JOURNAL OF INTERNATIONAL MARITIME SAFETY, ENVIRONMENTAL AFFAIRS, AND SHIPPING
https://doi.org/10.1080/25725084.2020.1804212

Taylor & Francis
Taylor & Francis Group

OPEN ACCESS Check for updates

Decision-making for cable routing at detailed ship design through life cycle and cost assessment

Muki Park[a,b], Byongug Jeong[a] and Mingyu Kim[c]

[a]Department of Naval Architecture, Ocean and Marine Engineering, University of Strathclyde, Glasgow, UK; [b]Electric Design Team, Samsung Heavy Industries Co., Ltd, Geoje-si, Republic of Korea; [c]Korea Centre for International Maritime Safety Cooperation (KMC), Sejong, Republic of Korea

ABSTRACT

This paper was to establish a practical approach to evaluating economic and eco-friendly designs for cable arrangement on the deck-side of offshore vessels. Three credible options were identified: acableway arrangement on the main deck alone; the arrangement using both the main deck and passageways; and the arrangement using passageway alone. Each design option was investigated, and their economic and environmental impacts were quantified in aholistic view by Life Cycle and Cost Assessment. The economic and environmental impacts were normalized into monetary values to evaluate the best design option overall. Results revealed that the cableway arrangement using only passageways was the best solution, showing that the total cost of the design was estimated at 308,573 USD, which was 130,010 USD less than the cost of the worst option using only the main deck. The case study proved the effectiveness of the proposed approach to determine an optimal design from avariety of choices, which offers insight into current problems that have underestimated the influence of ship designs on environmental impact. In order to enhance the cleaner production, the proposed approach can be widely applied to every part of shipbuilding such as designing of hull, piping and outfitting.

ARTICLE HISTORY
Received 18 January 2020
Accepted 10 June 2020

KEYWORDS
Offshore vessels; LCA; LCCA; shipbuilding; environmental impact; cable routing

Introduction

Since the Industrial Revolution, human activity has produced more and more pollutants, leading to surprising levels of climate change (Hawkins, Edwards, and Mcneall 2014). It is evident that the global growth rate of carbon dioxide (CO_2) has increased substantially fourfold since the middle of 20th century (Blunden, Arndt, and Hartfield 2018) and global temperatures have risen by 0.19 °C per century over the past 50 years, and 0.25 °C for the last 30 years (Vitasse, Signarbieux, and Fu 2018).

Given this, the concerns on environmental and climate problems have continued to increase across all industries including the marine sector (Hayman et al. 2000). As one of mitigation efforts in maritime industry, shipyards grapple with curbing the marine pollution from shipbuilding processes (Kim and Seo 2019), while ship operators are striving to satisfy a series of stringent environmental regulations and to reduce the environmental cost (Srivastava, Ölçer, and Ballini 2018). Energy Efficiency Design Index (EEDI) for new ships and Ship Energy Efficiency Management Plan (SEEMP) for existing vessels, introduced by International Maritime Organisation (IMO), are good examples of global efforts for cleaner ship operation. On the other hand, numerous efforts have been made to devise optimal ship designs and to apply them in practice, having the price competitiveness under the fierce circumstance of shipbuilding contracts (Bertram and Schneekluth 1998; Prinĉaud, Cornier, and Froelich 2010; Seddiek and Elgohary 2014).

Although there is a lot of research and development on new maritime technologies for hull form and machineries, there is a lack of consideration on the ship schematic design and production phases. Likewise, while there are a number of maritime regulations are progressively requiring curbing emissions from ship operations, there are no maritime regulations that stipulate the guidelines or targets for mitigating emissions from ship building phase.

Meanwhile, the shipbuilding industry has traditionally cantered around the hull structures and piping systems. However, as technology advances, modern ships tend to be automated and controlled electronically (Goulielmos and Tzannatos 1997), which emphasizes on the importance of cable design, selection, and arrangements.

For safety reasons, electrical cables should not be installed at the shortest distance when connecting from one equipment to another, but they should be laid through several paths according to the rules of

CONTACT Byongug Jeong byongug.jeong@strath.ac.uk Department of Naval Architecture, Ocean and Marine Engineering, University of Strathclyde, Glasgow G4 0LZ, UK

classification societies. In compliance with regulations, it is a common practice that the cable layout is simply determined by the designer's intuitive decision for the lowest cost and minimum installation time.

As onboard cable installations increase, questions may arise about whether the current design approach can ignore the environmental impact of the cable arrangement. It brings out the necessity of establishing an approach to evaluation of environmental impacts of ship design and production. At the same time, it should be noted that the economic burden imposed by contributing to cleaner production on the shipbuilding industry cannot be ignored.

On this background, this paper was motivated to answer the fundamental question of how the various designs of cable arrangement affect economic and environmental impacts during the onboard installation.

Critical review

Cable way arrangement

Over years, there have been several attempts to find an optimized cable arrangement for offshore vessels. Kabul, Gayle, and Lin (2007) introduced a Probabilistic Roadmap Method (PRM) to find optimized cable route in complex structure and conditions. This study proposed a variant of PRM using a constrained sampling coupled with a fast adaptive forward dynamics algorithm and efficient collision handling. It tested four different models, such as bridge, house, building, and car models, to find the optimal route targeting at the minimum cost. Neagu and Georgescu (2014) introduced met-heuristic algorithms and graph theory to determine optimal cable lengths and minimize cable costs in a wind farm field. By selecting economic indicators with several variants, the analysis of the cable route optimization at each design level was performed in consideration of overall costs including upgrade expenses, investment, and operating costs. However, these two studies considered the cost of installing and operating the cable, but did not take into account the comprehensive impact, such as the environmental cost to pay when the cable was selected.

In the marine field, Carstensen (1975) presented certain general aspects of shipboard installation costs for electrical and electronic systems that designers could use to plan a technically adequate installation at minimal cost. He encouraged designers to become familiar with shipyard procurement practice and material lead times and to improve the understanding of better practice to find the most cost-effective designs. A similar study on the cost of installing cables on ships was conducted by Carstensen (1978). Nevertheless, even in these cases, decisions were made only to reduce the length or the installation cost of the cable without regarding comprehensive economic and environmental considerations on these designs.

In summary, the current problem in terms of ship design and buildings as well as cable design is that there is some room to optimize ship design and construction to reduce the overall cost of ships. In general, shipyards are designing and building ships, and ship owners are purchasing the ships and paying for maintenance, insurance, and fuels. Current regulations require owners to pay other important costs required for their operations with respect to emissions. However, the emission costs incurred in shipbuilding were relatively unrecognized and out of regulation.

In view of this, this paper adopted Life Cycle Assessment (LCA) to evaluate the environmental impact for various cable arrangements.

Life Cycle Assessment (LCA)

Awareness and perception of the environment, particularly on the issues of the environmental pollution, and the depletion of energy and resources, have led to the thirst for more environmentally friendly methods in fierce competition in industry and business. In line with this, LCA started and has developed over the last 50 years (Blanco-Davis and Zhou 2014). LCA is a method of measuring the environmental impact of all processes within a product's life cycle. All products start with the extraction of raw materials and go through several stages of manufacturing steps, such as transformation and casting, including transportation, to become manufactured products, consumed, and eventually discarded or recycled to reach their end of life. Every step or process of a product's life affects the environment in exchange of using resources and energies (Rebitzer et al. 2004). LCA enables to quantify emissions at each life stage of a product, thereby helping us to identify potential areas to reduce emissions. As a result, we can finally determine the best processes of products in environmental perspective.

Application of LCA in industries

Not surprisingly, there have been some attempts to analyze the holistic environmental impacts in various industries. Roy et al. (2009) introduced LCA to evaluate an environmental load of agricultural field and results revealed that an environmental load of a product could be reduced by choosing alternative patterns of production, processing, packing, distribution, and consumption. Also, a study from Turconi, Boldrin, and Astrup (2013) presented how much greenhouse gases (GHG) such as NO_X and SO_2 could be reduced in the field of electricity generation. LCA was proven to be a useful tool for making decisions about the environmental consequences of implementing new technologies. The LCA was also applied to find proper building design at an early stage to reduce environmental impact (Schlegl et al. 2019). Basbagill et al. (2013) presented a method for applying LCA to early stage of the decision-making in order to inform designers of the relative environmental impact associated with building component materials and dimensioning choices. Bribián, Capilla, and Usón (2011) conducted an LCA study comparing some of the most commonly used building materials with eco-materials.

LCA has been used across industries and proven to be a good method to evaluate environmental impacts for certain products or systems. At the product design stage, however, the LCA application was limited to selecting components and materials.

LCA in marine and offshore field

LCA has been also applied as an environmental assessment tool in the marine and offshore sectors. Blanco-Davis and Zhou (2014) evaluated the environmental impact of ship retrofitting performance on installing ballast water treatment systems on board as well as on applying fouling release coatings. Similarly, Bengtsson, Andersson, and Fridell (2011) analyzed maritime fuels in a holistic view. However, these LCA studies were limited to the selection of existing equipment and fuels and did not extend to the design standpoint.

Shama (2005) used LCA to assess the rational use of construction and outfitting materials, energy consumption, and environmental impacts at all ship life stages including the design. A reasonable approach to estimate energy consumption and environmental impact was introduced. However, it did not provide specific examples of how the LCA methodology could be applied in the actual design phase. Wang et al. (2018) presented the optimal ship hull maintenance strategies for a short route hybrid ferry using LCA. The study also performed a design study for optimal hull maintenance, but it did not lead to the study of the outfitting design.

This paper adopted LCA as a decision tool for ship dress design, which was not covered in past research.

Life Cycle Cost Analysis (LCCA)

LCCA is a method of calculating the overall expense of a project or product over its entire lifespan. The difference between LCA and LCCA is that LCA is related to the environment, while LCCA is related to the cost. Although this paper addresses the importance of LCAs at the ship design stage, LCCAs can be considered to examine economic aspects that can be reduced by environmental costs (Fuller and Petersen 1996); (Fuller 2010).

Application of LCCA in industries

Val and Stewart (2003) conducted LCCA in selecting various materials. Results showed that using stainless steel, despite high initial costs, would be a better option than carbon steel. It suggested that stainless steel reinforcement could be cost-effective only if the construction cost using stainless steel was no more than about 14% higher than the construction cost of using carbon steel reinforcement in the building industry.

Similarly, there are some papers that provide a step-by-step project-based approach based on cost classification schemes. (Ehlen 1997) provided a step-by-step project-based approach to evaluate life-cycle costs and minimum performance requirements, and to determine the benefits and costs of various materials in building stage. However, although proper materials can be selected using LCCA, the study did not address determining the design direction, such as cables and pipe ways. Zakeri and Syri (2015) analyzed cost-effectiveness for various energy storage systems by means of LCCA.

Judging from the past research, LCCAs were widely applied to quantify the economic impacts of systems and projects. Nevertheless, there lacks the use of LCCA as a tool to determine the direction of the detailed design phase of ships.

Several studies have suggested the integration of LCA and LCCA in a manner that assesses the economic and environmental impacts on specific cases (Norris 2001) (Gratsos, Psaraftis, and Zachariadis 2009). As an extension of the previous studies, this study proposed an integrated approach of LCA and LCCA to investigate optimal cable routing for ships and offshore vessels.

Approach

This section introduces a proposed approach of the integration between LCA and LCCA to show how optimal designs can mitigate the environmental impact in the shipping industry as outlined in Figure 1.

Step1: this stage is to identify the problems that need decision making for practical design options; most widely used cable arrangement practices are selected in this stage.

Step2: this stage defines the scope of LCA for determining the list of environmental potentials to be concerned and LCCA for verification of life cycle cost. According to Iso (2006), LCA has the four stages described in Figure 2: Goal and scope definition (Stage 1); Life Cycle Inventory (LCI) analysis (Stage 2); Life Cycle Impact Assessment (LCIA) (Stage 3); and Life cycle interpretation (Stage 4). Each stage is mutually dependent as the result of one stage can be applied to another.

Figure 3 shows the framework of LCCA which also consists of four life phases as purchasing, installation, operation, and recycling.

Step3: this step is for collecting results. For each option, the results of the LCCA can be derived through

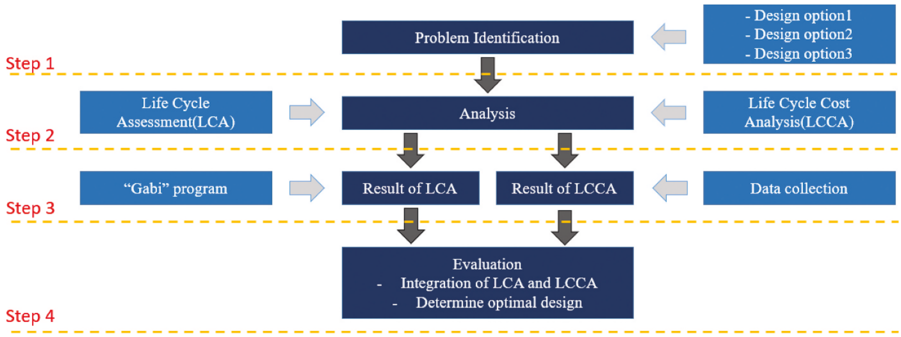


Figure 1. Diagram for LCA and LCCA.

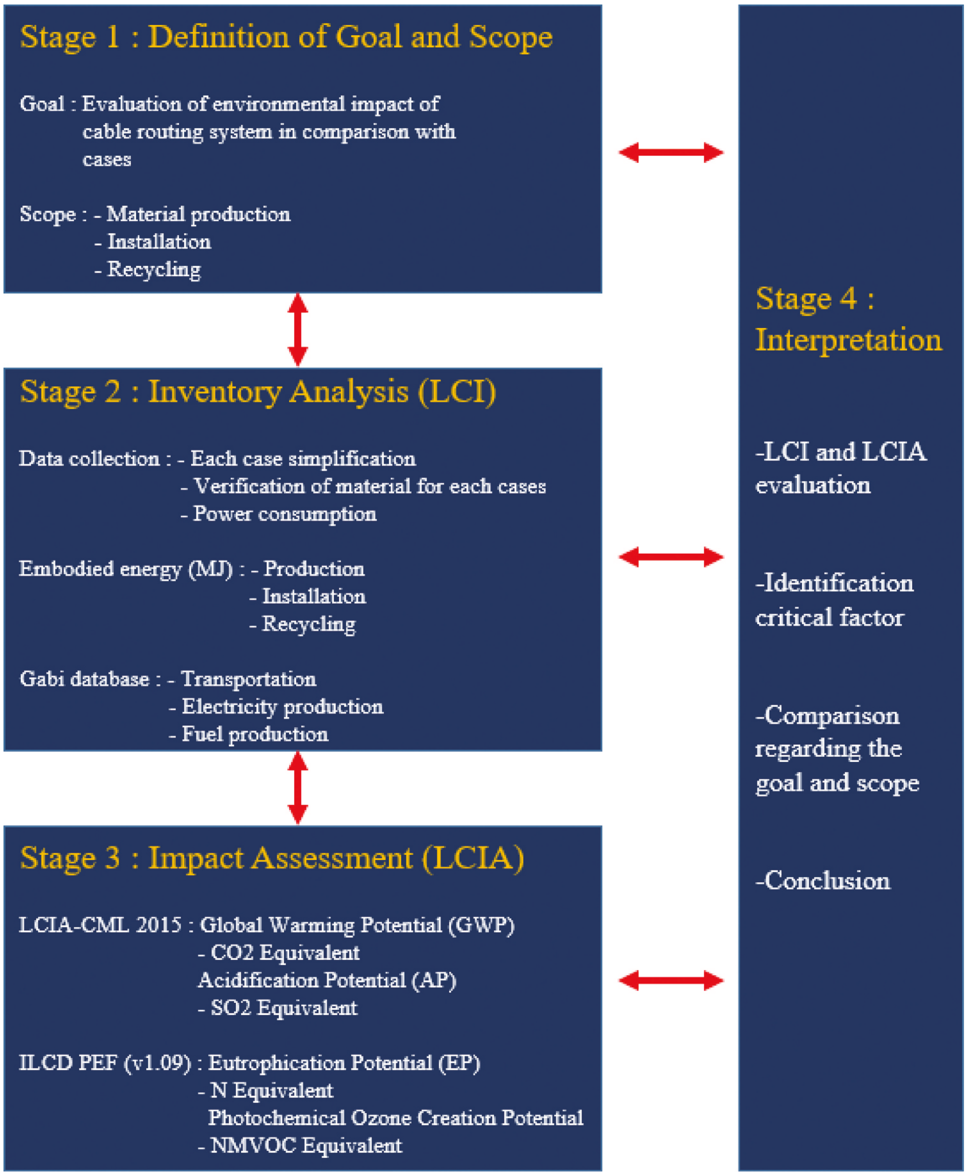


Figure 2. LCA framework.

data collection and the results of the LCA can be derived through the LCA framework.

Step4: this step combines the results of each LCCA and LCA to compare each option, thereby determining the optimal cable arrangement overall.

Step 1: problem identification

Overview of drillship, Dynamic Positioning System (DPS) and cable arrangement

Compared with other ships, offshore drill ships are subject to strict regulations on the layout of cables

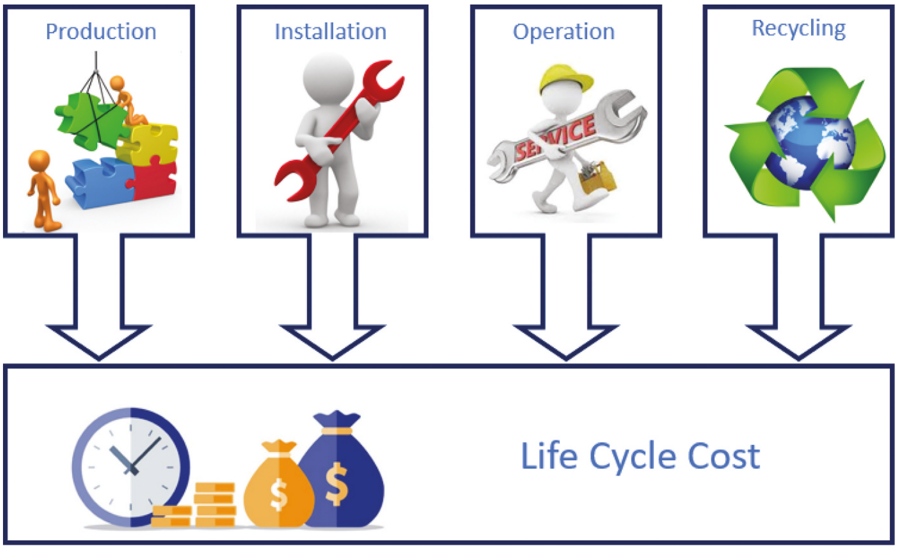


Figure 3. LCCA diagram.

on decks, due to their working characteristics and offshore environment.

Given that drill ships are specially designed for developing new oil and gas wells or scientific sea exploration purpose, the ships are equipped with DPS having an important feature for maintaining their position continually during the drilling process. As the safety requirements of DP level 3 are the most stringent, classification societies and IMO require all cables pertinent to the DPSs are to be segregated by A60 class protection division from one another in order to keep its survivability against an unwanted event such as a fire, flooding, and mechanical damage in any place (IMO 2017).

Typically, six positioning thrusters are installed on the bottom side of drill ships; three of them are installed after side and the others are installed forward side. Regarding the after side thrusters, three thruster rooms are individually prepared next to the three main switchboard rooms under A60 class protection condition respectively. Therefore, cable routes are automatically separated each other as illustrated in Figure 4.

However, the cables of the forward thrusters are not clearly separated due to the barriers of various compartment systems in the middle of drill ships such as tanks, moon pool or riser area. These cables, arranged between the main switchboard room and the forward thruster room as presented in Figure 5, are practically hard to be protected under A60 fire protection conditions. To respond to this problem, ship designers had to come up with ideas on rule-compliant cable arrangements. This paper is intended to identify the most acknowledged solutions and to compare these practices in terms of environment and cost.

Case ship

To compare the environmental impact of cable arrangements, a 96 K drillship, built in Samsung Heavy Industries in 2013, was selected as a case ship. The vessel is presently engaged in service in the Gulf of Mexico. This vessel has a feature of two passageways under the main deck area, continuous top deck area and main deck. By utilizing these passageways, several design options of the cable arrangement for DPS can be applied. The specifications of the case ship are listed in Table 1.

Options of cable arrangement between forward and after sides

The method of cable installation and supporting methods vary, but two methods are generally applied in practice. The most common method applied for weather side of the vessel or platform is the use of cable conduits, ducts or cable pipes with angle supporting systems. The second method almost applied for the inside installation of cable and tubing line on the marine vessel is the use of cable trays. Table 2 shows a brief description of these methods.

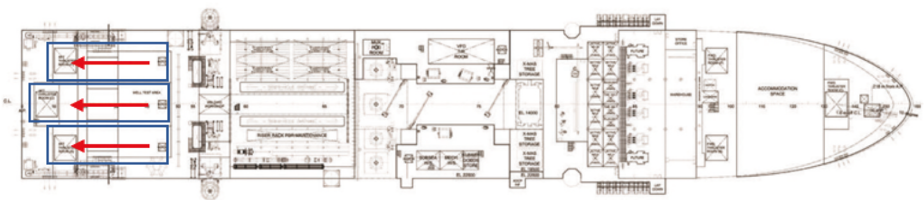


Figure 4. Cables between the after thruster room and main switchboard room.

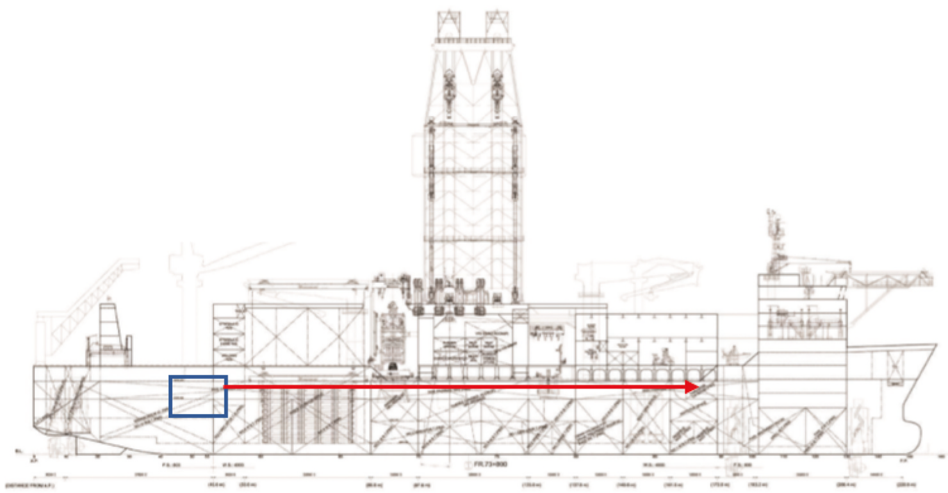


Figure 5. Cables between the forward thruster room and main switchboard room.

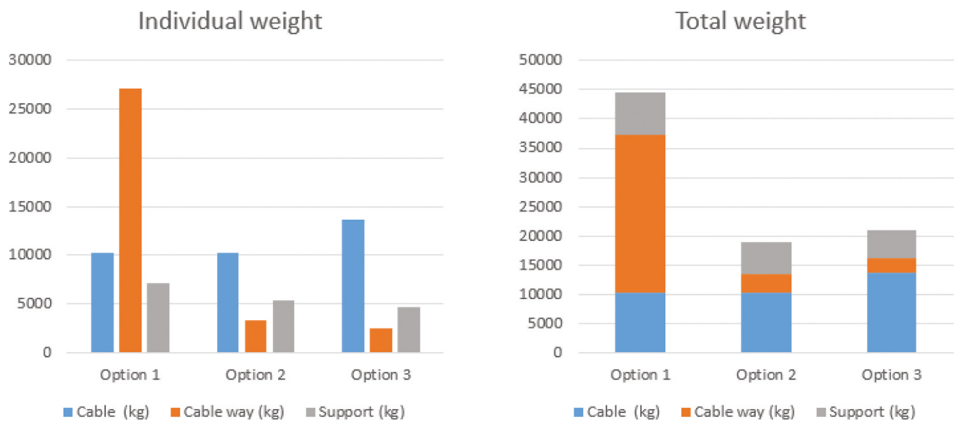


Figure 6. Weight of options.

Table 1. Specification of case ship.

Main dimensions	Metric	Operational capabilities	Metric
Total length	228 m	Drilling depth	12,000 m
Breadth, moulded	42 m	Drilling water depth	3,658 m
Depth, moulded	19 m	Riser tensioner load	1,633 MT

With these methods of cable installation, there may be various ways of installing cables from the main switchboard room to the propulsion chamber. However, given the hull structure, the shipyard had to limit the cable layout to three general approaches.

If there are no passageways from after side to forward side or even if there are passageways, cableways could be only installed on deck area, but in this case, cable has to be separated with steel pipes, because according to DNVGL (2015). Therefore, if installing all DP cables in the open deck, the cable pipes can be applicable. In other cases, the DP cables can be separated through ports and starboard passageways and the cables running through the open deck can be equipped with cable tray systems.

According to the class rule, when DP level 3 cables are installed on an open deck, the segregation using the piping systems is only allowed so that fire insulation is not necessary to be fitted in this case.

Although this arrangement is simple and does not require fire protection due to moon pool, the cable placements for each thruster become inevitably close.

The second arrangement is to use passageways, which is advantageous for new type drill ships having two passageways; one is located port side under the upper deck and the other is starboard side under the upper deck. According to the class rule, the cables under topside do not have to be separated by A60 fire condition if other cables are installed under the upper deck. Therefore, it can be installed on the cable tray, not cable pipe. However, it may be necessary to apply the insulation to segregate between the cables arranged in port and the starboard sides.

The last arrangement option is only using passageway. In this case, all cables will be installed in passageways. To comply with current rules, cables for center forward thruster have to be arranged in redundancy in order to keep the survivability of DPS at a single fault; two cables will be installed in port passageway and the other two cables will be installed in starboard

Table 2. Cable installation methods in practice.

Method	Shape	Note
Cable conduit, duct or cable pipe and angle supporting system		Commonly used for weather side
Cable trays		Almost used for inside installation of cable and tubing line

passageway. However, unlike other options, additional cables and equipment are required for automatic switching DPSs. If necessary, the cable insulation may be also needed to separate between the port and the starboard passages.

Table 3 is the summary of three options for DPS cable arrangements.

Step 2: LCA and LCCA

Definition of goal and scope

Table 4 summarises the method of cableway and cable's specification with three options for the case vessel.

Definition of the scope for this study (assumption).

Since different cables exist depending on the ship's specifications and systems, this study begins with the following assumptions:

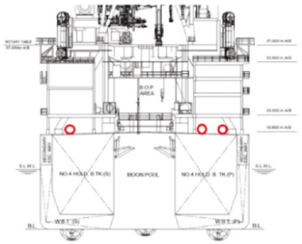
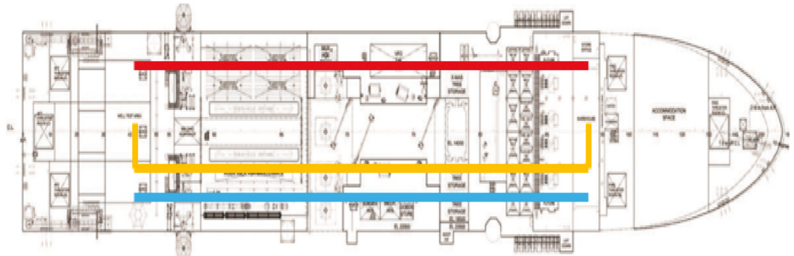
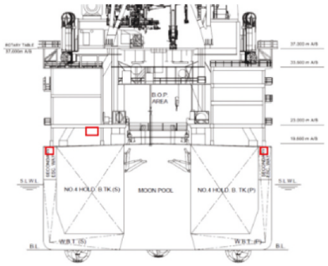
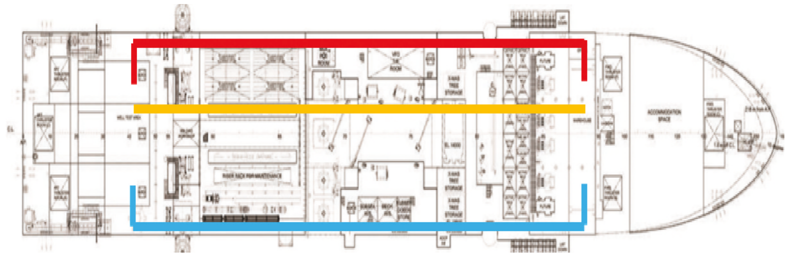
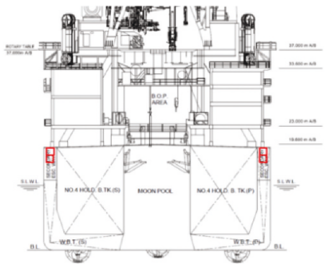
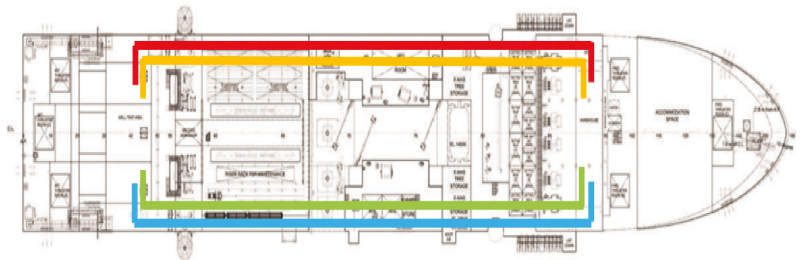
- This study is intended to be compared only for DP cables that are required to be installed in the ship.
- Of the DP cables, only the cables between the front and the rear of the ship are covered.
- Cables differ in type and size, but HV cables and LV cables are uniformly adopted in all cases.
- Cable pipe and tray are assumed to be the same in type and weight.
- Maintenance and repair are not considered during the operational time of the ship, but man-hour for regular inspection is considered for LCCA
- System performance is considered equal in three cases.

LCA and LCCA scope definition (evaluation criteria). Despite various evaluation criteria for environmental impacts, this paper adopted two most acknowledged standards: International reference Life Cycle Data System Product Environmental Footprint (ILCD PEF) and Life Cycle Impact Assessment by the institute of environmental sciences of the university of

Table 3. Options for cable arrangement.

Case	Arrangement	Advantage and disadvantage
Option 1	Three cable ways are installed on main deck using different cable pipes.	• No need fire protection • Heavy weight with pipes
Option 2	One cable way is installed using cable tray under topside module. The others are installed in port and starboard passageway separately using cable tray.	• Separation is the most obvious • Fire protection may be needed if necessary
Option 3	Two cable ways are installed in port passageway and the other cable way and additional back up cable way are installed in star board passageway using cable tray.	• The simplest cable way • Additional cables are needed

Table 4. Cable arrangement and materials.

Case	Cable for thruster	Cable way	Type of cable
Option 1	No1 cable (Red colour)	Cable pipe with support (150 m)	HV (high voltage): 2 pcs. LV (low voltage): 5 pcs.
	No2 cable (Yellow colour)	Cable pipe with support (150 m)	HV (high voltage): 2 pcs. LV (low voltage): 5 pcs.
	No3 cable (Blue colour)	Cable pipe with support (150 m)	HV (high voltage): 2 pcs. LV (low voltage): 5 pcs.
			
Option 2	No1 cable (Red colour)	Cable tray with support (150 m)	HV (high voltage): 2 pcs. LV (low voltage): 5 pcs.
			
	No2 cable (Yellow colour)	Cable tray with support (150 m)	HV (high voltage): 2 pcs. LV (low voltage): 5 pcs.
	No3 cable (Blue colour)	Cable tray with support (150 m)	HV (high voltage): 2 pcs. LV (low voltage): 5 pcs.
Option 3	No1 cable (Red colour)	Cable tray with support (150 m)	HV (high voltage): 2 pcs. LV (low voltage): 5 pcs.
	No2 cable (Yellow colour)	Cable tray with support (150 m)	HV (high voltage): 2 pcs. LV (low voltage): 5 pcs.
	No3 cable (Blue colour)	Cable tray with support (150 m)	HV (high voltage): 2 pcs. LV (low voltage): 5 pcs.
	Backup cable (Green colour)	Cable tray with support (150 m)	HV (high voltage): 2 pcs. LV (low voltage): 5 pcs.
			

Leiden (LCIA-CML). Analysis results using two different methods are, then, compared with each another.

In relation to LCCA, the total costs of the case arrangement can be classified into the following equation (1):

$$LCC = I + Repl + OM\&R + S \quad (1)$$

Where,

LCC=Total LCC in present value (PV) dollars of a given alternative

I=PV investment costs (if incurred at base date, they need not be discounted)

Repl=PV capital installation costs

OM&R=PV of non-fuel operating, maintenance, and repair costs

S=PV of scrapping costs

Inventory analysis (LCI) for LCA

Inventory analysis (LCI). Based on the above options and assumptions, data are collected as presented in Table 5. Figure 6 compares the material weights required for three credible options. It was shown that Option 1 would require greater materials than other two options.

This paper simply adopted the cable pipe size of 200A, which is the most commonly used on the main deck for drillship. Angle support size for cable pipes was assumed the 65A steel angel type, and 50A and 65A steel angle types for cableway. In particular, the width of the cable tray was generalized to 200 mm for Case 2 and 300 mm for Case 3 to cover the cables above.

Embodied energy for LCA. Energy is needed at every stage from production to installation and disposal or recycling. The energy flow was modelled based on the data collection as well as the database fitted in "GaBi", LCA software. Table 6 shows the energy consumption associated with the production, processing, and recycling of steel and cables.

Table 5. Weight for options.

Case	Member	Length (m)	Quantity (pcs.)	Total weight (kg)
Option 1	HV cable (7.82 kg/m)	150	6	7,038.0
	LV cable (1.43 kg/m)	150	15	3,217.5
	200A pipe (30.1 kg/m)	150	6	27,090.0
	65A angle support (5.91 kg/m)	1	1,200	7,092.0
Option 2	HV cable (7.82 kg/m)	150	6	7,038.0
	LV cable (1.43 kg/m)	150	15	3,217.5
	Width 200 mm tray (3.66 kg/m)	150	6	3,294.0
	50A angle support (4.43 kg/m)	1	1,200	5,316.0
Option 3	HV cable (7.82 kg/m)	150	8	9,384.0
	LV cable (1.43 kg/m)	150	20	4,290.0
	Width 300 mm tray (4.19 kg/m)	150	4	2,514.0
	65A angle support (5.91 kg/m)	1	800	4,728.0

Table 6. Embodied energy.

Unit: MJ/kg	Carbon steel (pipe, angle, tray)	Copper (cable)
Material Production	25.0–28.0	56.0–62.0
Deformation Processing	3.0–6.0	0.7–1.2
Recycling	6.6–8.0	12–15
Welding per meter	1–2.8	-

Note: the highest values were taken for the total energy

Data regarding cable manufacturing and recycling was referenced in Socolof et al. (2008). However, in case of the installation phase, it is more challenge to quantify the installation of cable pipe, cable tray, and cables, because it needs the evaluation of welding and bolting, and also cable pulling. Therefore, this activity is simplified into the energy that is needed to installed products per kg.

However, for the installation stage, it is more difficult to quantify the energy consumption for installing cable pipes, cable trays and cables, since it involves various processes such as welding and bolting, and cable pulling. This activity was simplified into the calculation of energy consumption based on product weight.

"GaBi" modeling. According to the collected information and data, LCA modeling was conducted by a commercial software, "GaBi". The model can be divided into three phases: 1) production; 2) installation; and 3) recycling. Figure 7 shows the LCA modeling on the "GaBi" interface.

(1) Production part

This study contains the four types of production parts; cable pipe, cable tray, angle support, and cable. In terms of cable pipe, cable tray, and angle support, they are generally manufactured by processing and welding the steel plates, which made from carbon steel. In the study, cable pipe or cable tray and angle support were modeled separately, because the factory that produces cable pipe and tray may differ from the factory-making angle supports. In addition, this model included the transport phase for the delivery of products between factories. All transportation distances were assumed 100 km. The copper was considered the main material used in the production of cables.

(2) Installation part

For the installation phase, all prepared products were combined into the assembly in consideration of energy consumption for installation and transportation. As mentioned earlier, each part of the cable systems can be replaced or repaired over the ship lifetime. However, the products were considered to one-time installation products that are not required for regular maintenance or replacement. Therefore, the operating phase was disregarded in the LCA model.

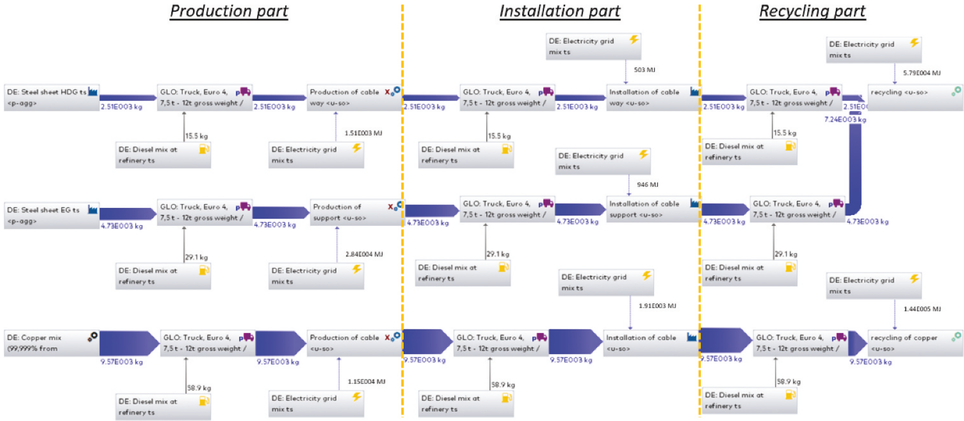


Figure 7. "GaBi" LCA modelling.

(3) Recycling part

It was assumed that each material should be divided into the steel part and cable part. The copper was considered recycled, but the other parts were regarded waste.

Life Cycle Cost (LCC)

The LCC is the simplest method for calculation of LCC in present and future. This study considered four phases of LCC; the initial investment and the installation cost; the maintenance cost; and the recycling cost. The initial investment cost represented the purchasing cost from the factory, including the transportation service. The installation cost was estimated based on the working time for installing the products in a shipyard as well as the cost of equipment carried and installed by the yard. Assumed these products were permanent in use, like LCA model, the maintenance cost only included annual inspection cost. Finally, the cost of recycling was calculated as "benefit" rather than "cost", because some costs are calculated as income when steel or copper is recycled. All costs of materials and labor were taken into account under conditions of shipyards in the Republic of Korea.

In addition, a discount factor is applied as one of the characteristics of LCC because the value of money can change over time. 3 % discount rate was applied to the analysis. According to collected data of LCC, the costs of three options and estimate of LCC are listed in Table 7. These costs were calculated at their present value based on the 20-year lifespan of the case ship.

Results (Step 3 and 4)

This section discusses the LCA and LCCA results, which are equivalent to Steps 3 and 4 in the proposed approach described in section 3.

Step 3: result of LCA and LCCA

Life Cycle Impact Assessment (LCIA)

By applying "GaBi" model, the results for each option were derived as shown in Table 8.

Table 7. LCC for options (unit: USD).

Cost Item (1)	Base date cost (2)	Year of occurrence (3)	Discount factor (4)	Present value (5) = (2) X (4)
Option 1				
Initial investment	150,418.4	Base date	Already in present value	150,418.4
Installation	84,192.9	Base date	Already in present value	84,192.9
OM&R (Operating, Maintenance and Repair)	5,677.9	Annual (for 20 years)	UPV20 14.88	84,487.4
Residual value	−14,494.1	20	SPV20 0.554	−8,029.7
Total LCC ($)				311,069.1
Option 2				
Initial investment	78,992.2	Base date	Already in present value	78,992.2
Installation	84,192.9	Base date	Already in present value	84,192.9
OM&R (Operating, Maintenance and Repair)	7,097.4	Annual	UPV20 14.88	105,609.3
Residual value	−11,169.7	20	SPV20 0.554	−6,188.0
Total LCC ($)				262,606.4
Option 3				
Initial investment	94,187.4	Base date	Already in present value	94,187.4
Installation	71,565.5	Base date	Already in present value	71,565.5
OM&R (Operating, Maintenance and Repair)	6,151.1	Annual	UPV20 14.88	91,528.1
Residual value	−14,342.0	20	SPV20 0.554	−7945.46
Total LCC ($)				249,335.5

Table 8. Total environmental impact of ILCD PEF and LCIA-CML.

				Option 1	Option 2	Option 3
ILCD PEF(v1.09)	GWP(incl. biogenic CO2)	CO2 eq.	kg	212,000	88,800	98,000
	ODP(Ozone Depletion)	CFC-11 eq.	kg	0.000000168	6.93E-08	7.63E-08
	Human tox (Cancer)	CTUh	CTUh	0.000495	0.000338	0.000426
	Human tox (Non cancer)	CTUh	CTUh	0.0352	0.0338	0.0439
	Particulate matter	PM 2.5 eq.	kg	33	19	23
	Ionising radiation	U235 eq.	kBq	14,200	5,890	6,480
	POCP(Photochemical Ozone Creation Potential)	NMVOC eq.	kg	365	167	191
	AP(Acidification)	H+ eq.	Mole	622	343	412
	EP(Eutrophication)	N eq.	Mole	1,370	627	714
	EP freshwater	P eq.	kg	0.595	0.255	0.283
	EP marine	N eq.	kg	133	61	69.5
	Eco tox (Ecotoxicity)	CTUe	CTUe	99,800	93,100	123,000
	Water	m^3 eq.	m3	10,500	4,420	4,880
	ADP elements + fossil	Sb eq.	kg	115	108	142
	GWP (excl. biogenic CO2)	CO2 eq.	kg	212,000	88,900	98,200
	Land use	C deficit eq.	kg	119,000	70,900	86,500
LCIA-CML 2015	GWP(Global Warming Potential) 100 years	CO2 eq.	kg	211,000	88,600	97,800
	AP(Acidification Potential)	SO2	kg	534	298	359
	EP(Eutrophication Potential)	Phosphate eq.	kg	56.3	26.6	30.6
	ODP(Ozone Depletion)	R-11 eq.	kg	0.000000165	6.83E-08	7.51E-08
	ADP(Abiotic Depletion Elements) element	Sb eq.	kg	32.5	30.2	40
	ADP fossil	MJ	MJ	2,060,000	895,000	1,000,000
	FAETP(freshwater Aquatic Ecotoxicity P ot) inf	DCB eq.	kg	1,430	1,250	1,630
	HTP(Human Toxicity Potential) inf	DCB eq.	kg	37,300	28,400	36,400
	MAETP(Marine Aquatic Ecotoxicity P ot) inf	DCB eq.	kg	32,200,000	21,800,000	27,400,000
	POCP(photochemical Ozone Creation Potential)	Ethene eq.	kg	39.4	18.5	21.3
	TETP(Terrestric Ecotoxicity Potential) inf	DCB eq.	kg	251	173	217
	GWP excl. biogenic carbon	CO2 eq.	kg	211,000	88,700	97,900
	GWP 100, excl. bio. C, incl LUC	CO2 eq.	kg	212,000	88,900	98,200
	GWP 100, incl. bio. C, incl LUC	CO2 eq.	kg	212,000	88,800	98,000
	GWP 100, Land Use Change only	CO2 eq.	kg	346	185	220

As mentioned above, this study adopted ILCD PEF and LCIA-CML with which GWP (Global Warming Potential) and AP (Acidification Potential), EP (eutrophication) and POCP (Photochemical Ozone Creation Potential) were estimated. In relation to GWP 100 years, option 1, option 2 and option 3 produces CO2 eq. of 211,000 kg, 88,600 kg and 97,800 kg respectively, whereas Aps, expressed "kg of SO2 eq.", are 534 kg for option 1, 298 kg for option 2, and 359 kg for option 3. Besides, for the EP, option 1, 2 and 3 were calculated at 133 kg, 61 kg and 69.5 kg of N eq. respectively. Lastly, for the POCP, those were 365 kg, 167 kg and 191 kg of NMVOC eq. correspondingly.

Production, installation, recycling and total emission by options are shown in Table 9.

As shown in Table 9, most of the pollution occurs at the stage of production from raw materials. In particular, CO2 eq. emissions were found to be the highest in

Table 9. Emission of each phase.

		CO2 eq. (GWP/kg)	SO2 eq. (AP/kg)	N eq. (EP/kg)	NMVOC eq. (POCP/kg)
Option 1	Production	145,000	429	94.6	279
	Installation	3,000	6	3.5	7
	Recycling	66,000	105	38.4	86
	Total	211,000	534	133	365
Option 2	Production	57,500	250	43.4	128
	Installation	1,800	3	1.7	3
	Recycling	31,100	48	17.6	39
	Total	88,600	298	61	167
Option 3	Production	62,300	303	49.5	145
	Installation	2,100	4	1.9	4
	Recycling	35,500	56	20	46
	Total	97,800	359	69.5	191

the production phase, they were 145,000 kg for option 1, 57,500 kg for option 2, and 62,300 for option 3. Although there was more emission in the recycling phase than in the installation, these emission levels were not as serious as those produced at the production stage. It should be noted that if pollution can be reduced at the production stage, it can significantly reduce the environmental impact overall. Figures 8 and 9 summarise the results of LCIA.

As a result, option 1 was found to be the largest pollution level with 211,000 kg of CO2 eq., 534 kg of SO2 eq., 133 kg of N eq., and 365 kg of NMVOC eq. Results of options 2 and 3 were not significantly different; option 2 had the least environmental impact for all emission category with 88,600 kg of CO2 eq., 298 kg of SO2 eq., 61 kg of N eq., and 167 kg of NMVOC eq.

Therefore, it can be concluded that with regard to the environmental impacts, option 2 is the best approach for the cable arrangement for the case ship.

Result of LCCA

According to Table 7 of LCC on section 4.2.3, each cost is represented in Figure 10.

As a result, the highest cost is the initial investment of the option 1 with $150,418.4 due to cable pipe weight, and installation cost is also higher than option 3. However, in the case of OM&R, case 2 have the highest cost among the options as $105,609.3 during the life cycle, finally, case 1 need the highest cost ($311,069.1) and case 3 need a lower cost ($249,335.5) than the others (See Figure 11).

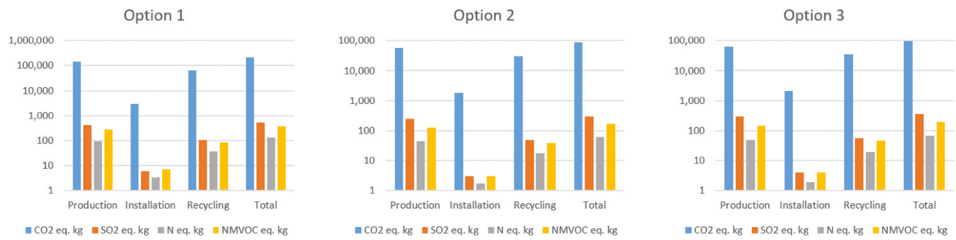


Figure 8. Emission by options.

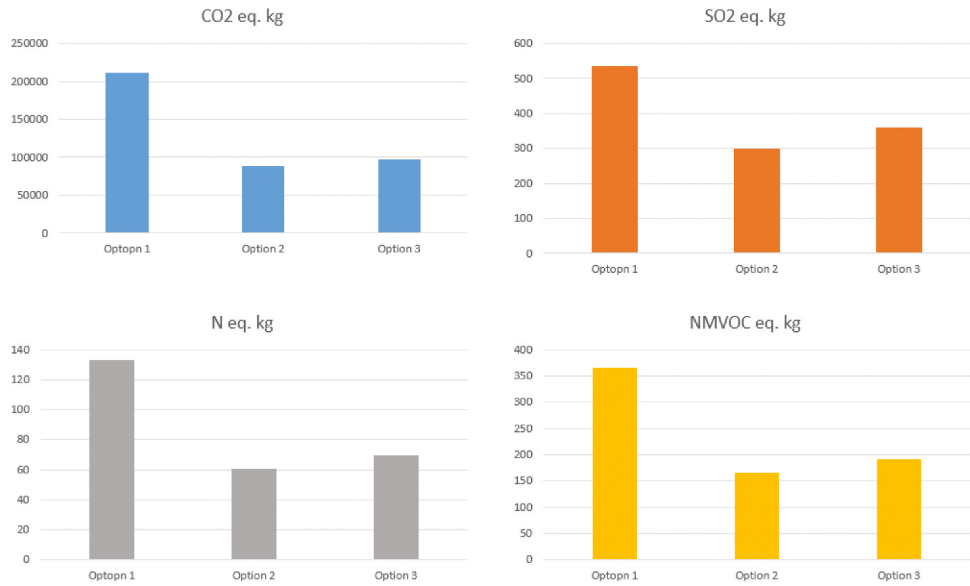


Figure 9. Total weight by emissions.

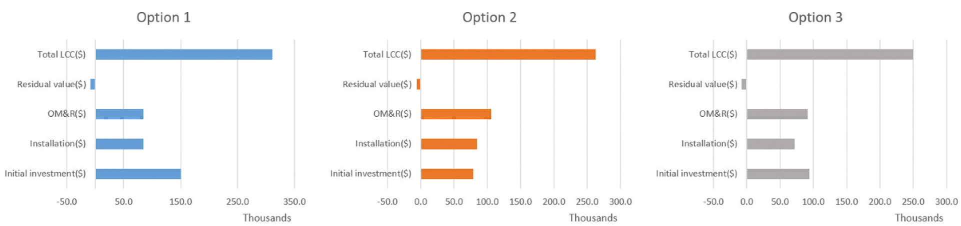


Figure 10. LCC for each options.

Step 4: integration of LCA and LCCA

LCA and LCCA have inherently different units of analysis: one is expressed by environmental elements such as CO2 eq. kg, SO2 eq. kg, N eq. kg, and NMVOC eq. kg; and the others are presented by a monetary value. In this case, the Multiple Criteria Decision Analysis (MCDA) can be applied to integrate these incompatible units into a single value. Instead of using normalization process that is commonly used for MCDA, this study attempted to directly convert the emission levels into the environmental costs which can be equivalent to the cleaning costs of those emissions.

According to the report of Carbon engineering that invested by Bill Gates, the plant can capture and remove a lot of CO2 by using the machine (Vidal 2018). And it is also reported to cost about 600 USD to reduce a ton of CO2. Kaminski (2003) estimated the price of SO2 reduction worth almost 1,000 USD per a ton, whereas Klimont, Amann, and Cofala (2000) reported that the unit reduction cost for NMVOC would be around 336 USD per a ton. Concerning nitrogen compounds, the data was found to be 1,940 USD per a ton, if the conventional SCR (Selective Catalytic Reduction) method was used, although the cost varies from case to case (Major 1999). By collecting those data, Table 10 presents the environmental costs for each option.

According to the above table, all the results were converted into the cost (i.e. USD), and it can be confirmed that the cost used to eliminate CO2 eq. would be 126,600, USD 53,160 USD and 58,680 USD for option 1, option 2 and option 3, respectively. The cost for the removal of SO2 eq. would be 534, USD 298 USD and 359 USD for option 1, option 2 and option 3. Regarding N eq., the costs were calculated at 258, USD 118.3 USD and 134.8,

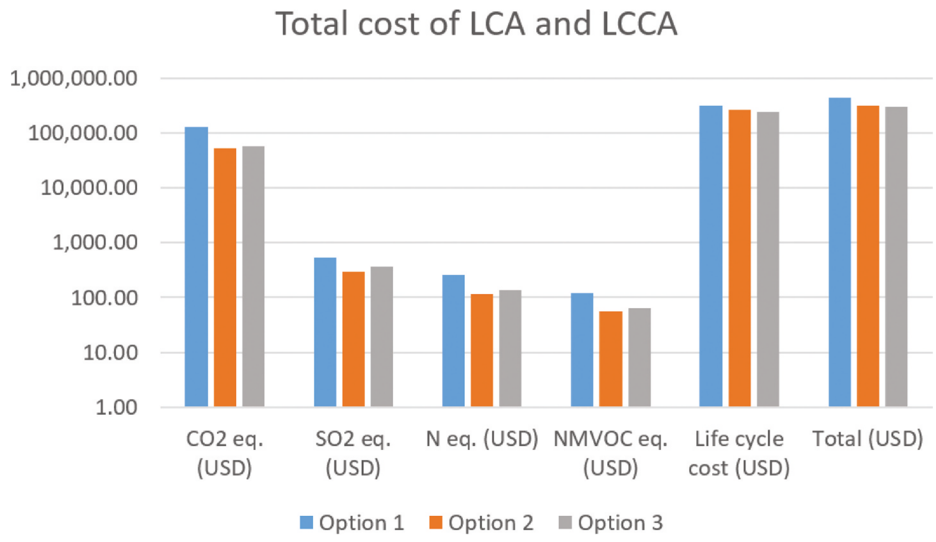


Figure 11. Compared LCC for each options.

Table 10. Total environmental cost for options.

	Option 1	Option 2	Option 3
CO2 eq. (USD)	126,600.0	53,160.0	58,680.0
SO2 eq. (USD)	534.0	298.0	359.0
N eq. (USD)	258.0	118.3	134.8
NMVOC eq. (USD)	122.6	56.1	64.2
Life cycle cost (USD)	311,069.1	262,606.4	249,335.5
Total (USD)	438,583.7	316,238.8	308,573.5

USD whereas those were 122.6, USD 56.1 USD and 64.2 USD to purify the NMVOC eq. for option 1, option 2 and option 3, respectively.

As presented in Figure 12, the total cost of the life cycle could be calculated as 438,583.7 USD for option 1, 316,238.8 USD for option 2 and 308,573.5 USD for option 3. Finally, it was confirmed that option 3 is the most environmental and cost-effective design across three credible designs.

Discussions

Up until now, detailed design of ships has not taken into account the life cycle for environmental factors and reasonable costs. This means that decisions have often been made on cableway designs, only considering material costs or installation costs at the design stage without regard to the analysis of various components. This practice leads the designers to neglect the holistic view of economic or environmental impacts on their designs. One of the novelties presented in this paper was to address these current problems and the limitations of designing cable arrangement for offshore projects. To respond to this issue, this paper presented an integrated approach of both LCA and LCCA to quantify the emissions and costs at a comprehensive level. To be specific, there have been three common practices on on-board cable arrangements for the drill ships. Results of analysis using the proposed approach clearly revealed the best option in terms of economic and environmental viewpoints. The greenest design was option 2 and the most economical design was option 3. It was found that, by incorporating these results, option 3 was the most effective design. The results of the study provide meaningful insights into how to reach more stable and sustainable ship designs.

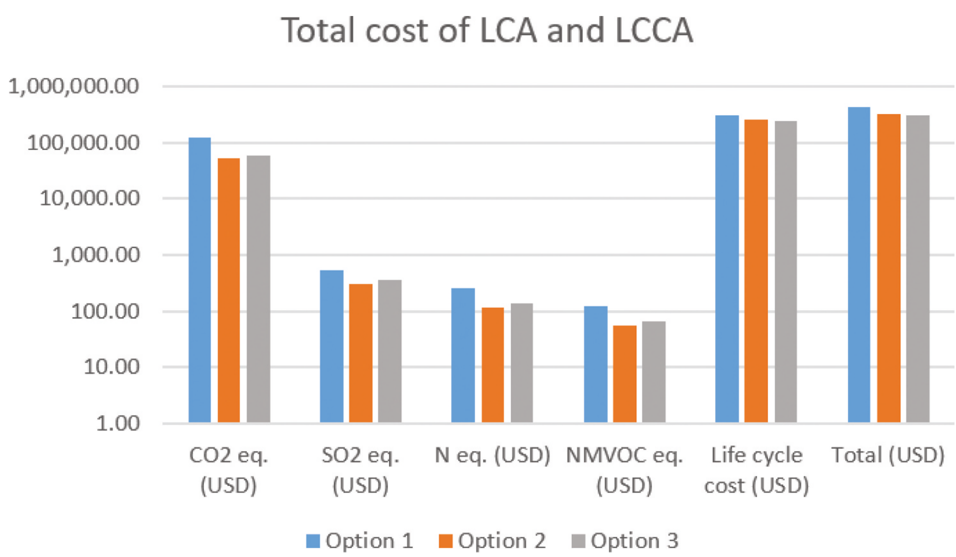


Figure 12. Total cost of LCA and LCCA.

As a preliminary study, the scope of the research was limited to investigating the cableway arrangement on the main deck of drillship, but the proposed approach can be extended to every corner of ship design as well as all the cableway and other components at the detailed design stage.

On the other hand, several assumptions were used for LCA and LCCA. In particular of cableways on the main deck of the drill deck used in the case study, cables between the front and back and subsequent equipment were not included in the analysis.

In addition, LCA modeling was conducted taking into account the due largely electricity as the main energy source. Taking into account extensive energy sources, such as water and fuels, we could have drawn a more accurate and reasonable conclusion. Nevertheless, it is strongly believed that these assumptions and limitations cannot distort the general tendencies or findings obtained from this study.

In addition, although the environmental elements and costs were calculated at the same weight in this study using converting from CO2, SO2, N, and NMVOC eq. to USD, we also recommend that setting different weights based on the importance of cost and environmental impact can give decision makers more flexibility.

The future study can be extended with more comprehensive factors and data, not necessarily limited to a certain part of cable arrangements for offshore vessels. The potential extension can be made into hulls, piping, and outfitting designs, which can guide us to confirm the excellence of the proposed approach.

Conclusions

Based on the research work discussed in this paper, the following conclusions can be drawn:

(1) It was found that the current practices in ship designs would need to be more proactively responded to changes in the environmental rules and regulations.

(2) LCA and LCCA were proven to be effective in contributing to finding out environmentally friendly and cost-effective designs. This method allowed us to quantify various marine emissions and costs from the life stages of the vessel.

(3) The quantitative and comprehensive results from the proposed approach helped us to determine the most optimal cable arrangement designs across three actual design options; that was the option 3 where all cables were proposed to be installed in passageways only, and the costs were estimated at 59,238 USD for the environment, 249,335.5 USD for the economy over the life cycle, thereby 308,573.5 USD for the total.

(4) Given the brevity of LCA and LCCA application to marine and offshore industries, this research is believed to be a preliminary study to demonstrate the benefits of those LCA and LCCA methods when considered in ship design processes.

Acknowledgments

This research is supported by Korea-UK Global Program in Offshore Engineering (N0001288) funded by the Ministry of Trade, Industry and Energy. Their supports are greatly appreciated.

Disclosure statement

No potential conflict of interest was reported by the authors.

ORCID

Muki Park http://orcid.org/0000-0002-9951-2705
Byongug Jeong http://orcid.org/0000-0002-8509-5824
Mingyu Kim http://orcid.org/0000-0003-0515-0684

References

Basbagill, J., F. Flager, M. Lepech, and M. J. B. Fischer. 2013. "Application of Life-cycle Assessment to Early Stage Building Design for Reduced Embodied Environmental Impacts." *Environment* 60: 81–92.

Bengtsson, S., K. Andersson, and E. Fridell. 2011. "A Comparative Life Cycle Assessment of Marine Fuels: Liquefied Natural Gas and Three Other Fossil Fuels." *Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment* 225: 97–110.

Blanco-Davis, E., and P. Zhou. 2014. "LCA as a Tool to Aid in the Selection of Retrofitting Alternatives." *Ocean Engineering* 77: 33–41. doi:10.1016/j.oceaneng.2013.12.010.

Blunden, J., D. S. Arndt., G. Hartfield., G. A. Weyhenmeyer., and M. G. Ziese. 2018. "State of the Climate in 2017." *Bulletin of the American Meteorological Society (BAMS), 99* (8), S1–S310.

Bribián, I. Z., A. V. Capilla, and A. A. Usón. 2011. "Life Cycle Assessment of Building Materials: Comparative Analysis of Energy and Environmental Impacts and Evaluation of the Eco-efficiency Improvement Potential." *Building and Environment* 46 (5): 1133–1140. doi:10.1016/j.buildenv.2010.12.002.

Carstensen, R. V. 1975. "Cost Considerations for Electrical/Electronic System Installation Design." *Journal Marine Technology SNAME News* 12: 378–389.

Carstensen, R. V. 1978. "A Cost Estimating Routine for Electric Cable Installation on Naval Ships." *Naval Engineers Journal* 90 (6): 81–86. doi:10.1111/j.1559-3584.1978.tb04317.x.

DNVGL. 2015. *DNVGL-RP-E306: Recommended Practice: Dynamic Positioning Vessel Design Philosophy Guidelines*. Oslo, Norway: DNVGL AS.

Ehlen, M. A. 1997. "Life-cycle Costs of New Construction Materials." *Journal of Infrastructure Systems* 3 (4): 129–133. doi:10.1061/(ASCE)1076-0342(1997)3:4(129).

Fuller, S. 2010. "Life-cycle Cost Analysis (LCCA). Whole Building Design Guide." *National Institute for Building Sciences*.

Fuller, S., and S. Petersen. 1996. *Life-cycle Costing Manual for the Federal Energy Management Program, NIST Handbook 135*. 1995 ed. Gaithersburg, Maryland: National Institute of Standars and Technology (NIST).

Goulielmos, A., and E. Tzannatos. 1997. "The Man-machine Interface and Its Impact on Shipping Safety." *Disaster Prevention and Management: An International Journal* 6 (2): 107–117. doi:10.1108/09653569710164062.

Gratsos, G. A., H. N. Psaraftis, and P. Zachariadis. 2009. "Life Cycle Cost of Maintaining the Effectiveness of a Ship's Structure and Environmental Impact of Ship Design Parameters: An Update." *RINA Conference on the Design and Operation of Bulk Carriers*, Athens, Greece.

Hawkins, E., T. Edwards, and D. Mcneall. 2014. "Commentary: Pause for Thought." *Nature Climate Change* 4 (3): 154–156. doi:10.1038/nclimate2150.

Hayman, B., M. Dogliani, I. Kvale, and A. M. Fet 2000. "Technologies for Reduced Environmental Impact from ships-Ship Building, Maintenance and Dismantling Aspects." *ENSUS-2000*, Newcastle upon Tyne, UK.

IMO. 2017. *MSC/Circular. 645: Guidelines for Vesseels with Dynamic Positioning Systems*.London, UK: International Maritime Organisation (IMO).

Iso, E. 2006. *ISO 14044-2006 Environmental Management–life Cycle assessment–Requirements and Guidelines*. Geneva, Switzerland: International Organization for Standarization (ISO).

Kabul, I., R. Gayle, and M. C. Lin. 2007. "Cable Route Planning in Complex Environments Using Constrained Sampling." *Proceedings of the 2007 ACM symposium on Solid and physical modeling*, 395–402. Beijing, China: ACM.

Kaminski, J. 2003. "Technologies and Costs of SO2-emissions Reduction for the Energy Sector." *Journal Applied Energy* 75 (3–4): 165–172. doi:10.1016/S0306-2619(03)00029-1.

Kim, A.-R., and Y.-J. Seo. 2019. "The Reduction of SOx Emissions in the Shipping Industry: The Case of Korean Companies." *Marine Policy* 100: 98–106. doi:10.1016/j.marpol.2018.11.024.

Klimont, Z., M. Amann, and J. Cofala. 2000. *Estimating Costs for Controlling Emissions of Volatile Organic Compounds (VOC) from Stationary Sources in Europe*. Laxenburg, Austria: International Institute for Applied Systems Analysis (IIASA).

Major, B. 1999. *Cost Analysis of NOx Control Alternatives for Stationary Gas Turbines*. Carlsbad, CA: ONSITE SYCOM Energy Corporation.

Neagu, B. C., and G. Georgescu. 2014. "Wind Farm Cable Route Optimization Using a Simple Approach." *2014 International Conference and Exposition on Electrical and Power Engineering (EPE)*, 1004–1009. Iasi, Romania: IEEE.

Norris, G. A. 2001. "Integrating Life Cycle Cost Analysis and LCA." *The International Journal of Life Cycle Assessment* 6 (2): 118–120. doi:10.1007/BF02977849.

Prinĉaud, M., A. Cornier, and D. Froelich. 2010. "Developing a Tool for Environmental Impact Assessment and Eco-design for Ships." *Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment* 224: 207–224.

Rebitzer, G., T. Ekvall, R. Frischknecht, D. Hunkeler, G. Norris, T. Rydberg, W.-P. Schmidt, S. Suh, B. P. Weidema, and D. W. Pennington. 2004. "Life Cycle Assessment: Part 1: Framework, Goal and Scope Definition, Inventory Analysis, and Applications." *Environment International* 30 (5): 701–720. doi:10.1016/j.envint.2003.11.005.

Roy, P., D. Nei, T. Orikasa, Q. Xu, H. Okadome, N. Nakamura, and T. Shiina. 2009. "A Review of Life Cycle Assessment (LCA) on Some Food Products." *Journal of Food Engineering* 90 (1): 1–10. doi:10.1016/j.jfoodeng.2008.06.016.

Schlegl, F., J. Gantner, R. Traunspurger, S. Albrecht, and P. Leistner. 2019. "LCA of Buildings in Germany: Proposal for a Future Benchmark Based on Existing Databases." *Energy and Buildings* 194: 342–350. doi:10.1016/j.enbuild.2019.04.038.

Schneekluth, H., and V. Bertram. 1998. *Ship Design for Efficiency and Economy* (Vol. 201, p. 202). Oxford: Butterworth-Heinemann.

Seddiek, I. S., and M. M. Elgohary. 2014. "Eco-friendly Selection of Ship Emissions Reduction Strategies with Emphasis on SOx and NOx Emissions." *International Journal of Naval Architecture and Ocean Engineering* 6 (3): 737–748. doi:10.2478/IJNAOE-2013-0209.

Shama, M. 2005. "Life Cycle Assessment of Ships." *Maritime transportation and exploitation of ocean and coastal resources: Proceedings of the 11th international congress of the international maritime association of the mediterranean*, 1751–1758. Lisabon, Portugal.

Socolof, M., J. Smith, S. Amarakoon, and D. J. U. S. E. P. A. Cooper. 2008. *Wire and Cable Insulation and Jacketing: Life Cycle Assessments for Selected Applications*. Washington, D.C.: United Stages Environmental Protection Agency (EPA).

Srivastava, A., A. I. Ölçer, and F. Ballini. 2018. "Decision Framework for Shipowners to Comply with Air Emission Reduction Measures: A Case Study of Methanol as A Fuel." In Ölçer A., Kitada M., Dalaklis D., and Ballini F. (eds) *Trends and Challenges in Maritime Energy Management*. WMU Studies in Maritime Affairs, vol 6. Springer, Cham. https://doi.org/10.1007/978-3-319-74576-3_29.

Turconi, R., A. Boldrin, and T. Astrup. 2013. "Life Cycle Assessment (LCA) of Electricity Generation Technologies: Overview, Comparability and Limitations." *Renewable and Sustainable Energy Reviews* 28: 555–565. doi:10.1016/j.rser.2013.08.013.

Val, D. V., and M. G. Stewart. 2003. "Life-cycle Cost Analysis of Reinforced Concrete Structures in Marine Environments." *Structural Safety* 25 (4): 343–362. doi:10.1016/S0167-4730(03)00014-6.

Vidal, J. 2018. "How Bill Gates Aims to Clean up the Planet." *The Guardian*, 4.

Vitasse, Y., C. Signarbieux, and Y. H. Fu. 2018. "Global Warming Leads to More Uniform Spring Phenology across Elevations." *Proceedings of the National Academy of Sciences* 115 (5): 1004–1008. doi:10.1073/pnas.1717342115.

Wang, H., E. Oguz, B. Jeong, and P. Zhou. 2018. "Life Cycle Cost and Environmental Impact Analysis of Ship Hull Maintenance Strategies for a Short Route Hybrid Ferry." *Ocean Engineering* 161: 20–28. doi:10.1016/j.oceaneng.2018.04.084.

Zakeri, B., and S. Syri. 2015. "Electrical Energy Storage Systems: A Comparative Life Cycle Cost Analysis." *Renewable and Sustainable Energy Reviews* 42: 569–596. doi:10.1016/j.rser.2014.10.011.