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The selection of an LNG terminal location by evaluating its potential impact on marine environments, safety, and costs

Majda Jurić[1], Čedomir Dundović[2], Tina Perić[3], Gorana Jelić Mrčelić[4]

[1] https://orcid.org/0000-0002-9323-4281
[2] https://orcid.org/0000-0001-6424-2410
[3] https://orcid.org/0000-0002-9531-0065
[4] https://orcid.org/0000-0002-6424-2215

[1] State Inspector's Office
Mike Tripala 6, 21 000 Split, Croatia, e-mail: majda.juric5@gmail.com
[2] University of Rijeka, Faculty of Maritime Studies
Studentska 2, 51000 Rijeka, Croatia, e-mail: dundovic@pfri.hr
[3,4] University of Split, Faculty of Maritime Studies
Ruđera Boškovića 37, 21 000 Split, Croatia, e-mail: {[3]tperic; [4]gjelic}@pfst.hr
corresponding author

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Abstract

In this paper, a new multi-step approach for the selection of an LNG terminal location (for offshore terminal, onshore terminal, or floating storage regasification unit – FSRU) was presented based on the holistic evaluation of the impacts of the potential LNG terminal.

The first step was to divide the entire observed area of the Adriatic Sea of the Republic of Croatia into smaller areas by using the geographic information system (GIS) and then selecting areas where the installation of an LNG terminal was technically feasible based on the pre-elimination criteria. Potential LNG terminal areas were selected by taking into account all pre-elimination criteria, and 14 areas were selected by using pre-elimination criteria in a GIS smart chart tool that enabled the analysis of spatial data.

The second step involved analyzing the elimination criteria of the 14 areas selected in the first step by pre-elimination criteria analyses. Six potential LNG terminal micro-locations were selected based on the defined elimination criteria.

In the third step, these six micro-locations were evaluated by experts by using 38 specific sub-criteria classified into five distinct groups: economic (11 sub-criteria), ecological (13 sub-criteria), safety (4 sub-criteria), traffic connection (6 sub-criteria), and gas needs (4 sub-criteria).

The fourth step involved making a multi-criteria expert analysis of the six locations selected in the previous step (for onshore terminals, offshore terminals, and FSRU) for the analysis of three different scenarios by the PROMETHEE (Preference Ranking Organization METhod of Enrichment Evaluation) method. In every scenario, one group of sub-criteria was selected as the most important according to its cumulative relationship with the other groups of criteria (scenario 1 – economic group; scenario 2 – ecological group; scenario 3 – safety group). A different importance (weight) was given to each of the sub-criteria.

The methodology presented in this paper can also be used for decision-making processes for other marine and coastal activities, where incorporating an ecosystem approach is necessary for taking into account safety and project costs; however, the selection of pre-elimination criteria, elimination criteria, and sub-criteria should be carefully adjusted to other situations or activities.

Introduction

Recently, due to the increasing concern about environmental factors and low carbon usage, the use of natural gas has been steadily increasing (Jeong et al., 2015). Liquefied natural gas (LNG) is a good energy carrier and is an alternative sustainable fuel available to the transportation sector (Liu et al., 2019). Individual countries, including Croatia, are seeking to diversify their natural gas supplies for a variety of reasons: economic, strategic, and energy security (Deja et al., 2019). One method of diversification is the construction of LNG terminals. One of the crucial problems of LNG terminal construction is site assessment. The practicality and reliability of LNG terminal site assessment methods have always been a focus of experts (Deja & Kabulak, 2014).

When choosing a location for the construction of LNG terminals (offshore terminals, onshore terminals, and floating storage regasification units – FSRUs), it is important to consider a number of factors, such as geographical factors, climatic factors, oceanographic features, gas network availability, market conditions, overall cost-effectiveness, etc. These factors, as well as many others, are usually analyzed in detail to select potential locations for LNG terminals, as required by different stakeholders. The problem pertaining to the selection of construction sites for LNG terminals should be investigated and solved using a set of multiple conflicting criteria (Bagočius, Zavadskas & Turskis, 2014). Traditional assessment systems are not comprehensive enough, or they are too complex, the indexes are not easy to quantify, etc. (Deja & Kabulak, 2014).

In this paper, a new approach to site selection for LNG terminals was developed to select the best location for an LNG terminal by taking into account marine environment protection but also safety and project costs.

The first step was based on pre-elimination criteria, which aimed to select areas where the installation of an LNG terminal was technically feasible. The entire observed area of the Adriatic Sea of the Republic of Croatia was divided into smaller areas by using a geographic information system (GIS) because it enabled us to merge mapping, statistical analysis, and database technologies (Becker, Burnell & Tetsuzan, 2012). It can also be applied as a sound basis for practically incorporating an ecosystem approach within marine spatial planning (Baldwin & Mahon, 2014). GIS modeling has proven to be a powerful tool for defining potential sites (Gimpel et al., 2015).

The second step was based on the evaluation of selected elimination criteria. Since it is difficult to measure and compare the different impacts of LNG terminals on the environment in a meaningful way, the different impacts of LNG terminals on the environment were grouped into five different groups of sub-criteria (impacts), which there then evaluated by experts. The sub-criteria were based on objective data and on expert opinions for determining the subjective criteria weights for the problem. This approach has already been used for the selection of construction sites for LNG terminals (Rousis et al., 2008; Bagočius, Zavadskas & Turskis, 2014; Jeong et al., 2015). Rousis et al. (Rousis et al., 2008) stated that it is essential to examine an adequate number of criteria and to calibrate these criteria according to their characteristics to perform a successful multi-criteria analysis. Bagočius et al. (Bagočius, Zavadskas & Turskis, 2014) used fifteen individual criteria categorized into four groups for site selection, while Jeong et al. (Jeong et al., 2015) considered a total of 47 factors derived from interviews with experts and analyzing the previous cases of site selection by various firms.

According to Bagočius et al. (Bagočius, Zavadskas & Turskis, 2014), many researchers argue that problems connected to LNG site selection should be solved by applying several different multi-criteria decision-making (MCDM) methods. Simple additive weighting (SAW) is the most widely used MCDM method (Hwang & Yoon, 1981; Chen, 2012; Yazdani-Chamzini et al., 2013; Bagočius, Zavadskas & Turskis, 2014). Complex proportional assessment (COPRAS) is an MCDM method widely used for the evaluation of complex processes by quantitative multi-criteria methods (Zavadskas & Kaklauskas, 1996; Kildienė, Kaklauskas & Zavadskas, 2011; Fouladgar et al., 2012; Bagočius, Zavadskas & Turskis, 2014). The technique for order preference by similarity to an ideal solution (TOPSIS) is an MCDM method based on the idea that the optimal solution is the most similar to the ideal solution (Hwang & Yoon, 1981; Pinter & Pšunder, 2013; Zavadskas et al., 2013; Bagočius, Zavadskas & Turskis, 2014).

Bagočius et al. (Bagočius, Zavadskas & Turskis, 2014) used three different MCDM methods (SAW, COPRAS, and TOPSIS) to select the best site for an LNG terminal from three possible locations based on fifteen individual criteria categorized into four groups. The model was based both on different objective data and on the investigation of expert opinions for determining subjective criteria weights for the problem. The best location for an LNG terminal was the best-ranked one by the SAW, COPRAS, and TOPSIS methods.

According to Liu et al. (Liu et al., 2019), there are not many research papers on the selection of LNG terminal sites because of the short period of LNG industry development. The industry has applied many comprehensive evaluation mathematical models, such as the linear weighted evaluation method (Liu, Qin & Mi, 2012), the nonlinear weighted evaluation method, the TOPSIS, and fuzzy comprehensive evaluation models (Hao & Dai, 2013); however, these rely too heavily on human evaluations to make them models applicable and feasible. Liu et al. (Liu et al., 2019) developed a comprehensive assessment method based on a cloud-matter element model and principal component analysis for LNG terminal site selection, but this method required the scientific establishment of a standard indices system for LNG terminals, Also, the classification and different indices systems resulted in different evaluation results.

In this paper, three different scenarios were analyzed where different importance was assigned to every sub-criterion (the criteria weight). The final analysis was carried out by using multi-criteria expert analysis – the PROMETHEE (preference ranking organization method of enrichment evaluation) method. PROMETHEE I allows the partial ranking of alternatives, and PROMETHEE II allows the complete ranking of alternatives (Brans, Mareschal & Vincke, 1984; Brans & Vincke, 1985; Brans, Vincke & Mareschal, 1986). The PROMETHEE method was chosen as the most appropriate method for multi-criteria decision-making because it is simple (Lazim, Waimun & Alireza, 2018), user-friendly, very successful for real-life planning (Ulengin, Topcu & Sahin, 2001). It also allows a priority list to be formed by simultaneously taking into account all of the criteria with different importance and different measurement units (Murat, Kazan & Coskun, 2015).

The aim of this paper is to present the methodology for the selection of LNG terminal locations based on the holistic evaluation of the potential impacts of the LNG terminal on a marine environment. The presented methodology can also be used for the decision-making process for other maritime activities, where incorporating an ecosystem approach is an important issue.

Methods

The possible locations of an LNG terminal along the East Adriatic Sea, i.e., the area under the sovereignty of the Republic of Croatia, were considered.

The first step was to divide the entire observed area of the Adriatic Sea of the Republic of Croatia into smaller areas by using the GIS: EsriArcGIS 10.1 – a smart charts tool that enables the analysis of spatial data (ESRI, 2021). Areas were selected where the installation of an LNG terminal is technically feasible based on the pre-elimination criteria. The GIS approach is useful for collecting, integrating, and understanding large amounts of interdisciplinary information/data (Baldwin & Mahon, 2014). The development of the geodatabase for the Adriatic Sea included the collection, management, and processing of GIS data. Data for the geodatabase was collected and defined using scientific literature, expert scientific opinions, and government sources. The geodatabase was created using EsriArcGIS 10.1. Data compilation, standardization, and processing were done because the collected GIS data required additional processing and preparation into thematic layers (environmental data, different marine and coastal activities, and National Parks).

The minimum values of the pre-elimination criteria are shown in Table 1. Fourteen potential LNG terminal areas were selected by taking into account all pre-elimination criteria.

Table 1. Pre-elimination criteria

Pre-elimination criteria	Onshore	Offshore	FSRU
Minimum depth of the sea (m)	15	30	15
Maximum depth of the sea (m)	–	100	–
Minimum distance from settlements with minimum 1000 inhabitants (km)	2	2	2
Minimum distance from tourist destinations (km)	5	5	5
Minimum distance from National Parks and Nature Parks (km)	10	10	10
Maximum distance from the gas network (km)	20	20	20
Minimum distance from various warehouses (km)	2	–	2
Minimum distance from various mariculture farms (km)	5	5	5

The second step was based on the elimination criteria analyses of 14 areas selected in the first step during pre-elimination criteria analyses. The elimination criteria are listed in Table 2. Six potential LNG terminal micro-locations were singled-out based on these criteria.

The elimination criteria were based mainly on general safety criteria of the selected location (max. wind speed (m/s), wind direction, max. wave

Table 2. Elimination criteria

ELIMINATION CRITERIA	Max wind speed (m/s)	Wind direction	Max wave height (m)	Wave period (s)	Access to the transport infrastructure (roads, railways)	Navigational route access	Navigational route/Waterways	Max distance from mainland gas connection (km)
SPECIFIC CONDITION	25	NNE and SE	9	7	no	Min. width 600 m	Situated at navigational route/waterways for large ships and/or small vessels	20

Table 3. Elimination sub-criteria

THE GROUP OF THE SUB-CRITERIA	SUB-CRITERION	CODE
ECONOMIC (higher amount or higher grade = higher costs or possible earnings losses)	Construction price (*US dollars*)	E 1
	Management and maintenance costs (*US dollars*)	E 2
	Activation/deactivation of nearby industrial and residential zones (onshore terminals) (*US dollars*)	E 3
	Impact on land depreciation (onshore terminals) – by expert evaluation (*from 1 to 10*)	E 4
	Impact on increasing employment in the area (onshore and offshore terminals) – by expert evaluation (*from 1 to 10*)	E 5
	Impact on possible increase in traffic density and negative consequences for existing traffic – by expert evaluation (*from 1 to 10*)	E 6
	Development of touristic and other economic activities in the zone of influence (onshore and offshore terminals) – by expert evaluation (*from 1 to 10*)	E 7
	Operational difficulties – costs due to possible temporary shutdown of terminals (*US dollars*)	E 8
	Operational difficulties – costs due to restarting terminal operation after natural disasters (*US dollars*)	E 9
	Costs due to possible accidents (*US dollars*)	E 10
	Closing or remediation costs (*US dollars*)	E 11
ECOLOGICAL – by expert evaluation (*from 1 to 10* – higher grade = more negative impact)	Impact on the marine environment – possible negative changes	EK 1
	Impact on the air – possible negative changes	EK 2
	Impact on land (onshore terminals) and on the seabed (offshore terminals)	EK 3
	Impact on the biodiversity	EK 4
	Impact of meteorological parameters (wind) on marine pollution	EK 5
	Impact on the climate	EK 6
	Impact on seawater chemical parameters	EK 7
	Impact on seawater physical parameters	EK 8
	Impact on sea currents	EK 9
	Impact on biological parameters	EK 10
	Impact on the landscape	EK 11
	Impact on the protected areas	EK 12
	Impact of noise	EK 13
SAFETY – by expert evaluation (*from 1 to 10* – lower grade = greater possibility of protection)	Wildfire	S 1
	Explosion	S 2
	Frostbite when spilling liquefied gas	S 3
	Accidents – marine environment pollution – oil spills and other liquids from ships	S 4
TRAFFIC CONNECTION – by expert evaluation (*from 1 to 10* – higher grade = more distant sea routes/higher technical requirements/ greater relief)	Proximity to existing land transport routes – sea routes and pipelines (onshore and offshore terminals)	PR 1
	Proximity to existing sea traffic routes (onshore and offshore terminals)	PR 2
	Proximity to existing pipeline transport routes (onshore and offshore terminals)	PR 3
	Availability of free land (onshore terminals)	PR 4
	Possibility of upgrading, reconstruction or adaptation of already existing terminals	PR 5
	Relief damage and repair options	PR 6
GAS NEEDS – by expert evaluation (*from 1 to 10* – higher grade = lower gas demand/less difficulty)	Local gas needs	PL 1
	Regional gas needs	PL 2
	Cross-border gas needs	PL 3
	Possibility of gas storage	PL 4

height (m), wave period (s), and navigational route/waterways) and on general economic criteria (access to the transport infrastructure (roads, railways), navigational route access, and max. distance from mainland gas connections (km)). The third step included experts' evaluation of 38 specific sub-criteria classified into five distinct groups of sub-criteria: economic (11 sub-criteria), ecological (13 sub-criteria), safety (4 sub-criteria), traffic connection (6 sub-criteria), and gas needs (*4 sub-criteria*). In total, 38 different sub-criteria were selected to create a method that was applicable to three different terminal types (offshore terminal, onshore terminal, and FSRU) (Table 3). To evaluate the values of non-measurable sub-criteria (with a grade from 1 to 10) for six different locations, a specific survey of experts was conducted between September 2016 and December 2016. The questionnaire with a blank table of sub-criterion evaluation (similar to Table 4, with sub-criterion in rows and six different locations selected in the previous step, but blank) was mailed to experts. The mean values of the sub-criteria provided by the experts are given in Table 4.

The fourth step was to make a final analysis of the six locations selected in the previous step by using three different scenarios with a different importance for each sub-criterion – the criteria weight (expressed in % – Table 5) for onshore terminals,

Table 4. The values of every sub-criterion based on the survey of expert opinions

SUB-CRITERIA GROUP	SUB-CRITERIA (CODE)	Location 1	Location 2	Location 3	Location 1a	Location 2a	Location 3a
ECONOMIC	E 1	100	150	120	80	130	100
	E 2	10	15	12	8	13	10
	E 3	5	6	7	1	1	1
	E 4	7	8	9	1	1	1
	E 5	7	6	5	6	5	4
	E 6	5	6	7	4	5	6
	E 7	5	7	8	4	5	6
	E 8	9	9	9	7	7	7
	E 9	9	8	9	7	6	5
	E 10	7	9	8	8	10	9
	E 11	10	10	10	8	10	9
ECOLOGICAL	EC 1	9	10	8	7	9	7
	EC 2	7	9	8	6	8	7
	EC 3	8	10	9	7	9	8
	EC 4	7	9	8	6	8	7
	EC 5	9	8	7	8	7	6
	EC 6	9	8	6	8	7	5
	EC 7	8	9	6	6	7	5
	EC 8	8	7	5	9	8	6
	EC 9	6	4	2	7	5	3
	EC 10	9	8	6	8	7	5
	EC 11	7	8	9	6	7	7
	EC 12	8	9	9	7	10	10
	EC 13	8	9	7	4	4	5
SAFETY	S 1	10	10	9	8	9	6
	S 2	10	10	10	9	9	8
	S 3	3	3	3	1	1	1
	S 4	9	8	7	8	6	5
TRAFFIC CONNECTION	PR 1	1	2	5	3	4	2
	PR 2	1	2	4	2	3	5
	PR 3	1	4	5	3	5	6
	PR 4	4	2	3	1	1	1
	PR 5	1	2	3	2	3	4
	PR 6	6	8	9	3	4	5
GAS NEEDS	PL 1	3	4	2	5	6	6
	PL 2	1	2	3	6	5	7
	PL 3	4	2	3	5	3	5
	PL 4	1	2	3	4	4	4

offshore terminals, and FSRU. In every scenario, one group of sub-criteria was selected as the most important according to its cumulative relationship with other groups of criteria. In scenario 1, the advantage was given to the economic group (35%) over the ecological (30%) and safety groups (15%). In scenario 2, the advantage was given to the ecological group (40%) over the economic (30%) and safety groups (10%). In scenario 3, the advantage was given to safety (35%), over the ecological (25%) and economic groups of the criteria (15%).

For this purpose, multi-criteria analysis using the PROMETHEE method I and II were used (Visual PROMETHEE beta version 0.93.1.1). PROMETHEE I allowed the partial ranking of alternatives, and PROMETHEE II allowed the complete ranking of alternatives. In PROMETHEE I (partial ranking), the positive outranking flow (leaving flow) and negative outranking flow (entering flow) were determined. The positive outranking flow showed the degree of domination, while the negative outranking flow showed the degree of

Table 5. Three different scenarios with different sub-criteria group importance (%) and different sub-weight (importance) (%)

		SCENARIO 1		SCENARIO 2		SCENARIO 3	
SUB--CRITERIA GROUP	SUB--CRITERIA (CODE)	Total sub-criteria group weight (%)	Sub-criteria weight (%)	Total sub-criteria group weight (%)	Sub-criteria weight (%)	Total sub-criteria group weight (%)	Sub-criteria weight (%)
ECONOMIC	E 1	35	8.40	30	7.20	15	4.00
	E 2		7.35		6.30		3.00
	E 3		0.70		0.60		0.20
	E 4		2.45		2.10		0.20
	E 5		1.05		0.90		0.20
	E 6		1.75		1.50		2.00
	E 7		1.05		0.90		2.50
	E 8		4.20		3.60		0.20
	E 9		2.45		2.10		0.20
	E 10		3.50		3.00		0.75
	E 11		2.10		1.80		1.75
ECOLOGICAL	EC 1	30	5.40	40	7.20	25	3.50
	EC 2		3.00		4.00		2.50
	EC 3		2.70		3.60		2.25
	EC 4		2.40		3, 20		2.00
	EC 5		1.20		1.60		1.00
	EC 6		1.20		1.60		1.00
	EC 7		0.30		0.40		0.25
	EC 8		2.70		3.60		1.75
	EC 9		3.00		4.00		2.00
	EC 10		1.80		1.80		1.50
	EC 11		3.00		4.00		3.00
	EC 12		1.80		1.80		3.00
	EC 13		1.50		3.20		1.25
SAFETY	S 1	15	6.00	10	4.00	35	14.00
	S 2		6.00		4.00		14.00
	S 3		0.75		0.50		1.75
	S 4		2.25		1.50		5.25
TRAFFIC CONNECTION	PR 1	10	2.50	10	2.50	15	0.50
	PR 2		2.50		2.50		6.00
	PR 3		2.50		2.50		1.00
	PR 4		1.00		1.00		0.25
	PR 5		0.50		0.50		5.75
	RP 6		1.00		1.00		1.50
GAS NEEDS	PL 1	10	2.50	10	3.00	10	7.00
	PL 2		2.50		3.00		2.00
	PL 3		2.00		2.00		0.50
	PL 4		3.00		2.00		0.50

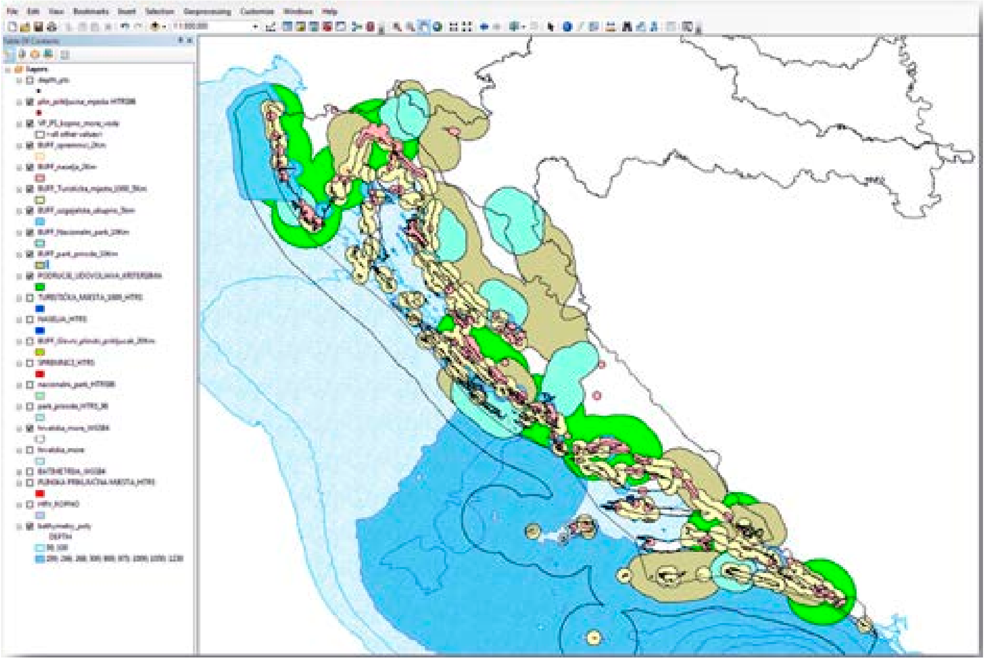


Figure 1. Fourteen locations selected by the pre-elimination criteria – marked in green

submission. In PROMETHEE II (complete ranking), the net outranking flows were determined. The ranking was arranged in ascending order, where the best location is the one with the highest rank. Because the problem of a maximum was applied here, not the problem of a minimum, the last-ranked location was the best. The results were corroborated by the PROMETHEE chart.

Results

Potential LNG terminal areas were selected by taking into account pre-elimination criteria by GIS. Figure 1 shows the 14 areas selected by the pre-elimination criteria marked in green.

Based on the defined elimination criteria, six potential locations suitable for an onshore terminal, offshore LNG terminal, and FSNU construction were singled-out.

Figure 2 shows Location 1 (42°33.3’N and 18°14.5’E) in Area 14 suitable for onshore LNG terminal construction. It is sheltered from NNE wind but is exposed to SE wind. The distance from a mainland gas connection (Dubrovnik) is 14 km, and there is land infrastructure (roads).

Figure 3 shows three locations suitable for offshore LNG terminal construction: a) Location 1a (44°48’N and 13°51’E) in Area 1: The West Coast of Istria – Pula; b) Location 2 (43°22’N and 16°15’E) in Area 11: Central Adriatic – The South Side of the Šolta Island; c) Location 3 (44°11.9’N and 14°59.5’E) in Area 6: The Vir Sea.

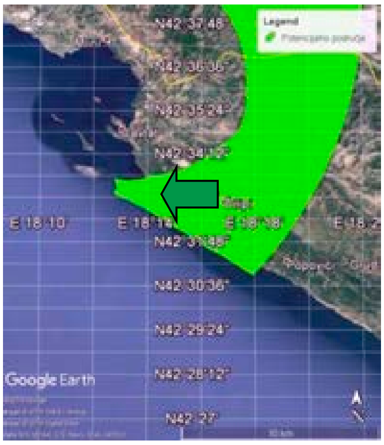


Figure 2. Location suitable for onshore LNG terminal construction: Location 1 (42°33.3' N and 18°14.5' E) in Area 14: the Southern Adriatic, Cavtat

Location 1a (44°48’N and 13°51’E) meets the majority of the elimination criteria: the location is situated in the territorial waters of the Republic of Croatia, out of traffic separation schemes and navigational routes, and close to the submarine gas pipelines leading from Pula (Fažana) to the Ivana A platform. The depth of the sea is satisfactory (deeper than 30 m), but it is exposed to all winds, which will limit the operability of an offshore LNG terminal.

Location 2 (43°22’N and 16°15’E) meets the following elimination criteria: the distance from the mainland is 5 km, the sea depth is satisfactory (deeper than 30 m), and the distance from a mainland gas connection is about 20 km (Trogir). The location is exposed to NNE and SE winds.

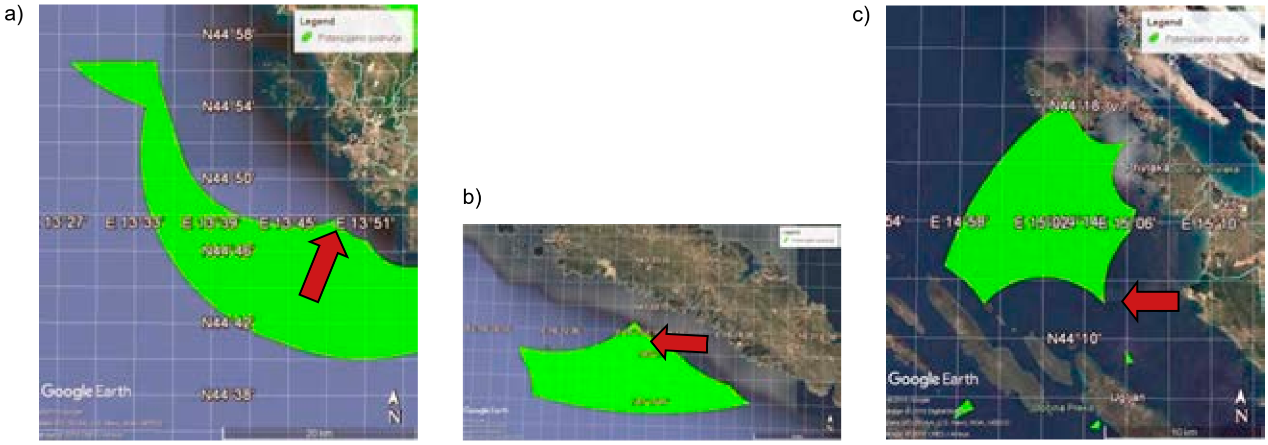


Figure 3. Locations suitable for offshore LNG terminal construction: a) Location 1a (44°48' N and 13°51' E) in Area 1: the West Coast of Istria – Pula, b) Location 2 (43°22' N and 16°15' E) in Area 11: Central Adriatic – the South Side of the Šolta Island and c) Location 3 (44°11.9' N and 14°59.5' E) in Area 6: the Vir Sea

Location 3 (44°11.9'N and 14°59.5'E) meets the following elimination criteria: it is situated out of navigational routes, the sea depth is satisfactory (deeper than 30 m), and the distance from a mainland gas connection (Zadar) is about 20 km. The location is exposed to NNE wind.

Figure 4 shows **Location 2a** (45°4.9'N and 14°17.6'E) in Area 3, which is suitable for onshore LNG terminal construction and FSRU installation. It meets the following elimination criteria: the location is situated 3 km from a main navigational route (Vela Vrata), it is protected from NNE winds, the distance from a mainland gas connection is 12 km (Labin), but mainland transport infrastructure (roads and railways) is weak, which will impact the economic group of sub-criteria.

Figure 5 shows **Location 3a** (45°11.1'N and 14°31.4'E) in Area 4 suitable for FSRU installation. It is well-protected from NNE and SE winds, the depth of the sea is 60 m, and there is good mainland transport infrastructure. It is situated close to a mainland gas connection (Omišalj) and 1.5 km from LNG vessels anchorage.

Figure 4. Location suitable for onshore LNG terminal construction and FSRU installation: Location 2a (45°4.9' N and 14°17.6' E) in Area 3: the Kvarner Bay

Figure 5. Location suitable for FSRU installation: Location 3a (45°11.1' N and 14°31.4' E) in Area 4: the Bay of Rijeka

Areas 2, 5, 7, 8, 9, 10, 12, and 13 are not suitable for the construction of LNG terminals.

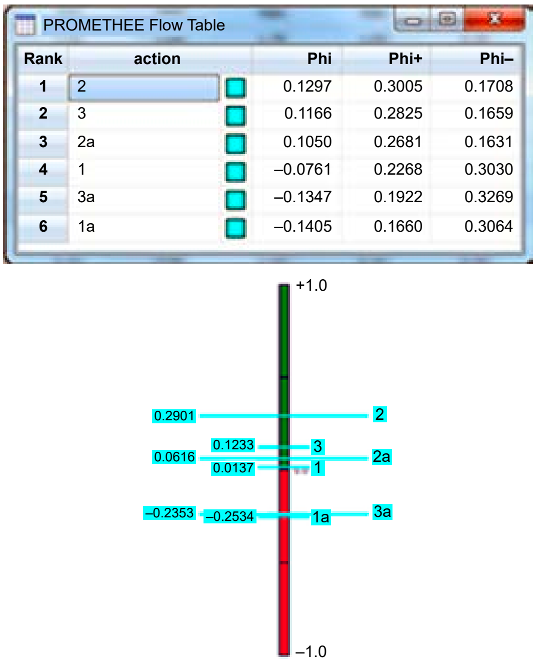
Area 2 is located on the navigational route Vela Vrata; therefore, it was eliminated by the elimination criteria: navigational route/waterway (if the location is situated on a navigational route/waterway for small and/or large vessel, the location is eliminated due to its negative impact on navigational safety) for the construction of an FSRU or offshore LNG terminal. The navigation in the navigational route Vela Vrata is regulated by the document *Naredba o plovidbi u prolazu u* šibensku *luku, u Pašmanskom tjesnacu, u prolazu Mali* Ždrelac *i Vela vrata, rijekama Neretvom i Zrmanjom, te o zabrani plovidbe Pelješkim, Koločepskim, Unijskim kanalom i kanalom Krušija, dijelovima Srednjega kanala,* *Murterskoga mora i* Žirjanskoga *kanala* (Narodne Novine, 2007).

Area 5 is not situated in the territorial waters of the Republic of Croatia, so it was not considered. Area 7 is not located along the main navigational route, but it is situated in a small-vessel navigational route. In addition, SE winds create large waves in this area, making it unsuitable for FSRU installation or onshore LNG terminal construction. This potential location cannot be taken into account for offshore LNG terminal construction because it is situated in the Murter Sea waterway. Area 8 is strongly exposed to NNE and SE winds, and it is situated in the main navigational route of the port of Šibenik, as well as in small-vessel navigational routes. The western part of area 9 between the island of Šolta, Čiovo Peninsula, and the island of Brač is situated along main navigational routes. The eastern part of area 9 (the Brač Channel) is protected from NNE winds, but it is exposed to SE winds and, therefore, was discarded. Area 10 is located in the main waterways, and it is exposed to all winds, especially SE winds, so it was discarded. Area 12 does not meet the elimination criteria because it is situated along the main navigational route of the Port of Ploče. Area 13 does not meet the elimination criteria because it is situated along the navigational route of the Pelješac Channel and is also strongly exposed to SE winds (the eastern part of the area is also exposed to NNE winds).

The final analysis was carried out by using three different scenarios with different importance given to the sub-criteria – the criteria weight for onshore terminals, offshore terminals, and FSRU. All three scenarios were analyzed for each of the six locations selected by the pre-elimination and elimination criteria. For this purpose, multi-criteria analyses of the PROMETHEE methods I and II were used.

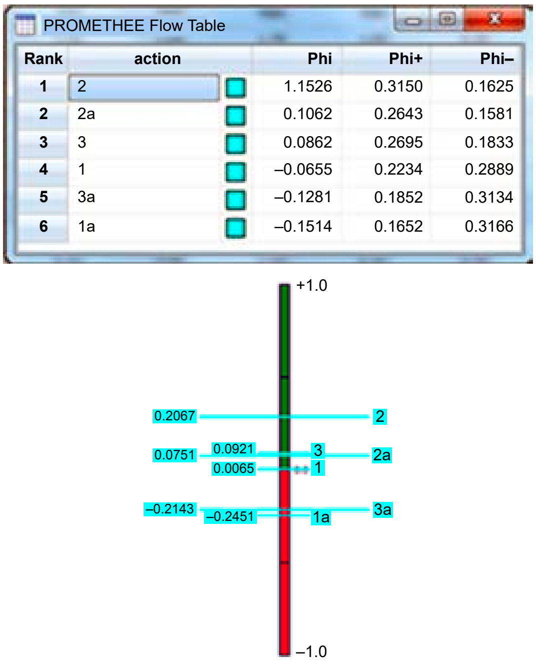
In **scenario 1** (Fifure 6), the worst-ranked location was location 1a (West coast of Istria, Pula – offshore), indicating that it was the best location for LNG terminal construction. Location 3a (the Bay of Rijeka – FSRU) was the next, with an absolute difference of 0.0058, and it was followed by location 1 (South Adriatic, Cavtat – onshore). The best-ranked, i.e., the worst location, was location 2 (Central Adriatic – south side of the island of Solta – offshore).

In **scenario 2** (Figure 7), the worst-ranked location was location 1a (West coast of Istria, Pula – offshore), indicating that it was the best location for LNG terminal construction. Location 3a (the Bay of Rijeka – FSRU) was the next, with an absolute difference of 0.0233, and it was followed by location 1 (South Adriatic, Cavtat – onshore). The best-ranked, i.e., the worst solution, was location 2 (Central Adriatic – south side of the island of Solta – offshore).


PROMETHEE Flow Table

Rank	action		Phi	Phi+	Phi–
1	2	🟦	0.1297	0.3005	0.1708
2	3	🟦	0.1166	0.2825	0.1659
3	2a	🟦	0.1050	0.2681	0.1631
4	1	🟦	–0.0761	0.2268	0.3030
5	3a	🟦	–0.1347	0.1922	0.3269
6	1a	🟦	–0.1405	0.1660	0.3064

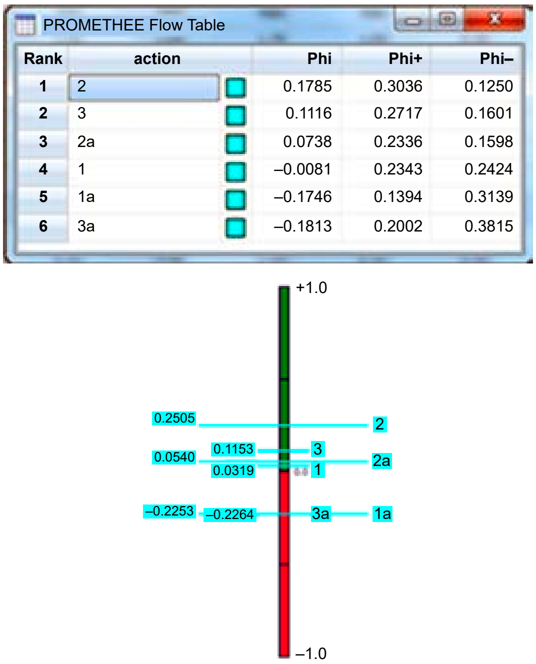
Figure 6. The PROMETHEE flow table and PROMETHEE chart for Scenario 1. Locations: 1: South Adriatic, Cavtat (onshore), 1a: West coast of Istria, Pula (offshore), 2: Central Adriatic – south side of the island of Solta (offshore), 2a: the Kvarner Bay (FSRU/ onshore), 3: the Vir Sea (offshore), 3a: the Bay of Rijeka (FSRU)


PROMETHEE Flow Table

Rank	action		Phi	Phi+	Phi–
1	2	🟦	1.1526	0.3150	0.1625
2	2a	🟦	0.1062	0.2643	0.1581
3	3	🟦	0.0862	0.2695	0.1833
4	1	🟦	–0.0655	0.2234	0.2889
5	3a	🟦	–0.1281	0.1852	0.3134
6	1a	🟦	–0.1514	0.1652	0.3166

Figure 7. The PROMETHEE flow table and PROMETHEE chart for Scenario 2. Locations: 1: South Adriatic, Cavtat (onshore), 1a: West coast of Istria, Pula (offshore), 2: Central Adriatic – south side of the island of Solta (offshore), 2a: the Kvarner Bay (FSRU/ onshore), 3: the Vir Sea (offshore), 3a: the Bay of Rijeka (FSRU)

In **scenario 3** (Figure 8), the worst-ranked location was location 3a (the Bay of Rijeka – FSRU), indicating that it was the best location for LNG terminal construction. Location 1a (West coast of Istria, Pula – offshore) was the next, with an absolute difference of 0.0067, and it was followed by location 1 (South Adriatic, Cavtat – onshore). The best-ranked, i.e., the worst solution, was location 2 (Central Adriatic – south side of the island of Solta – offshore).



Rank	action		Phi	Phi+	Phi–
1	2	🟦	0.1785	0.3036	0.1250
2	3	🟦	0.1116	0.2717	0.1601
3	2a	🟦	0.0738	0.2336	0.1598
4	1	🟦	–0.0081	0.2343	0.2424
5	1a	🟦	–0.1746	0.1394	0.3139
6	3a	🟦	–0.1813	0.2002	0.3815

Figure 8. The PROMETHEE flow table and PROMETHEE chart for Scenario 3. Locations: 1: South Adriatic, Cavtat (onshore), 1a: West coast of Istria, Pula (offshore), 2: Central Adriatic – south side of the island of Solta (offshore), 2a: the Kvarner Bay (FSRU/ onshore), 3: the Vir Sea (offshore), 3a: the Bay of Rijeka (FSRU)

Discussion

In this paper, a new multi-step approach to the selection of LNG terminal locations was presented based on the holistic evaluation of the impacts of potential LNG terminals.

The first step was based on the pre-elimination criteria, which aimed to select areas where the installation of an LNG terminal is technically feasible. The possible locations of an LNG terminal along the East Adriatic Sea, i.e., the area under the sovereignty of the Republic of Croatia, were considered. The entire observed area of the Adriatic Sea of the Republic of Croatia was divided into smaller areas by using GIS.

The selected pre-elimination criteria were: minimum depth of the sea, maximum depth of the sea, minimum distance from settlements with a minimum of 1000 inhabitants, minimum distance from tourist destinations, minimum distance from National Parks and Nature Parks, maximum distance from the gas network, minimum distance from various warehouses, and minimum distance from various mariculture farms. Fourteen areas were selected as potential LNG terminal locations by using these pre-elimination criteria.

The second step was based on the evaluation of eight selected elimination criteria: maximum wind speed (25 m/s), wind direction (wind direction NNE and/or SE are elimination wind directions due to their negative impact on navigational safety), maximum wave height (9 m), wave period (7 s), access to transport infrastructure (if there is no access to roads or railways, the location is eliminated), navigational route/waterway (if the location is situated along navigational route/waterways for large ships and/or small vessels, it is eliminated due to its negative impact on navigational safety), navigational route access (minimum width of 600 m), and maximum distance from a mainland gas connection. Six locations were selected as potential offshore terminal, onshore terminal, or FSRU locations by using these elimination criteria. In addition, the elimination sub-criteria were selected and classified into five distinct groups of sub-criteria (economic, ecological, safety, traffic connection, and gas needs), and three different scenarios were analyzed where a different importance was assigned to every sub-criterion. To evaluate non-measurable sub-criteria (grade from 1 to 10), a survey of experts was conducted.

All three scenarios were analyzed by using multi-criteria expert analysis – the PROMETHEE method – for each of the six locations selected by the pre-elimination and elimination criteria. In scenario 1, the advantage was given to the economic group; in scenario 2, the advantage was given to the ecological group; in scenario 3, the advantage was given to the safety group of criteria.

Considering the results of the PROMETHEE analyses for all three scenarios, location 1a (the West coast of Istria, Pula) was the best location for an offshore LNG terminal, location 3a (the Bay of Rijeka) was the best location for an FSRU, and location 1 (South Adriatic, Cavtat) was the best for onshore LNG terminal construction.

It can also be concluded that it is essential to examine an adequate number of criteria that reflect the optimal for the selected aim – the selection of an LNG terminal location by taking into account marine environment protection, as well as safety and project costs – to select the proper methodology.

Problems pertaining to the selection of construction sites for an LNG terminal should be solved using a set of multiple conflicting criteria (Cork & Bentiba, 2008; Sonne & Bomba, 2008; Liu, Qin & Mi, 2012; Bagočius, Zavadskas & Turskis, 2014; Deja & Kabulak, 2014; Jeong et al., 2015). Selecting as many criteria as possible is important, as is the evaluation of these criteria to reduce the impact of subjective thinking (Bagočius, Zavadskas & Turskis, 2014). The authors also emphasize that the weights of the criteria groups determined by the scenarios are important for ranking different potential LNG terminal locations.

Conclusions

In this paper, a new multi-step approach to the selection of LNG terminal locations (for offshore terminal, onshore terminal, as well as floating storage regasification unit – FSRU) was presented based on the holistic evaluation of the impacts of the potential LNG terminal.

The first step was based on pre-elimination criteria, which aimed to select areas where the installation of an LNG terminal was technically feasible. The entire observed area of the Adriatic Sea of the Republic of Croatia was divided into smaller areas by using GIS.

The second step was based on the evaluation of the selected elimination criteria. Six locations were selected as potential offshore terminal, onshore terminal, or FSRU locations by using the elimination criteria.

The elimination sub-criteria were selected and classified into five distinct groups of sub-criteria (economic, ecological, safety, traffic connection, and gas needs), and three different scenarios were analyzed by using multi-criteria expert analysis – the PROMETHEE method – where a different importance was assigned to every sub-criterion (scenario 1 – economic group; scenario 2 – ecological group; scenario 3 – safety group).

It can also be concluded that it is essential to examine an adequate number of criteria that reflect the optimal aim – the selection of an LNG terminal location that takes into account marine environment protection and safety and project costs, as well as selecting the proper methodology.

The presented methodology incorporates all of the advantages of GIS and the PROMETHEE methods, such as simplicity, practicability, and success in real-life planning. It also allows a priority list to be formed by simultaneously taking into account all of the criteria with different importance and different measurement units.

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