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# The Fundamentals of a Course on the Environmental Impacts of Ships

Patricia A. Coker
*University of New Orleans*, pcoker@uno.edu

The Fundamentals of a Course on the Environmental Impacts of Ships

A Thesis

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Patricia Coker

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## Acronyms

ABS – American Breau of Shipping

EEDI – Energy Efficiency Design Index

GHG – Greenhouse gas

GWP – Global warming potential

IMO – International Maritime Organization

LEED – Leadership in Energy and Environmental Design

MVeP – Marine Vessel environmental Program

ODP – Ozone depletion potential

PNA – Principles of Naval Architecture

SNAME – Society of Naval Architects and Marine Engineers

VOCs – Volatile organic compounds

## Introduction

As the human population grows, the awareness of their impact on the environment has also increased. There is much evidence of this: The increase in hybrid and electric cars on the road. Campaigns to reduce energy and water use in homes and businesses have sprouted up. Most cities provide recycling services to every building. However, there has been little effort from the shipping industry to join the movement of reducing the environmental impact of human activity. Considering that 70 percent of the earth's surface is covered with water and about 50 percent of the world's population lives within 60 miles of a coastline as of 2002 (King, Roberts and Payne), the shipping industry has great opportunity to impact the earth's environment.

We must educate those involved in the shipping industry in order to become the leaders in the environmental movement. A few professionals have taken the time to start the education process by writing papers on environmental subjects dealing with ships. If the reality of producing environmentally friendly ships is to take root and continue in the future, we need to start instilling the topic of the environment in the university education similar to subjects such as hydrodynamics and structures. With 103,460 ships in the global fleet, the ship industry has the opportunity to largely reduce the impact on the environment by humans (Lloyd's Register).

Currently, there is not a class in the naval architecture curriculum devoted to teaching the impacts of ships on the environment in any of the larger naval architect and ocean engineering university programs. Therefore, the purpose of this thesis is to develop a curriculum that can be used for a semester course. The regulations and technologies mentioned are meant strictly for illustration. When this thesis is published, the current regulations and technologies at the time of writing will be obsolete and replaced by stricter regulations and more advanced technologies. Currently there are multiple regulations being developed and will be implemented in the next couple of years. Regulations never stand still and neither do the technologies developed to comply with them. The overreaching philosophy, environmental awareness, will, however, remain.

Leadership in Energy and Environmental Design (LEED) is a rating system for green buildings and can also be used as guidance for many of the impacts which will be discussed. LEED was used a starting basis for the development of this thesis as it incorporates the use of materials, human factors, energy, water, and promotes the use of innovative technologies. The Society of Naval Architects and Marine Engineers (SNAME) has started the release of Technical and Research Bulletins for the Marine Vessel environmental Program (MVeP) which outline one specific impact per bulletin, why it is harmful, what can be done to improve the impact, and how to analyze the severity of the impact. As these guides are released, they will be a great supplemental source to this thesis.

The structural, hydrodynamic, cost and operation components drive the design of a marine vessel. The environmental impact component is typically not included in that list and it should be. Many of the environmental impacts which will be discussed will seem to be common sense to naval architects. However, they are not being explicitly incorporated into the ship design process because they are not instilled early on in the education process and are, therefore, not a natural thought when designing a ship.

When weighing decisions during the design process, the U.S. Coast Guard suggests using a Technological Analysis Factor when they discuss designing the Offshore Patrol Cutter, Table 1. They are stressing the environmental impact of their vessels and weigh the potential environmental impact of each decision highly. The rest of the marine industry is starting the transformation to priorities similar to those of the U.S. Coast Guard.

**Table 1: Technological Analysis Factors used when designing the OPC**

| Evaluation Criteria | Weighting | Rationale |
|---|---|---|
| Potential Environmental Impact | 40% | Primary decision driver |
| Cost | 20% | Systems that are not technologically matured do not have sufficient data available on cost. The current cost estimate is based on initial procurement costs. Due to limited data reliability and lack of life cycle cost data, cost is weighted lower. |
| Ship Impact | 20% | Due to the early stage in ship design, it is still possible to affect design and minimize the ship operational impacts. |
| Technology Readiness (TRL) | 10% | Technologies must be able to reach maturity (TRL9) within the three years of OPC acquisition schedule. While crucial for the OPC acquisition, this criterion has a lower priority. |
| Vendor Capacity (MRL) | 10% | Original Equipment Manufacturers (OEMs) must prove their manufacturing readiness (TRL9) to produce the technology, in the quantity and quality needed by the OPC. |

There are multiple parties which are stakeholders in the life of a ship. The focus of this thesis will be on the naval architect's value as a stakeholder and what impacts they can influence. Others involved in a ship's life can also have an influence and will be mentioned but will not be the focus. For example, route optimization will appear in every impact as a means of affecting the severity of the impact. A naval architect does not make the decision on the route a ship will take but they can provide tools, which will be discussed later, to help the operators take the route which will have the least impact.

This thesis brings together the research conducted by marine biologist on the effects of human marine activity on the animals and the engineers who have studied the causes of the human marine activities.

## Assignments and Projects

The development of the thesis was approached with the mindset of developing information for a class for undergraduate Naval Architecture students. During research and writing, possibilities for assignments were noted. Before each impact is covered, students can list impacts in that category as an introduction to the topic before the lecture occurs. Bonus for impacts not covered in the lecture.

There are analysis methods in some of the categories which can be used as example problems for assignments. At the end of the class when all impacts are covered the following problems cover a summary:

- What are three links between impacts?
- What impacts are mentioned in the report aida.de/aidacares (Germanischer Lloyd)?
- What are three alterations to a ship that can be done which affect multiple impacts?

At the University of New Orleans, senior design projects from previous classes are kept for reference to future classes. A project for an environmental impact class could consist of analyzing a previous senior design project and listing the positive and negative aspects of the ship pertaining to the environmental impact of the ship. This would give the students exposure to a senior design project before they must complete one as well as bring all the impacts together relating to one ship.

## What is Green?

The first question that must be conquered when considering the environmental impacts of ships is what does the term “green” mean? Words that are typically associated with being green are recycling, energy efficiency, environmentally friendly, and high performance. Recycling water bottles to make a raft and life jackets (Figure 1) can be considered a “green” practice.

**Figure 1: Water bottles recycled to make a raft and life jackets**

The umbrella that all these phrases are under is the purpose of not having a negative impact on the environment, in essence being invisible to the environment. A stealth ship is one that is not able to be detected because it blends into the environment. This is the ultimate form of an environmentally friendly ship as it does not change the environment it is in. The only part of stealth technology that is not ideal is radar detection. We want to be able to see other ships and boats on radar to avoid collisions which can cause more impacts on the environment as we will see later. The introduction of something not natural in the environment or that changes the natural environment is an impact. The phrases “not natural” or “does not exist” will be read often when describing impacts.

The environmental impacts of a ship can be broken down in many different ways. One way is into four categories with subcategories Figure 2. This breakdown allows for refinement of the components based on necessity for analysis.

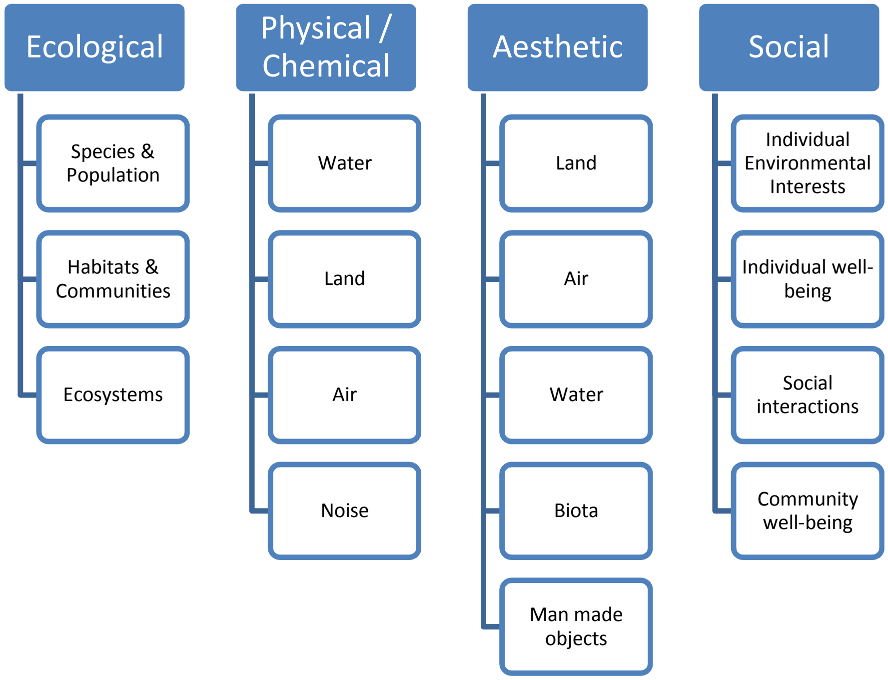


**Figure 2: Environmental categories and components (Benvenuto and Figari)**

Another ways is dividing the impacts by hydrosphere, atmosphere, biosphere and geotechnical (geosphere). This would separate the impacts on living organisms (biosphere) from the others. The structure in this report has the impacts broken down into five categories with a possible sixth; land, air, resources, water, and human factors with aesthetics as a possibility. The ship life cycle consists of the design, construction, operation, and decommission. Each of these steps can further be broken down, especially the operation stage. The class can easily be restructured to fit any of these three formats based on the decision of the professor.

## Ship Life Cycle

When breaking down the impacts there are two main schemes that can be used, either the impact categories as previously discussed or by the ship life cycle. The ship life cycle is commonly presented in four stages; design, construction, operation and decommission. During each phase, decisions are made which will determine the severity of the impacts on the environment. The impact can occur during the phase it is determined in or during another phase. As each impact is introduced, when it is determined and when it occurs with respect to the ship life cycle will be discussed. Two tables, similar to Table 2, will be developed. One will display when each impact is decided and one when each impact occurs. In the table for the decision making, the "O" represents the opportunity for the naval architect to make decisions to affect each impact and the "X" represents the opportunity for others to affect each impact.

**Table 2: Life Cycle and Impact Categories**

| | Design | Construction | Operation | Decommission |
|---|---|---|---|---|
| Land - above water | O | X | X | O X |
| Land - below water | O | | X | |
| Air - materials/gas | O | X | X | X |
| Air - noise | O | X | X | X |
| Water - materials | O | | | |
| Water - heat | O | | | |
| Water - noise | O | | X | |
| Resources - physical | O | X | O X | X |
| Resources - energy | O | X | X | X |
| Human Factors | O | X | X | X |
| Aesthetic | O | | X | |

When discussing what each impact is and why it is an impact, you will realize that most of the emphasis throughout this report will be placed on the operations phase as that is the phase where the majority of impacts occur. The operation phase could be further broken down into working time, renovation, and other time, however, this will not be done when the tables are developed.

The design phase is also mentioned in every impact since the naval architect always has the opportunity to have an influence on the severity of each impact. The occurrence of impacts during the design phase will not be covered as that is influenced by the company and by architects and civil engineers who design and build the buildings used for offices. Those professionals are the ones responsible for the environmental impact of the buildings. The naval architects who use the buildings have a responsibility to use the tools provided to reduce the impact similar to the operators of ships using the tools provided by naval architects.

The development of these tables can be completed by the students as an in class exercise or as a homework assignment. When the students fill in the tables it requires them to have an understanding of the impact in order to know when it is influenced and when it occurs.

## Control Volume

A control volume is “the region of space over which the attention is focused” according to Mackenzie L. Davis (McGraw Hill). For example, when doing a beam analysis what is the control volume or in other words what is the region we are analyzing?

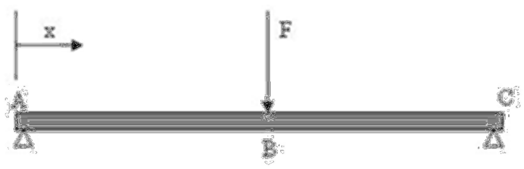


Figure 3: A beam analysis example of control volume

In this problem the control volume is the beam. There are outside forces which are acting on the beam but we only care about the point of impact on the beam not the source of the force. The same goes for the support reactions.

When applying the concept of a control volume to analyzing the impact of a ship on the environment there are many different clouds that can be drawn. The control volume when we are designing a ship can be exactly ship, similar to the beam problem. If we do this, then we care what is on its way out of the ship but not where those things go. However, we stated before that an ideal ship is invisible to the environment; therefore we need to know what the environment is around the ship in order to make a comparison. For this we can draw the cloud of the control volume slightly outside of the ship so we can analyze the environment directly outside of our ship, such as the water and the air. As we get further into the course, you will see that the impact of a ship extends much further than the immediate surroundings. The ship can leave behind impacts everywhere it travels, and it can travel all over the world. With this thought, the control volume should be drawn around the whole earth.

# Impacts on Land

The impact of ships on the land can be divided into what happens above the waterline and what happens to the land below the waterline. In other words, we can divide it into what we can see and what we cannot see.

## Above Water

As a ship moves through water, it creates waves. These waves contain energy and can have an impact on the water surface environment and, if they reach land, on the land environment. When wake wash reaches land it can cause erosion (carrying sediment away from the shoreline) or accretion (carrying sediment onto the shoreline) of beaches, channel beds, and banks, altering the structure of the land (Stumbo, Osborne and MacDonald). Waves "evolve" as they propagate. Waves measured near the vessel are not the same as waves that reach the shore. Waves leave the ship in multiple directions and at multiple velocities. They will interact with each other causing the wave spectrum to change. The short waves are slow moving and long waves are fast moving. Therefore, the long waves will reach the beach first.

Waves carry energy and it is the energy which has a negative impact on the shoreline. The energy deposited by waves on the shoreline is able to be calculated in the amount of energy deposited on one unit of shoreline.

$$E = \frac{1}{2}\rho g \zeta_a^2 L_w$$

Rho is the density of the water, g is gravity, $\zeta_a$ is the amplitude of the wave, and $L_w$ is the length of the wave. E is the energy of the wave per one unit of breadth or shoreline (Bhattacharyya 24).

As the waves travel along the water surface, wake wash can affect other vessels and structures, ultimately causing a safety issue. In this case the steepness of the wave is the factor which causes the impact rather than the energy. As a steep wave passes by a vessel it was cause the vessel to roll and pitch which can affect its stability and cause discomfort for the crew and passengers onboard. When an impact affects humans, it is linked to the Human Factors impact category as well. If in deep water, the length of the dominant wave ($L_w$) which leaves the ship can be calculated by the ship's speed (v) and gravity (g). Water is considered deep if the depth is at least half the wave length.

$$L_w = 2\pi \frac{v^2}{g}$$

The faster the ship is traveling the faster the dominant wake waves will travel.

Waves "evolve" as they propagate. The energy and steepness of a wave near the ship will not be the same as those measurements at the shoreline. The impact of wake wash depends upon the environment in which the vessel is traveling. An environment with other vessels will be affected by the wave steepness. In an environment where the wake wash reaches a shoreline, the energy will cause the impact.

Therefore, route optimization will play a key factor in the severity of the impact of wake-wash, which is not determined by a naval architect. When the hull and propulsion system are designed, the naval architect can create a manual to let operators know how the speeds, RPMs, etc. compared to the wake-wash created. Then the operator can use that manual and the known environment through which they are traveling to adjust to reduce the impact.

A naval architect can make decisions during the design phase which will affect the wake-wash. The shape of the hull and the type of propulsion used are dictated by the naval architect and the design committee. When designing the hull form, the resistance (including wake resistance) is a consideration. The characteristics of the wake-wash should also be considered. The naval architect must know where the ship will be traveling and at what speeds it will be traveling close to a shoreline in order to able to minimize the wake-wash impact.

Corrosion has an impact on the land and on the water, as will be seen in the Impact on Water section (Germanischer Lloyd). Corrosion can cause pieces of metal to be released into the water and these will eventually be washed onto land. Obviously, metal on beach is not a natural occurrence and therefore it will have an impact on the beach environment.

The material which is chosen to use to construct a ship will determine the corrosion impact and the impact during the decommissioning phase. When a ship is being "recycled", whether the material of the ship can actually be recycled can affect the amount of material which will end up in a landfill rather than being reused. The type of material being used is determined by the design team but what happens with it during decommissioning is not always under their control.

Material ending up in landfills also occurs during the construction process. While that is not under the naval architect's jurisdiction, the material the naval architect specifies can affect the materials which can be recycled versus thrown away.

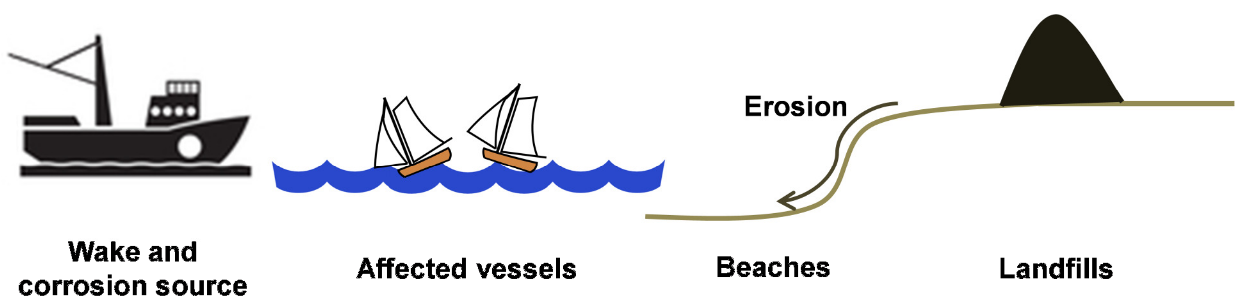


**Figure 4: Process of the impact on land above water**

Figure 4 shows the process of how a ship impacts the land above water. Wake and corrosion originate from a ship. The wake affects vessels and causes erosion on beaches. Some of the corrosion during the operation phase and the material not recycled during the operation renovations and decommission phase will end in landfills.

### Below Water

It is not always obvious that marine vessels can have an impact on the land below the water since it is not always visible. However, there are organisms, such as clams and oysters, which rely on the ocean floor for survival. Therefore, any movement or change to the ocean floor is an impact on their possibility of survival. This impact will occur during the operation phase of the ship life cycle since it relies on the ship using its propulsion system.

Most of the change to the environment on land under water is due to movement of the sediment on the seabed. When marine vessels dock in a shallow area, their propulsion system (prop wash) can move the sediment and create holes, also called bottom scouring. When the wake from boats travels towards a beach, it transfers sediment along with it, termed sediment transportation. Any time sediment from the ocean floor is disturbed, there is the possibility that pollution previously deposited will be stirred up and cause more of an impact (McKesson, Remley and Karni). If bottom scouring or sediment transport does occur, then the impact translates into the category of Impact on Water.

The effects of propellers also extend to the wildlife which lives on the seafloor. Off the shores of the Florida Keys, paths through the sea grass can be seen which are left behind by small craft, similar to Figure 5.

**Figure 5: Propeller scar in eelgrass (MIT Sea Grant College Program)**

Larger ships can have the same impact. It all depends on the draft of the ship and the depth of the water. Routing through deeper waters can eliminate this impact on the land below water. This is one impact that the naval architect does not always have control over.

### Exercises

Assignments relating to the Impacts on Land can be calculating the energy and wave length of waves from a ship. Reference for these problems can be taken from the Resistance and Propulsion class currently in the UNO NAME curriculum.

As previously mentioned, Table 3 and Table 4 show when the Impacts on Land above and below water are determined and when these impacts occur. When determining the impact of the ship on land, the aspects during the design phase are within the naval architect's domain and the aspects during the operation phase are not. Therefore, an "O" and an "X" are used to distinguish, respectively. The impacts on land above water occur during the construction, operation and decommission phases of the ship life cycle while the impact below water only occurs during the operation phase.

### Table 3: When Impacts are Determined

| | Design | Construction | Operation | Decommission |
|---|---|---|---|---|
| Land - above water | O | X | X | O X |
| Land - below water | O | | X | |

### Table 4: When Impacts Occur

| | Design | Construction | Operation | Decommission |
|---|---|---|---|---|
| Land - above water | | X | X | X |
| Land - below water | | | X | |

## Impacts on Air

The impact of ships on the air environment can be divided by the type of impacts; materials or gas and noise. When exploring the impact on the air, it is easier to make this division and considered each type separately.

### Material/Gas

When people discuss being "green" or environmental impacts, the first type of impact on their minds are air emissions. Air emissions can be the most visual when they are seen as smoke coming out of stacks at industrial plants (Figure 6) or exhaust coming out of vehicles on the road.

**Figure 6: Air Emissions from an Industrial Plant (The Izaak Walton League of America)**

**Figure 7: Air Emissions from a Ship (Officer of the Watch)**

The emissions from Figure 6 look similar to that in Figure 7. The emissions from land based sources are similar to those from marine sources with the further complication that marine sources move, and thus are in many different environments, which may have different sensitivities. There are many regulations which are continuously being updated as new research is completed dictating limits on the type of emission allowed and their quantity. For example, currently the US EPA regulates the emissions from gasoline and diesel engines on ships.

The marine field produces about three percent of the total GHG emission (Vergara, McKesson and Walczak). The primary contributor to ship gas emission is the engine. There are many factors, such as type of engine and engine speed, which affect the amount an engine will emit. The principal emissions from a ship are sulfurous oxides ($SO_x$), nitrous oxides ($NO_x$), carbon monoxide (CO), carbon dioxide ($CO_2$), and hydrocarbon (HC) (Benvenuto and Figari).

Nitrous oxides emissions are affected by injection system timing, turbocharger systems and specifications, valve timing, compression ratio, engine speed, engine load, and swirl in combustion space (Hellen). It is difficult to optimize these characteristics but by trying to do so, the amount of emissions could be reduced as well as the energy efficiency of the engine. With an increase in engine load, nitrous oxides will increase in the emissions. Low-speed diesel engines tend to have the largest nitrous oxide emissions and are the most energy efficient.

Unlike nitrous oxides, carbon monoxide decreases with engine load; hence why it is difficult to optimize all the characteristics of an engine. The carbon monoxide emission does not alter significantly between low-speed and high-speed diesel engines. Carbon dioxide and sulfurous oxide emissions do not depend on the engine load. However, carbon dioxide emission when using diesel and fuel oils directly correlates with the amount of fuel used (King, Roberts and Payne). All the carbon in the exhaust only comes from the fuel. Therefore the type of fuel chosen will directly affect the about of carbon exhaust.

Emissions are able to be measured and can be predicted throughout the use of a ship's engine. If the initial emission measurements are taken, then the current emissions can be interpolated using constant measurements of characteristics of the engine. Lloyd's Register of Shipping proposed a quantitative evaluation of the exhaust gas emissions produced by marine engines (Benvenuto and Figari). A high speed craft example is used to illustrate this evaluation method in Benvenuto and Figari's paper.

**Table 5: Exhaust gas emissions for a trip of a high speed craft**

| | e [kg/ton] | N [kg] | a | M [kg] | T [kg] |
|---|---|---|---|---|---|
| $NO_x$ | 59 | 31.27 | 0.55 | 1.623 | 32.89 |
| CO | 8 | 4.24 | 1.7 | 0.68 | 4.92 |
| HC | 2.7 | 1.431 | 1 | 0.135 | 1.566 |
| $CO_2$ | 3250 | 1723 | 0.7 | 113.8 | 1836 |
| $SO_x$ | 42 | 22.26 | 0.7 | 1.47 | 23.73 |

In Table 5, the emission rates for normal seagoing condition (N), maneuvering (M), and for the whole trip (T) are quantified per Lloyd's Register. The coefficient "e" is the specific steady state emissions (mass of emission with respect to fuel consumption) and the coefficient "a" is the ratio between the maneuvering and stead-state emissions. It is assumed that the diesel engines are shut down after maneuvering and power is supplied by a land source. Maneuvering produces fewer emissions than normal seagoing condition. This analysis can allow for a ship operator to determine route optimization for the least amount of emissions based on the local environment.

Since emissions are dependent on engine load and the speed traveled, route optimization can be used to help reduce the emission over a trip. We have already mentioned using route optimization to reduce the impact on land and we will see that it is also a tool for reducing energy and fuel consumption. Therefore, all of these impacts must be considered when determining a ship course. A naval architect can assist operators in determining a route which has the lowest impact by providing tools such as graphs which show engine load and the correlated emissions or speed versus air emissions.

There are four efficiencies which translate the amount of energy in the fuel to the amount of kinetic energy which reaches the shaft ($E_{k\text{-shaft}}$) , combustion ($\eta_{comb}$), heat transfer ($\eta_q$), thermodynamic ($\eta_{td}$), and mechanical ($\eta_m$).

$$E_{k-shaft} = \eta_m \eta_{td} \eta_q \eta_{comb} m_f H_u$$

The energy in the fuel can be found by the amount of fuel ($m_f$) and the lower calorific value of fuel or the amount of energy in the fuel ($H_u$). These four efficiencies help us to understand how gas and heat are emitted from the engine process. The combustion efficiency describes the amount of fuel which does not combust (how many bonds were not broken). The fuel which does not combust is released as chemical energy waste in the form of CO and HC gas. There is no heat emitted with this stage (Xiros). The other three efficiencies will be addressed in their respective impacts.

There are also many alternatives to the traditional diesel and gas engines being developed. Biodiesels, nuclear power, and liquid natural gas (LNG) are among the most advanced.

“Global warming potential” (GWP) and “ozone-depleting potential” (ODP) are indicators of the environmental impact of hazardous materials (King, Roberts and Payne). GWP is the ratio of the warming caused by a substance to the warming caused by a similar mass of carbon dioxide. ODP refers to the amount of ozone depletion caused by a substance. These indicators can be used to measure the impact of material and gas discharges and can also be used to compare the impacts by various options of engine emissions during design.

There are methods to improve the emissions of engines currently in use. They can be divided into two methods. The primary method is engine modification and the secondary is exhaust gas cleaning. The secondary method is used on some truck emissions by the use of cyclones.

IMO has developed a set of regulations which will be implemented in three steps, Table 6. The $NO_x$ limit in units of grams is based on the power of the engine in units of kilowatts.

**Table 6: IMO/EU Regulations (Caterpillar Marine Power Systems)**

| Tier | Date | $NO_x$ Limit (g/kWh) | | |
|---|---|---|---|---|
| | | n<130 | 130≤n≤2000 | n≥2000 |
| Tier I | 2000 | 17.0 | $45*n^{-0.2}$ | 9.8 |
| Tier II | 2011 | 14.4 | $44*n^{-0.23}$ | 7.7 |
| Tier III | 2016 | 3.4 | $9*n^{-0.2}$ | 1.96 |

During the construction and decommissioning processes, there are emissions from the equipment being used; cranes, trucks, generators. Other than gas emissions, there is also heat emission from the welding which takes place. This is not in the scope of the naval architect but it can be affected by those in charge.

To be considered in the Human Factors impact is the emissions of volatile organic compounds (VOCs) from the materials used in the interior of the ships. These can come from simple items such as furniture and paint.

### Noise

Noise pollution into the air is the cause of complaints by people who live along waterways with heavy marine traffic. This is especially common with ferries since their routes are between populated areas and along rivers and canals. The design of the engine, such as air intake and exhaust, and the wake-wash from the vessels create the majority of airborne noise, internally and externally to the vessel. The material which is used to insulate the engine room can determine the extent of the noise which penetrates into the air as well as the water (Impact on Water - Noise). The machinery onboard and the ship traveling through water can excite vibrations in the hull which can generate noise waves in the air and in the water (Badino, Borelli and Gaggero). The noise caused by vibrations of the hull are not profound at large distances however they can affect those onboard the ship significantly.

The airborne noise from engines also affects the Human Factors impact with numerous regulations determining the acceptable working condition for the crew on board and comfort levels for passengers (Badino, Borelli and Gaggero) (i.e. ABS and IMO).

However, regulations specific towards noise pollution outside of the ship are limited. Most of the current regulations are at the local level driven by complaints from the population in the affected area. It is difficult to coordinate a normative approach because impact levels of noise vary between geographic areas and depend on the characteristics of the coastal area (Badino, Borelli and Gaggero). Therefore, it is difficult to provide a broad reaching regulation. As has been said before, an impact occurs when the natural level is increased. As you read in the Impact on Water - Noise section, any little bit of noise will raise the overall level in the environment so any amount of noise from a ship in an impact.

Mufflers can be attached to intake and exhaust of machinery such as engines, gas turbines, and ventilation fans. One type of muffler, reactive mufflers, reduces the noise emission by reflecting the noise back to the source. The simplest reactive muffler is an expansion chamber which changes the cross-sectional area which prevents some of the acoustic energy from entering the chamber exhaust pipe.

$$M_R = 10\log_{10}\left[1 + \frac{1}{4}\left(m - \frac{1}{m}\right) sin^2(kL)\right]$$

$M_R$ is the muffler transmission loss in units of decibels, m is the area ratio between the exhaust line and expansion chamber cross-sectional areas, k is the wave number of sound, and L is the length of the chamber. This equation is valid when the wave length is less than 80% of the largest transverse diameter (SNAME Group of Authorities).

The noise produced by pumps ($L_{Wav}$) can be predicted with relative ease using the pump power (H) in horsepower, pump speed (R) in rpms, and the pressure rise aross the pump (p) in psi (SNAME Group of Authorities). For nonreciprocating pumps the equation is

$$L_{Wav} = 15 + 10\log_{10} H + 15\log_{10} R$$

The resultant value is the airborne sound power in decibels. For piston pumps the equation is

$$L_{Wap} = 75 + 30\log_{10}\left(\frac{p}{3000}\right)$$

The SNAME Marine Engineering book is a good tool for the naval architect and marine engineer to use. It provides a sequence of steps to take during the design phase to ensure the noise level is controlled.

When in operation, the exhaust gases released through the funnel at high speeds and inlet and outlet ducts for heating, ventilation and air-conditioning cause airborne noise. These sources are not in a concentrated area of the ship but spread throughout the ship, causing a complex noise field radiating from the ship (Badino, Borelli and Gaggero). The sources and levels of noise can vary between different operating modes of the ship.

**Table 7: Noise Sources in Operating Modes (Badino, Borelli and Gaggero)**

| Operating Mode | Noise Source |
|---|---|
| Ship sailing along the coast | Main propulsion engines and their exhaust discharges |
| Ship maneuvering (entering and exiting the harbor) | Bow and stern thrusters, auxiliary propulsors, winches, windlasses, etc. and main engines in the non-design conditions |
| Ship at quay (no cargo processing) | Auxiliaries |
| Ship loading or unloading (equipment for cargo processing in function) | Cranes, buckets, ramps, and other charging/discharging means |

For the first operating mode (sailing), the speed at which the ship is traveling will have an effect on the amount of noise generated. Although the speed and route are not under the naval architect's domain, it would be beneficial for the naval architect to know at what speeds the ship will be traveling when near areas where ambient noise levels are low. Then during the design process, consideration can be taken when choosing an engine and other components which effect airborne noise. During the operation phase, route optimization and maintenance will dictate the noise emissions. The naval architects and marine engineers can help the operators cause the least impact on the environment by providing information about the best and worst engine loads for airborne noise emissions and an appropriate maintenance schedule to reduce noise.

In September 2012, faculty from the University of Genova published a paper outlining a simplified method for analyzing the noise emissions of a ship calling on ISO regulations for existing standards and distances (Badino, Borelli and Gaggero). They describe the noise field radiated by ships, Figure 8, in reality compared to a computer generated model. Although these methods are recent, they are a step in the direction of incorporating local regulations into international regulations for airborne noise emissions.

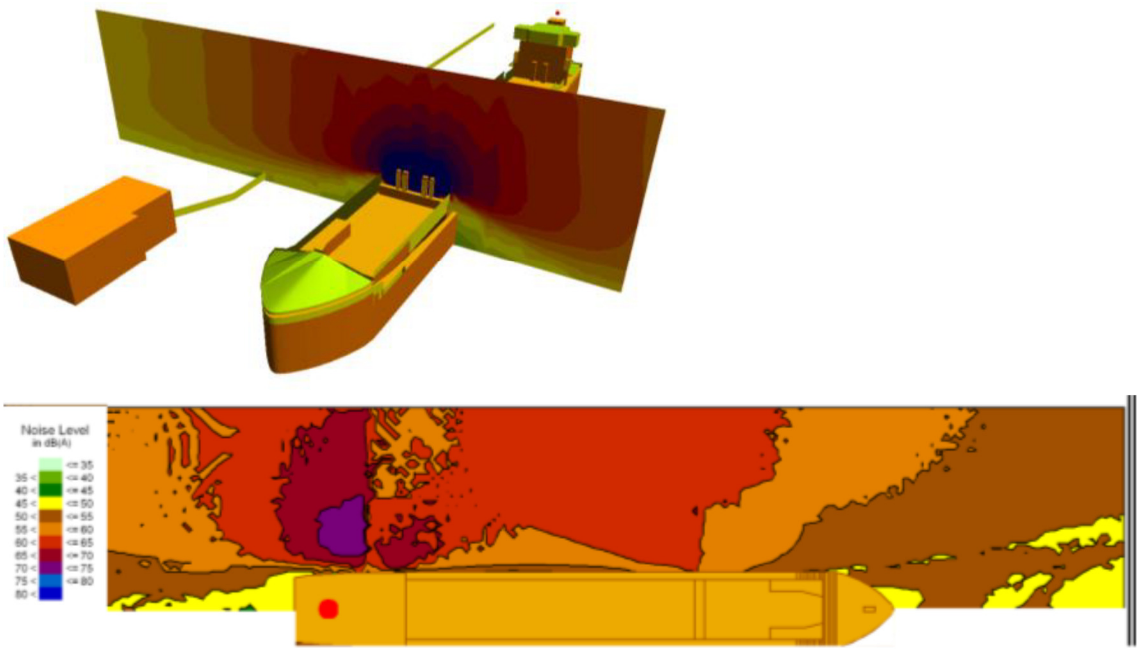


**Figure 8: Predicted noise field for a multipurpose ship (Badino, Borelli and Gaggero)**

The construction process can produce an extreme amount of noise with the equipment being used and the movement of material. The noise made by equipment at the shipyard and on the ship will not be covered since this is not under the scope of a naval architect, as stated previously.

### Heat

Heat can be released into the air changing the natural ambient temperature. As previously discussed, one of the efficiencies of the engine can help us understand how heat is emitted. The thermodynamic efficiency comes from the second law of thermodynamics which states that entropy is ever increasing which in turn means that not all of the heat can be turned into mechanical energy (work) and it is released as hot gas. The mechanical efficiency is affected by the friction in the moving parts (Xiros). Although the friction does not release as much heat as caused by the thermodynamic efficiency, it is still significant enough to be considered. The engine choice is the largest dictator of the amount of heat that will be released when the ship is operating. The equipment choice during the construction and decommission phase will dictate the heat emissions during those phases. This occurs in all engines so the impact will occur in the construction, operation and decommission phases.

### Exercises

Homework assignments can consist of modeling the emissions throughout the trip of a ship, similar to the example shown in Table 5. Also, the noise reduction from various muffler sizes can be calculated in order for the students to gain an understanding between the muffler size and the reduction in noise.

The three categories of air impacts have been added to the tables below. Like every impact, the naval architect has the opportunity to affect both impacts during the design phase. Others can influence during the other phases, construction, operation, and decommission. Material and noise emission into the air occur during the construction, operation, and decommission of ships.

**Table 8: When Impacts are Determined**

| | **Design** | **Construction** | **Operation** | **Decommission** |
|---|---|---|---|---|
| Land - above water | O | X | X | O X |
| Land - below water | O | | X | |
| Air - materials/gas | O | X | X | X |
| Air - noise | O | X | X | X |
| Air - heat | O | X | X | X |

**Table 9: When Impacts Occur**

| | **Design** | **Construction** | **Operation** | **Decommission** |
|---|---|---|---|---|
| Land - above water | | X | X | X |
| Land - below water | | | X | |
| Air - materials/gas | | X | X | X |
| Air - noise | | X | X | X |
| Air - heat | | X | X | X |

## Impact on Water

The impact of ships on the water environment can be subdivided, similar to air, by the type of impact; materials, heat, and noise.

### Materials

The impact of ships on the water environment can consist of materials which are released and are not naturally occurring. The Navy and Environmental Protection Agency (EPA) have compiled a list of 39 discharges which adversely affect the marine environment (NAVSEA). Ballast water, paint toxins, corrosion, deck run off, and grey water (McKesson, Remley and Karni) will be covered in this report.

Most ships, especially those whose load changes between routes, rely on ballasting in order to maintain stability. Many of ships are traveling long distances with the same ballast condition. This presents an environmental impact issue when a ship loads with large amounts of ballast water at its route origin and then travels out to sea or across an ocean and then must de-ballast. When a ship collects ballast water, it also takes in plants, animals, viruses, and bacteria from their natural environment and when it de-ballasts it transfers them to an environment where they may not exist. Introducing a non-native organism into an environment can affect every species there by changing the food chain. The worst impact when a non-native organism causes the extinction of a native organism. Regulations state that ships must empty their ballast water and fill again at specified distances. One regulation that is currently in place is Annes VII implemented by MARPOL.

Anti-fouling paints are commonly used on hulls of ships in order to prevent marine growth and ultimately improve the performance. By doing this, it will effect and hopefully improve the fuel consumption and energy efficiency of a ship. However, many anti-fouling paints along with hull coatings and bottom paints contain toxins. When they are released into the water, they are absorbed by mussels, barnacles, worms, and other smaller organisms. The toxins are passed up through the food chain as the smaller organisms are eaten and can eventually reach humans (McCoy and Johnson). Tin based paints are regulated by MARPOL Annex VIII.

Similar to toxins from paints, corrosion can have multiple impacts on the environment; releasing materials into the water, fuel consumption, and energy use. Every ship will go through a hull restoration and new hull coating will be applied during the operation phase. This is another opportunity to reduce the toxins released when the ship is in the water.

The ship discharges many fluids which could be contaminated and be harmful to the environment. Coolant water can get mixed with oil and then when it is discharged back into the sea it is in the form of oily water. Sewage and grey water are regulated in the US by the Uniform National Discharge Standards because they can contain cleaning fluids and other toxins (U.S. Coast Guard). Treated grey water can be discharged overboard depending on local regulations. By reducing the amount of contaminants used on board and reducing the amount of water used, the impact of ship discharges will also be reduced. Another option is the use of environmentally friendly products which will have less of an impact if they are discharged.

**Figure 9: Corrosion Impact (Haus)**

Corrosion, such as seen in Figure 9, releases metals into the water and causes resistance of the hull moving through the water, affecting the fuel consumption and energy use of the ship. Like the toxins, the metals released can be absorbed by smaller organisms and have an impact on those farther up the food chain.

A ship is cleaned and hosed down in order to keep the deck clean and safe for those aboard. However, when the deck is hosed down and the water is allowed to run off the edge into the water, it carries whatever was on the deck with it. This can include discharges from cargo, cleaning products, automobile oil from ferries, etc.

Since 1988, garbage from shipping has been controlled by Annex V of the MARPOL Convention, outlawing all disposal of plastic and regulating the disposal of garbage into the sea. However, trash pollution into the water from ships has not disappeared since illegal dumping still occurs. This is one impact that regulation enforcement can eliminate completely.

Previously mentioned in Impacts on Air - Material/Gas, although not as prominent with discharges into water, GWP and ODP indicators can be used to judge the environmental impact of discharges into the water and can be used to compare various options during the design process.

Accidents are not only harmful to the humans involved, but can also affect the marine life. As seen with the Deep-water Horizon oil spill in 2010, humans were harmed along with the release of 4.9 million barrels (780,000 $m^3$) of oil into the water (Hoch). Pictures were shown on the news of birds, whales (Figure 10) and many other animals covered in oil and there were many reports on deaths of these animals. In 1989, the Exxon Valdez spilled 11 million gallons (41639.5 $m^3$) of crude oil into the Prince William Sound. Due to this accident, the Oil Pollution Act of 1990 was enacted. This act addressed the prevention, response, and payment for oil pollution. Specifically related the the naval architect, it implemented requirements such as double hulls for tank ships and barges in US waterways by 2015. This regulation was also implemented by the IMO with the same time frame (Talley, Jin and Kite-Powell). Unfortunately, many times it takes an accident for a change in regulation to occur.

Figure 10: Whale Covered in Oil from the Deep-water Horizon Oil Spill (Goldenberg)

The area of a medium fuel oil spill can be estimated using the volume of oil (Benvenuto and Figari 227).

$$A_{max} = \pi {R_{max}}^2 = 10^5 V^{0.75}$$

V ($m^3$) is the volume of oil released into the water, R (m) is the maximum radius of the released oil and A ($m^2$) is the maximum area the oil will spread.

When an accident occurs involving a ship, other contaminants besides oils can be released into the water. All ships contain fluids which are needed for operation and are harmful to animals. Some ships carry cargo, both fluids and solids. During an accident, the cargo could be spilled into the seas. It is rare to find fluids or solids on a ship which are natural to the sea environment and therefore, any of the fluids or solids released will have an impact on the environment under water.

Although it is highly regulated and most ships have a cleaning system on board, grey water (shower water, cooling water) can be an impact if it is not treated properly before it is released into the sea. Grey water can be an issue during the operation phase when in port and while traveling. This impact can be affected during the design process by accounting for a treatment system on board or with storage tanks.

### Heat

Ships produce heat and can release it into the water as an impact called thermal scarring.

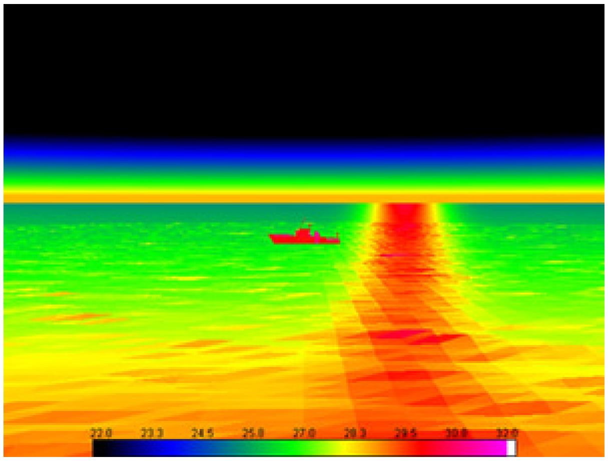

Figure 11: Thermal scarring of a ship's path and heat emitted by a smaller vessel

The military has been using the concept of thermal scarring for years to detect and categorize ships and submarines by the trail of heat they leave in their wake and by their heat signature (IR signature), Figure 11. While the military has been using it to protect and defend their country from enemies, we are looking at it from the view of protecting and defending marine animals from anthropogenic influence.

Thermal pollution is an impact that is not often discussed with environmental impacts of ships (McKesson, Remley and Karni). It is the discharge of heated effluents into the sea which can cause a rise in ocean temperature. Warmer water contains less oxygen which can affect the reproduction of many marine animals such as trout and salmon, Figure 12.

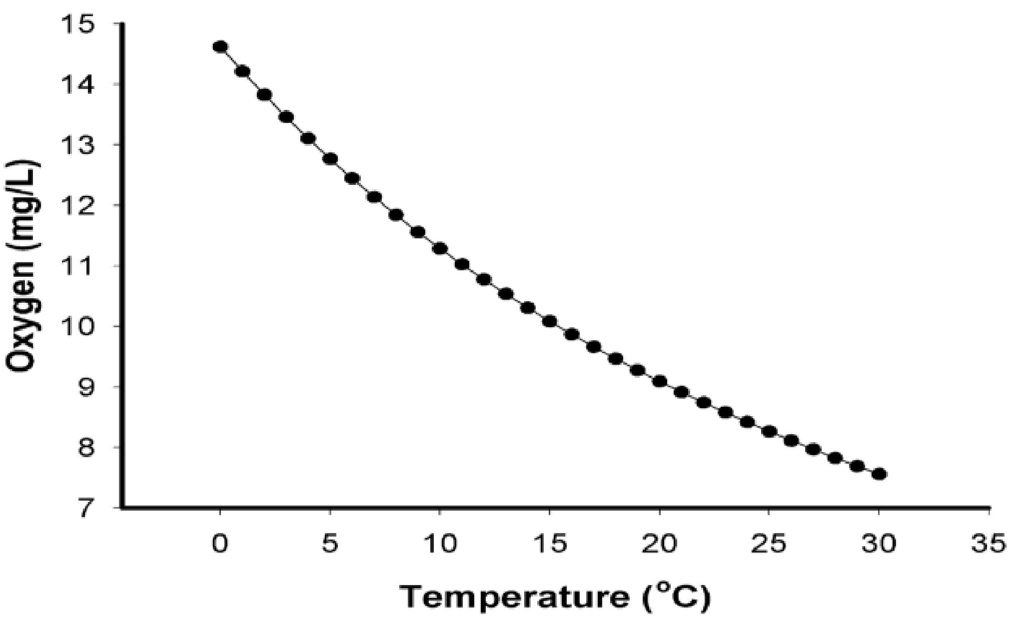


Figure 12: Solubility of oxygen in water with temperature change

With the rise in temperature, the fish respiratory cycle speeds up and they need more oxygen. This does not correlate well with less oxygen in the water at higher temperatures.

Figure 13 shows the distribution of heat discharges from a vessel with high speed diesel engines. Exhaust, cooling water, and shaft power are the three main sources.

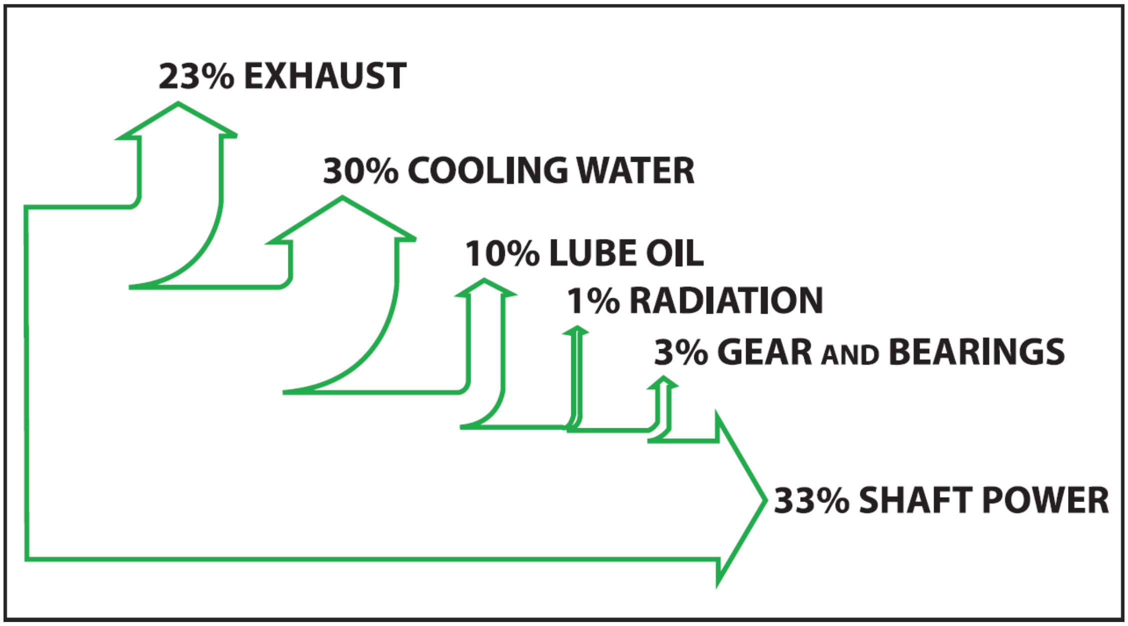


**Figure 13: Typical heat balance of a vessel with high-speed diesel engines**

The release of heat from the shaft power and cooling water originates with the engine caused by heat transfer efficiency and mechanical efficiency. The materials are not able to handle all the heat which is produced in the engine. The coolant water is used to prevent the materials from melting by allowing the heat to be released into the water. This water is either discharged in to the sea ultimately raising the temperature of the surrounding water. The heat can also be collected to be used in other areas of the ship such as hot water or a/c heating. The mechanical efficiency can also be cooled with water and the heat can be transferred to the sea water (Xiros).

There are limited resources available which discuss the heat sources on a vessel and how they can be altered to reduce the impact. This is an area which is in need of further research.

### Noise

The most obvious impacts are those that have a visual aspect. However, there are impacts which occur below the waves and are not able to be seen. Noise in the water that is not produced by the natural environment can affect various aspects of marine life. For example, noise disrupts animal communication which can lead to effects on reproduction. It is not just the individual ship noise that creates an impact. There are many other marine vessels, industrial plants, etc. that interact with the water and create excess noise.

Any noise that is generated that is above the natural noise level is considered an impact. Figure 14 illustrates the relation of the hearing range of animals which are found in water compared to noises which are generated by humans. For example, the frequency range of noise produced by the majority of marine vessels and structures is about 0.01 to 1 kHz which is the hearing range of fish, whales and some seals and dolphins. The sonar from submarines falls into three main ranges, 0.1 to 0.5 kHz, 1 to 10 kHz, and 50 to 200 kHz which are frequencies audible by most marine animals.

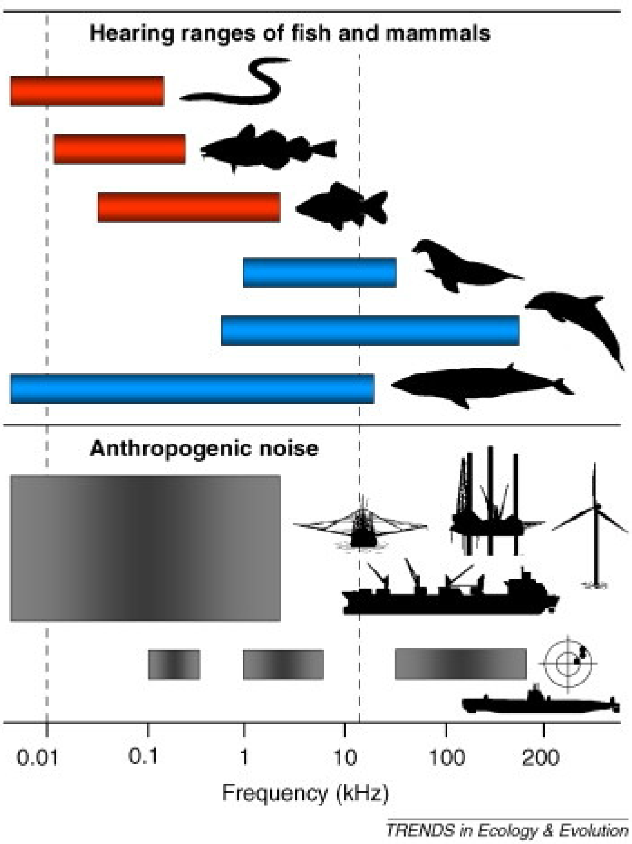


**Figure 14: Hearing Range of Animals and Human-Generated Noise (Queeney)**

As can be seen by Figure 14, it is safe to say that every animal in the water can be affected by anthropogenic noise with respect to frequencies. Therefore, all noise generated by humans has an impact on the environment of animals.

Any noise at all that is released into the water, no matter the level, is an impact because the effect of sound is cumulative. For example, you have a bowl of water with one drop of food coloring that is the “natural environment”. If you add one more drop it will still increase the color in the water and decreases the opacity. This analogy is even more apt when we recall that the marine animals use sound for navigations, where humans use sight. Thus, this analogy illustrates the idea that “one more drop” of noise increases the “opacity” of the water provides a helpful tool for understanding the animal impact.

Noise is generated by any vibrations which occur in the ship. If you look at a sound speaker when it is producing noise, the cover vibrates. It is those vibrations which produce the air pressure waves that are “noise”. In the case of ships, the largest contributors are the propulsion systems, mechanical systems, generation of electricity, and hydrodynamic effects (Bahtiarian). The worst systems are those that are near or below the waterline because they have the shortest path from the source to water. The vibrations from a ship and its components can be estimated using a multi-modal system. The Principles of Naval Architecture (PNA) from SNAME is a resource which will explain the calculation process.

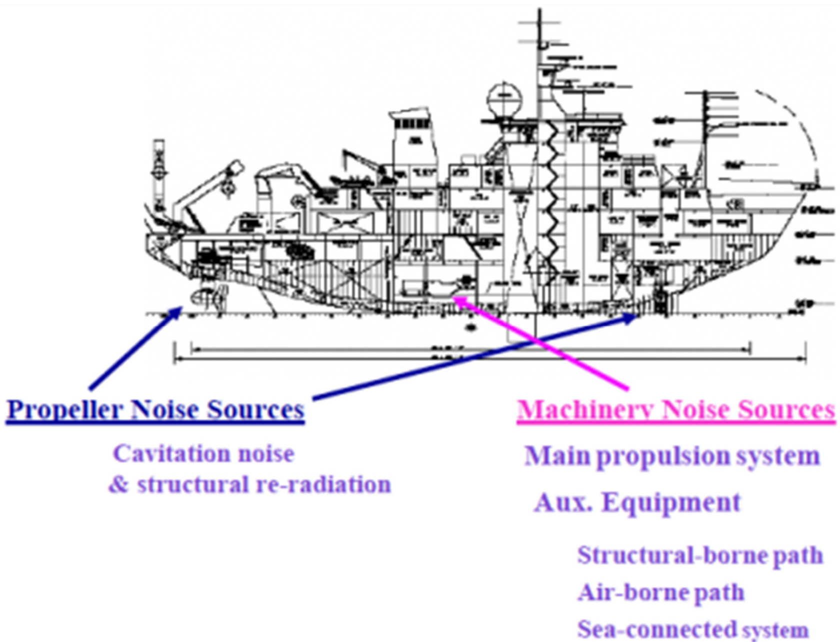


**Figure 15: Noise Origin in Ships (Fischer)**

Figure 15, highlights the systems which cause the majority of noise on a ship, most of which are low in the ship or even below the waterline.

It was previously stated that vibrations cause noise. While this principally refers to mechanical vibration, vibrations can also be caused by friction and turbulent flow, which also causes resistance. Therefore, anything that causes turbulent flow, such as marine growth, in turn causes noise.

Noise propagates directly out from the source while dissipating. Therefore, the closer the source to the water, the greater the noise impact into the water will be. The propeller will be the largest contributor to noise pollution because the noise it causes is already in the water and will propagate further. Changing the speed of the propeller will change the frequency of the noise it produces. One way to analyze the noise is by the cavitation inception speed (Bahtiarian). A propeller has not been made yet which will have a low noise production at all speeds. Every propeller has at least one speed which will cause noise to be created.

The sound pressure level (SPL) is a measure of noise usually in decibels relative to one micro Pascal (μP), and is inclusive of the natural noise and the noise added by the ship. The measurement can be affected by the distance from the source and the environment through which the noise is traveling. SPL is reported in decibels (dB). The source level (SL) is the measure of the noise independent of the environment. It is the sum of the SPL and the propagation loss (PL).

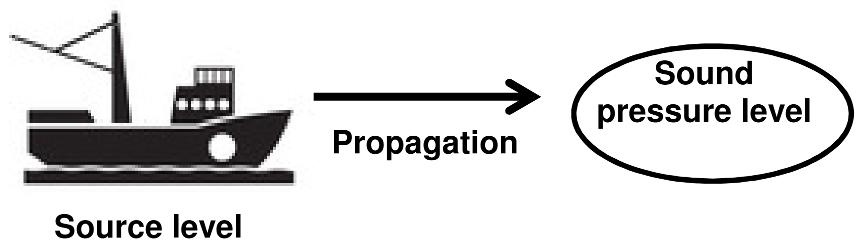


Figure 16: The SL is the sum of the SPL and the PL

The radiated noise level (RNL) is the measure at a specified radius. The RNL is used to compare the noise from ships but is not used as the measure for the amount of noise generated by a ship.

$$RNL = SPL + 20\log_{10}\frac{r}{1m}\ (dB)$$

RNL in the equation above is the radiated noise level measured scaled to a distance of 1 meter. r is the radius at the point of measurement. The RNL is a more accurate method for comparing radiated noise because it is scaled to a uniform distance. For further clarification on measuring and comparing noise generated by ships, NATO STANAG 1136 (NATO, 1995) or the ANSI/ASA S12.64 standard, (ANSI/ASA, 2009) are excellent sources.

A decibel is a measure in the form of a ratio of pressures. The following equation is used to determine the decibel using known pressures. The ratio of the actual pressure (P) to the reference pressure ($P_{ref}$) is often stated as one pressure value.

$$dB = 10\log {}^{P}/_{P_{ref}}$$

Looking at an example in Table 10, we are able to measure the sound in dB from each piece of equipment in the ship. From there we use the above equation to back out the pressure ratio.

Table 10: Decibel calculation example

| Equipment | Pressure | dB |
|---|---|---|
| Generator | 1.00E+09 | 90 |
| Engine | 1.00E+09 | 90 |
| Propeller | 1.00E+10 | 100 |
| Miscellaneous Auxiliaries | 1.00E+04 | 40 |

We can add the pressure ratios with a result of 12,000,010,000. From there we use the same equation to convert it back to dB. The total dB for all the equipment is 100.8 dB. If we were to add the dB the result would be 320dB which is vastly different than the accurate result of 100.8

dB. Another example: If the natural SPL in a region is 100 dB and a ship generating an SL of 100 dB passes through, the total SPL would be 103 dB. This is only an increase of 3dB. If the same ship was to pass through an area with a natural SPL of 50 dB, the total SPL would be 100 dB, double the natural SPL.

The last example shows that the same ship will affect each area in a different magnitude. Therefore, there cannot be one level regulated for noise level. The amount of noise a ship can produce without significant impact on the environment depends on its route, the environment in the regions it travels to and the marine life in the region. One area might have a higher natural noise level and therefore it takes more noise from the ship to disrupt the environment.

### Exercises

Calculations can be completed by the students relating to the radiated noise level of ships with the goal of them making a comparison between ships. Also relating to noise, a simple vibrations problem, such as the vibration amplitude of the engine can be given as homework. Reference for this can be found, as previously mentioned, in the vibration PNA from SNAME. They could also research what other discharges occur from a ship that are not covered in the lectures, where they originate and what can be done to prevent them from reaching the sea.

The three types of impacts in the water were added to the tables. The naval architect can make decisions during the design phase to reduce the impacts and other can make decision during the operation phase to reduce the impact from materials and noise. All three types of impacts occur during the operation phase of the ship life cycle.

**Table 11: When Impacts are Determined**

| | Design | Construction | Operation | Decommission |
|---|---|---|---|---|
| Land - above water | O | X | X | O X |
| Land - below water | O | | X | |
| Air - materials/gas | O | X | X | X |
| Air - noise | O | X | X | X |
| Air - heat | O | X | X | X |
| Water - materials | O | | X | |
| Water - heat | O | | | |
| Water - noise | O | | X | |

**Table 12: When Impacts Occur**

| | Design | Construction | Operation | Decommission |
|---|---|---|---|---|
| Land above water | | X | X | X |
| Land below water | | | X | |
| Air - materials/gas | | X | X | X |
| Air - noise | | X | X | X |
| Air - heat | | X | X | X |
| Water - materials | | | X | |
| Water - heat | | | X | |
| Water - noise | | | X | |

# Impact on Resources

## Physical Consumables

Every ship must be built with material and almost every ship must run on a type of fuel. Every material that is taken from the environment creates an impact since it changes the natural condition. We have heard to save paper in order to save the trees. The same concept goes for every type of material. The substances to make the materials come from the environment and all substances are in limited supply. It is the beginning of the material's life that the actual impact occurs before it is used to construct a ship. For example, ships are primarily made of steel. Iron and other elements, most common being carbon, are combined to create various grades of steel. Iron comes from the Earth's crust and is in limited supply.

The materials which will be used for construction of the ship are determined by the naval architect during the design process. Many of the materials are dictated by codes for safety purposes, then from there the naval architect can make decisions which will dictate the amount of material which can be recycled during decommissioning, the amount of recycled materials used to build the ship during the construction phase, and other aspects which will determine the total impact on the environment by the physical consumables on the ship. The materials chosen can also influence other impacts such as Impacts on Air - Noise, Impact on Water - Heat, Impact on Water - Noise, and Impact on Resources - Energy by the amount of reduction in vibrations and insulation they provide.

The distance material travels affects the total impact during the construction phase. Materials are harvested or produced in one place, then they might be used to construct a piece of equipment, and finally they make their trip to the shipyard. During all those travels they are transported on ships and trucks which have their own impacts on the environment. The shorter a material travels from its origin to the shipyard, the less the impact from transportation. Therefore, whether it is the naval architect or the shipyard who determines the materials ordered, the origin of the materials and equipment should be considered.

Many ships will be renovated or altered during the operation phase. This is another opportunity for the naval architect to reduce the impact using some of the same methods used during the design phase. The same thought process should be applied during renovation planning as during the design phase.

The end of the life of the material is just as important as the beginning. The fiberglass used might be of the most concern as it is not able to be recycled so all of it will be in a landfill eventually. The amount of materials used is an easy aspect to determine. One important ratio to determine is the amount of total materials used versus the amount of recycled content or rapidly replenishing materials used. Rapidly renewable products such as bamboo, linoleum, cork, poplar, wool, and steel are less of a burden on the environment when they are harvested (King, Roberts and Payne). This will help determine the impact during the decommissioning phase of the life cycle. The amount of recyclable materials used to construct the ship will reduce the amount of materials which end their life in a landfill.

Evidence of the limited supply of crude oil to produce fuel is in the consistent rise of fuel prices. Owners want to operate their ships with the least amount of cost. Therefore, making their ship more fuel efficient is not only good for the environment; it is also good for the owner's wallet. Draining a natural source from the earth, such as crude oil, will affect other aspects of the natural environment within the earth.

Fuel consumption is determined during the design process with respect to the resistance of the hull and engine choice and during operation with respect to the route. The easiest change to reduce fuel consumption is to use fuel energy more efficiently for propulsion and onboard equipment (Hochkirch and Bertram). When determining the route a ship will take, the weather, current, traffic into and out of ports, and other environmental (ex. wind and currents) and human aspects will impact the amount of fuel consumed. However, as stated previously this is out of the scope of the naval architect but the naval architect will need to know the predicted routes in order to design an efficient ship. The naval architect can provide information to the operator, such as graphs, which will help them determine the best route for fuel consumption. For example, a graph can be constructed of RPM of the engine versus the fuel consumption or the speed versus the resistance working against the movement of the ship. Previously mentioned was a graph of speed versus air emissions. If the fuel consumption is then overlaid on this graph it will help the operator optimize the two factors to obtain the least environmental impact. These tools will help the operator determine the appropriate route, whether it be direct or indirect.

The consumption of fuel is also discussed when determining energy consumption. Many of the ways to reduce energy consumption can also be applied to the reduction of fuel consumption. The most effective way of reducing fuel consumption is to substitute fuel power by renewable energies (Hochkirch and Bertram).

The equipment on the ship contributes to the physical consumable impact. The parts must be replaced and sometimes it is the whole piece of equipment. Maintenance schedules can affect the life cycle of equipment and its parts. The longer the life cycle of equipment, the less it needs to be replaced and therefore, the less equipment which will end up in landfills or, hopefully, go through the recycling process. Lubrication oil is used in many pieces of equipment on a ship and must be changed on a consistent schedule. The old oil ends up becoming a physical harm to the environment if it is not recycled. Similar to fuel consumption, oil consumption, albeit on a small scale, should be reduced.

### Energy

Energy is probably the most discussed impact as it has a direct correlation with the cost of operation of a ship. Every owner would like their ship to be the most energy efficient in order to reduce the cash outflow and increase profits. The impact of energy coordinates with many of the impacts previously discussed. Consumables, such as fuel, are used to produce energy on a ship. With this being the case, energy efficiency could be considered a Physical Consumables impact. However, there is much to be discussed about energy efficiency so it will be left as a separate impact from Physical Consumables.

Resistance affects the amount of power needed to push the ship through the water and therefore affects the energy efficiency of the engine. All types of resistance are included, air, wind, residual and wave resistance. Resistance has been discussed previously in the sections Impacts on Land - Above Water, and Impact on Water - Materials and Noise. The smoothness of the hull and the fouling on the hull can be controlled which in turn can control energy efficiency. The lifting mode, either dynamic or static, can have an effect on the amount of resistance encountered as well as the hull design. Bulbs, flaps and other appendages can be optimized in order to reduce the amount of power needed to propel the ship through the water because this will have a direct impact on the energy consumption. The smoothness and fouling control must be optimized with Impact on Water - Materials when choosing hull coatings which include toxins.

Similar to almost every other impact discussed, route optimization plays a role in the energy consumption of the ship because it has an effect on the required power. Again, the route is under the scope of the operators not the naval architect. However, the naval architect can provide information about the amount of energy consumed versus the speed (Figure 17), wave conditions, and other factors to help the operator choose the most efficient route.

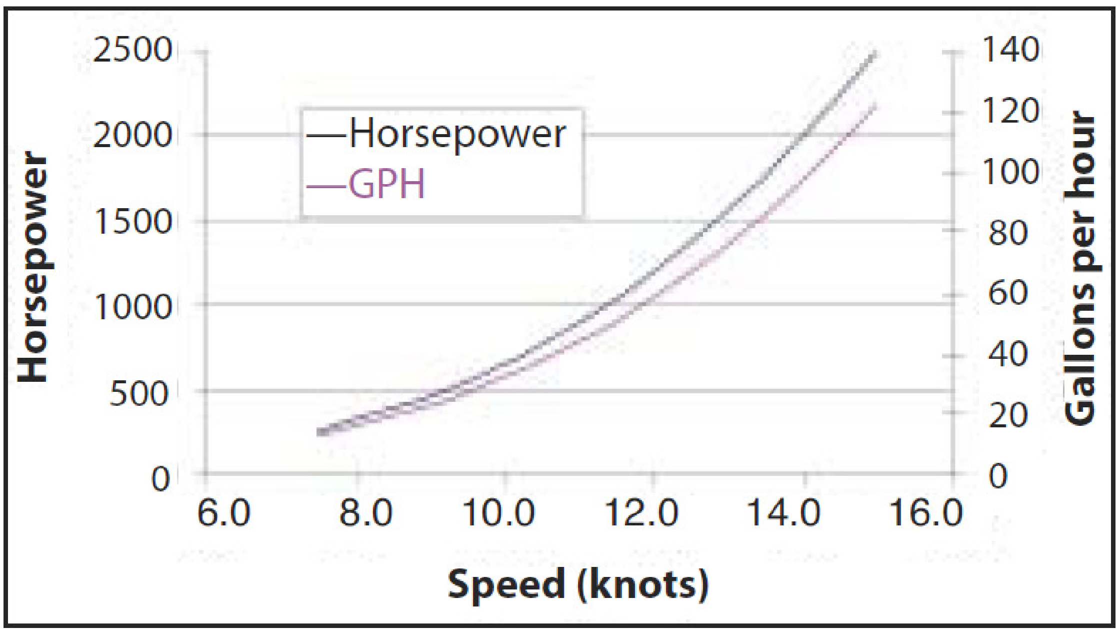


**Figure 17: Example of graph showing the fuel consumption at various speeds and horsepower**

Figure 17 is an excellent example of a tool a naval architect can provide to operators in order to assist their decision making. One line on a graph where the horizontal axis is either speed or RPM and the vertical axis is their fuel consumption along with horsepower in increasing values.

Although it will not be covered here since technology is constantly changing, there are many advances in alternative fuel sources and alternatives to fuel (i.e. wind and solar power) which can increase the energy efficiency of the ship as well as better every other impact to keep in mind during the initial brainstorming stage. With either traditional fuels or with renewable energies, a reduction in required power for propulsion will increase the efficiency of energy use (Hochkirch and Bertram) and will decrease the amount of consumables (i.e. fuel) needed.

The largest consumer of energy on a cargo ship is the propulsion system. The propulsion system mainly includes motors and thrusters. Some ships may use diesel prime movers to power their thrusters. In this case, fuel consumption is the impact affected.

The energy consumption on a ship, other than in the propulsion system, is very similar to that in a building. On a cruise ship the hotel load is a large consumer of energy. Small aspects of the ship in the outfitting, such as lighting, batteries (U.S. Coast Guard), and pumps as well as the air conditioning/heating system, consume energy and can add up to increase the energy consumption impact. The materials chosen to construct the hotel and living quarters can have an impact on the amount of use of the air conditioning/heating system. One difference is the water usage on a ship. The water makers use energy to create water for toilets, showers, sinks, etc. and treatment systems use energy to minimize the contaminants before it is discharged overboard. Therefore, reducing the amount of water used will also reduce the amount of energy consumed to treat the water. One practice for reducing water usage is by using “low-flow” plumbing fixtures.

When choosing materials this impact, as well as the Physical Consumables impact, needs to be considered. The material used for the hull will also affect the Physical Consumables impact and the resistance of the ship.

### Exercises

By performing an electric load analysis, the students are able to have a better understanding of the distribution of energy consuming items on the ship and they can pinpoint ways to reduce the electrical load.

The naval architect has the power to influence both resources impacts during the design phase and the physical consumables impact during the operation phase. Others have influence for both impacts during the other three phases of the ship life cycle. Both impacts occur during the construction, operation, and decommission phases.

**Table 13: When Impacts are Determined**

| | Design | Construction | Operation | Decommission |
|---|---|---|---|---|
| Land - above water | O | X | X | O X |
| Land - below water | O | | X | |
| Air - materials/gas | O | X | X | X |
| Air - noise | O | X | X | X |
| Air - heat | O | X | X | X |
| Water - materials | O | | | |
| Water - heat | O | | | |
| Water - noise | O | | X | |
| Resources - physical | O | X | O X | X |
| Resources - energy | O | X | X | X |

**Table 14: When Impacts Occur**

| | Design | Construction | Operation | Decommission |
|---|---|---|---|---|
| Land above water | | X | X | X |
| Land below water | | | X | |
| Air - materials/gas | | X | X | X |
| Air - noise | | X | X | X |
| Air - heat | | X | X | X |
| Water - materials | | | X | |
| Water - heat | | | X | |
| Water - noise | | | X | |
| Resources – physical | | X | X | X |
| Resources - energy | | X | X | X |

## Human Factors

Many of the impacts previously discussed have included components which fall under the Human Factors category. The wake-wash from a ship can cause discomfort to those relaxing on a beach or on another craft. Noise from passing ships can disturb homeowners on the river and noise from the construction sites can reach businesses and neighborhoods. Noise inside the ship can have a harmful effect on the crew. The crew size can have an influence on the fatigue felt by the crewmen. If a worker is feeling fatigue, their decision making skills and reaction times decrease affecting their safety. The size of accommodations and the lighting provided in work areas affect the crew, their work, and their safety. Natural light in work areas increases awareness and production. LEED can also be used as guidance for the accommodation spaces on a ship. It addresses the indoor climate (i.e. indoor air quality, thermal comfort, daylighting). For example, LEED encourages the use of materials which do not emit volatile organic compounds (VOCs) which have adverse health effects on humans.

The ABS Guide for Crew Habitability on Offshore Installations regulates the whole body vibrations, accommodation area, and noise levels. IMO has also produced a set of guidelines dealing with Human Factors. The ultimate goal of all human factors regulations is to ensure the safety of the crew and the safety of those in close proximity to marine vessels and structures. By following the guidelines put forth by regulation bodies and classification societies, the performance of the crew will increase and the probability for accidents on the ship and with the ship and other vessels or structures will decrease.

Designer-NOISE is a software program which monitors noise onboard the ship which will help the operators and the crews regulate the noise. If this is done it can lower the effect noise has on the crew, decreasing injury and increasing their productivity.

The impact of a ship during its life is determined during every phase and occurs during every phase.

**Table 15: When Impacts are Determined**

| | Design | Construction | Operation | Decommission |
|---|---|---|---|---|
| Land - above water | O | X | X | O X |
| Land - below water | O | | X | |
| Air - materials/gas | O | X | X | X |
| Air - noise | O | X | X | X |
| Air - heat | O | X | X | X |
| Water - materials | O | | | |
| Water - heat | O | | | |
| Water - noise | O | | X | |
| Resources - physical | O | X | O X | X |
| Resources - energy | O | X | X | X |
| Human Factors | O | X | X | X |

**Table 16: When Impacts Occur**

| | Design | Construction | Operation | Decommission |
|---|---|---|---|---|
| Land above water | | X | X | X |
| Land below water | | | X | |
| Air - materials/gas | | X | X | X |
| Air - noise | | X | X | X |
| Air - heat | | X | X | X |
| Water - materials | | | X | |
| Water - heat | | | X | |
| Water - noise | | | X | |
| Resources – physical | | X | X | X |
| Resources - energy | | X | X | X |
| Human Factors | | X | X | X |

## Aesthetics

Imagine relaxing on a beach and you look out at the water and see a ferry covered in advertisement. That would be an eye sore and ruin a beautiful view. Although it seems trivial to most naval architects and operators, the visual aspect of a ship can be a type of pollution to the serenity of an environment (McKesson, Remley and Karni). If a ship is painted the color of the ocean and sky, it will blend into the environment more and decrease the amount of visual pollution. On the other hand, imagine a ferry which travels along a coastline which is heavily populated. The ferry company has the opportunity to advertise on the ferry and make it into a moving billboard. As of this writing, information was not found about the effects of the colors of ships on the sea animals.

## Analysis

There are certificate programs being developed and awarded by many regulatory organizations. For example, Energy Efficiency Design Index (EEDI) was developed by the IMO in an effort to reduce greenhouse gas (GHG) emissions. As of the beginning of 2013, EEDI has been added to the MARPOL Annex VI and is a requirement for new ships (Det Norske Veritas). The concept of EEDI is actual $CO_2$ emissions divided by the transport work to obtain the EEDI value for a ship. The specific formula is very extensive and might prove too much to be covered in this class.

There are many studies currently in progress, such as MVeP, which are trying to develop a way to assess the impact of ships in a quantitative manner. As has been previously mentioned, this is very difficult due to the geographic specific nature of most of the impacts.

## Conclusion

The naval architect has influence over every impact during the design process. If it is not addressed there, then it is out of the hands of the naval architect and into those of the operators and owners. It is vital for the impacts to be addressed during the design period along with every other design aspect.

Route optimization has an effect on most of the impacts. However, the route is not determined by the naval architect. Is there a way for the naval architect to help the operator determine a route which will have the lowest impact on the environment?

The U.S. Military have become great environmental role models for the industry. They are going above the regulations and have been conducting research on the new technologies and their reliability and the trends of future regulations. Greenhouse gas emission and water discharge are expected to be the focus of future regulations (U.S. Coast Guard). It is important to consider the possibilities for future regulations if you want the ship to be considered “green” for 20 to 30 years.

Ultimately the end user or owner will be the driving force on the environmental impact of their ships. Without the owner’s support, the environmental aspect of a ship will not be considered unless it is otherwise enforced by governmental regulations or classification societies. Companies who work as owners have come together to form the Sustainable Shipping Initiative (Figure 18) and are cooperating together in order to determine ways which the shipping industry can contribute and thrive in a sustainable future.

**Figure 18: A group of companies who plan how shipping can contribute and thrive in a sustainable future (Lloyd's Register)**

On the other hand, without the support of the naval architect and other designers, the ship would not be able to be operated with a reduced impact. For all the technology designed into the ship to reduce the environmental impact to be effective, it is vital that the operation of the technology is easy to read and use, and all information is given to the operator to ensure that the best decisions can be made with the least impact.

## Further Research

This thesis leads to many other topics which can be researched and developed into separate reports and theses. Naval architects are not the only stakeholders in the ship industry and ships are not the only marine piece which has an impact on the environment.

One aspect is to expand the control volume to include ports. Cargo ships transport containers to ports but their journey does not end there. By altering the operation of ports, it is possible to decrease the time a ship spends in port waiting to be unloaded. When a ship is idling in port, it is still in operation and still making an impact on the environment around it. Vergara, McKesson, and Walczak have explored this topic in their paper.

Ultimately, a thesis could be completed on the impact of the life cycle of a container between destinations. The life of a container, the movement on a truck, the movement and drayage in the origin port, traveling on a ship, the movement and drayage in the destination port and another trip on a truck, has many steps which have impacts on the environment that can be reduced by optimization and maintenance.

The role of the operator was not explored yet the decisions and actions by the operator can have a major influence with the impact of the ship during the operation and decommissioning phases. As was stated multiple times, the routing of the ship between destinations affects every impact.

There is a correlation between the ship industry and other ocean stakeholders. The World Ocean Council has brought together the ocean business community to combine efforts to reduce the impact of humans on the ocean (Lloyd's Register). The interaction between all the industries which are affected by the ocean and which affect the ocean can be analyzed. Are there improvements in the methods of the way these companies interact which can reduce the impact on the environment?

There is also the issue of direct contact between boats and animals. For example, propellers harm manatees, Figure 19, and coral on a daily basis in the Florida Keys.

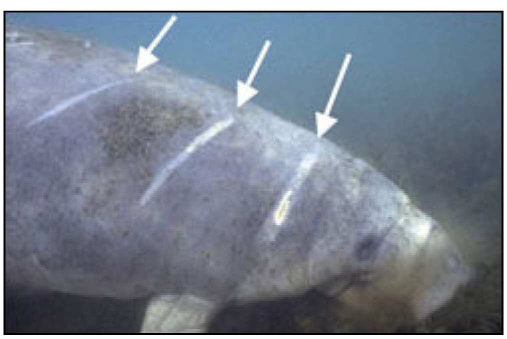

**Figure 19: Propellers cause scars on manatees in southern regions (i.e. The Florida Keys)**

This direct impact does not fall into one of the specific categories previously discussed and is almost always limited to smaller pleasure crafts in specific geographical areas. A naval architect or those who design equipment such as propellers for smaller craft have the opportunity to develop technology which can reduce the harm done to animals when contact is made. On the other hand, it is the regulations for speeds and routes that must be up to date and enforced to reduce the impact on marine animals. Although this type of impact does not fall under the majority of naval architects' job description it is an impact that needs to be addressed.

In the Ship Life Cycle section, it was mentioned that the operation phase can be broken down into work time, renovation and repairs, and other time. A study on the transition between these stages in the operation phase and how to reduce the impacts and increase the down time would be useful for owners and operators.

As previously mentioned, currently there is research into an analysis method for the impacts ships create and quantifying them. This research will continue and will always need to be re-analyzed in order to stay current with the conditions of the earth as they change.

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# Appendices

## Appendix A – Sources of Impacts

Throughout this report, each impact has been discussed along with the sources that cause the impact. Here, the sources and decision opportunities are listed and the impact which they affect are indicated,

**Table 17: List of sources and decisions, and what impact they influence**

| | Land – Above water | Land – Below water | Air – Materials / Gas | Air – Noise | Water – Materials | Water – Heat | Water – Noise | Resources – Physical consumables | Resources – Energy |
|---|---|---|---|---|---|---|---|---|---|
| Route Optimization | X | X | X | X | X | X | X | X | X |
| Propeller | X | X | | | | | X | X | X |
| Engine | X | | X | X | | X | X | X | X |
| Hull Form | X | | | | | | X | X | X |
| Hull coatings and paints | | | | | X | | | X | X |
| Materials | X | | | X | X | X | X | X | X |

## Appendix B – MVeP Categories

MVeP is being developed by SNAME as a series of guides which will help owners, operators, and designer when working to create a “green” ship. Although at the current time only EE1.5: Energy Efficiency – Hull and Propeller Operations and Maintenance has been released for purchase. The rest of the guides will be published in time. Each of these guides will be excellent resources for class.

**Table 18: MVeP T&R Guides which are published or development**

| | | |
|---|---|---|
| Energy Efficiency | **EE1** | **Energy Optimization Measures** |
| | EE1.1 | Lighting |
| | EE1.2 | HVAC |
| | EE1.3 | Pump and Piping Systems |
| | EE1.4 | Mechanical Equipment Operations & Maintenance |
| | EE1.5 | Hull & Propeller Operations & Maintenance |
| | EE1.6 | Route Optimization |
| | EE1.7 | Vessel Speed Optimization |
| | EE1.8 | Waste Heat and Energy Recovery |
| | EE1.9 | Hull Optimization. |
| | EE1.10 | Electrical Power Generation & Distribution. |
| | **EE2** | **Innovations** |
| | EE2.1 | LNG |
| | EE2.2 | |
| | EE2.3 | Renewable Energies |
| | **EE3** | **Carbon Foot Print Reduction** |
| Air Emissions | **AE1** | **Nitrogen Oxides (NOx).** |
| | **AE2** | **Sulfur Oxides (SOx)** |
| | **AE3** | **Particulate Matter (PM)** |
| | **AE4** | **Volatile Organic Compounds (VOCs)** |
| | **AE5** | **Other Green House Gases (GHGs).** |
| | **AE6** | **Ozone-Depleting Substances** |
| | **AE7** | **Port Air Emissions** |
| Emissions to Water | **WE1** | **Oily Water** |
| | **WE2** | **Non-Indigenous Species Control** |
| | WE2.1 | Ballast Water and Sediment |
| | WE2.2 | Hull Fouling. |
| | **WE3** | **Sanitary Systems** |
| | **WE4** | **Solid Waste** |
| | **WE5** | **Incidental Discharges** |
| | **WE6** | **Structural Protection of Oil** |
| General Measures | **GM1** | **Materials: Reduction/Reuse/Recycle/Construction** |
| | **GM2** | **Hotel Water Use: Reduction/Reuse/Recycle** |
| | **GM3** | **Ocean Health and Aquatic Life** |
| | GM3.1 | Underwater Noise |
| | GM3.2 | Wake Wash and Shore Protection |
| | GM3.3 | Lighting |
| | **GM4** | **Hazardous Materials Control-Inventory Program** |
| | **GM5** | **Ship Recycling** |

## Vita

The author was born in Fort Myers, Florida. She obtained her Bachelor’s degree in Civil Engineering from Florida Atlantic University in 2010. She joined the University of New Orleans Naval Architecture and Marine Engineering graduate program to pursue a Master’s degree. While in graduate school she has participated in the Society of Naval Architects and Marine Engineers (SNAME) research program, Marine Vessel Environmental Program. She chairs the SNAME student chapter.