



Grant Agreement number: 314286

Project acronym: MUNIN

Project title: Maritime Unmanned Navigation through Intelligence in Networks

Funding Scheme: SST.2012.5.2-5: E-guided vessels: the 'autonomous' ship

D10.2: New ship designs for autonomous vessels

Due date of deliverable: 2015-07-31

Actual submission date: 2015-09-22

Start date of project: 2012-09-01

Project Duration: 36 months

Lead partner for deliverable: MRTK

Distribution date: 2015-09-22

Document revision: 1.0

Project co-funded by the European Commission within the Seventh Framework Programme (2007-2013)		
Dissemination Level		
PU	Public	Public
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	

Document summary information

Deliverable	10.2 New ship designs for autonomous vessels
Classification	Public

Initials	Author	Organisation	Role
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Rev.	Who	Date	Comment
0.1	ØJR	2015-03-15	First outline
0.2	ØJR	2015-06-21	Added more on prerequisites
0.3	ØJR	2015-08-12	Restructured, moved HazId to 9.2
0.4	HCB	2015-08-21	Comments CML, More from 9.3, actual ships
0.5	ØJR	2015-08-31	Some external examples
0.6	HCB	2015-09-14	Further contributions
1.0	ØJR	2015-09-22	Final editorials

Internal review needed:

yes

no

Initials	Reviewer	Approved	Not approved

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Executive summary

The work with the MUNIN project has shown that the original concept of a retrofit of unmanned capabilities to a handy size bulk carrier is not very realistic as costs will be too high compared to the benefits. This document discusses the experiences gained and what the constraints are for an unmanned ship to succeed as a business proposition. In addition, the document will also provide a more concrete example of a likely longer term deep sea container shipping operation and how this can be arranged to make it a likely proposal. The same is done for an offshore supply type vessel.

Deliverable D10.1 describes similar examples for short sea trades, based on the same constraints as identified here.

The reader is also directed to deliverable D9.3 which goes into more detail on the cost-benefit analysis of unmanned merchant ships. This document uses some figures from that study, but in a more qualitative way.

List of abbreviations

ALARP	As Low As Reasonably Practicable
BTU	British Thermal Unit
CBA	Cost-Benefit Assessment
ECA	Emission Control Area
EIA	Energy Information Agency (USA) www.eia.gov
HDTV	High Definition TV
HFO	Heavy Fuel Oil
IR	Infrared
LNG	Liquefied Natural Gas
MBtu	Million BTU
MDO	Marine Diesel Oil (normally mix of HFO and MGO)
MGO	Marine Gas Oil (Closer to normal automotive diesel)
MW	Mega Watt = 1000 kW
NO _x	Nitrogen Oxides
PM	Particulate Matter (Soot, hydrocarbons etc.)
RCO	Risk Control Option
SO _x	Sulphur Oxides (mainly SO ₂)
SCC	Shore Control Centre
SFOC	Specific Fuel Oil Consumption (g/kW)
SSS	Short Sea Shipping

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1. Introduction

This document, together with deliverable D10.1 /3/, discusses the constraints for realization of unmanned ships in deep sea and short sea settings respectively.

The reader is also directed to deliverable D9.3 /2/ which goes into more detail on the cost-benefit analysis of unmanned merchant ships. This document uses some figures from that study, but in a more qualitative way.

1.1 Scope

The MUNIN project has shown that the original concept with a dry bulk carrier with minimum retrofit is not very realistic as costs will be too high compared to benefits. However, the research and the public interest have also shown that unmanned shipping is indeed an attractive proposal, if the business proposal takes the inherent constraints of unmanned shipping properly into consideration.

This document will discuss and list some of the constraints that have been identified and will present some examples of realizations that are possible business cases in short and longer terms. As expected, these proposals will mainly fall into three categories related to the constraints:

1. New hull forms having no accommodation section and different design of superstructure as lookouts or other bridge crew is not needed.
2. New types of fuel that may be used due to lower overall energy requirements, both in terms of complete voyage and as momentary power requirements. This includes LNG as fuel with virtually no pollution hazards except for GHG effects.
3. Alternative operational principles, e.g., barge type shipping with engine and cargo units as separate entities where, e.g., a manned engine unit can handle approach and departure, convoy type sailing with one manned and several unmanned ships and possibly other principles..

This document includes a simple and qualitative cost-effectiveness assessment as the complexity of interaction between constraints is too high to do a more thorough analysis today. New tools are needed to do this with any significant degree of accuracy. The project has done a more thorough cost-benefit analysis on one type of future ship, the unmanned bulker. This is documented in D9.3 /2/. This ship type is, however, not discussed here. The reader is referred to D9.3 for more information on that concept.

Given the commercial interest in the concept of unmanned shipping, it is still safe to say that unmanned ships have a high potential for increasing efficiency and reducing costs in shipping and at the end of MUNIN much more is known about how the obstacles can be overcome. In this document, obstacles have been described as constraints to show that it

is really possible to implement unmanned ship and create a viable business model using them.

The results presented here have been systemized by MARINTEK, but the material has been based on discussions in a workshop in the MUNIN project as well as discussions with other stakeholders.

1.2 Structure of document

Section 2 discusses the challenges and obstacles to unmanned shipping. These are converted into a set of constraints that are described in section 3. Section 4 discusses the fuel use issues in more detail as the CBA in D9.3 shows that the fuel cost is a very important factor in shipping. Section 5 includes some more details on the constraints on the business models that also have to be taken into consideration.

Sections 6 to 7 will propose two business cases for a deep sea container ship and an offshore supply vessel.

Section 8 will give a brief conclusion to the report.

Deliverable D10.1 will similarly discuss issues related to short sea shipping in Europe. This will be based on the same constraints as have been described here.

2. Main challenges for unmanned ships

2.1 Risk assessment and safety issues

The results of the MUNIN risk assessment are described in deliverable D9.2 /1/. The risk assessment also includes a list of risk control options (RCO) which is repeated in Table 1. If the RCO means a significant constraint on the operation or design of the unmanned ship, the reference column gives a link to the appropriate description in Chapter 0.

Table 1 – Risk control options

RCO	Risk Control Option	Ref.
1	Careful design of SCC and SCC manning as well as training of personnel.	3.2
2	Design of on board systems for easy maintenance and accurate monitoring of maintenance state. Must also be fast to repair.	3.4, 3.7
3	Ship should be unmanned at all times.	3.1
4	Need to avoid heavy or otherwise dangerous weather – use of weather routing	3.13
5	Need good sensor and avoidance systems. Selected systems must also be redundant so that a single failure does not disable critical functions.	3.10
6	Ship should be directly controlled in heavy or complex traffic.	3.11
7	Need redundant power generation, distribution, propulsion and steering	3.9
8	Automated fire extinguishing systems are required in all relevant areas. Note that no crew makes this simpler as areas are smaller and that CO ₂ more safely can be used.	3.6
9	A ship without accommodation section is much easier to secure against stowaways in enclosed spaces.	3.1
10	Cybersecurity measures are important, including alternative position estimation based on non-GPS systems. The SCC may be particularly vulnerable. Data links must also have sufficient redundancy.	3.10
11	Improved cargo monitoring and planning is required.	3.15

2.2 Economy

WP9 has performed a cost benefit analysis in more detail for one specific class of ship, an unmanned dry bulk carrier. This section will go through some main issues directly related to cost savings or increase and try to draw some conclusions on the effects this will have on the types of unmanned ships. This is a qualitative assessment. Refer to deliverables from WP9 and in particular D9.3 for more detailed analysis results.

Note also that the work in WP9 and 10 has been done in parallel and with slightly different objectives, so there are some differences in the models used as well as in the interpretation of the models. WP9 has also done more work on prognosis on development of costs over the coming 20 to 25 years while this report restricts its analysis to the situation today.

2.2.1 General cost model

Stopford /7/ has calculated the cost of running a 10 year old Cape Size bulker in 2005 and some of the relevant details are shown in the figure. The left hand side is a breakdown of the total costs to the right. The lower right shows the final share of the total cost attributable to manning and fuel. "Fuel" is the fuel for the main engine (HFO) while "Diesel" is the fuel for auxiliary engines (normally MGO).

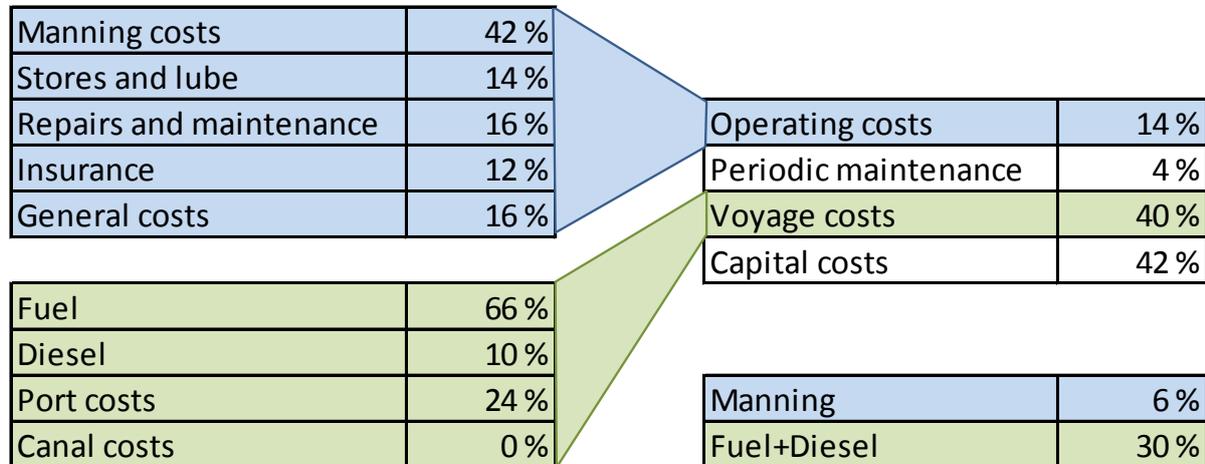


Figure 1 – Total cost of running a Cape Size bulker in 2005

With the sudden decline in fuel costs, they are comparable today (2015) to what they were in 2005, but if we consider a new build in 2015 rather than a 10 year old ship in 2005, one can probably expect that the relative portion of both crew cost and fuel cost will be reduced due to lower manning and more efficient energy systems. Also, capital costs will likely be higher due to increase in prices and considering that it is a new ship. This may mean a share of fuel costs on perhaps around 25% of the total running costs and manning costs of 5%. Slow steaming will further reduce the fuel cost although it will also decrease revenue per day.

2.2.2 Summary of the main effects of the cost factors

Table 2 summarizes the issues discussed in following sub-section and shows expected impact on capital cost (CC) and operational cost (OC) as well as referencing issues in the constraints section (Ch. 0) that are derived from these criteria. A minus (-) means reduction and a plus (+) means increase. Where there are parenthesis around the plus or minus, it means that this expectation varies considerably and may even be opposite in some cases.

As is clear from the discussion, it is very difficult to assess a final outcome of a full cost benefit analysis as there are many interacting factors, including effects of future regulations, which will have an effect on the costs.

Table 2 – Impacts on operational and capital costs

Cost issue	CC	OC	Constraint
Remove accommodation	-	-	3.1
Less complex mechanical systems	-	-	3.4
Redundant propulsion	+	(+)	3.9
More complex IT systems and communication	+	(-)	3.6, 3.10, 3.12
More advanced cargo handling	+	(-)	3.5, 3.15
Shore Control Centre	+	-	3.2, 3.11, 3.13
Fuel type – no HFO	-	+	3.7, 4
Short sea automated loading and discharge	+	-	3.5
Maintenance and off-hire	+	(-)	3.1, 3.4, 3.7, 3.8

2.2.3 General capital costs

As fuel costs probably will be higher for unmanned ships (see 2.2.4), the ship will probably have to be built without accommodation section and with less complex technical systems on board to correspondingly reduce capital costs. Necessary and additional computer systems, redundant engines, power distribution and IT will on the other hand increase capital costs as will more advanced instrumentation and sensor systems. It may also be necessary to have more complex systems for cargo monitoring and conditioning as no one is onboard to monitor and handle cargo related incidents. However, the expectation is that unmanned ship may be somewhat cheaper to build.

2.2.4 Fuel costs

As discussed above, fuel is in many cases a dominant factor in the overall cost for operating a ship. This is more so for deep sea and long distance shipping, but it is important also for other trades. However, changes in regulations and new technology will also impact how conventional shipping uses fuel and it is in general very difficult to assess how the comparison for future ships will actually end out. This is discussed in more detail in Section 4.

2.2.5 Other operational costs

Manning the SCC will increase costs, but less than the savings on not having crew onboard. Reduced crew costs also include no provisions for the crew, trips home, insurance etc.

For short-sea shipping one will also have to consider full automation of loading and discharge operations. This has a great potential of reducing operational costs, while it certainly will increase capital costs. For deep sea trade, shore side services are not that dependent on being automated.

2.2.6 Off-hire and maintenance

Improved maintenance regime may lead to reduced maintenance costs and cost of off-hire, including better planned dry dockings. On the other hand, as maintenance only can be done onboard during port calls, one may see that the length of the dry docking increases. One will probably have to use more durable and expensive materials for, e.g. coatings, but this may to some degree be retrieved by having higher availability and less maintenance work.

2.3 Legal and contractual issues

Insurance and contractual seems to be manageable for unmanned shipping. The key element here is to provide sufficient proof that the system is reliable and safe and that legal liabilities can be maintained within reasonable boundaries.

Legally, the establishment of internationally accepted codes and regulations for unmanned ship will take a long time. Until this happens, one needs to rely on unilateral agreements with flag and port states to be allowed to set up specific trading arrangements. This means that general unmanned tramp shipping is a very long term proposal while liner or short sea shipping can be established relatively fast. National trade only requires acceptance from the one nation where operations are taking place.

Signals from flag state and port state authorities are that many will be willing to accept deviations from national rules on manning and equipment as long as it can be documented to be safe.

These issues will probably have little impact on cost, but they will have an impact on the possible business models. This is discussed further in section 5.

2.4 Public opinion

The general impression from MUNIN is that there is relatively little resistance from the general public against unmanned ships. There are some worries about the fate of the maritime professions, but this should not be a large issue: Relatively few ships will be unmanned, there will be jobs in the SCC and autonomous shipping will strengthen the competitiveness of European shipping in general, possibly creating more jobs in this sector than today.

Another issue that should not be underestimated is that the public may be sceptical to large ships operating autonomously in heavy traffic and close to shore. It may be better to use direct remote control or other features in these areas. However and in the longer run, if special legislation is passed for traffic management of autonomous ships, this becomes more likely to be an acceptable operational mode also close to shore and in heavy traffic.

2.5 Environmental issues

In general, one can assume that the environmental gains of unmanned shipping will be significant. Some of the issues that can be mentioned are tabulated below.

Table 3 – Some examples of environmental benefits

Environmental benefit	Constraint
Less accidental spills, safer ships	3.1, 3.9, 3.10
Cleaner fuels, less noxious emissions to air	3.7
Greenhouse gas (GHG) emissions	3.9
More controlled management of ballast and other discharge	3.4, 3.15
More goods transport on sea	3.5

The actual emission of greenhouse gases (GHG) will depend on the type of fuel and operations. As discussed in section 4, this is a very complex issue.

3. Constraints for an autonomous ship

This section summarizes the identified constraints that have to be considered when a business model for unmanned shipping is created.

3.1 No crew on board at all

The safety analysis has assumed that the risk of danger to human life on own ship is zero as there are no crew. It is quite clear that this is an important point from a safety perspective as injuries and deaths at sea mostly are related to accidents solely associated with activities on own ship. Thus, the attractiveness of autonomous shipping in terms of increased safety relies heavily on having no crew on board during most or for the entire voyage.

This is also an important point as no crew also means that one may remove the accommodation and associated life support systems which have a large impact on capital and operational costs. Energy consumption in the accommodation is significant.

Note in particular that even a small boarding crew, if they stay on board for longer times, need some sort of life support that will increase cost, require maintenance, take up space and offset some of the safety gains. Particularly boarding and leaving the ship in open sea is both a safety risk and can be a costly affair. Thus, the boarding crew originally foreseen in MUNIN should be replaced with an escort boat or direct shore control in coastal waters.

3.2 No passengers

An obvious extension to the previous point is that unmanned ships should not carry passengers. In addition to the arguments above, the mustering and evacuation of passengers during emergencies is dependent on assistance from more experienced crew which is not available in these cases.

This restriction may also apply to fairly short voyages, e.g., with highway ferries which would otherwise be an interesting case for unmanned shipping.

3.3 Need for high quality shore control centre

The shore control centre (SCC) is a critical part of the autonomous ship system and needs sufficient manning with qualified personnel. This will incur an additional cost on operation, but probably less than the manning cost would be elsewhere.

The SCC in control of a specific ship may also be changing from time zone to time zone so that it can avoid using night shift. This is however an issue with some legal implications, if it is decided that the SCC will take the role of the master in a legal sense.

Finally, one should also note that the SCC will be a significant security risk unless it can be assured that no unauthorized personnel can access the premises. As the SCC has

direct control of the ships, an intruder can, e.g., ground a ship to block the approach to a large port.

3.4 Simplified design of autonomous ship systems

The endurance of the ship on long voyages as well as the impossibility to do corrective work on the ship during the voyage requires systems that have low maintenance requirements. This can be achieved by minimizing number of and complexity of ship systems that cannot be operated reliably without continuous maintenance. This should include the removal of the accommodation section and all life support system, may imply ballast free operation to avoid problems with pumps and ballasting, use of improved coating and so on. The operation of the HFO system is a special issue that is described elsewhere.

Diesel-electric propulsion with generators and engines on deck, e.g., in easily replaceable containers, is in this context an interesting concept. However, today's generators will use smaller engines with significantly lower efficiency than the large two-stroke diesel engines. This may be a problem versus fuel costs for large ocean going vessels.

This constraint may both lower and increase capital costs of the ship dependent on how it is applied. Operational costs should normally be significantly reduced, except perhaps for more advanced coating materials.

Ballast free operation has been exemplified in various types of ships. DNV-GL has launched one concept for a medium sized (6200 TEU) container ship called "Quantum".



Figure 2 – Quantum container ship concept by DNV-GL /15/

The ship is relatively wide which is claimed to minimize need for ballasting during voyage. However, some ballast is still necessary and particularly during loading and discharge when it may be difficult to maintain a reasonable trim without ballast tanks.

It is possible to improve further on the ballast issue if, e.g. a more trapezoidal or v-shaped hull form is used. Dependent on other factors, this may, however, decrease fuel efficiency.

With future requirements to ballast water treatment, there are also economic factors that may give added value to designs that remove the need for using ballast tanks.

3.5 Automated loading and discharge for short sea shipping

Use of unmanned ships in short sea trades will probably depend on automated loading and discharge as no crew is onboard to assist. This is also important to keep operational costs as low as possible. This will either incur a higher capital costs or an increase in port fees, but a lower operational cost for the ship itself.

For ships calling on large to medium sized hub or feeder ports, this may not be a big problem as these ports usually have advanced shore side systems for cargo handling. For ships calling on smaller ports without much infrastructure on shore, this needs to be considered carefully.

3.6 More extensive fire detection and extinguishing systems

The unmanned ship will probably need more advanced fire detection and extinguishing systems. As no persons can respond to a fire alarm, it needs to be handled on the ship automatically or under control of SCC.

On the other hand, as no persons are onboard, one may safely make use of CO₂ extinguishing in all enclosed spaces. However, it must be safeguarded against release if stowaways or shore personnel can enter these spaces.

3.7 Use of HFO and other fuels such as LNG

The need for processing of HFO on board and problems of switching between HFO and MGO during port calls in ECA areas makes it challenging to use HFO on board. There is a fairly complex fuel processing system associated with HFO that may be difficult to operate reliably without humans on board unless some developments in these systems are made.

Dependent on developments in general sulphur content requirements in IMO and developments in scrubber and catalyst technology, various solutions to this problem can be seen. One interesting option is the use of LNG which is very clean and at least in lean burn mode have acceptable emissions even without any exhaust cleaning.

3.8 Preventive and periodic maintenance

Systems must be monitored and the autonomous ship will need facilities for detecting technical problems long before the equipment fail. Today's technical shipping operations are to a large extent based on continuous technical maintenance by the crew as well as repairs by the crew when something breaks down. In addition, the ship is normally put in dry dock for several weeks each 2-3 years. While in dry dock, the ship undertakes major overhaul and repairs that cannot be done during operation.

An unmanned ship cannot base technical operations on routine repair being undertaken while sailing, with the exception of work that can be done during port calls. Other technical maintenance must be done while in dry dock. Other technical work, e.g. cargo hold cleaning must likewise be automated or done while in port. Particularly for SSS, port stays and port approaches tend to be relatively short.

The criticality and complexity of monitoring and maintenance planning will increase as voyage lengths increase. Thus, shorter voyages may be preferable for initial autonomous ship concepts.

3.9 Redundancy in propulsion and energy systems

Technical failures have been identified as a major risk that can cause various types of hazards. Redundancy of critical systems is a necessary measure to decrease the risks associated with such failures, particularly in the propulsion and steering systems.

In the 2014 EMSA report /6/, loss of control, which is a typical consequence of engine or propulsion failure, represents 27% of incidents at a count of 781 incidents. This gives an indication of the potential problem related to single drive trains when no crew is onboard to repair.

Redundancy will mean that critical systems are duplicated in a manner where an error in one system does not significantly impact the function of the alternative system. In practical terms it means that at least all critical electronic systems must be duplicated, that the propulsion and drive train systems must be doubled and that electrical power distribution needs to be redundant.

As will be discussed in section 4 various alternative arrangements have the drawback that they normally are less energy efficient than having one larger engine.

A possible and likely consequence of this is higher capital costs as well as higher operational costs. The latter factor will depend much on type of ship and operation as many ships in special trades already use highly redundant systems onboard.

3.10 More advanced and more secure IT systems

The autonomous ship will need much better instrumentation than conventional ships, including visible light and IR cameras to get an object classification capability at least as good as on a manned bridge.

The ship will also require more communication bandwidth for operation than a conventional ship and it will need redundant communication channels. This may or may not increase costs as satellite communication is getting lower in price and more and more common also on conventional ships. As the crew typically is the biggest user of bandwidth, one can actually expect that the unmanned ship may use less communication bandwidth than the manned ship.

A special constraint is that the bulk of traffic for an unmanned ship will be *from* the ship to shore in the form of sensor signals. This is opposite the normal traffic pattern where, e.g. web browsing and uploading music or films create much more traffic *to* the ship. Most satellite links today are asymmetric in that they offer more capacity to the ship than from it.

Cyber security is a critical issue for the unmanned ship. All control signals must be electronically signed and possibly encrypted. The ship systems should be equipped with safeguards that make it impossible to control by people illegally entering the ship. The SCC is particularly vulnerable for attack and need to have strict access control mechanisms and regimes.

Critical ICT systems also need to be redundant. This applies to sensor and control systems, computer networks and communication systems.

3.11 Direct control or special traffic regulation in heavy traffic

An unmanned ship that can operate completely autonomously in general and dense ship traffic without direct human control or by using special rules for right of the way is a challenging prospect. The operation in heavy traffic has also been identified as a non-acceptable risk, unless proper risk control options are employed. For MUNIN the primary risk control option is direct control, either by an onboard team or by remote control in heavy traffic areas. In the future, more advanced automated systems may also be possible.

It is possible to create an autonomous control system that sails the unmanned ship at least as safely as a manned ship even in congested waters. Advanced formation control has been demonstrated both for flying and floating unmanned vehicles. The challenge for an unmanned ship is mainly the interactions with manned ships, where the forecast of the ship's behaviour is less certain. Such a system would require very advanced and complex situation analysis and manoeuvring algorithms that would be costly to develop and difficult to verify with respect to their safety properties. This would make it difficult

to get acceptance by authorities and probably also by the general public, at least for the near future.

Thus, it may be prudent at this stage not to rely on autonomous technology for navigation in congested waters. Early in the MUNIN project, the proposal was to use a boarding crew that manned the ship more or less according to international regulations and took it safely to port. This is possible and may be a good way to solve port state legislative problems related to unmanned ships. However, as discussed in 3.1, a very attractive option with the unmanned ship is to remove all accommodation functions and areas. This would obviously impact the boarding crew's working conditions. This may not have a big impact on short passages, but any delays or longer passages would require some support functions for the crew that would negate some of the gains of removing the accommodation areas. Using this approach also causes some safety issues and costs related to boarding or disembarking from a ship some distance from the shore.

A more attractive option may be to make use of the normally much higher and cheaper data bandwidth available close to shore to implement direct remote control. Mobile 4G or 5G networks should be available in many areas and this gives a high capacity and high reliability communication link for direct remote control. If desired, one can transmit high definition live video to the control team as well as all relevant and necessary dynamic information from the ship. The link would have very low latency and would be well suited to remote control operations

Another similar alternative would be to use an escort ship to shepherd the unmanned ship into port from some offshore operation. This is more costly, but could be relevant in situations where shore based infrastructure is less developed or where the direct control needs to go over longer periods, e.g., a transit through the English Channel or the Straits of Malacca and Singapore. This requires the same dedicated line of sight communication as described above, but it would probably be implemented by e.g. direct radio link with microwave technology in this case.

If the latter approach was implemented, this could also be used to run convoys of unmanned ships in deep sea crossings or during concept testing where one manned mother ship guided the unmanned ship in the convoy. The line of sight communication link would in this case connect the mother ship to the unmanned slaves.

An alternative proposal is to give autonomous ship special rules for right of way in congested waters. For national waters, this is feasible, but would be a problem to implement in international channels where innocent passage applies. The latter case would probably require some form of agreement in IMO. Special right of way rules would make it much simpler to implement the necessary sensor and control systems.

3.12 High capacity line of sight communication link

As noted above, it may be more convenient to guide the ship in heavy traffic from a land position or from an escort boat when in congested areas and near shore.

For direct guidance, the ship will need a high capacity (on the order of 3-5 megabits per second) data link for direct transfer of HDTV and sensor and guidance signals. This needs to be secure and safe. The technology is readily available and may even be implemented using 4G or 5G mobile technology.

3.13 Heavy weather avoidance is more important

Certain complex operations like sailing in very rough weather can be challenging for unmanned ships. However, as sensor and on-board control systems evolve and as high capacity communication systems make remote control easier, it is not unrealistic to foresee that unmanned ships can operate as safely as manned ships in all equivalent conditions. However, this issue must be taken into consideration and for initial tests one may want to avoid this situation if possible. This will require good weather routing systems as well as specific weather related fail to safe routines on the ship.

3.14 Documented safety and security

It will be critical to provide convincing documentation that unmanned shipping is at least as safe and secure as manned shipping. This will be a key factor in getting reasonable insurance and contractual terms, in the absence of statistical evidence for the safety of such ships.

This type of documentation will also be a prerequisite for getting approval from flag and coastal states to operate unmanned ships.

3.15 Dangerous or difficult to handle cargo

There may be limits to what cargo an unmanned ship can carry. If the cargo cannot safely be handled without regular human inspection or intervention, it cannot be carried on an unmanned ship without new types of automation.

Measures to avoid such situations include:

- Better vetting of cargo before loading (avoid humidity in cereals or iron ore etc.)
- Dangerous cargo may not be permitted if crew is needed to safeguard it.
- High value cargo that may be attractive to pirates may not be carried.

This has to be analysed on a case by case basis and the restriction may be lifted if suitable monitoring and automation systems are installed.

4. Specific fuel cost issues

In general, the most efficient and lowest operational cost ship engine is a direct drive slow speed large diesel engine running on HFO. However, both the use of HFO and having only one engine has been identified as a problem area for the unmanned ship.

The impact of the fuel and engine configuration on the total cost of the unmanned ship is very high and this section will go through some of the issues that will have an effect. It is a very complex trade-off between the different factors. Before realization of an unmanned ship concept, this will need to be analysed much more carefully for the selected business cases.

Again, the reader should refer to deliverable D9.3 /2/ for a more quantitative analysis of these issues.

4.1 Benefit of large engines and the problem of two engines

Redundancy requirements will not allow the use of one large engine unless a very high reliability can be guaranteed. As the efficiency of a diesel engine normally decreases with the reduction of the stroke length and size of engine, fuel oil consumption will typically increase with two smaller engines rather than one large.

The figure shows the relative specific fuel oil consumption (SFOC) as a function of the engines power in MW under a constant set of operating conditions. The data is taken from the MAN data sheets /8/ for a selection of two stroke engines, with rated output power (MW) with 6 cylinders and at 75% optimized load range, high load. The baseline (0%) is the largest engine (42 MW with 6 cylinders) and the graph shows relative increasing consumption as engines get smaller, but still with 6 cylinders. This is very simplified, but shows the general relationship.

One can observe that the highest reduction in efficiency is mainly for medium and small engines below about 10 MW. This indicates that plants with high installed power, above 20 MW in total, do not lose that much efficiency.

On the other hand, two propellers have benefits in terms of how well energy on the shafts is converted to speed of the ship. This is further discussed in D9. 3 /2/ and it is claimed that the Maersk EEE (installed power 2*32 MW) in total saves 4% fuel compared to a single engine system¹. Also, capital costs is said to be lower as more standardized and easier available engines can be used. Thus, using two propellers may reduce fuel consumption and total costs, if the efficiency of the engines themselves is not decreased too much.

¹ <http://www.ship-technology.com/projects/triple-e-class/>

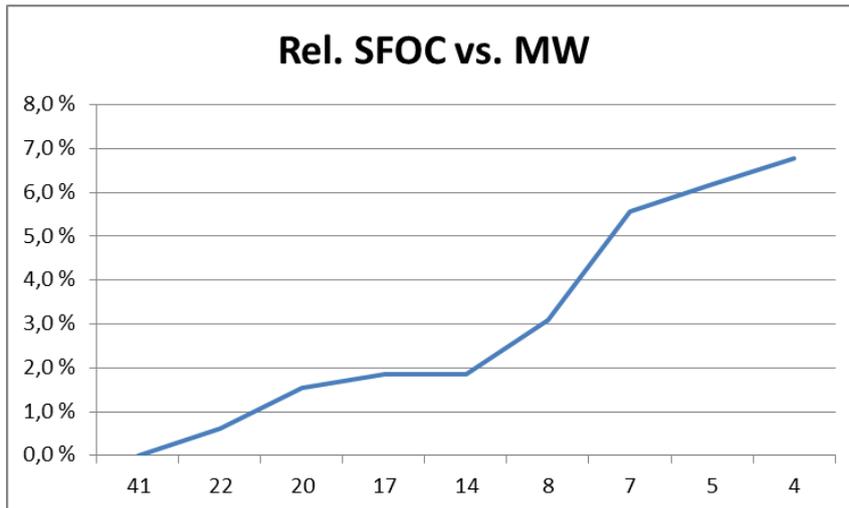


Figure 3 – Selection of 2 stroke MAN engines: Relative SFOC vs. engine power

This means that large ships may in some cases use a two engine configuration and still be economically competitive with conventionally manned ships with regards to fuel related costs.

4.2 Very low cost of HFO

The main differences between manned and unmanned ships in terms of fuel costs are that a much higher operational cost may be assumed for unmanned if HFO cannot be used. Using distillates will certainly be problematic as MGO prices are from 60 to 100% higher than HFO, independently of HFO price fluctuations.

However, with generally reduced fuel prices, which are the case at time of writing, the comparison between savings on other factors than fuel (including crew) will be much more in favour of the latter.

Figure 1. North Sea Brent crude oil spot prices in three cases, 1990-2040

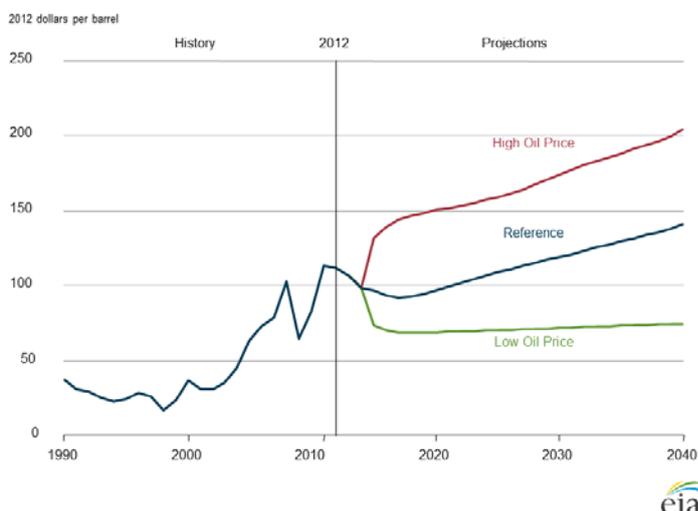


Figure 4 – North Sea crude oil spot prices, US\$ per barrel /13/

4.3 Fluctuation in fuel prices

The impact on fuel prices on the feasibility of various technical configurations is further complicated by the fluctuation in prices of the different fuel types. One factor in this is the changes in crude oil prices as illustrated in Figure 4 /13/.

The figure shows development in oil prices and projections by the US EIA. This projection was made before the recent drop in prices and even the low estimates have not caught this issue. This illustrates the uncertainty of this type of forecast.

4.4 Doing pre-processing of HFO on land

The problem with HFO on board an unmanned ship is related to complex processing of the fuel before it can be used by the engine. This includes settling, separation, heating, filtering and adjustment of the injection systems. The often unknown properties of the fuel require analysis and adjustments of the engine systems before the fuel can be used safely.

It may be possible to do parts of this processing and analysis on land before the fuel is loaded on board the autonomous ship. This will add capital and operational costs, but probably less than what is the case if one has to operate with MGO. Also, as the ship operates in a form of liner traffic, it will regularly call on a port where processed fuel is available.

4.5 LNG as alternative fuel

LNG is a very clean fuel that has the potential of creating new engine concepts that require very little manual intervention and maintenance. There are still some problems with LNG, but these are rapidly being addressed as more experience is being built.

One problem with LNG is the somewhat more complex fuel lines and bunkering arrangement. Special rules apply to ships using gas fuel to avoid fire hazards in the engine room. On the other hand, this is well known technology and any increase in cost for these systems may be offset by simpler fuel management systems in general. There is no need for separation, heating and other processing of HFO and there is no need for alternative arrangements for operations in emission control areas (ECA).

Another and more acute problem is the size of the storage tanks. LNG has significantly lower energy density than HFO per volume unit and the use of cylindrical heavily insulated storage tanks may use excessive space onboard. A rough estimate is that one needs twice the volume of LNG storage compared to HFO.

However, for an unmanned ship without accommodation section it may be cost effective to install the larger fuel tanks needed for LNG in the area where the accommodation would have been. Also new membrane LNG tank technology removes the restriction of using cylindrical tanks.

LNG, when used in suitable engines, will also solve all SO_x, NO_x and Particulate Matter (PM) emission problems independently of area and expected regulation level. It will also reduce CO₂ emissions with up to about 25% when the engine is designed and operated properly.

The price of LNG has always been lower than for MGO and close to or even below that of HFO in periods. Future developments are difficult to foresee, but the expectation is that the cost of LNG will not be a limiting factor, given that it can save costs on fuel processing and operations in ECA.

The price problem is normally restricted to the higher capital costs required. Today LNG machinery and fuel systems are significantly higher than for HFO systems. This may change as LNG becomes more common as fuel, also on larger ships.

Availability of LNG is also often quoted as a problem. For liner type shipping, this should be less of a problem as the availability will be required only in the ports actually called on and these would be known a fairly long time in advance of commencing operations.

The relationship between the prices of different types of fuel will vary dependent on time and area. This is particular true for the relationship between gas (LNG) and fuel oil.

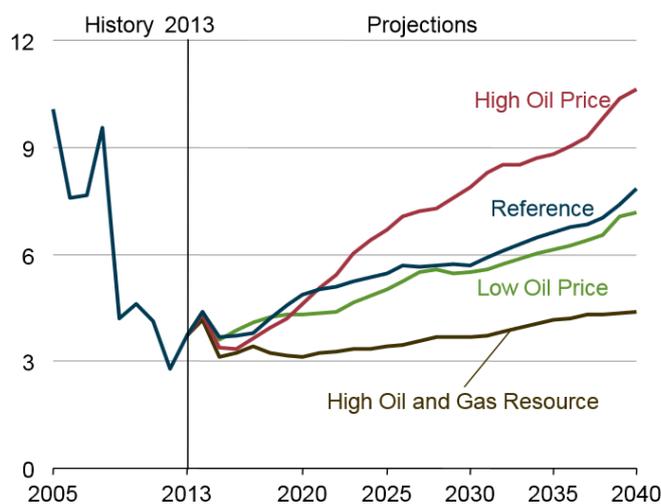


Figure 5 – Average Henry Hub spot prices for natural gas, US\$ per MBtu /13/

Figure 5 shows natural gas prices since 2005 as well as predictions towards 2040 /13/. As can be seen from the graph in Figure 4, there is little historical correlation between gas and crude oil prices, except for the period approximately after 2008.

Prices of LNG vary geographically and substantially more than prices of HFO. Projections by US EIA /13/ indicate that natural gas will sell for 3 to 8 US\$ per MBtu (Million British Thermal Units) in the period 2015 to 2014. HFO has an energy content of about 41 MBtu per metric ton. This indicates an equivalent LNG price of US\$ 123 to 328 in the same period. This is less than half the projected price of HFO, but is probably

not correct when dealing with LNG delivered to ships as bunkers (see also Figure 5). Other sources reported that at the end of 2013, LNG prices corresponded to about 60% of HFO prices and 40% of MGO prices, based on energy content /14/. Thus, LNG will probably be cheaper than HFO, but it is unclear by how much.

There are a number of very positive reports available on the use of LNG and in general a large and positive industry interest /9/, /10/, /11/.

4.6 Lower efficiency of diesel-electric propulsion

An interesting proposal is to use diesel-electric propulsion with generator sets in containers on deck for easy replacement. This would allow low maintenance electric engines to be used in propulsion systems while also providing redundancy and easy maintenance in the power generation systems. One could also consider replacing the generator sets with batteries or fuel cells when new technology becomes available.

One problem with this approach is that most generator sets use smaller 4 stroke engines with lower energy efficiency than the larger 2 stroke engines. As an example, a 9 MW 4 stroke motor may have a relative SFOC that is 12% higher than the large 41 MW engine in Figure 3 /8/.

Using diesel-electric propulsion will also decrease efficiency due to losses in conversion from and to electric energy. Typical generator efficiency may be around 97% /8/ and the electrical engine is also not 100% efficient. Losses in cables and switches also have to be accounted for, so a lower fuel efficiency of 5-7 % is probably realistic.

However, electric propulsion also increases flexibility and will have significant benefits in variable load cases. By using, e.g., three or four generator sets one can always run combustion engines at optimal RPM, independent of actual ship speed. By adding storage units, e.g. batteries or capacitors, one can also rapidly change load on the propeller without changing speed of generators. Maintenance is much lower and by having generator sets on deck in containers, it is easy to replace one to do maintenance on shore between voyages. Thus, the complete picture is very difficult to establish without going into a very detailed analysis of technical solution and operations profile.

4.7 Effects of emission regulations

One also needs to consider the effects of the introduction of NO_x and SO_x emission limits in Emission Control Areas (ECA) and globally. If the new SO_x global emission limit of 0.5% enters into force, this will also have an impact on existing manned shipping in that they either have to install scrubbers or use low Sulphur fuels. Either will increase the relative cost compared with unmanned ships. Existing regulations in ECAs have stricter requirements and here it is normally implemented by switching to MGO in these areas.

As will be discussed in the next section, this causes operational problems as well as an increased cost compared to clean fuel systems.

4.8 Problem of changing fuel during the voyage

The problem of fuel changes during voyage is illustrated in Figure 6. It shows number of registered engine stops during operation in and near respectively Long Beach and San Francisco Bay Area in the period 2004 to 2011 /4/. In 2009 the ECA regulations came into force which forced many ship operators to switch to low sulphur fuel before entry to port. When adjusted for the yearly number of calls /5/, the data shows an increase from 5 stops per thousand ships in 2004-2008 to 11 stops per thousand in 2010-2011.

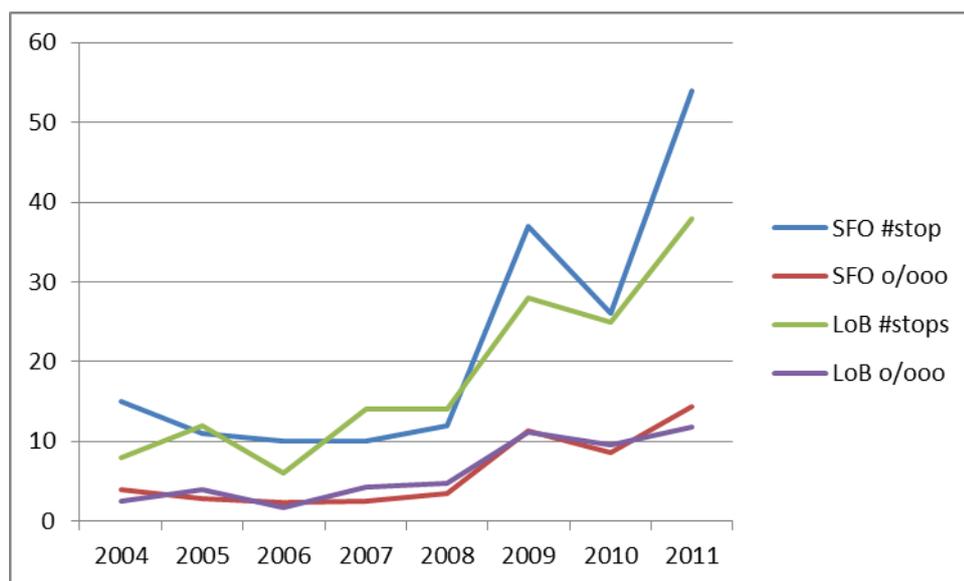


Figure 6 – Engine stops outside Long Beach (LoB) and San Francisco (SFO)

The problem occurs because the HFO and MGO fuels are very different in viscosity and in need for heating. The process of changing normally takes several hours and in this period one must very carefully adjust heating and other machinery parameters so that engines systems tolerate the change in physical characteristics.

Thus, by going to cleaner fuels there is also a reduction of technical problems that can also lead to economic losses due to off-hire or by arriving late in the port. This is of course also a significant safety risk and accidents can easily happen when the engine stops.

4.9 Energy use in other areas of the ship

On a conventional ship, the accommodation section may account for up to 10% of energy use on the ship /12/. In addition, about 5% may be used for steam generation which under way is mainly used in fuel processing. Not using HFO will reduce the need for fuel heating and steam. This is a potentially large saving for unmanned ships.

5. Business model issues

The constraints that have been identified in section 0 and the corresponding cost-benefit issues will obviously have an impact on the business models that are possible for unmanned ships, at least in the short run. With technical and regulatory developments, the picture will most likely change.

This section will describe a few obvious limitations based on the known constraints.

5.1 Fixed home ports and liner shipping

The unmanned ship needs various types of support functions in the ports it calls on. This includes shore control, remote guidance, fuel processing, maintenance and other functions. Until unmanned shipping becomes a more common operational method, this will make tramp type shipping less interesting. Short and medium term legal issues will also make it difficult and costly to call on arbitrary ports. Thus, various forms of liner shipping are more realistic alternatives today.

5.2 Fleet management issues

Introducing one unmanned ship in a large fleet of conventional ship will increase owner's operational costs as specialized manning has to be used for the one ship. This will create a threshold for introduction of unmanned ships in more general fleet type operations.

This may make it more interesting to initially look at smaller and more specialized operations where the problems of having few ships may be reduced. This can be various forms of short sea shipping, including supply services to offshore installations.

5.3 Fuel types and redundancy requirements

The problems with redundancy and not being able to use HFO may make it less interesting to use unmanned technology on medium size bulkers or general cargo ships. Very large ships may still have good performance with two main engines and smaller ships in more complex trades are less sensitive to the fuel cost issues.

This may mean that the initial MUNIN case with a handy size bulk carrier is less realistic. These ships will also be hit by the fleet management problem as well as the liner issues. Many of these ships are in tramp trades.

5.4 No passengers

As discussed in chapter 3, it is probably unrealistic to look at business models involving carrying passengers. Exceptions may be very short ferry stretches where sufficient safeguards are in place to make it unlikely that an accident would require passengers to leave the ship before professional assistance can be provided or where passengers have the means and knowledge to make the necessary safety arrangements themselves.

6. The unmanned deep-sea container ship

For conventional deep sea shipping it is normally the cost of alternative fuels or engine arrangements which will be a dominant factor. As Maersk has shown that it makes sense to build the large EEE class with two engines and shafts, this proposition could also be applied to other large vessels. In this case we have looked at a 10 000 TEU container ship in the trade between China (Shanghai) and west coast of USA, e.g. Los Angeles.

The ship could be quite similar to the DNV-GL proposed Quantum concept discussed briefly in section 3.4 and documented in /15/.

Table 4 – Overview of constraints for large container

Constraint	Solution
1. No crew	Relatively simple ships (6.1)
2. No passengers	Ok
3. Quality SCC	Ok
4. Simple design	Relatively simple box ship, no ballast system (6.2)
5. Automated cargo	Container fastening/release required (6.3)
6. Fire protection	Ok
7. Fuel issues	LNG or MGO, alternatively HFO processing on land (6.4)
8. Maintenance	Ok
9. Redundancy	Twin two- or four-stroke, podded propulsion (6.5)
10. Secure ICT	Ok
11. Heavy traffic	Short approach, no channel (6.6)
12. Direct control	Ok
13. Heavy weather	Ok
14. Documented safety	Ok
15. Dangerous cargo	Container monitoring (6.3)

The table gives a brief overview of how the constraints have been dealt with and where it says "Ok" it means that it can easily be satisfied as described elsewhere in this report. Some more critical constraints are specifically addressed below.

The cost-benefit analysis for Quantum does not directly apply to the corresponding unmanned ship. The main issues are:

- LNG may be more attractive for unmanned as there is space available where the accommodation used to be.
- Azipods are not so interesting for unmanned ships as shore support and tugs probably would be necessary for port operations in any case.

- A twin-skeg ship would be needed for redundancy. Diesel-electric may also be a better alternative to reduce maintenance. This would also further increase space for LNG tanks, although some deck space must be used for generator sets.
- It would perhaps be worth-while to investigate other hull forms that would remove the need for ballast altogether.

Other than this, many aspects of the analysis can be used.

6.1 No need for crew

Large container ships are relatively simple ships and crew are mostly needed for routine onboard operations that in any case have to be automated or removed in an unmanned ship. The exception to this may be monitoring and maintenance of non-standard containers and in particular reefer and controlled atmosphere containers.

Looking at container shipments, statistics on claims is not so easy to come by, but from 2000 it was reported that about 14% of container related claims were related to missing temperature control /16/. However, claims were in many cases related to mishandling of containers before they were loaded on the ship or after arrival and there is no accurate figures on how many containers need manual intervention during sea voyage.

One must in any case install monitoring systems so that such claims can be restricted to those cases where a technical failure on board is cause for the loss. Also, by improving the vetting of container before they are loaded on the ship one can reduce many of the technical issues.

Cargo operations are fairly demanding, but these can be performed by shore crew, boarding the ship after berthing. Large container ships will always rely on shore cranes and equipment for cargo handling.

6.2 Simple ship type

The container ship is a fairly simple ship type and normally intended for shore based cargo handling. It is also a ship type that can make good use of additional deck space when accommodation is removed.

It would be useful to look at possibilities for simplifying the ballast system, but this may be difficult as the ship normally need to adjust ballast during loading and discharge to keep the stability under control. However, with more advanced cargo planning, one may perhaps manage to do away with the ballast system, e.g. based on the Quantum concept /15/.

With no accommodation and no ballast, the ship will have very few auxiliary systems that can fail and should be much more maintainable than conventional ships. There is

still an issue on cargo monitoring and control as well as on the handling of reefer containers, but this should not impact under-way operations much.

6.3 Automated cargo operations

Containers will require on ship crew during fastening and release of containers. This is, however, no worse than for current ships. Assistance will be needed to connect reefer containers to power sources and for securing and lashing the containers.

During transit no particular attendance is required. However, for safe operation at sea, all on shore container operations must be of high quality so that accidents are avoided. This includes knowing actual weight and content of containers, full control of in-container stowage and good planning of the loading and discharge of the ship.

Monitoring of containers may require dedicated bandwidth for measurement signals. Temperature control or other control signals may in some cases be required.

6.4 Fuel type

The Quantum concept suggests use of LNG or combined fuels. Given the ECA-restrictions and the difficulties inherent in fuel changes, alternatively the added complexity with scrubbers or catalytic converters, it seems that either LNG or MGO are the best alternatives. With no superstructure and more compact machinery, it may be that space loss due to LNG tanks may be compensated for. With current prices, LNG seems an attractive alternative.

6.5 Engine configuration

The most interesting configuration would be two electric propulsion motors operating a twin-skeg configuration. This would get many of the fuel savings while also providing an easy to maintain system and sufficient redundancy for deep sea operation.

Alternatively, one could also use two LNG powered engines directly driving the same propeller and rudder configuration.

Azipods are not relevant for this type of unmanned ship for reasons as noted above.

6.6 Simple sailing

The sailing between USA and China is a relatively simple operation with short passages between sea and port and with no channels. Legally, the operation would only require the cooperation between the two coastal states and the flag state.

It would probably not be worth-while to call on more than preferably one, but at most a few ports on each side. This simplifies port approach operations and would also simplify cargo planning which may be a benefit when implementing a ballast free ship.

7. The unmanned offshore supply vessel

The second example vessel is an offshore supply vessel. These ships goes in more or less fixed round trips from a shore base to a number of offshore platforms with various supplies, including food for crew, spare parts, consumables like diesel oil or lube oil etc. The ships are normally operating exclusively in national waters and both base and platforms have advanced ICT infrastructure to support the ships.

Table 5 – Overview of constraints for supply vessel

Constraint	Solution
1. No crew	Good infrastructure on base/platform (7.1)
2. No passengers	Ok
3. Quality SCC	Ok
4. Simple design	Short voyages (7.2)
5. Automated cargo	Needs development, platform crew (7.1)
6. Fire protection	Ok
7. Fuel issues	Already runs on MGO/LNG (7.2)
8. Maintenance	Ok
9. Redundancy	Already diesel-electric (7.3)
10. Secure ICT	Ok
11. Heavy traffic	Short approach, national waters (7.4)
12. Direct control	Ok
13. Heavy weather	Ok
14. Documented safety	Ok
15. Dangerous cargo	No intervention onboard (7.5)

This case is interesting for the following reasons:

- The technical solutions on the today's manned ships are more or less satisfying the more complex requirements for unmanned ships (redundancy, no HFO). The economic gains of unmanned shipping would be significant.
- The trade represents relatively short voyages between sites with very advanced infrastructure in terms of cargo handling and ICT.
- Working conditions on these ships are not optimal in heavy weather and also in terms of noise and other factors. The ships are relatively small.

The challenging aspects are in cargo handling at the platforms as well as the general safety regime in the oil and gas industry.

7.1 No crew

Sailing the supply ship may be demanding in the North Sea during winter time and more attention will have to be paid to heavy weather operation. On the other hand, most supply ships are fairly uncomfortable working places with much sea movement and noise in addition to inconvenient working hours and stay away from home.

Cargo operations at the platform will be a challenge as crew are used to fasten deck cargo or cargo hoses for loading and discharge. This operation has to be automated or handled by crew from the platform, lowered down on deck to do the cargo handling operations.

Manoeuvring close to the platforms are safety critical and requires use of high redundancy dynamic positioning systems, heave compensation cranes etc. However, communication infrastructure is excellent around the platform and these operations could be undertaken from a control room ashore or on the platform.

Likewise, base approaches will normally be in areas with good communication infrastructure so shore control in critical phases should not be a problem.

The main challenge is the cargo operations at the platform.

7.2 Relatively short voyages - diesel electric propulsion

The supply voyages are relatively short, from a few days to less than a week typically. For each round-trip it will call on the home base where maintenance can be made. Ship complexity is less of an issue than for deep-sea ships.

The ships are often equipped with diesel-electric propulsion and are less sensitive to the cost issues of operating on MGO instead of HFO. Several supply ships in the Norwegian sector of the North Sea is also operating on LNG.

These ships have fairly complex systems on board, but due to short sailing times, the complexity in itself and often adverse weather conditions, one must as a rule assume that crew intervention is not an option even on manned vessels. An argument could be made that an unmanned vessel may not decrease availability of the vessel to any significant degree, compared to a manned vessel.

7.3 High redundancy

These ships are fairly advanced and have a high redundancy level on energy production and propulsion. This is mainly for station keeping at platform. This means that there are no or few additional costs related to increased redundancy.

7.4 National waters and short approaches

The bases and the platforms are in national and usually particularly controlled waters which allows for sailing restrictions for other ships. Also, bases are normally located

close to the open sea, which minimized transit through coastal and more trafficked waters.

7.5 Cargo handling onboard

The supply ships carry dangerous cargo and there are possibilities that deck cargo needs attention. However, it should be possible to ensure cargo safety before leaving port or platform and in any case one may argue that one cannot generally rely on it being possible for the crew to intervene when problems occur.

8. Conclusions

This report has gone through some of the constraints that apply to the use of unmanned ships in general. The main conclusion from this is that unmanned ships are not always equally useful and that relative simple and controlled operational scenarios are where this type of ship fits best. Having no crew onboard to handle technical problems is one of the main constraints and requires solutions that have technical reliability, simplicity and no need for maintenance or intervention during voyage.

Another conclusion is that unmanned ships should be designed from scratch for their intended purpose. Unmanned ships have many constraints that need to be catered for in the design, but they do also offer many opportunities for more cost-effective designs. This applies to general arrangement and cargo spaces, machinery and propulsion solutions as well as the possibility to avoid the accommodation sections.

Two specific cases have also been discussed: One a long distance intercontinental liner ship and one short distance scheduled transport vessel. It is believed that both have potential for realization, but the supply ship is probably the one which is easiest to get into operation as it will normally only involve flag state and one coastal state.

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