120	0.1	2.8	12	33.6
Dry Provision	120	0.2	2.8	24	67.2
Refrigerated Provision	120	0.6	2.8	72	201.6
Garbage	120	0.4	2.8	48	134.4
Catering Spaces				**234**	**655.2**

Hotel Services					
Name	**No of Crew**	**m2/Crew**	**Height [m]**	**Area [m2]**	**Volume [m3]**
Laundry	120	0.45	2.8	54	151.2
Wardrobe	120	0.5	2.8	60	168
Linen Stores	120	0.2	2.8	24	67.2
Dirty Linen Store	120	0.16	2.8	19.2	53.76
Hotel Services				**43.2**	**440.16**

Technical Spaces in the Accommodation/Offices					
Name	**No of Decks**	**m2/deck**	**D-height [m]**	**Area [m2]**	**Volume [m3]**
AC/Ventilation Fan Rooms	2.5% of total ventilated volume			141.1225	591.0334
Lift					
Accommodation/Offices	6	6.4	2.8	38.4	107.52
Operations area	6	2.2	2.8	13.2	36.96
Main Stairs	6	13	2.8	78	218.4
Technical Spaces			8.4	**271**	**954**

Engine & Propulsion System						
Item	**System**	**Unit**	**Power (kW)**	**Weight (tons)**	**Aux (ton)**	**Total (tons)**
1	Thrusters retractable(Azimuth)	3	1600	22	2	72
2	Thrusters Contra-rotating(Azimuth)	2	3000	55	2	114
3	Thrusters (Tunnel)	2	1800	13.8	1	29.6
4	Wartsila 6L32 Gen Set	6	25000	58		348
5	Emergency Generator	2	400			
						563.6

MACHINERY & TANKS			
Machinery, Speed & Power			
Machinery Type	Diesel Electric Propulsion System with redundant power		
	Trial Condition	Service Condition	In Port
Speed (kn)	15	12	
Installed Power [kW]	15000		0
Transit Power [kW]	6000	5400	
DP power [kW]	4800	4320	
Load factor	100%	90%	0%
Sea Margin	0	15%	0%
Emergency Generator [kW]	800	720	720
Load factor			
Total Installed Power [kW]	15800		

Engine & Machineries Room						
Name	No of Units	m^2/kW	m^3/kW	Height [m]	Area [m2]	Volume [m3]
Engine Room 1	1	0.012	0.054	4.5	190	855
Engine Room 2	1	0.012	0.054	4.5	190	855
Pump Room 1	1	0.006	0.025	4.5	89	400.5
Pump Room 2	1	0.006	0.025	4.5	89	400.5
Steering Gear & Thruster Rms	3	0.008	0.197	8	130	3120
Engine W/S & Store	1	0.001	0.005	4.5	18	81
Switchboard Room 1	1	0.005	0.018	3.5	81	283.5
Switchboard Room 2	1	0.005	0.018	3.5	81	283.5
Engine Control Room 1	1	0.002	0.007	3.5	32	112
Engine Control Room 2	1	0.002	0.007	3.5	32	112
Propulsion Room 1	1	0.005	0.023	4.5	82	369
Propulsion Room 2	1	0.005	0.023	4.5	82	369
Emergency Gen Room	1	0.001	0.004	2.8	22	61.6
Electrical W/S	1	0.001	0.003	3.5	12	42
Electrical Store	1	0.001	0.003	3.5	12	42
Welding W/S	1	0.001	0.003	3.5	12	42
Deck Workshop	1	0.001	0.003	3.5	12	42
Rigging Stores	1	0.001	0.002	3.5	9	31.5
Elevator Equipment	1	0.001	0.002	2.8	10	28
Server Room	1	0.001	0.001	2.8	8	22.4
Incinerator Room	1	0.002	0.006	2.8	36	100.8
Engine Casings & funnels	2	0.002	0.074	21	28	1176
Mooring Equipment Room	2	0.001	0.005	3	12	72
Engine & Machineries Spaces					1269	8901.3

Tanks Spaces						
Name	Consump g/kWh	Consump ton/day	Round Trip (days)	Endurances (days)	Margin factor	Volume [m3]
Fuel Oil Consump (transit)	180	26	3.5	50	1.2	122
Fuel Oil Consump (DP)	190	22		50	1.2	1476
Lube Oil	2	0.76	3.5	50	1.2	53
	L/crew/ day	m3/day				
No of Crew	120					
Fresh Water	200	24		42	1.2	1210
Sewage	75	9		42	1	378
Ballast Water						3000
Heeling tanks						1500
Total						7738

Outdoor Deck Spaces						
Name	No of units	Length [m]	Breadth [m]	Height [m]	Area [m2]	Volume [m3]
Life saving equipment						
Hyperbaric Life Boat	2	16	4.4	5.6	141	788
Lifeboats	4	13.4	4.4	4.4	236	1038
Mooring Deck Foward	1	28	22		616	0
Outdoor Deck Spaces					993	1826

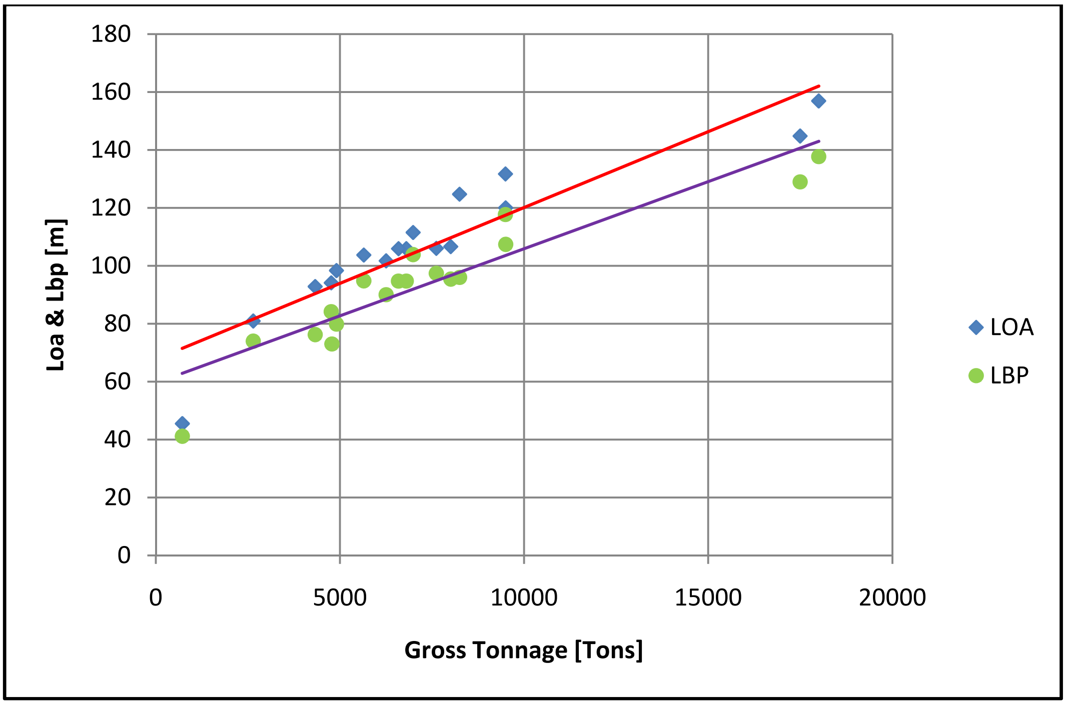
Technical Spaces						
Diving Systems - Concept A						
Name	**No of Units**	**Length [m]**	**Breadth [m]**	**Height [m]**	**Area [m2]**	**Volume [m3]**
Compressor Room	1	15.6	7.8	4.5	121.68	547.56
Gas Stores/gas panel	1	15.6	7.8	8	121.68	973.44
Diving Machinery 1	1	8	7.8	4.5	62.4	280.8
Diving Machinery 2	1	8	7.8	4.5	62.4	280.8
DDC Rooms	1	17	23	3.5	391	1368.5
Marine Electrical W/S	1	5.4	4	3.5	21.6	75.6
SAT Control Room	1	11.8	3	3.5	35.4	123.9
Bell Dive Control Room	1			3.5	72	252
Moonpool	2	4.8	4.8	10	23.04	230.4
Air Dive Control Room	1	4	3.2	3.5	12.8	44.8
Air Dive Station	1	6	5.4	3.5	32.4	113.4
ROV Equipment Store	1	3.6	3	3.5	10.8	37.8
ROV Trafo	1	5	3	3.5	15	52.5
ROV Control Room	1	5.6	5.4	3.5	30.24	105.84
Heated Suit Room	1	4	2.4	3.5	9.6	33.6
Washing & Drying Room	1	4	3.6	3.5	14.4	50.4
Breathing W/S & Store	1	4	3.6	3.5	14.4	50.4
ROV W/S	1	4.8	4.2	3.5	20.16	70.56
Passage ways	35% of total spaces for diving system				418.11	1463.665
Diving Systems Spaces					**1489**	**6156**

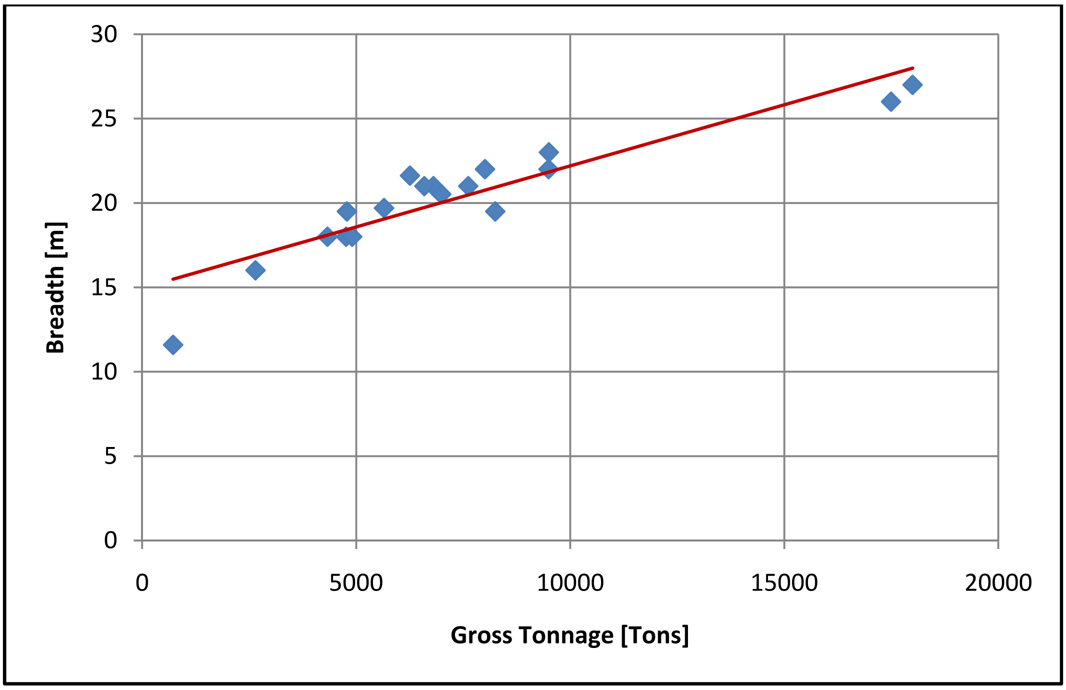
Technical Spaces						
Diving Systems - Concept B						
Name	**No of Units**	**Length [m]**	**Breadth [m]**	**Height [m]**	**Area [m2]**	**Volume [m3]**
Compressor Room	1	15.6	7.8	4.5	121.68	547.56
Gas Stores/gas panel	1	15.6	7.8	8	121.68	973.44
Diving Machinery 1	1	8	7.8	4.5	62.4	280.8
Diving Machinery 2	1	8	7.8	4.5	62.4	280.8
DDC Rooms	1	17	23	3.5	391	1368.5
Marine Electrical W/S	1	5.4	4	3.5	21.6	75.6
SAT Control Room	1	11.8	3	3.5	35.4	123.9
Bell Dive Control Room	1			3.5	72	252
Moonpool	2	4.8	4.8	10	23.04	230.4
Heated Suit Room	1	4	2.4	3.5	9.6	33.6
Washing & Drying Room	1	4	3.6	3.5	14.4	50.4
Breathing W/S & Store	1	4	3.6	3.5	14.4	50.4
Passage ways	35% of total spaces for diving system				418.11	1463.665
Diving Systems Spaces					**1368**	**5731**

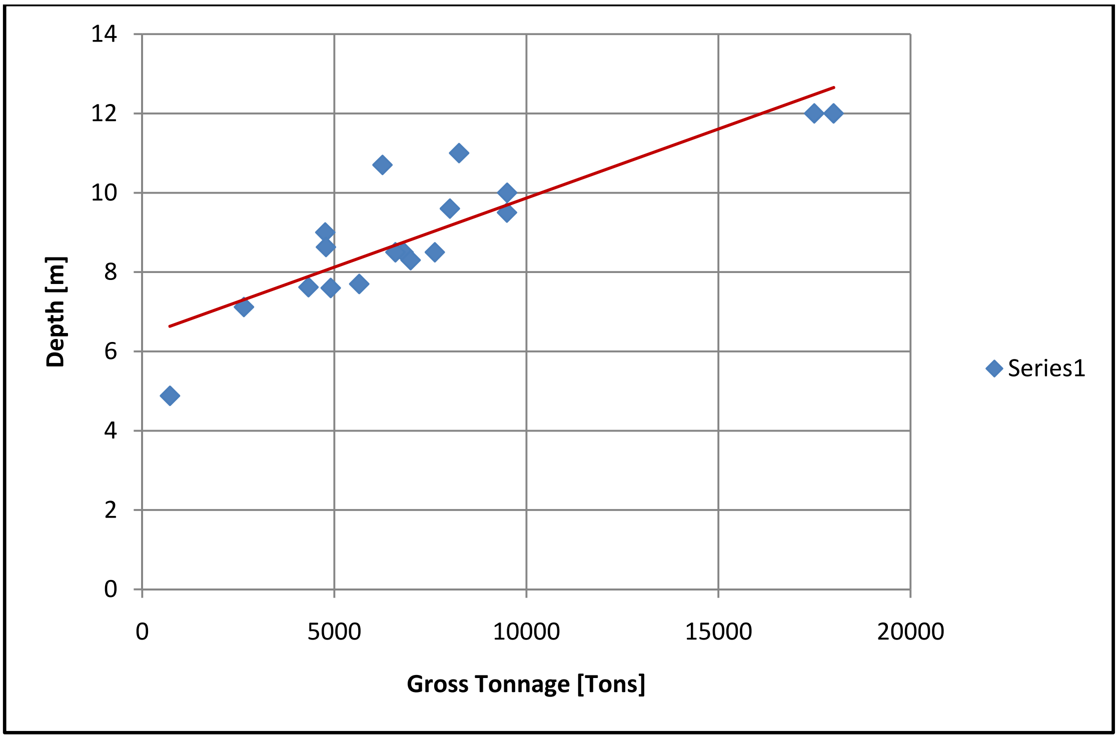
Technical Spaces						
Diving Systems - Concept C						
Name	**No of Units**	**Length [m]**	**Breadth [m]**	**Height [m]**	**Area [m2]**	**Volume [m3]**
Compressor Room	1	15.6	7.8	4.5	121.68	547.56
Gas Stores/gas panel	1	15.6	7.8	8	121.68	973.44
Diving Machinery 1	1	8	7.8	4.5	62.4	280.8
Diving Machinery 2	1	8	7.8	4.5	62.4	280.8
DDC Rooms	1	17	23	3.5	391	1368.5
Marine Electrical W/S	1	5.4	4	3.5	21.6	75.6
SAT Control Room	1	11.8	3	3.5	35.4	123.9
Bell Dive Control Room	1			3.5	72	252
Moonpool	2	4.8	4.8	10	23.04	230.4
Air Dive Control Room	1	4	3.2	3.5	12.8	44.8
Air Dive Station	1	6	5.4	3.5	32.4	113.4
Heated Suit Room	1	4	2.4	3.5	9.6	33.6
Washing & Drying Room	1	4	3.6	3.5	14.4	50.4
Breathing W/S & Store	1	4	3.6	3.5	14.4	50.4
Passage ways	35% of total spaces for diving system				418.11	1463.665
Diving Systems Spaces					**1413**	**5889**

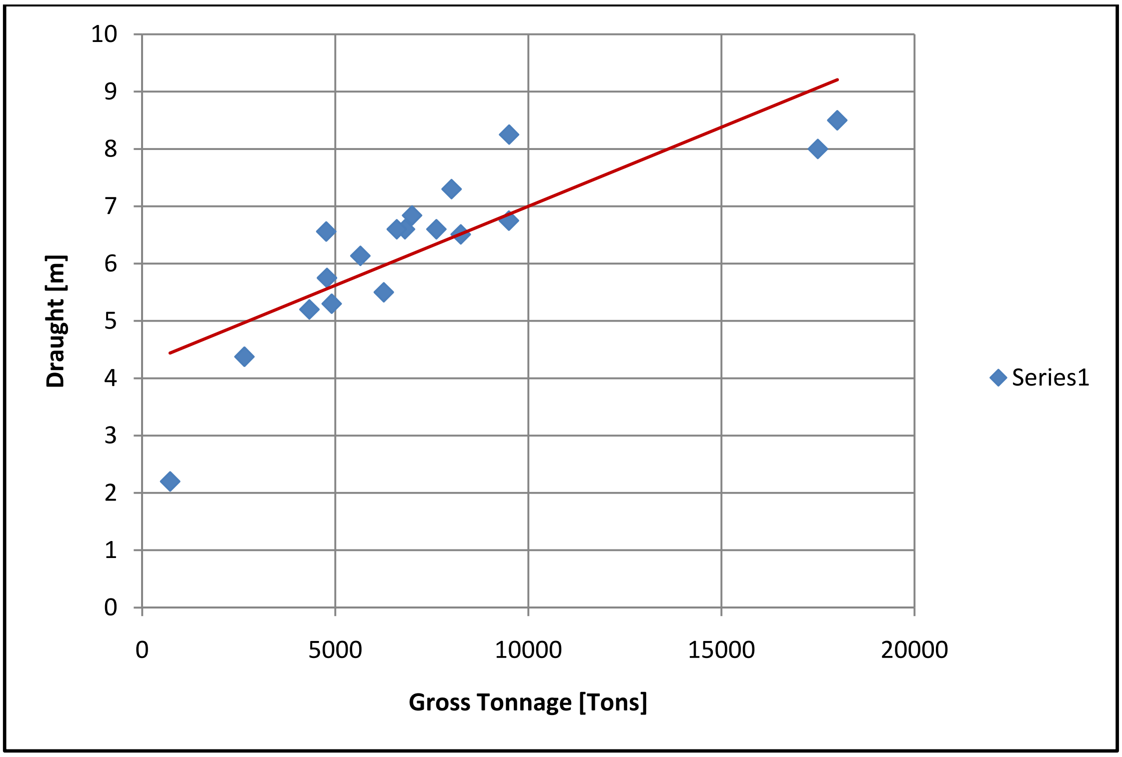
Appendix IV DSV Statistics

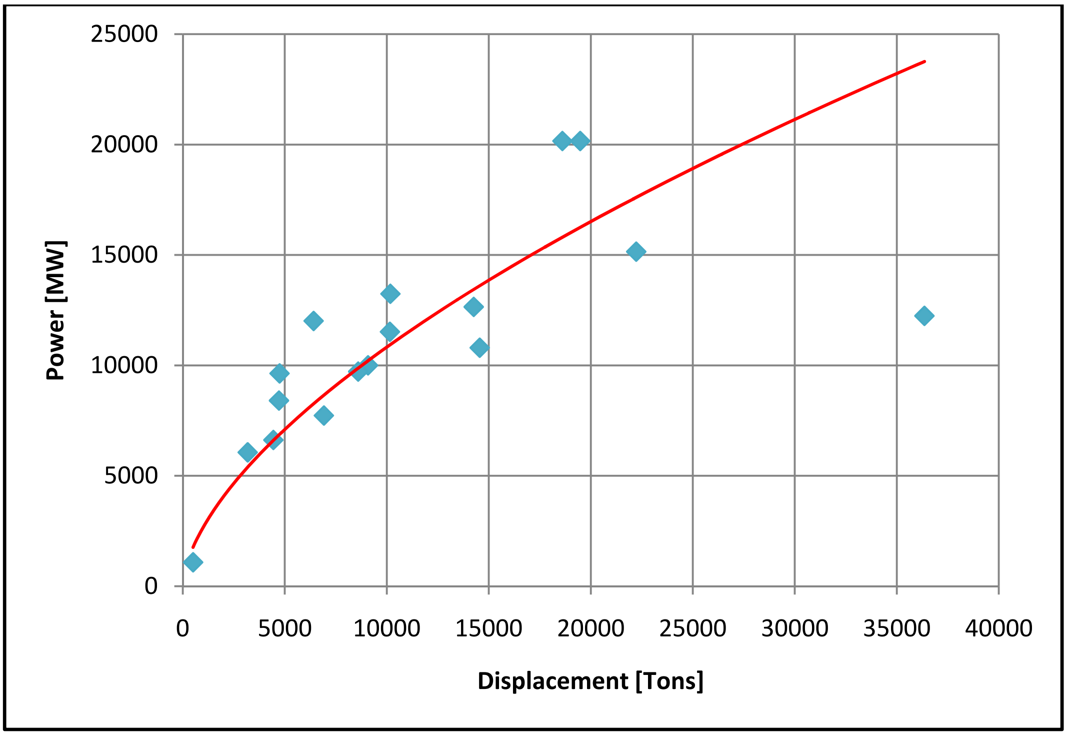
Ship Data	Seven Atlantic	Acergy Havila	Skandi Arctic	Skandi Salvador	TOISA PEGASUS	Olympic Challenger	Bibby Topaz	Skandi Achiever	Acergy Discovery	Seven Pelican	Acergy Harrier	Acergy Osprey	Seamec III	Rockwater 1	Bar Protector	Sarku Sambag	Gulmar Falcon
Built	2010	2010	2009	2009	2009	2008	2007	2007	1990	1985	1985	1985	1983	1983	1981	1975	1975
CAPEX ($)	200 000 000	181 187 000				65 530 000								35 000 000			11 293 094
DWT (ton)	11885	7 250	11500	3600	7800	3900	5337	9434	4645	2043	2350	3104	2067	1530	4670	163	1636
GT (ton)	17496	9 500	18000	6802	9494	6590	8009	7617	8248	4763	4782	6254	4327	4905	6987	720	2645
Length Overall (m)	144.79	120	156.9	105.9	131.7	105.9	106.6	106	124.7	94.1	83.4	101.7	92.82	98.35	111.49	45.5	80.93
Length (BP) (m)	128.96	107.4	137.7	94.7	117.7	94.7	95.4	97.4	96	84.17	73	90.02	76.23	79.87	103.87	41.15	73.97
Breadth Moulded (m)	26	23	27	21	22	21	22	21	19.5	18	19.5	21.62	18	18	20.52	11.59	16.01
Draught (m)	8	8.25	8.5	6.6	6.75	6.6	7.3	6.6	6.51	6.56	5.75	5.5	5.2	5.3	6.84	2.2	4.376
Depth (m)	12	10	12	8.5	9.5	8.5	9.6	8.5	11	9	8.63	10.7	7.62	7.6	8.3	4.88	7.12
Service Speed (knots)	13.6	12	17	15.5	13	15	12	12	12	12	12.5	12	12	12.5	12	12	12
Max Speed (knots)		17					15								15.5		15
Consumption (tons/day)											12	16	18.5		24		
Total Power: Mcr kW	20160	12648	20160	10800	12240	15150	11520	10000	9720	12012	8405	7728	6620	9635	13240	1082	6060
Rho Seawater (ton/m3)	1.025	1.025	1.025	2.025	3.025	3.025	1.025	1.025	1.025	1.025	1.025	1.025	1.025	1.025	1.025	1.025	1.025
Lwl	131.5	109.5	140.5	96.6	120.1	96.6	97.3	99.3	97.9	85.9	74.5	91.8	77.8	81.5	105.9	42.0	75.4
L/B	5.57	5.22	5.81	5.04	5.99	5.04	4.85	5.05	6.39	5.23	4.28	4.70	5.16	5.46	5.43	3.93	5.05
B/D	2.17	2.30	2.25	2.47	2.32	2.47	2.29	2.47	1.77	2.00	2.26	2.02	2.36	2.37	2.47	2.38	2.25
Froude Number (-)	0.19	0.19	0.24	0.26	0.19	0.25	0.20	0.20	0.20	0.21	0.24	0.21	0.22	0.23	0.19	0.30	0.23
C_B	0.68	0.68	0.60	0.55	0.69	0.56	0.65	0.66	0.69	0.63	0.56	0.63	0.61	0.61	0.68	0.47	0.60
Displacement (ton)	18610	14263	19483	14556	36359	22228	10154	9082	8598	6413	4715	6918	4441	4745	10176	505	3181
DWT/Displ	0.64	0.51	0.59	0.25	0.21	0.18	0.53	1.04	0.54	0.32	0.50	0.45	0.47	0.32	0.46	0.32	0.51


180
160
140
120
100
80
60
40
20
0
0
5000
10000
15000
20000
Loa & Lbp [m]
Gross Tonnage [Tons]
LOA
LBP

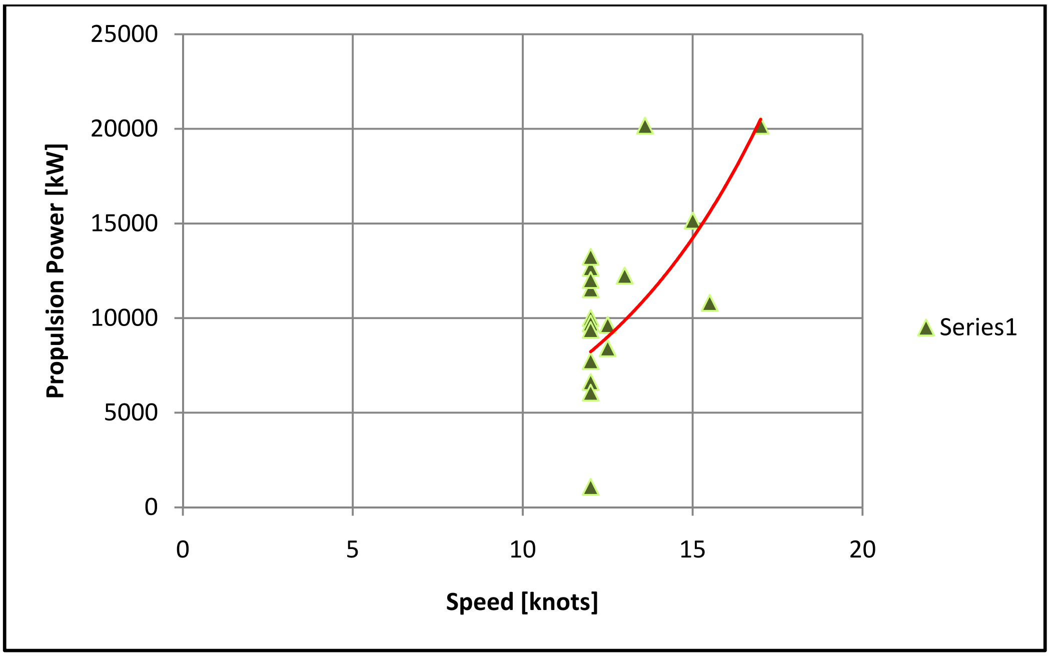

30
25
20
15
10
5
0
0
5000
10000
15000
20000
Breadth [m]
Gross Tonnage [Tons]


14
12
10
8
6
4
2
0
Depth [m]
0
5000
10000
15000
20000
Gross Tonnage [Tons]
Series1


10
9
8
7
6
5
4
3
2
1
0
Draught [m]
0
5000
10000
15000
20000
Gross Tonnage [Tons]
Series1

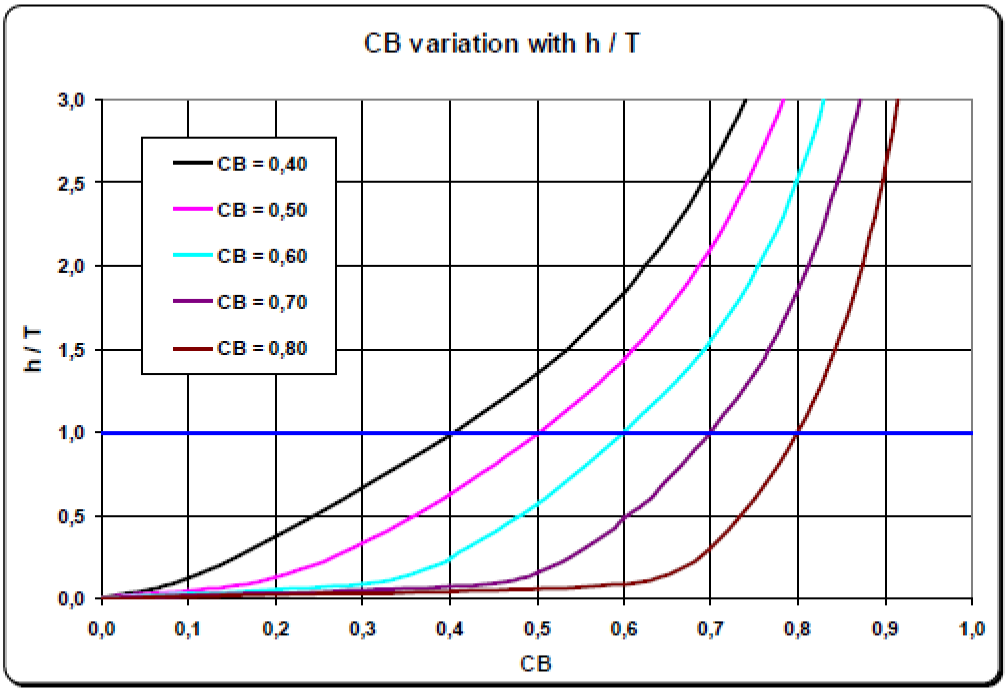


25000
20000
15000
10000
5000
0
Power [MW]
0
5000
10000
15000
20000
25000
30000
35000
40000
Displacement [Tons]

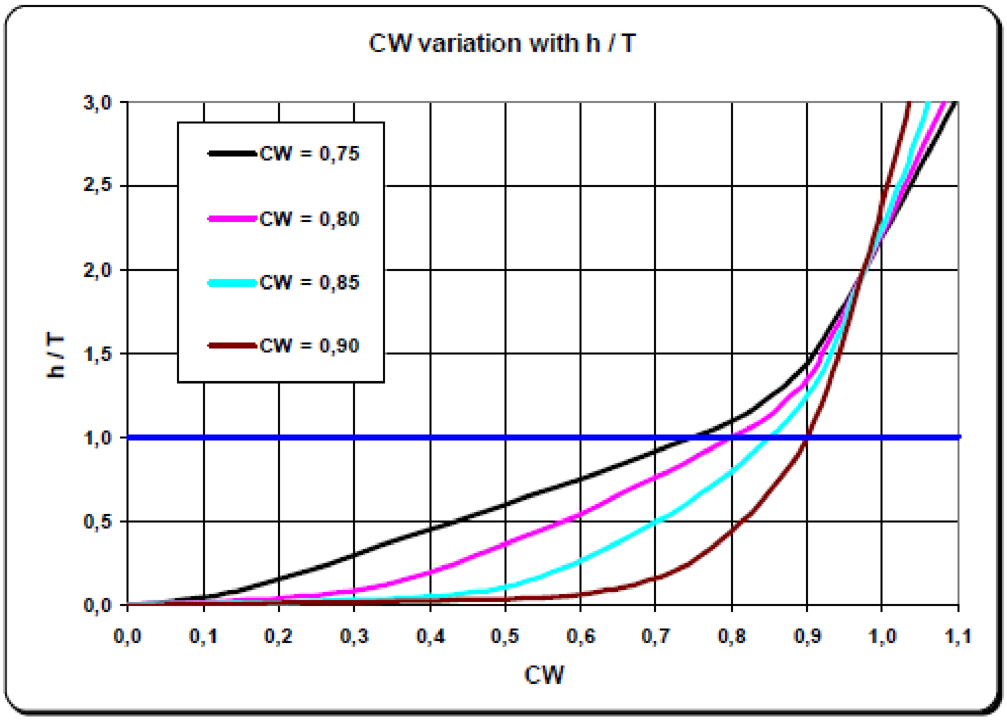


25000
20000
15000
10000
5000
0
Propulsion Power [kW]
0
5
10
15
20
Speed [knots]
Series1

Appendix V Hull Volume and Deck Area estimation



$$HullVolume = CB(h) \times L_{pp} \times B \times h$$



$$DeckArea = CW(h) \times Lpp \times B$$

(Source: Levander 2004)

h/T		Length	Beam WI	Volume	Area	CB(h)	CW(h)
0.29	Bottom	90	21	1814	1890	0.48	0.58
0.93	Tank Top	94	21	5862.78	1974	0.66	0.84
1.43	Tw Deck	114	23	6790.98	2622	0.74	0.92
1.93	Main Deck	116	23	7377.02	2668	0.79	0.94
2.33	Deck 1	70	23	3696.56	1610	0.82	0.98
2.73	Deck 2	70	23	3786.72	1610	0.84	1.02
3.13	Deck 3	56	23	3101.504	1288	0.86	1.06
3.53	Deck 4	26	23	1506.96	598	0.90	1.08
3.93	Bridge	14	23	811.44	322	0.90	1.08
3.93	Sky lobby	12	21	635.04	252	0.90	1.10

CB(h) and CW(h) have been obtained by interpolation in the chart of CB and CW variations with h/T for the design block coefficient and waterplane area coefficients respectively.

Appendix VI Costs Analyses

CAPEX OF CONCEPT A

MATERIAL AND LABOUR	Unit	Value	Coeff NOK/unit	Coeff h/unit	Material MNOK	Labour 1000 hrs
Cost Group:						
Ship General	LWT	5233	2000.00	5	10.47	26.17
Payload related:						
Hatches	Weight	30	20000.00	10	0.60	0.30
Hull and Forcastle	Hull Weight	1756	6000.00	30	10.53	52.67
Deckhouse, Casing & Funnel	Dh Weight	520	6000.00	50	3.12	26.02
Interior Outfitting	Area	3039	15000.00	25	45.59	75.98
Machinery	Installed Power	15800	3000.00	2	47.40	31.60
Ship Outfitting	Gross Volume	32354	1000.00	0.2	32.35	6.47
Sub-total					**150.06**	**219.20**
Inflation margin	%	70			**105.04**	
Total	**LWT**	**5233**	**48749**	**42**	**255.11**	**219.20**
Reserve	%	**5**	**2437**	**2**	**7.50**	**10.96**
Material & Labour cost	**LWT**	**5233**	**51186**	**44**	**262.61**	**230.16**

SUMMARY OF CAPEX	h/LWT	Hours	NOK/h	Price MNOK	Price NOK/kg
Design	10	52331.074	350.00	18.32	3.50
Labour + Overhead	44	230163.38	400.00	92.07	17.59
Material				262.61	50.18
Subtotal				372.99	
Building time financing (interest x time/2)	10% x time/2			27.97	5.35
Total Production Cost				**400.97**	**76.62**
Profit	8%			32.08	
Financing, Payment	3%			12.03	
Broker fees	1%			4.01	
Building Price			**Cost**	**449.08**	**86**
			Cost/DWT	**65217 NOK/ton**	
			Cost/GT	**44417 NOK/GT**	

CAPEX OF CONCEPT B

MATERIAL AND LABOUR	Unit	Value	Coeff NOK/unit	Coeff h/unit	Material MNOK	Labour 1000 hrs
Cost Group:						
Ship General	LWT	5086	2000.00	5	10.17	25.43
Payload related:						
Hatches	Weight	30	20000.00	10	0.60	0.30
Hull and Forcastle	Hull Weight	1721	6000.00	30	10.33	51.64
Deckhouse, Casing & Funnel	Dh Weight	520	6000.00	50	3.12	26.00
Interior Outfitting	Area	3039	15000.00	25	45.59	75.98
Machinery	Installed Power	15800	3000.00	2	47.40	31.60
Ship Outfitting	Gross Volume	31919	1000.00	0.2	31.92	6.38
Sub-total					**149.13**	**217.34**
Inflation margin	%	70			**104.39**	
Total	**LWT**	**5086**	**49845**	**43**	**253.51**	**217.34**
Reserve	%	**5**	**2492**	**2**	**7.46**	**10.87**
Material & Labour cost	**LWT**	**5086**	**52338**	**45**	**260.97**	**228.20**

SUMMARY OF CAPEX	h/LWT	Hours	NOK/h	Price MNOK	Price NOK/kg
Design	10	50859.981	350.00	17.80	3.50
Labour + Overhead	45	228202.76	400.00	91.28	17.95
Material				260.97	51.31
Subtotal				370.05	
Building time financing (interest x time/2)	10% x time/2			27.75	5.46
Total Production Cost				**397.81**	**78.22**
Profit	8%			31.82	
Financing, Payment	3%			11.93	
Broker fees	1%			3.98	
Building Price			Cost	**445.54**	**88**
			Cost/DWT	**64703 NOK/ton**	
			Cost/GT	**44668 NOK/GT**	

CAPEX OF CONCEPT C

MATERIAL AND LABOUR	Unit	Value	Coeff NOK/unit	Coeff h/unit	Material MNOK	Labour 1000 hrs
Cost Group:						
Ship General	LWT	5156	2000.00	5	10.31	25.78
Payload related:						
Hatches	Weight	30	20000.00	10	0.60	0.30
Hull and Forcastle	Hull Weight	1732	6000.00	30	10.39	51.97
Deckhouse, Casing & Funnel	Dh Weight	525	6000.00	50	3.15	26.24
Interior Outfitting	Area	3039	15000.00	25	45.59	75.98
Machinery	Installed Power	15800	3000.00	2	47.40	31.60
Ship Outfitting	Gross Volume	32081	1000.00	0.2	32.08	6.42
Sub-total					**149.52**	**218.29**
Inflation margin	%	70			**104.67**	
Total	**LWT**	**5156**	**49295**	**42**	**254.19**	**218.29**
Reserve	%	**5**	**2465**	**2**	**7.48**	**10.91**
Material & Labour cost	**LWT**	**5156**	**51760**	**44**	**261.67**	**229.21**

SUMMARY OF CAPEX	h/LWT	Hours	NOK/h	Price MNOK	Price NOK/kg
Design	10	51564.92	350.00	18.05	3.50
Labour + Overhead	44	229206.67	400.00	91.68	17.78
Material				261.67	50.75
Subtotal				371.40	
Building time financing (interest x time/2)	10% x time/2			27.85	5.40
Total Production Cost				**399.25**	**77.43**
Profit	8%			31.94	
Financing, Payment	3%			11.98	
Broker fees	1%			3.99	
Building Price			Cost	**447.16**	**87**
			Cost/DWT	**64938**	NOK/ton
			Cost/GT	**44604**	NOK/GT

Appendix VII Loan Repayment plan for Vessel and Mission Equipment

Concept A - Vessel

CAPEX			interest	6%
89827935			Period	15
			Principal($)	89827935
		End of period payment,	A ($(=	-9 248 933
End of Year	**CAPEX [$]**	**Interest [$]**	**Amount Paid [$]**	**Balance [$]**
1	89827935	5389676.12	-9248933	85968678.97
2	85968679	5158120.74	-9248933	81877867.21
3	81877867	4912672.03	-9248933	77541606.73
4	77541607	4652496.4	-9248933	72945170.63
5	72945171	4376710.24	-9248933	68072948.37
6	68072948	4084376.9	-9248933	62908392.76
7	62908393	3774503.57	-9248933	57433963.83
8	57433964	3446037.83	-9248933	51631069.15
9	51631069	3097864.15	-9248933	45480000.79
10	45480001	2728800.05	-9248933	38959868.34
11	38959868	2337592.1	-9248933	32048527.93
12	32048528	1922911.68	-9248933	24722507.10
13	24722507	1483350.43	-9248933	16956925.03
14	16956925	1017415.5	-9248933	8725408.02
15	8725408	523524.481	-9248933	0.00

Concept B - Vessel

CAPEX			interest	6%
89237988			Period	15
			Principal($)	89237988
End of period payment,			A ($(=	-9 188 190
End of Year	**CAPEX [$]**	**Interest [$]**	**Amount Paid [$]**	**Balance [$]**
1	89237988	5354279.27	-9188190	85404077.26
2	85404077	5124244.64	-9188190	81340132.01
3	81340132	4880407.92	-9188190	77032350.05
4	77032350	4621941.00	-9188190	72466101.18
5	72466101	4347966.07	-9188190	67625877.37
6	67625877	4057552.64	-9188190	62495240.13
7	62495240	3749714.41	-9188190	57056764.65
8	57056765	3423405.88	-9188190	51291980.65
9	51291981	3077518.84	-9188190	45181309.61
10	45181310	2710878.58	-9188190	38703998.31
11	38703998	2322239.90	-9188190	31838048.33
12	31838048	1910282.90	-9188190	24560141.34
13	24560141	1473608.48	-9188190	16845559.94
14	16845560	1010733.60	-9188190	8668103.66
15	8668104	520086.22	-9188190	0.00

Concept C - Vessel

CAPEX			interest	6%
$ 89511555			Period	15
			Principal($)	89511555
End of period payment,			A ($(=	-9 216 357
End of Year	**CAPEX [$]**	**Interest [$]**	**Amount Paid [$]**	**Balance [$]**
1	89511555	5370693.28	-9216357	85665890.89
2	85665891	5139953.45	-9216357	81589487.27
3	81589487	4895369.24	-9216357	77268499.43
4	77268499	4636109.97	-9216357	72688252.32
5	72688252	4361295.14	-9216357	67833190.38
6	67833190	4069991.42	-9216357	62686824.73
7	62686825	3761209.48	-9216357	57231677.13
8	57231677	3433900.63	-9216357	51449220.68
9	51449221	3086953.24	-9216357	45319816.85
10	45319817	2719189.01	-9216357	38822648.78
11	38822649	2329358.93	-9216357	31935650.63
12	31935651	1916139.04	-9216357	24635432.60
13	24635433	1478125.96	-9216357	16897201.48
14	16897201	1013832.09	-9216357	8694676.49
15	8694676	521680.59	-9216357	0.00

Mission Equipment

CAPEX			interest	6%
$ 52162690			Period	15
			Principal($	52162690
End of period payment,			A ($(=	-5370815
End of Year	**CAPEX [$]**	**Interest [$]**	**Amount Paid [$]**	**Balance [$]**
1	52162690	3129761.42	-5370815	49921636.97
2	49921637	2995298.22	-5370815	47546120.42
3	47546120	2852767.22	-5370815	45028072.87
4	45028073	2701684.37	-5370815	42358942.47
5	42358942	2541536.55	-5370815	39529664.25
6	39529664	2371779.85	-5370815	36530629.33
7	36530629	2191837.76	-5370815	33351652.32
8	33351652	2001099.14	-5370815	29981936.69
9	29981937	1798916.20	-5370815	26410038.12
10	26410038	1584602.29	-5370815	22623825.64
11	22623826	1357429.54	-5370815	18610440.41
12	18610440	1116626.42	-5370815	14356252.06
13	14356252	861375.12	-5370815	9846812.41
14	9846812	590808.74	-5370815	5066806.39
15	5066806	304008.38	-5370815	0.00

Appendix VIII AHP Analysis

Main Evaluation Criteria Analysis					
	Op. Flexibility	**Costs**	**Sustainability**	**Op. Efficiency**	**Deck Space**
Op. Flexibility	1	1	3	0.333333333	3
Costs	1	1	3	0.333333333	5
Sustainability	0.333333333	0.333333333	3	3	0.333333333
Op. Efficiency	3	3	0.333333333	1	2
Deck Space	0.333333333	0.2	3	0.5	1
	5.666666667	**5.533333333**	**12.33333333**	**5.166666667**	**11.33333333**

Attributes	**Op. Flexibility**	**Costs**	**Sustainability**	**Op. Efficiency**	**Deck Space**	**Average**
Op. Flexibility	0.176470588	0.180722892	0.243243243	0.064516129	0.264705882	**0.19**
Costs	0.176470588	0.180722892	0.243243243	0.064516129	0.441176471	**0.22**
Sustainability	0.058823529	0.060240964	0.243243243	0.580645161	0.029411765	**0.19**
Op. Efficiency	0.529411765	0.542168675	0.027027027	0.193548387	0.176470588	**0.29**
Deck Space	0.058823529	0.036144578	0.243243243	0.096774194	0.088235294	**0.10**

Op. Flexibility	**Concept A**	**Concept B**	**Concept C**
Concept A	1	0.333333333	1
Concept B	3	1	3
Concept C	1	0.333333333	1
	5	**1.666666667**	**5**

Op. Flexibility	Concept A	Concept B	Concept C	Average
Concept A	0.2	0.2	0.2	**0.2**
Concept B	0.6	0.6	0.6	**0.6**
Concept C	0.2	0.2	0.2	**0.2**

Op. Flexibility	Priority	Average
Concept A	0.2	0.04
Concept B	0.6	0.11
Concept C	0.2	0.04
	1	**0.19**

Sub Criteria Analysis		
LCC	CAPEX	OPEX
CAPEX	1	0.333333333
OPEX	3	1
Sum	4	1.333333333

LCC	CAPEX	OPEX	Average
CAPEX	0.25	0.25	0.25
OPEX	0.75	0.75	0.75
Sum	1	1	1.00

LCC	Priority	Aggregate
CAPEX	0.25	0.06
OPEX	0.75	0.17
Sum	1.00	0.22

CAPEX	Concept A	Concept B	Concept C
Concept A	1	0.2	0.333333333
Concept B	5	1	3
Concept C	3	0.333333333	1
	9	**1.533333333**	**4.333333333**

CAPEX	Concept A	Concept B	Concept C	Average
Concept A	0.111111111	0.130434783	0.076923077	0.11
Concept B	0.555555556	0.652173913	0.692307692	0.63
Concept C	0.333333333	0.217391304	0.230769231	0.26

CAPEX	Priority	Aggregate
Concept A	0.11	0.01
Concept B	0.63	0.04
Concept C	0.26	0.01

OPEX	Concept A	Concept B	Concept C
Concept A	1	3	7
Concept B	0.333333333	1	5
Concept C	0.142857143	0.2	1
	1.476190476	**4.2**	**13**

OPEX	Concept A	Concept B	Concept C	Average
Concept A	0.677419355	0.714285714	0.538461538	0.64
Concept B	0.225806452	0.238095238	0.384615385	0.28
Concept C	0.096774194	0.047619048	0.076923077	0.07

OPEX	Priority	Aggregate
Concept A	0.64	0.11
Concept B	0.28	0.05
Concept C	0.07	0.01

Sustainability	Concept A	Concept B	Concept C
Concept A	1	5	3
Concept B	0.2	1	0.333333333
Concept C	0.333333333	3	1
	1.533333333	**9**	**4.333333333**

Sustainability	Concept A	Concept B	Concept C	Average
Concept A	0.652173913	0.555555556	0.692307692	**0.63**
Concept B	0.130434783	0.111111111	0.076923077	**0.11**
Concept C	0.217391304	0.333333333	0.230769231	**0.26**

Sustainability	Priority	Aggregate
Concept A	0.63	**0.12**
Concept B	0.11	**0.02**
Concept C	0.26	**0.05**

Op. Efficiency	Concept A	Concept B	Concept C
Concept A	1	7	5
Concept B	0.142857143	1	0.333333333
Concept C	0.2	3	1
	1.342857143	**11**	**6.333333333**

Op. Efficiency	Concept A	Concept B	Concept C	Average
Concept A	0.744680851	0.636363636	0.789473684	**0.72**
Concept B	0.106382979	0.090909091	0.052631579	**0.08**
Concept C	0.14893617	0.272727273	0.157894737	**0.19**

Op. Efficiency	Priority	Aggregate
Concept A	0.72	**0.21**
Concept B	0.08	**0.02**
Concept C	0.19	**0.06**

Sub Criteria Analysis		
Deck Space	**Deck Ops.**	**Supply Serv.**
Deck Ops.	1	1
Supply Serv.	1	1
Sum	**2**	**2**

Deck Space	Deck Ops.	Supply Serv.	Average
Deck Ops	0.5	0.5	0.50
Supply Serv.	0.5	0.5	0.50
Sum	**1**	**1**	**1.00**

Deck Space	Priority	Aggregate
Deck Ops	0.50	0.05
Supply Serv.	0.50	0.05
Sum	**1.00**	**0.10**

Deck Ops	Concept A	Concept B	Concept C
Concept A	1	1	3
Concept B	1	1	3
Concept C	0.333333333	0.333333333	1
	2.333333333	**2.333333333**	**7**

Deck Ops	Concept A	Concept B	Concept C	Average
Concept A	0.428571429	0.428571429	0.428571429	**0.43**
Concept B	0.428571429	0.428571429	0.428571429	**0.43**
Concept C	0.142857143	0.142857143	0.142857143	**0.14**

Deck Ops	Priority	Aggregate
Concept A	0.43	**0.02**
Concept B	0.43	**0.02**
Concept C	0.14	**0.01**

Supply Serv.	Concept A	Concept B	Concept C
Concept A	1	3	5
Concept B	0.333333333	1	3
Concept C	0.2	0.333333333	1
	1.533333333	**4.333333333**	**9**

Supply Serv.	Concept A	Concept B	Concept C	Average
Concept A	0.652173913	0.692307692	0.555555556	**0.63**
Concept B	0.217391304	0.230769231	0.333333333	**0.26**
Concept C	0.130434783	0.076923077	0.111111111	**0.11**

Supply Serv.	Priority	Aggregate
Concept A	0.63	**0.03**
Concept B	0.26	**0.01**
Concept C	0.11	**0.01**

Design Alternatives	Op. Flexibility	LCC		Sustainability	Op. Efficiency	Deck Space		Total
		CAPEX	OPEX			Deck Ops	Supply Serv.	Weight
Concept A	0.04	0.04	0.11	0.12	0.21	0.02	0.03	**0.57**
Concept B	0.11	0.01	0.05	0.02	0.02	0.02	0.01	**0.25**
Concept C	0.04	0.01	0.01	0.05	0.06	0.01	0.01	**0.18**
1.00								**1.00**