

AUMD CONCEPT DESIGN

DESIGN OF AN AUTONOMOUS UNDERWATER MAINTENANCE DREDGER

A teaser to the maritime industry

Project: R&D AUMD

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Abstract

A hopper dredger was chosen as a first autonomous concept design, since dredgers, next to Offshore and Passenger Vessels, are part of C-Job Naval Architects' main market segments. By submerging a Trailing Suction Hopper Dredger (TSHD) a major benefit was identified in ship's resistance and required vacuum for the dredge pump. The first aspect due to reduction in wave making and -breaking resistance, the second due to reduced suction depth relative to the pump. In addition, an increased part of the ship's volume would generate displacement resulting in additional payload and a new arrangement of the vessel could be created resulting in a reduction in overall hull girder loads and reduced steel weight. To prove these insights, a comparative study was performed between a conventional, manned TSHD and the Autonomous Underwater Maintenance Dredger (AUMD). During this study the following aspects were quantified: hydrodynamic resistance, power requirements, sustainable power supply, general arrangement, redundancy / maintenance. The operational profile of the conventional TSHD, was used as a reference for the new concept. The developed concept showed very promising, both from operational as well as sustainability point of view. Some of the key benefits of the design are reduced dredge pump power (2x175 kw versus 2x675 kW), reduced propulsion power (2x575 kW versus 2x1100 kW), low OPEX, zero emission power supply and reduced hull girder loads. Amongst others, based on this concept design, C-Job feels strongly that Autonomous vessels have an enormous potential on (operational) improvements for ship operators. Not only by omitting the ship's crew, but by fully utilizing the opportunities this presents.

1. C-JOB STEPS INTO AUTONOMOUS SHIP CONCEPT DESIGNS

C-Job Naval Architects recently included Autonomous Shipping as one of the topics within the R&D portfolio, since it is closely related to the main design objectives within C-Job. Namely Autonomous Shipping is closely related to a reduction of total cost of ownership, safe operations and it creates opportunities for sustainable designs. As C-Job is mostly involved in the development of concept and basic design of maritime objects but not as much involved in automation systems, sensing-, navigation- and situational awareness technology, C-Job aims to merely focus on the conceptual design of autonomous vessels as a whole considering out of the box solutions. The current concept design is one of such examples.

As C-Job focusses mostly on 3 core market segments, i.e. Offshore (Wind), Dredging and Passenger vessels, the current concept design resulting in an Autonomous Underwater Maintenance Dredger.

Although it is not foreseen that the current concept design will be sailing in the upcoming years, at least not in the current scale, the concept does show the high potential of autonomous shipping, merely if the design fully utilizes the full range of design options autonomous shipping offers. On the longer term, C-Job aims to develop Autonomous Vessels fully from scratch which should lead to most efficient and optimal designs.

2. FIRST PRINCIPLES OF THE AUMD

In the early stage of the development of the Autonomous Underwater Maintenance Dredger (AUMD) concept, full utilization of the opportunities of unmanned operation was envisaged. The following arguments supported the final concept as laid down in this document, a summary of these can be found in figure 1.

2.1. ILO92-Convention

The ILO92-convention [1], concerning the crew accommodation on board ships, is applicable for every seagoing vessel above 500 tons. One of the criteria laid down in this convention, is the need for an open deck space for crew off duty. As the AUMD is not provided with an onboard crew, the need for such open deck spaces, nor any other crew related accessories (accommodation space) is not present anymore. As of such considerations, the application of a submarine design became optional and the potentials were assessed.

2.2. Power reduction expectations

As of the application of a submarine design, a reduced power was expected because of the reduced vacuum requirements by the dredging pump, as well as a reduction in propulsion power. Firstly, the required vacuum would reduce due to the relatively close vicinity of the riverbed to the dredge pump. Secondly, the propulsion power would reduce due to the lack of wave making as well as wave breaking resistance, because of sailing submerged, instead of in the interface between water and air. On the opposite, some additional frictional resistance is to be expected as of the additional wetted surface area. The resulting total reduction in power requirement still had to be verified.

2.3. Near shore / maintenance dredging

Following the lack of on-board crew and therefore the resulting self-sufficiency, it was foreseen that a significant amount of data communication should take place. This, in relation to vessel-shore as well as vessel-vessel communication, optional remote control, situational awareness and vessel monitoring point of view. As the current state-of-the-art in satellite data communication does not show sufficient bandwidth nor speed, a compromise was made to reduce the required amount of data to be sent over

satellite communication. This, in combination with the option to refuel and perform maintenance in close vicinity, resulted in the choice to design a dredger operating in near-shore areas. It follows from the operational profile of a near-shore dredger that it should mainly be active in the field of maintenance dredging and not related to sand-winning projects.

2.4. Fully buoyant

As of the fully submerged hull, the entire volume contributes to the buoyancy of the AUMD. Especially for dredgers involved in sand winning projects, the deadweight of the vessel limits the soil carrying capacity instead of the volume of the hopper. Although not considered relevant for the maintenance dredger, and therefore not anymore considered in the remainder of this document, it is seen as one of the potential benefits of the submerged design.

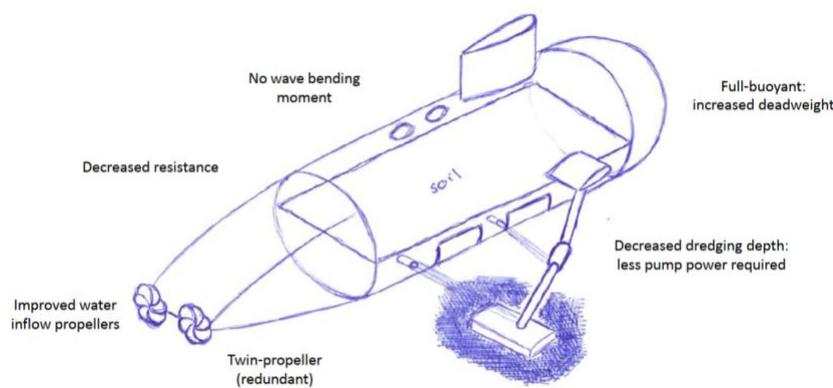


Figure 1. Summary of conceptual design benefits.

3. CONCEPTUAL DESIGN AUMD

Starting from the fundamental insights as depicted in the previous paragraphs, several design choices were made to emphasize the true benefits of the design. These design choices, as well as the consequential benefits themselves, are quantified in the following sections.

3.1. Manoeuvrability and Redundancy

Since (maintenance) dredging requires a very accurate ability to dynamically position the vessel along a pre-determined track, manoeuvrability is one of the key aspects of the vessel. This, in combination with the unmanned operations, led to the choice for the installation of 2 (redundant) azimuthing thrusters in the aftship and 2 tunnel thrusters in the foreship. The combination of these (together with a proper DP/DT system, with DP2 functionality) should enable the vessel at all time, inclusive undesired malfunctioning, to keep in position. In order to have ample thrust at low speed, the azimuthing thrusters are equipped with propeller nozzles.

3.2. Hull shape (flat bottom)

Since the AUMD will operate mainly in shallow waters and near river beds, a compromise had to be found in the hull shape considering hydrodynamic efficiency on the one hand and operating the vessel as near to the riverbed as possible. It was chosen to develop a flat-bottomed submarine as found from [2], resulting in the hull shape as can be seen in figure 2.

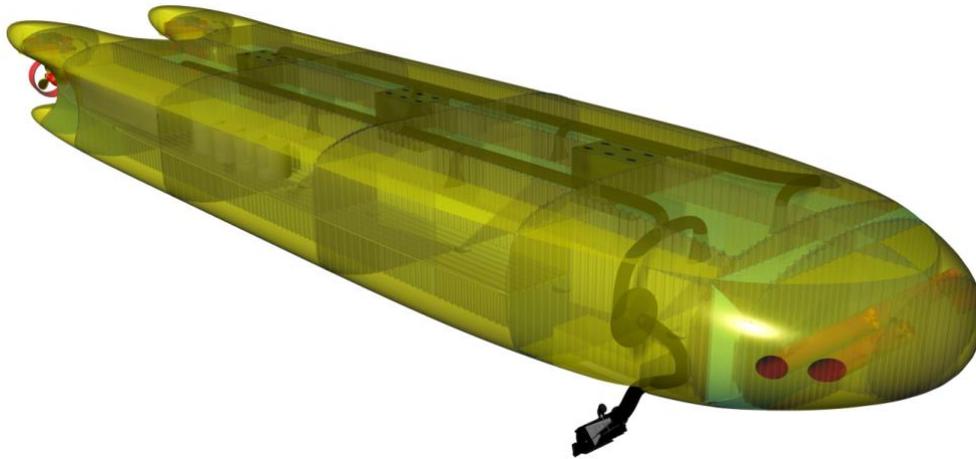


Figure 2. Render of concept AUMD.

As the AUMD will sail close to the seabed, the vessel might be prone to the squat effect (as opposed by the propellers) as well as the creation of a sand/water mixture flow through the propellers resulting in early wear of the propellers. Therefore, a protective propeller heel was envisioned to prevent both from occurring.

3.3. Power requirements

Since the main advantages were expected to be found in the power requirements of the AUMD, an overview was created of the main power consumers. These are the propulsion and dredging systems and for these a best practice approach was considered to estimate their requirements as accurate as possible. For remaining auxiliary equipment, a power estimation was made based on comparable ship types. In the next sections, these are described in more detail.

3.3.1 Propulsion power

A two-fold power / speed analysis was conducted based on the Holtrop / Mennen prediction method, firstly for free sailing condition, secondly for dredging condition. From the prediction method, which is mainly built up from viscous-, form-, wave- and appendage resistance, the wave resistance was omitted as of the submerged operating condition. The input as indicated in Table 1 was used for the determination of the total resistance in both operating conditions.

Table 1. Input Power / Speed analysis.

| | Units | Free sailing condition | Dredging condition |
|----------------------------------|-------------------|------------------------|--------------------|
| Length | [m] | 80 | 80 |
| Speed | [kn] | 11 | 2 ^a |
| Wet hull area | [m ²] | 3900 | 3900 |
| Wet appendage area | [m ²] | 54 | 54 |
| Diameter tunnel thrusters | [m] | 1.0 | 1.0 |
| Draghead resistance ^b | [kN] | - | 258 |

^a 2 Knots is a commonly seen sailing speed in dredging condition.

^b As obtained from model tests of a comparable dredger as designed within C-Job Naval Architects.

The above data results in a propulsion requirement as specified in Table 2.

Table 2. Resistance and propulsion requirement AUMD.

| | Units | Free sailing condition | Dredging condition |
|------------------|-------|------------------------|--------------------|
| Total Resistance | [kN] | 126 | 263 |
| Propulsion power | [kW] | 1072 | 408 |

As the required propulsion power appeared low in comparison to equivalent dimensioned vessels, a verification of the resulting level of acceleration was performed. This, since the operational profile of a hopper dredger shows on a regular basis periods of acceleration from zero up to maximum transit speed. Considering the maximum available power as presented in Table 2, the AUMD will be able to accelerate in reasonable time (8 minutes, see Figure 3) from zero to maximum speed, which was deemed acceptable.

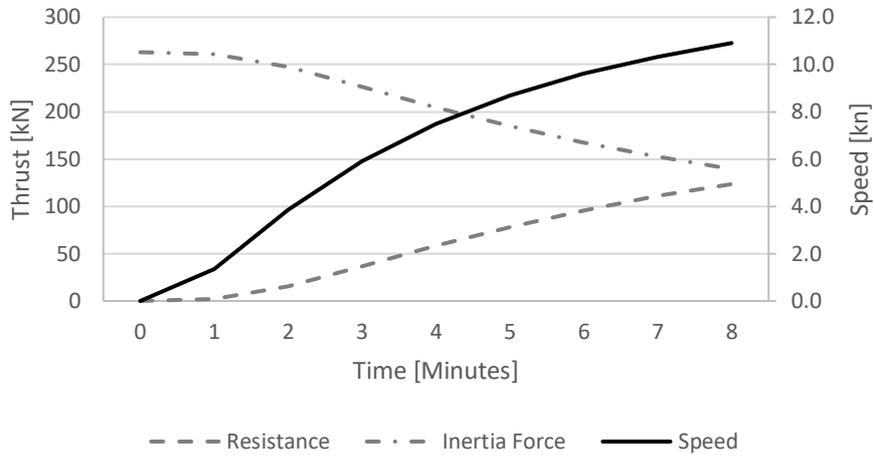


Figure 3. Level of acceleration.

3.3.2. Dredging power

The analysis of required dredging power was based on a mathematical model as provided in [3]. Herein, the formula (1) is considered in the determination of required dredge pump power:

$$P_{Pump} = \frac{Q_{Tot} \cdot \Delta p_{loss,tot}}{\eta_{Pump}} \quad (1)$$

Where Q_{Tot} is the total mixture flow, which is a parameter solely dependant of the dredged soil and the hopper dimensions. Since these are not directly influenced by the current AUMD concept, the exact details are deemed irrelevant here. However, the parameter $\Delta p_{loss,tot}$, which is the pressure loss over the dredging system from draghead to discharge, is strongly affected by the current concept. The pressure loss is divided in the following components:

$$\Delta p_{loss,tot} = \Delta p_{su,loss} + \Delta p_{dis,loss} + (\Delta p_{abs,dis} - \Delta p_{abs,draghead}) \quad (2)$$

Where:

$$\Delta p_{su,loss} = (1 + f_{fitting}) \cdot \frac{1}{2} \cdot \rho_{mix} \cdot v_{mix}^2 + \frac{0.01 \cdot l_{pipe}}{D_{pipe}} \cdot \frac{1}{2} \cdot \rho_{mix} \cdot v_{mix}^2 + \rho_{mix} \cdot g \cdot H_{su} \quad (3)$$

$$\Delta p_{dis,loss} = f_{fitting} \cdot \frac{1}{2} \cdot \rho_{mix} \cdot v_{mix}^2 + \frac{0.01 \cdot l_{pipe}}{D_{pipe}} \cdot \frac{1}{2} \cdot \rho_{mix} \cdot v_{mix}^2 + \rho_{mix} \cdot g \cdot H_{dis} \quad (4)$$

$$\Delta p_{abs,draghead} = \rho_{water} \cdot g \cdot H_{depth,draghead} + p_0 \quad (5)$$

$$\Delta p_{abs,discharge} = \rho_{water} \cdot g \cdot H_{depth,discharge} + p_0 \quad (6)$$

Considering the input data from Table 3, a dredge pump power of 261 kW was obtained. Divided over two dredge pumps, this results in two drive trains each having a power of 135 kW.

Table 3. Input data dredge pump power analysis.

| | Units | AUMD |
|-------------------------------------|---------------------|-----------|
| ρ_{soil} | [t/m ³] | 1.30 |
| Mixture speed | [m/s] | 3.75 |
| $f_{fitting}$ (suction / discharge) | [-] | 1.5 / 2.0 |
| Suction pipe length | [m] | 9.00 |
| Discharge pipe length | [m] | 40.00 |
| Dredging pipe diameter | [m] | 0.85 |
| Suction depth | [m] | 6.25 |
| Discharge head | [m] | 3.50 |
| Depth draghead | [m] | 35.00 |
| Discharge depth | [m] | 25.25 |
| Dredge pump efficiency | [-] | 0.90 |

3.3.3. Electrical load balance

In order to be sufficiently redundant, as in emergency conditions no repairs can be performed due to the lack of on board crew, the single line diagram as indicated in Figure 4 was considered.

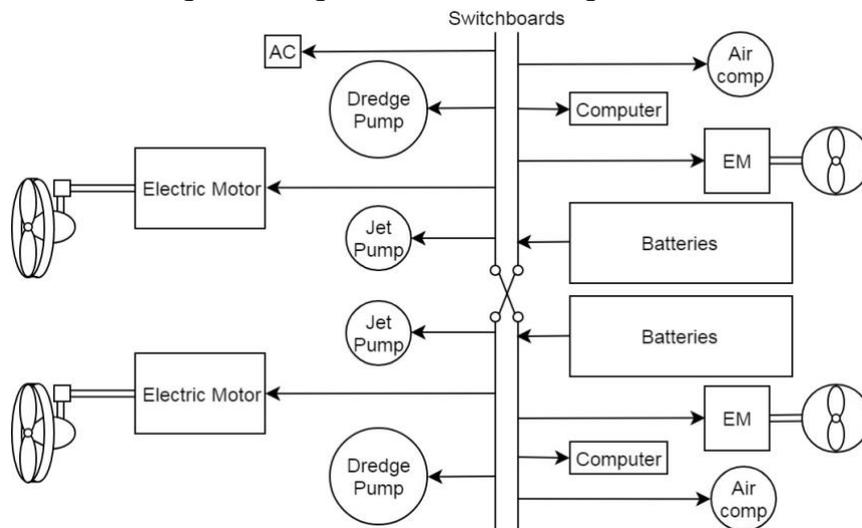


Figure 4. Single line diagram.

In order to be able to determine the capacity of the batteries indicated, an estimation of the electrical load balance was made, considering the main operational conditions of the AUMD. This overview is indicated in appendix A. The total required power appears to be 1600 kW.

3.4. Principal dimensions and General Arrangement

Table 4 indicates the principal dimensions of the AUMD, whereas the concept General Arrangement Plan can be found in Appendix B. For comparative purposes the main characteristics of the reference vessel are indicated in the table as well. Here it can be clearly seen that with respect to the power supply a considerable reduction was achieved.

Table 4. Principal dimensions.

| | Units | AUMD | Reference vessel |
|-----------------------|-------|-------------------|-------------------|
| Length over all | [m] | 80 | 113 |
| Breadth | [m] | 20 | 18 |
| Draught | [m] | 8.5 | 7.2 |
| Dredging depth | [m] | 35 | 30 |
| Displacement | [t] | 10316 | +/- 11900 |
| Transit speed | [kn] | 11 | 11 |
| Propulsion power | [kW] | 2x 575 | 2x 1100 |
| Dredge pump power | [kW] | 2x 175 | 2x 675 |
| Total installed power | [kW] | 1600 ^a | 3550 ^b |

^a The total installed electrical power considering the electrical load balance in all operating conditions.

^b The total installed propulsion and dredging power, no auxiliary systems power nor hotel load included.

3.4.1. Buoyancy, Trim and Heel

Submarines are very sensitive for trim, heel and buoyancy changes. Therefore, ample attention is paid in this concept phase on these aspects. Similarly, the automation system should be capable of providing sufficient stability and buoyancy during all operational conditions as well, which requires analysis speed as well as sufficient pump and compressor capacity. Especially, in dredging condition this will result in detailed monitoring of trim and heel resulting in adjustments in ballast. In order to enable the AUMD to control all motions, 2 trim tanks (fore / aft) and central ballast tanks (spread over PS and SB) are arranged. Figure 5 shows the trim polygon of the AUMD, which indicates the operable ranges having zero trim and enough buoyancy. As can be seen, the current concept shows a trimming moment by the bow, which might be solved by increasing the length of the vessel and apply some more ballast tanks (or fixed ballast) in the aft.

One of the benefits of the current design is the AUMD's open top side of the hopper, herewith no sloshing effect will be generated in the hopper, which is beneficial in the control of trim and heel.

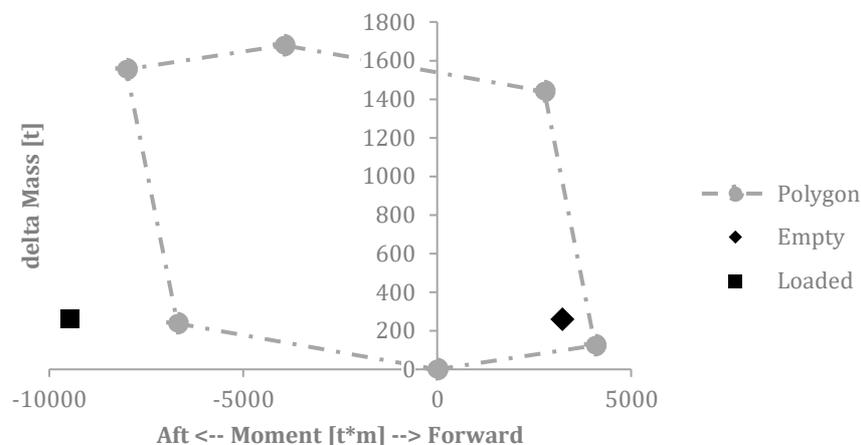


Figure 5. Trim polygon AUMD.

3.4.2. Global hull girder loads

The dimensioning of the AUMD's hopper anticipates on the new options in the general arrangement of the vessel. As such, the hopper was made longer and narrower compared to similar vessels of this size. For instance, the ratio over the hopper- and vessel length to width ratio is beyond unity, whereas for comparable vessels an average ratio of 0.83 is found, which is a direct consequence of the area involved in accommodation space. This higher ratio is directly in relation to the global hull girder loads, since by these means the buoyancy distribution is more equal to the soils weight distribution, which induces less bending moment. As a direct consequence the amount of required steel reduces, resulting in a relatively higher payload. Especially for higher density soil types (i.e. sand) this aspect will lead to significant reductions in steel weight and herewith fuel consumption.

3.4.3. Overflow principle

Since the AUMD appears to have ample buoyancy, an open top hopper appeared to be feasible. This also enabled the provision of an overflow system, i.e. a means to relieve pure water from the hopper, by means of openings in outer hull. Although a maintenance dredger is involved in dredging of low-density soils with large settling times, such system seemed feasible especially once taking care of large settling distances. Such long settling distance is enforced by providing the openings at the farthest distance relative to the location of discharge of the soil.

3.5. Specific requirements for unmanned operations

Because of the unmanned, autonomous operations several design aspects should get special attention. This is because crew cannot anticipate on failures of equipment, collision avoidance, maintenance and more. The below aspects have been considered in the current concept.

3.5.1. Docking station and modular equipment

Since the AUMD will be in port on a regular basis (expected is to have the vessel in port on a daily basis) the application of a docking station for recharging and modular equipment become attractive. By these means equipment can be maintained, replaced, recharged without a (large) consequence in deployability. This resulted in the choice for a full electric design, powered by batteries. In addition, by the design of a full electric system, the amount of rotative machinery (which is prone to maintenance) is reduced.

Similarly, the entire dredging system (pipelines, dragheads) will be fitted out in such a way that it can be easily exchanged in port and maintenance can be performed on shore.

3.5.2. *Survivability*

For emergency purposes, which could consist of lack of power, hull structural failure, machinery failure etc, an option should be made available to access the AUMD from the outside. Therefore, space reservation for a diver's lock has been integrated in the design to ensure access from within harbour environment (inspection) but also in submerged condition. Further requirements to accessibility of the vessel is still pending as the vessel is not intended to provide access to people on a daily basis, however access needs to be guaranteed at least for maintenance purposes.

3.5.3. *Situational awareness / Detection*

In order to enable the AUMD to navigate safely, which means it will have sufficient capabilities in detecting traffic and other obstacles and other vessels will be able to detect the AUMD, ample provisions have been considered. The main situational awareness technology on board will exist of radar, AIS, optical cameras combined with a forward-looking sonar. To improve the AUMD's range of data communication, a preliminary option was considered to have a towed surface communication vehicle (TSCV) carrying all indicated situational awareness systems with a wired connection to the AUMD. This way for instance a regular 4G or 5G network might be used for communication purposes and other vessels will be able to detect the TSCV and herewith the AUMD.

4. TOTAL COST OF OWNERSHIP

One of the key advantages envisioned for the AUMD, is the total cost of ownership. In order to quantify this aspect a Capex / Opex study was performed. Although in the current status of design only estimates can be provided, it gives some insights in the economic feasibility of the concept. As not to provide an overly optimistic view on the operations of the AUMD compared to conventional dredgers, a most conservative approach was considered in the cost estimate which at all times should result in a lower actual cost of ownership of the AUMD.

4.1. **Main cost drivers**

The total costs are divided in initial investment costs (Capex) and operational costs (Opex). By these means both the total costs are estimated as well as the return of investment time (ROI). For the ROI a period up to 10 years is deemed acceptable for the deploy ability of the AUMD, as such reducing the economic risk of taking the step towards autonomous shipping.

The differences in Capex considered in this study consist of:

- Reduction hull construction costs (+ interior etc.) accommodation areas;
- Increased hull construction costs due to complex submarine design;
- Cost comparison dredging equipment, resulting in a minor cost reduction;
- Increased costs for power supply, comparing MGO in reference vessel to battery package in the AUMD;
- Additional costs for situational awareness technology;
- Cost increase due to overhaul of main machinery once in operational lifetime;
- Cost increase due to expected decrease in scrap value of the AUMD.

The differences in Capex between the conventional reference vessel and the AUMD resulted in a total of € 5.2 million.

The differences in Opex considered in this study consist of:

- Cost reduction in fuel (battery charging);
- Maintenance costs are assumed to be equal, although due to less rotative machinery actual costs are expected to reduce;

- Reduction in crew costs, considering that still some shore-based crew is required for monitoring and maintenance purposes;
- Increased costs in automation software.

The differences in Opex between the conventional reference vessel and the AUMD resulted in a total of € 0.8 million per year.

Considering the above cost breakdown, the ROI is appreciated after 6.5 years of operation which is a very promising period. Considering this ROI, the concept is deemed economically feasible however, more in-depth research is required to prove the assumptions made.

5. CONCLUSION

This paper showed the high potential of an Autonomous Underwater Maintenance Dredger, where it should be noted that although promising from technical and economical point of view, many challenges need to be solved. Amongst others these are related to acceptance of autonomous operations by the society, regulatory challenges (allowance of submarines in port), legal aspects for autonomous / unmanned operations as a whole, but also availability of port facilities (automated mooring, battery charging facilities and vessel monitoring agencies). However, these are all expected to be solved in the upcoming years by force of the global maritime industry.

Furthermore, the current concept is just one of the examples showing the opportunities of autonomous shipping. However, C-Job foresees many other opportunities which could bring even more benefits. For dredging in particular, such might be in relation to higher density soil types, deep sea (mining) trades but also in the scale size of the dredger.

Although C-Job acknowledges many challenges still need to be overcome, the concept of the AUMD does show promising in itself. Moreover, the concept underlines the possibilities of autonomous unmanned shipping in the future.

REFERENCES

- [1] International Labour Conference (ILO) No. 92 – Convention concerning Crew Accommodation on Board Ship (Revised 1949) – Part III, Article 12.
- [2] H. Sutton. *US Navy Diesel-Electric Submarine Concept Shallow Water Submarine (SWS)*. url: http://www.hisutton.com/images/SWS_cutaway_large.jpg.
- [3] S. Miedema. OE4607 Introduction Dredging Engineering. MSc Offshore & Dredging Engineering, Delft University of Technology, 2016.

Appendix A – Electric load balance.

| Systems | # | Power at full load (kW) | Installed electric power (kW) | Nominal absorbed power (kW) | Transit | | | | Dredging | | | |
|----------------------------------|----|-------------------------|-------------------------------|-----------------------------|--------------|-------------|----------------|-----------------------------|--------------|-------------|----------------|-----------------------------|
| | | | | | # in service | Load factor | Utility factor | Average absorbed power (kW) | # in service | Load factor | Utility factor | Average absorbed power (kW) |
| <i>Propulsion Systems</i> | | | | | | | | | | | | |
| Azimuth motor | 2 | 536 | 575 | 558 | 2 | 0.93 | 1.00 | 1072 | 2 | 0.36 | 1.00 | 408 |
| Tunnel thruster motor | 2 | 140 | 155 | 146 | 2 | 0.90 | 0.05 | 14 | 2 | 0.90 | 0.35 | 98 |
| <i>Propulsion support</i> | | | | | | | | | | | | |
| Sea water cooling pumps | 2 | 15 | 20 | 19 | 2 | 0.75 | 1.00 | 30 | 2 | 0.75 | 1.00 | 30 |
| Lube oil pumps | 2 | 5 | 7 | 6 | 2 | 0.71 | 1.00 | 10 | 2 | 0.71 | 1.00 | 10 |
| <i>Dredging Systems</i> | | | | | | | | | | | | |
| Main Dredge pump | 2 | 135 | 175 | 169 | 0 | - | - | - | 2 | 0.77 | 1.00 | 270 |
| Jetwater pump | 2 | 165 | 210 | 206 | 0 | - | - | - | 2 | 0.60 | 0.80 | 202 |
| Jetpump draghead | 2 | 70 | 90 | 88 | 0 | - | - | - | 2 | 0.78 | 0.80 | 112 |
| Digital valves | 40 | 3 | 3 | 3 | 0 | - | - | - | 20 | 0.97 | 0.01 | 0 |
| Bottom doors | 5 | 30 | 32 | 31 | 0 | - | - | - | 0 | - | - | - |
| <i>Ballast tanks</i> | | | | | | | | | | | | |
| Air compressors | 4 | 14 | 18 | 18 | 0 | - | - | - | 0 | - | - | - |
| Air blowers | 4 | 4 | 6 | 5 | 0 | - | - | - | 4 | 0.67 | 0.90 | 14 |
| Trim pumps | 4 | 80 | 100 | 100 | 4 | 0.80 | 0.20 | 64 | 4 | 0.80 | 1.00 | 320 |
| <i>Navigation Systems</i> | | | | | | | | | | | | |
| Sensors | 1 | 90 | 100 | 92 | 1 | 0.90 | 1.00 | 90 | 1 | 0.90 | 1.00 | 90 |
| Computers | 1 | 2 | 2 | 2 | 1 | 1.00 | 1.00 | 2 | 1 | 1.00 | 1.00 | 2 |
| Coolers | 1 | 2 | 2 | 3 | 1 | 1.00 | 1.00 | 2 | 1 | 1.00 | 1.00 | 2 |
| Total power (kW) | | | 3348 | | | | | 1284 | | | | 1559 |

Appendix B – General arrangement plan.

