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# Leveraging the 4th Industrial Revolution Technology for Sustainable Development of the Northern Sea Route (NSR)—The Case Study of Autonomous Vessel

**Sung-Woo Lee [1], Jisung Jo [2,*] and Sewon Kim [3]**

[1] General Policy Research Division, Korea Maritime Institute, Busan 49111, Korea; waterfront@kmi.re.kr
[2] Port Research Division, Korea Maritime Institute, Busan 49111, Korea
[3] Intelligent Mechatronics Engineering Department, Sejong University, Seoul 05006, Korea; sewonkim@sejong.ac.kr
* Correspondence: jisungjo@kmi.re.kr

**Abstract:** The Fourth Industrial Revolution (4IR) technology has been applied to various industrial areas not only to improve economic efficiency but also to obtain environmental and safety benefits. We paid attention to the unresolved issues of Arctic development to establish a balance between economic feasibility and social values and suggest the 4IR technologies as the solution for this. The master concept of application of the 4IR technology to NSR sailing is presented. Further, we conducted a case study for autonomous vessels. A cost breakdown structure model is specified to compare the total costs of traditional and autonomous vessels. Then, we conducted scenario analysis to investigate the economic and social effects of autonomous vessels by season and route. The results show that autonomous vessels have economic benefits compared to the traditional vessel even in the winter season, and if we realize autonomous vessels in the NSR, there are more cost saving effects than in the Suez Canal Route (SCR) in any season. As for the environmental benefits, autonomous vessels have lower gas emissions and reduced water disposal compared to the traditional vessel. Further, autonomous vessels could be a solution to provide a better crew working environment by minimizing the number of people on board. The contribution of this research is that, first, we utilize real fuel oil consumption measurement data to estimate the voyage expenses, and, second, this is a novel attempt of applying the 4IR technology as a solution for the Arctic development issue. In this respect, this research is expected to serve as a cornerstone for future research, and it will help to establish Arctic development strategies in Arctic or non-Arctic countries.

**Keywords:** sustainable development; NSR; 4IR; autonomous vessel; social value; economic value



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## 1. Introduction

The Suez Canal blockage in 2021 has highlighted the issue of supply chain vulnerability and the need for alternative maritime routes [1]. Russian officials mentioned that this event showed the potential of the Northern Sea Route (NSR) as a Suez Canal Route (SCR) alternative [2,3]. The Russian government has been trying to develop the NSR. In 2018, President Putin targeted the NSR annual traffic of 80 million tons by 2024 and, in March 2020, signed the "Basic Principles of Russian Federation State Policy in the Arctic to 2035", which indicated developing the Northern Sea Route as a globally competitive national transport corridor as one of Russia's main national interests in the Arctic [4].

Many studies had investigated the economic feasibility of the NSR even before the climate change phenomenon was discussed in earnest [5]. Most of the research proved the economic competitiveness and commercial potential of the NSR compared to the SCR [6–9]. Interestingly, some argued that the NSR could have competitiveness only under specific circumstances and conducted research to investigate the key factors which could influence the competitiveness of the NSR. Liu and Kronbak [10] conducted scenario analysis with three main factors affecting the economic viability of the NSR the most—the navigable time of the NSR, the ice-breaking fee, and bunker prices—and showed the conditions which make the NSR more competitive than the SCR. Wang et al. [11] utilized a discrete choice model to assess the impact of factors on the competitiveness of the NSR and SCR by different vessel types—container shipping and oil/general cargo/bulk shipping. For container shipping, companies are willing to switch their route to the NSR if ice conditions and the profit margin of NSR transit improve. Additionally, in the case of bulk shipping, the size of the company matters. The medium companies are likely to switch, while the large companies are likely to resist switching their route to the NSR.

Recently, some researchers started to take the environmental and safety issues into the NSR competitiveness investigation, implying the importance of these aspects in the NSR. Dia et al. [8] included the environmental costs consisting of the costs of air pollutants and global warming into the total shipping costs of the NSR. Then, they conducted scenario analysis with different fuel types. This approach is meaningful in the sense that there are few studies considering the environmental aspects, and that the International Maritime Organization (IMO) 2020 carbon and sulfur cap regulation came into force from January 2020. Wan [12] performed a cost–benefit analysis and showed the significant fuel reductions in the NSR compared to the conventional route (SCR), and the corresponding reductions in air pollutants and greenhouse gas emissions. The safety issue is also one of the important concerns of NSR navigation. Zhang et al. [13] mentioned two main accident scenarios when sailing in the Arctic. The first case is getting stuck in the ice, and the second one is ship–ice collision, which causes serious crew life damage. Hong [14] also pointed out the safety challenges of Arctic shipping including the insufficient emergency response (search and rescue), satellite communication, forecasting weather, and sea ice and waves.

Previous studies are meaningful in the sense that they considered the environmental costs as part of total shipping costs and developed the risk assessment model for safe Arctic navigation. In addition to these attempts, we would like to leverage the Fourth Industrial Revolution technology (4IR) to balance between two different values—economic value and social value, such as the environment and safety in NSR development. In practice, the 4IR technologies have been applied to various areas. Luthra and Mangla [15] identified 18 key challenges to initiate the 4IR technologies to develop sustainability of supply chains in the manufacturing sector in India. Some have tried to leverage the 4IR technologies in the logistics area [16,17]. Yavas and Ozkan-Ozen [16] investigated the effects of Industry 4.0 on logistics centers and 12 critical criteria that could affect the new shape of logistics centers. Further, Tang and Veelenturf [17] introduced real examples to show how companies leverage the 4IR technologies to improve economic efficiency and pursue the social value at the same time. According to Lee and Jo [18,19], the extremely cold weather in the Arctic makes people hard to settle, which causes the severe lack of the manpower issue. Additionally, the unpredictable ice conditions of the NSR increase the concerns of safe voyage, crew welfare, and environmental pollution such as oil spills from ship accidents [18–20]. In this respect, it is time to find the alternative for the sustainable development of the NSR, and the 4IR technology could provide some possible solutions as it does in other fields.

The main purpose of this research is to suggest the concept of applying the 4IR technology to the sea port and marine transportation in NSR. Further, to show the applicability and the effects of technology related to the suggested autonomous marine transportation on both economic and social values, we conducted a case study for autonomous vessel. In the case study, a cost breakdown structure was utilized, and we compared the total shipping costs of a conventional vessel and an autonomous vessel in the NSR. Additionally, we conducted scenario analysis to investigate the economic and environmental effects of autonomous vessels by season (ice condition) and route. All the acronyms/abbreviations used in the manuscript are summarized in the appendix for better understanding of the readers (Appendix A).

## 2. Materials and Methods

### 2.1. Model Specifications

We specified the total cost structural model. It consists of three parts—the capital costs, the operation costs including salary and education fees, and the fuel costs for the voyage. The total cost is as shown below:

$$\begin{gathered} TC_i = CC_i + [(N_i \times SC) + (N_i \times EC)] + (FUC \times FCon_i) \\ s.t.\ FCon_i = RP_i \times EF_i \times T_i, \\ CO_i = \sqrt{\alpha_0 FCon_i + \alpha_1} \\ i = traditional\ vessel,\ degree\ one,\ degree\ two \end{gathered} \quad (1)$$

where $TC_i$ is total costs of the $i$th vessel type, $CC_i$ is capital costs of the $i$th vessel type, $N_i$ is the number of crew members of the $i$th vessel type, $SC$ is the average annual salary per person, $EC$ is the average annual education costs per person, $FUC$ is the fuel oil unit costs per ton, $FCon_i$ is the fuel oil consumption of the $i$th vessel type in tons, $RP_i$ is the required power of the $i$th vessel type, $EF_i$ is the engine efficiency of the $i$th vessel type, $T_i$ is the shipping time, $CO_i$ is the carbon emission quantity of the $i$th vessel type, and $\alpha_0$ and $\alpha_1$ are parameters obtained from the onboard measured data which are 1.73 and 0.001, respectively.

The fuel oil consumption is the prime contributor of VoyEx. It needs to be precisely calculated. In this research, the real onboard measurement fuel oil consumption data were expanded on the year scale. The fuel oil consumption and greenhouse gas measurements reference Kim and You's work [21,22] measuring a conventional LNG carrier's operation data such as power, speed, and fuel oil consumption. According to their work, the VoyEx, the fuel consumption, and Carbon Dioxide ($CO_2$) can be formulated as Equation (1). Figure 1 presents an example of a relation chart of the fuel oil consumption and the greenhouse gas emissions due to the power required by the ship's engine.

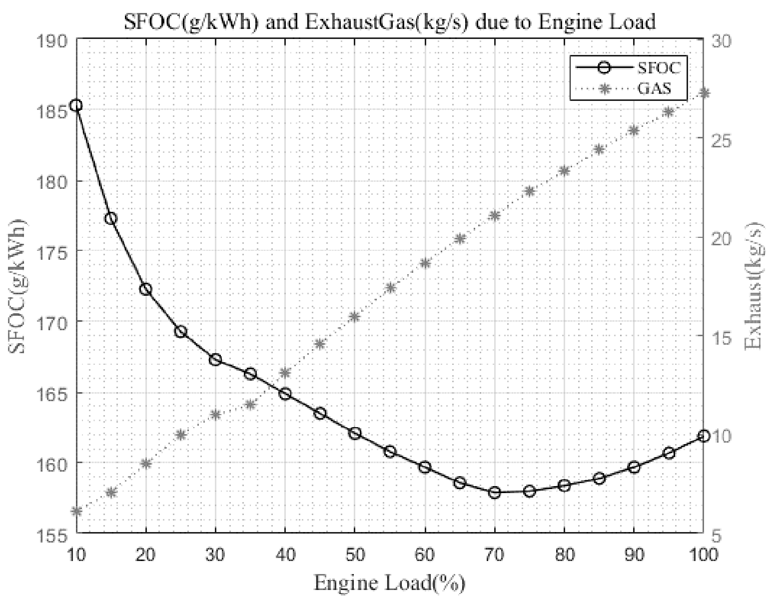


**Figure 1.** Fuel oil consumption and gas emission relation example of LNG.

Figure 2 is an example of the data for fuel consumption measurement (VoyEx) due to voyage progress. The fuel oil consumption modeling of Equation (1) is based on real measurement data.

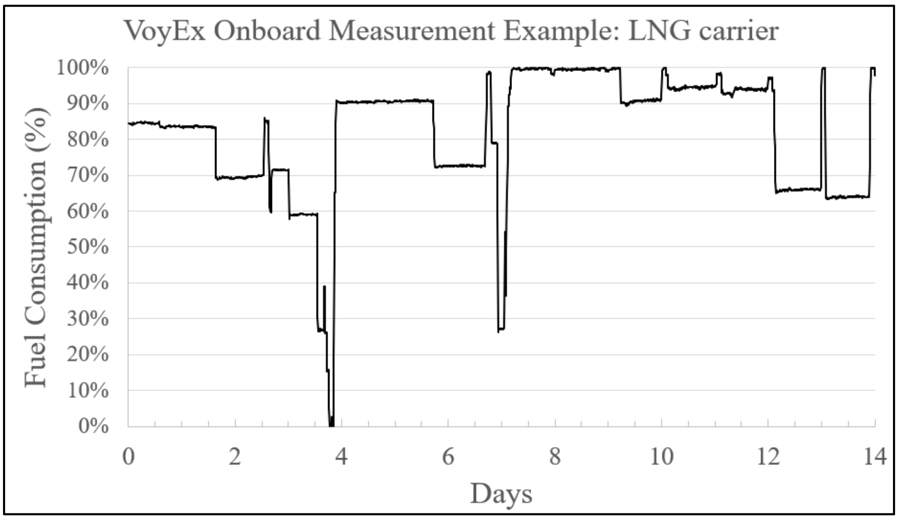


**Figure 2.** VoyEx onboard measurement of LNG Carrier.

### *2.2. Scenario Design*

The route simulation scenarios were designed to analyze the cost discrepancies depending on the season (ice) and the degree of the autonomous vessel. Scenarios The in-house autonomous routing simulation tool is hired and this is validated in Kim's work [23]. The scenario 1, 2, and 3 compare the total cost of the autonomous vessel at the NSR under the seasonal conditions of summer, spring and fall, and winter. In particular, scenario 4 was designed to compare the total expense between the SCR (conventional route) and the NSR (the Artic route) in winter conditions. The scenarios of the simulation cases are summarized below.

- Scenario 1 is the comparison between total costs of vessel type *i* which is in summer (without ice condition) and NSR;
- Scenario 2 is the comparison between total costs of vessel type *i* which is in spring and fall (with broken ice condition) and NSR;
- Scenario 3 is the comparison between total costs of vessel type *i* which is in winter (with brash ice condition) and NSR;
- Scenario 4 is the comparison between total costs of vessel type *i* which is in winter and the Suez Route.

The main contributor of the total cost is fuel consumption. Fuel consumption modeling was based on the heavy fuel oil main engine modeling that references Kim's work [21].

## 3. Results

### *3.1. The Concept of Application of the 4IR Technology on NSR Sailing*

Lee and Jo [18] suggested the master concept of applying new technologies to the Arctic region. They paid attention to the drawback of the 4IR technologies. According to their argument, it is definitely true that the 4IR technology would bring economic growth and the corresponding higher quality of lives. However, at the same time, it could disrupt the labor market and yield greater inequality. In this manner, they insisted on the Arctic region, which has chronic issues of manpower shortages, poor conditions for settlement, and difficulties in rescue operations, as the best testing grounds for the 4IR technologies. Figure 3 is the summary of their master concept centering on the technology. It consists of five parts: automated exploring/mining, autonomous ground transportation, automated storage, automated handling, and autonomous marine transportation.

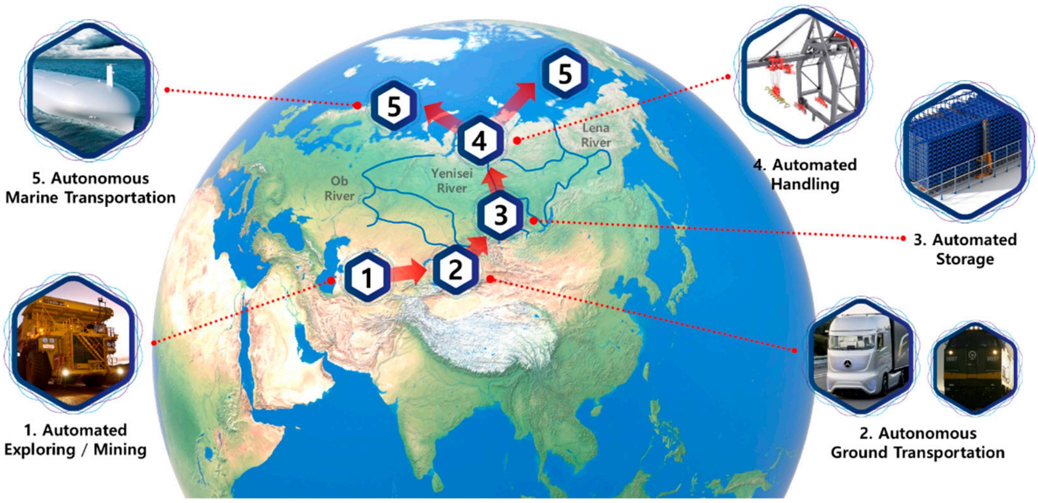


**Figure 3.** The summary of the master concept.

In this research, we would like to specifically examine the technologies for the fifth part, autonomous marine transportation. Figure 4 is the 4IR technology application to seaports and marine transportation. For autonomous marine transportation, autonomous vessels and the corresponding infrastructures at the ports or gas terminals are required. The infrastructure of the ports and gas terminals in the Arctic for autonomous vessels is as follows:

- Autonomous berthing and mooring support facility—If autonomous vessel degree two of the IMO autonomous ship level is achieved, then the number of crew is reduced to two. In that case, the crew only focus on the navigation and maintenance work. Therefore, the port and the gas terminal need a facility that supports autonomous berthing, pilotage, and mooring. The facility includes the sensors that guide the autonomous berthing and approach route and the mooring facility that uses magnetic power without mooring.
- Shore control center for remote operation—It is highly possible for degree one and two autonomous vessels to be supported by a remote operation control scheme where the shore control center (gas terminal) leads the voyage operation. Therefore, the shore control center needs to have a vast communication infrastructure that can exchange the data between the shore control center and the autonomous vessel. The navigation function and the process control function should be considered (equipped together) as well. The role of the current vessel traffic center and pilotage will be transferred to the shore control center.
- Maintenance and repair center—the maintenance of the autonomous vessel tends to be minimized during the voyage because of the limitation of the crew; therefore, overall and repair operations are conducted in the gas terminal.
- Autonomous loading and unloading arm—An LNG cargo needs to be loaded and unloaded with human intervention. If the autonomous vessel is equipped with an autonomous loading and unloading facility, then the gas terminal needs to be equipped with the corresponding functions.

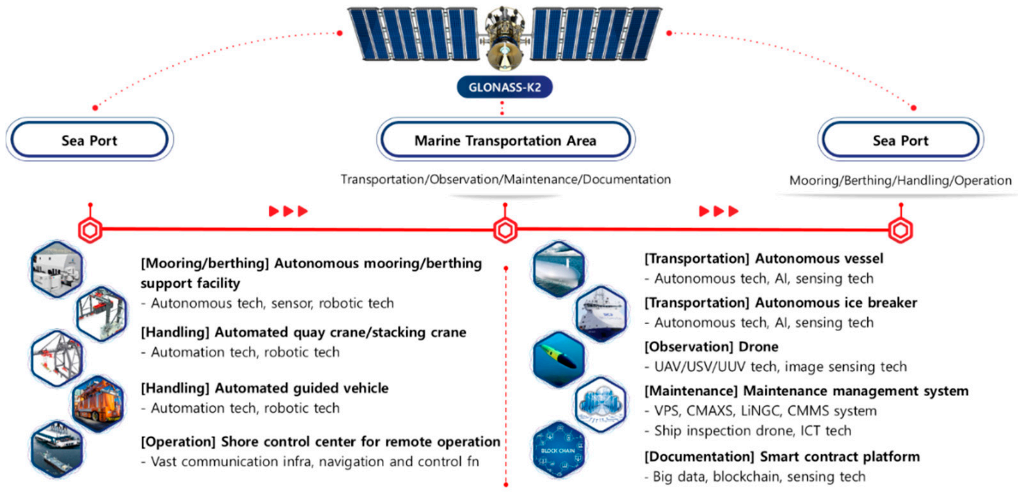


**Figure 4.** The 4IR technology application to NSR.

### *3.2. Case Study*

#### 3.2.1. The Economic Benefits

The authors of this manuscript aimed to investigate the economic and social benefits of applying autonomous vessels to the Northern Sea Route. To quantify the benefits of the autonomous vessel application in the NSR, three target vessels were hired in this study. The target vessels are a traditional vessel, a degree one autonomous vessel, and a degree two autonomous vessel. The function and the corresponding autonomous levels are defined as shown in Table 1. The traditional vessel is a human-operated vessel such as a container ship or an LNGC for the comparison group that reveals the economic and the social value differences with autonomous vessels.

**Table 1.** The functionality and equipment of target vessel.

| | Traditional Vessel | Degree One | Degree Two |
|---|---|---|---|
| Function | Human-operated commercial vessel | Autonomous solution can assist the crew's voyage | Autonomous solution can navigate by itself without human intervention |
| IMO autonomous level | 0 | 1~2 | 3~4 |
| Additional equipment compared to traditional vessel | | Routing and collision avoidance solution, additional sensors (LiDAR, motion reference unit, camera) | Routing and collision avoidance solution, additional sensors (LiDAR, motion reference unit, camera), satellite communication with onshore, predictive maintenance and repair solution |

Table 2 shows the total expense of a traditional vessel, a degree one autonomous vessel, and a degree two autonomous vessel, over the lifetime of the vessels. Since an autonomous vessel has not yet been commercialized, the authors simplified the cost structure and the operating scenarios based on the data from Daewoo Shipbuilding & Marine Engineering, the Korea Offshore & Shipbuilding Association, and the Drewry Report 2020. The total expense of the traditional vessel is averaged based on the DSME ship database that includes more than 500 vessels. The composites of the capital expenditure (CapEx), operational expenditure (OpEx), and voyage-related expenditure (VoyEx) were calculated based on an average of a conventional LNG carrier. Capex, Opex, and VoyEx represent three categories of business expenditures. In this case, Capex is the capital expenditure that builds the ship.

Opex is about the costs for a company to run its business operations. Thus, the salary, education fee, maintenance, and insurance would be included. Lastly, VoyEx, voyage-related expenditure, contains fuel, the port charge, and the loading/uploading charge. This component is structured based on the Drewry Report.

**Table 2.** The scenarios of total expenses by vessel type (units: million dollars).

| Factors | | 1st Year | | | 20th Year * | | |
|---|---|---|---|---|---|---|---|
| | | Traditional | Degree One | Degree Two | Traditional | Degree One | Degree Two |
| Capex | | 12.38 | 13.61 | 14.23 | 247.60 | 272.24 | 284.55 |
| Opex | Salary | 2.68 | 0.54 | 0.21 | 53.45 | 10.69 | 4.28 |
| | Education | 0.93 | 0.19 | 0.07 | 18.60 | 3.73 | 1.49 |
| VoyEx | Fuel | 10.78 | 9.70 | 8.62 | 215.53 | 193.98 | 172.42 |
| Total | | 26.76 | 24.04 | 23.13 | 535.18 | 480.64 | 462.74 |
| Differences with Traditional | | | 2.72 | 3.62 | | 54.55 | 72.44 |

* Cumulative values over 20 years.

Lasserre [24] defined the Arctic class vessel Capex to be 20% larger than the conventional sea-going vessel with a similar class vessel. Therefore, we consider this additional CapEx for the Arctic operation. Furthermore, the additional CapEx due to the autonomous degree is obtained by the calculated price of the equipment in Table 1 and supplementary installation cost. We assumed that the ship owner purchases the vessel with 100% debt, twenty-year loan periods, and amortization with a 10% interest rate. Further, the concept of autonomous vessels adds automation systems to the traditional vessel. Thus, the costs of degrees one and two are only 10% and 15% greater than those of the traditional vessel.

Additionally, for operation expenses, we assumed the number of crew members to be 25 for a traditional vessel, 5 for degree one, and 2 for degree two. The continuing education fee would be USD 37,000 each per year, and the salary per year would be USD 107,000. The crew salary and education cost include the Arctic area special expenses. According to Sakjuja [25], additional ice training is required to voyage in the NSR. The composite of the expenses of the vessel is from the Drewry Report 2020.

Fuel oil consumption is the prime contributor of VoyEx. We utilized the real onboard measurement fuel oil consumption data and calculated the fuel costs according to formula 1. As a result, the fuel costs were calculated to be USD 10.78 million per year for a traditional vessel, USD 9.70 million for a degree one vessel, and USD 8.62 million for a degree two vessel. According to Pham's work [26], the Arctic class vessel consumes 30~40% more fuel than the vessel under the sea-going case without ice. Degree one and two autonomous vessels can save the VoyEx by actively using the navigation toll that enables energy-efficient routing and just-in-time arrival without an anchorage time. A vessel generally consumes additional fuel and emits gas during anchorage. Moreover, this just-in-time operation reduces the fouling effects on the autonomous vessel's hull that is the power contributor of the fuel consumption. Accordingly, the autonomous vessel has the evident advantages in efficiency compared to the traditional vessel operation. Since there is no consensus about what insurances and maintenance fees will be for various vessels, we do not consider these in our estimates. Lastly, we estimated that port charges and loading/unloading charges have the same value, and therefore they are not included in our analysis.

As it can be seen in Table 2, degrees one and two are economically better than traditional vessels. In the case of capital expenses, degree two is the highest at USD 17 million per month, followed by degree one and the traditional one. However, autonomous vessels far surpass traditional vessels in the area of operational expenses and voyage expenses. In short, the higher the level of autonomy, the higher the capital expense, but the lower the operational cost.

In the first year, the cost difference between the traditional vessel and degree one is USD 3.62 million. As time goes on, in the 20th year, it increases by USD 72.44 million. The main factor that affects this phenomenon is the number of seafarers on board. Thus, in the long run, the economic benefits of replacing people with advanced technology are larger than the capital costs.

According to Phams' research [26], the total cost expense of the NSR can be estimated due to seasons, and the SCR (South Canal Route through the Suez Canal) can also be compared. Figure 5 presents the two routes: NSR and SCR to Yamal LNG2 plant from South Korea. Phams' work [26] established that the summer season is under a no ice condition, the spring and fall seasons have broken ice conditions, and the winter season has brash ice conditions. Therefore, the authors evaluated the change in the total cost of the traditional and the autonomous vessels according to the seasons, as seen in Table 3, based on Pham's work [26]. According to the analysis, the degree two autonomous vessel saves about USD 47 million, 61 million, and 72 million under summer, spring/fall, and winter conditions, respectively. Additionally, the degree two autonomous vessel can save USD 96 million in the SCR route within 20 years because the distance and the period of voyage are increased, meaning the route optimization solution of the autonomous vessel can save more VoyEx. Moreover, the improvement in the total cost is pictured in the first-year operation. The 1-year total costs of the voyage according to scenarios 1~4 are summarized in Table 3.

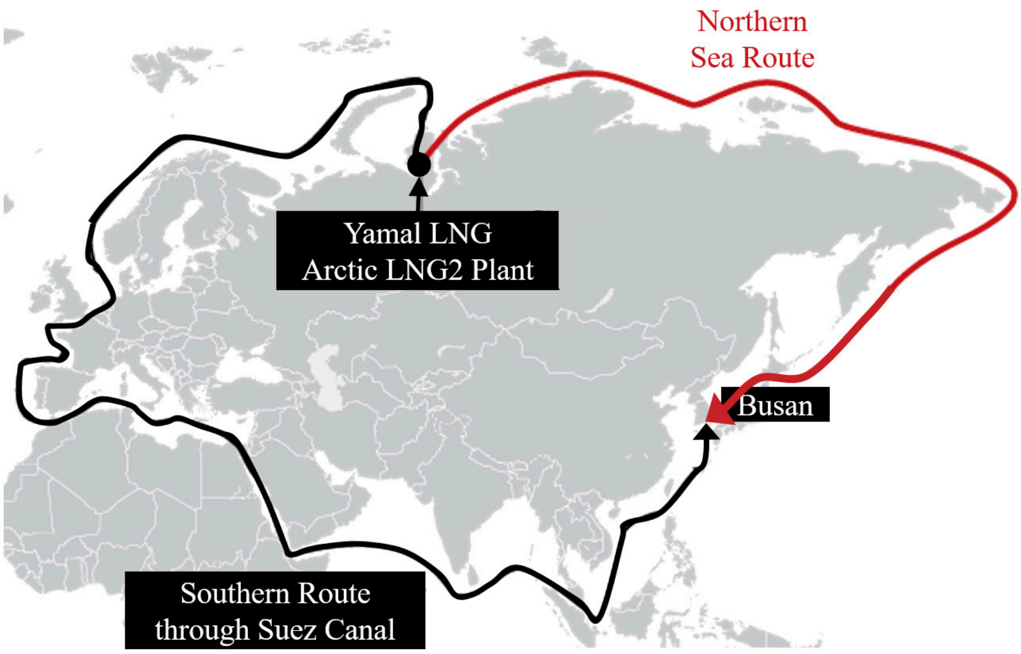


**Figure 5.** NSR and SCR comparison.

**Table 3.** The scenarios of total expenses by season (units: million dollars).

| Scenario | Season | Route | Total Cost | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | Traditional | | Degree One | | Degree Two | |
| | | | 1st Year | 20th Year | 1st Year | 20th Year | 1st Year | 20th Year |
| 1 | Summer (without ice condition) | Northern Sea Route | 17.43 | 348.46 | 15.65 | 312.94 | 15.14 | 301.29 |
| 2 | Spring/Fall (with broken ice condition) | Northern Sea Route | 22.53 | 450.90 | 20.24 | 404.94 | 19.48 | 389.87 |
| 3 | Winter (with brash ice condition) | Northern Sea Route | 26.89 | 535.18 | 24.15 | 480.64 | 23.25 | 462.74 |
| 4 | Winter Suez Route | Southern Sea Route | 31.08 | 621.69 | 28.01 | 560.24 | 26.27 | 525.32 |

### 3.2.2. The Social Benefits

The autonomous vessel not only provides a benefit in economic terms but also contributes to social benefits. Representative values are environmental improvement and crew welfare. There is no doubt that Arctic shipping is one of the main culprits for gas emissions in the Arctic region. Therefore, an eco-friendly shipping method is important in Arctic operation. In this regard, the autonomous vessel can be advantageous in Arctic operation.

The autonomous vessel can be beneficial for reducing emissions in three respects. First, gas emissions would be reduced due to the vessel's advanced routing and less fuel oil consumption. Actually, $CO_2$ emissions would be proportional to the fuel oil consumption. According to Kim [21], carbon dioxide ($CO_2$) gas emissions of an Arctic class LNG carrier could be formulated as the root form of the polynomial of fuel oil consumption that is based on a real ship engine's operation data. Based on this relation, the environmental effects of autonomous vessels can be assessed by comparing the traditional vessel in a qualitative way. In addition, water disposal and garbage amounts have inverse relations with the crew members. According to Table 4, when the gas emissions and water disposal of the traditional vessel in the NSR are the reference point (100%), those of degree 1 in the NSR can be reduced by 22% and 75%, respectively. The environmental benefits become larger as the level of autonomy increases. As we can expect, compared to the NSR, the gas emissions and water disposal of the traditional vessel are larger by 16% and 70%, respectively. Additionally, similar to the NSR case, degree one and two vessels in the SCR are more environmentally beneficial than the traditional vessel.

**Table 4.** The environmental benefit by using the qualitative approach due to autonomous vessel degree.

| Social Value | Environmental Benefit | Traditional | Degree 1 | Degree 2 |
|---|---|---|---|---|
| NSR (Scenario 3) | Gas Emissions | 100% | 78% | 62% |
| | Water Disposal | 100% | 25% | 10% |
| SCR (Scenario 4) | Gas Emissions | 116% | 90% | 72% |
| | Water Disposal | 170% | 37% | 25% |

Additionally, autonomous vessel operation would be a virtuous alternation to improve the crew working environment. The Arctic area is a harsh working condition for crews. Referring to Borchis [27], crews are operated in harsh environments such as strong and continuous vibration during icebreaking, low temperatures and remoteness, and polar nights without the sun under winter darkness. Ultimately, autonomous vessels can be a solution that improves crews' welfare. Russia, Japan, and Norway researched the application of autonomous vessels, terminals, and platforms in this regard. Equnoirs' unmanned offshore gas platform is a representative example of the autonomous operation concept [28].

## 4. Discussion

In this research, we proposed the concept of application of the 4IR technology to NSR sailing. In practice, Kronshtadt Technology, Russia technology company, signed an agreement with Morspetsservice and SeaEnergy, both part of MT Group, to deploy autonomous navigation systems on commercial shipping fleet [29,30]. Kronshtadt Technology has a plan to equip twenty cargo-passenger vessels with this system. The first attempt to install the system in the lead ship of the series, MSS Pioneer and MSS Avangard, will start in 2021. It implies Russia's active movement forward utilizing autonomous vessel in NSR.

Further, we showed the economic and social benefits of autonomous vessels by conducting scenario analysis. As you can see in Tables 2 and 3, the autonomous vessel (both degree one and two) is economically better than the traditional one, and this is also true even in the winter season. These results are consistent with some previous research [31,32]. Akbar et al. [31] provided the evidence of the considerable cost saving effects of autonomous vessel. They showed introducing the autonomous daughter ships reduced operation costs by 11% on average, and operating autonomous mother ships with advanced daughter routes gives further benefits including around 20% reduction in operational cost compared to the cost of conventional vessel with simple daughter routes only. Ghaderi [32] focused on the crew costs of autonomous vessel and the results indicated that the implementing autonomous technology reduces the costs which would benefits to short sea shipping operators. Also, in this research, we assessed the environmental effects of autonomous vessel compared to the traditional one. The amounts of gas emission and water disposal of autonomous vessel are smaller than those of traditional one, and these effects are getting larger as the level of autonomy increased. In addition, we pointed out the autonomous vessel sailing NSR could improve the welfare of crew by replacing people with autonomous technology. Previous research also importantly dealt with the social value of autonomous vessel [33–35]. Gu et al. [33] reviewed the literature on autonomous vessel and one of the ten thematic categories they defined there is regarding the environmental impact. Hogg and Ghpsh [34] mentioned the positive environmental impact of autonomous vessel. Lastly, Rødseth [35] presented seven benefits of unmanned ships, and 'improved working condition' and 'better environmental performance' are included among them.

In this research, we simplified the cost structure model and the route simulation scenarios to fit the research purposes. It is meaningful that, first, we utilized the real onboard fuel oil consumption measurement data to calculate the voyage expenses. Further, this research is a novel attempt to leverage the 4IR technologies in the Arctic area as the solution for balanced development between economic and social aspects.

To realize autonomous vessels in the artic area, the technology hurdles need to be considered. The representative hurdles for the autonomous vessel realization are as follows:

- Meteorological data accumulation—Meteorology forecast is the conclusive factor that can determine the efficiency and safety of autonomous vessels in the Arctic area. However, meteorological data in the Artic have been rarely studied.
- Route decision making solution model with ice—The state of the art for autonomous vessel route decision-making algorithms does not consider icebergs in the Arctic. To realize autonomous vessels in the Artic, a route decision-making algorithm based on iceberg conditions is essential.
- Autonomous process—the whole process of the LNG process that includes loading/unloading, vaporizing, liquefaction, and heating operations needs to be autonomous.

These are necessary issues to be considered to actually adopt and commercialize autonomous vessels in the NSR. However, simultaneously, these could be good research topics for the future as well. We believe that this research will lay the groundwork for better research on the application of the 4IR technologies in the Arctic area to pursue the economic and social values at the same time. In addition, we suggest a further study related to economic efficiency and environmental protection of the whole export process of Arctic resources from origin to destination based on the implementation of 4IR technology. Further, the research which investigates the economic and social effects of applying 4IR technology by stakeholders of supply chain would be interesting.

**Author Contributions:** Conceptualization, S.-W.L. and J.J.; methodology, J.J. and S.K.; software, S.K.; validation, J.J. and S.K.; formal analysis, J.J. and S.K.; investigation, S.K.; resources, S.-W.L. and J.J.; data curation, J.J. and S.K.; writing—original draft preparation, S.-W.L., J.J. and S.K.; writing—review and editing, J.J. and S.K.; visualization, S.-W.L., J.J. and S.K.; supervision, S.-W.L. and J.J.; project administration, S.-W.L. and J.J.; funding acquisition, S.-W.L. and J.J. All authors have read and agreed to the published version of the manuscript.

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## Appendix A

Table A1 summarizes all the acronyms/abbreviations used in the manuscript.

**Table A1.** The List of acronyms and abbreviations used in the manuscript.

| Acronyms/Abbreviations | Explanation |
|---|---|
| 4IR | The 4th Industrial Revolution |
| NSR | Northern Sea Route |
| SCR | Suez Canal Route |
| IMO | International Maritime Organization |
| CO2 | Carbon Dioxide |
| CapEx | Capital expenditure |
| OpEx | Operational expenditure |
| VoyEx | Voyage-related expenditure |

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