A DECISION SUPPORT MODEL FOR SITE SELECTION OF OFFSHORE WIND FARMS

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Renewable Energy Sources

The exploitation of renewable energy sources has gained enormous interest during recent years. A rising awareness of environmental issues, due to :

- The increase in negative effects of fossil fuels on the environment
- The precarious nature of dependency on fossil fuels imports
- The advent of renewable energy alternatives

Has forced many countries to use R.E.S.

Among R.E.S this time, wind energy is the fastest growing energy recourse worldwide

In recent years, the installation of wind farms in offshore areas has gained popularity

Offshore wind farms are the most technologically advanced form of wind energy exploitation

Offshore Wind Energy

Description of the *problem*

- Even though (offshore) wind power project developers have to complete an environmental impact assessment, few wind energy projects are finally constructed without debates.
- The appropriate siting of a wind farm is a laborious task.

The multi-criteria nature of the *problem*

- Decision-making has to take into consideration several conflicting objectives, because of the increasingly complex social, economic, technological and environmental factors that are present.
- Different groups of decision-makers become involved in the process, each group bringing along different criteria and points of view.
- Traditional single-criterion decision-making is no longer able to handle these problems.

Offshore Wind Energy Cont.

The spatial nature of the *problem*

- Also, as the factors that play a role to wind farm siting (social, economic, technological and environmental) are spatially dependent, it seems evident that the use of geographic information systems (GIS) poses benefits for site selection.

- One of the most common GIS based technique that have been designed to facilitate decision making in site selection, land suitability analysis and resource evaluation is Multi-Criteria Analysis (MCA) (*Malczewski,1999*).

In this Paper

- We present a theoretical framework of selecting an (offshore) wind farm location based on a spatial cost-revenue optimization which combines multi-criteria analysis (MCA) with geographic information system (GIS).
- The proposed framework consists of three stages:
  - ✓ The first stages excludes sites that are infeasible for wind farms based on criteria were defined by responsible authorities.
  - ✓ The second stage identifies the best suitable sites that derived from the first stage, based on social environmental and economic criteria.
  - ✓ The third stage includes the sensitivity analysis.

Literature review

- *Baban* and *Parry* (*2001*) proposed wind farm location criteria for UK based on a questionnaire of public and private sectors and GIS-based raster operations
- *Hansen* (*2005*) aimed at developing a multi-criteria evaluation method for analysing the trade-offs between choice alternatives with different environmental and socio-economic impacts with fuzzy logic approach in GIS.
- *Rodman* and *Meentemeyer* (*2006*) use a rule-based GIS model to predict suitable sites for large and small scale wind turbines in the Greater San Francisco Bay Area. Three models are created individually: a physical model, an environmental model and a human impact model.
- *Tegou et al., (2010)* combine AHP with GIS to find suitable areas for wind energy development on the Greek island of Lesvos, based on a five stages procedure.
- *Haaren* and *Fthenakis* (*2011*) proposed a novel GIS-based multi-criteria methodology for wind farm site selection.
- *Vagiona* and *Karanikolas* (*2012*) applied a GIS-based AHP model to select feasible sites for offshore wind farms in Greece
- Same procedures are followed by *Aras et al*., (*2004*) and *Bennui et al*., (*2007*).

Software and Data

- The proposed methodological framework can be implemented using any GIS system with overlay capabilities
- ArcGIS 10.4.1 [ESRI]
- Vestas V80-2MW wind turbine
- The floating platform, is a submerge construction which consists of four peripheral cylinders and one central shaft connected by a metal mesh-grid
- Case study:Aegean Sea

Data sets of:

- ✓ **Marine protected areas** [*OpenGeodata.gov*]
- ✓ **Greek territorial waters** & **boundaries** [*EuroGeographics*]
- ✓ **Sea depth** [*Hellenic Navy Hydrographic Service*]
- ✓ **Wind potential** [*Hellenic Centre for Marine Research*]
- ✓ **Electricity grids** [*Hellenic Electricity Distribution Network Operator*]
- ✓ **Ports** [*EuroGeographics*]
- ✓ **Residential areas** [*OpenGeodata.gov*]
- ✓ **Ship routes** [*EuroGeographics*]
- ✓ **Underwater cables** [*Hellenic Centre for Marine Research*]

Description of the methodology

The first stage of the methodology addresses the issue of defining the bounding constraints. These constraints are based on 4 basic criteria, which are set by responsible authorities and analysed as follows (*Ministry of Environment Energy and Climate Change*):

1st stage: Exclusion phase

Exclusion criteria

1. Development of offshore wind farms within 6 nautical miles from shore.
2. Ensure the technical possibility of installing wind turbines at specific sites.
3. Avoid areas with any significant impact on the environment
4. Minimize the visual impact of the facilities. The criterion applies only for observation points where there is or it is expected to be significant anthropogenic activities.

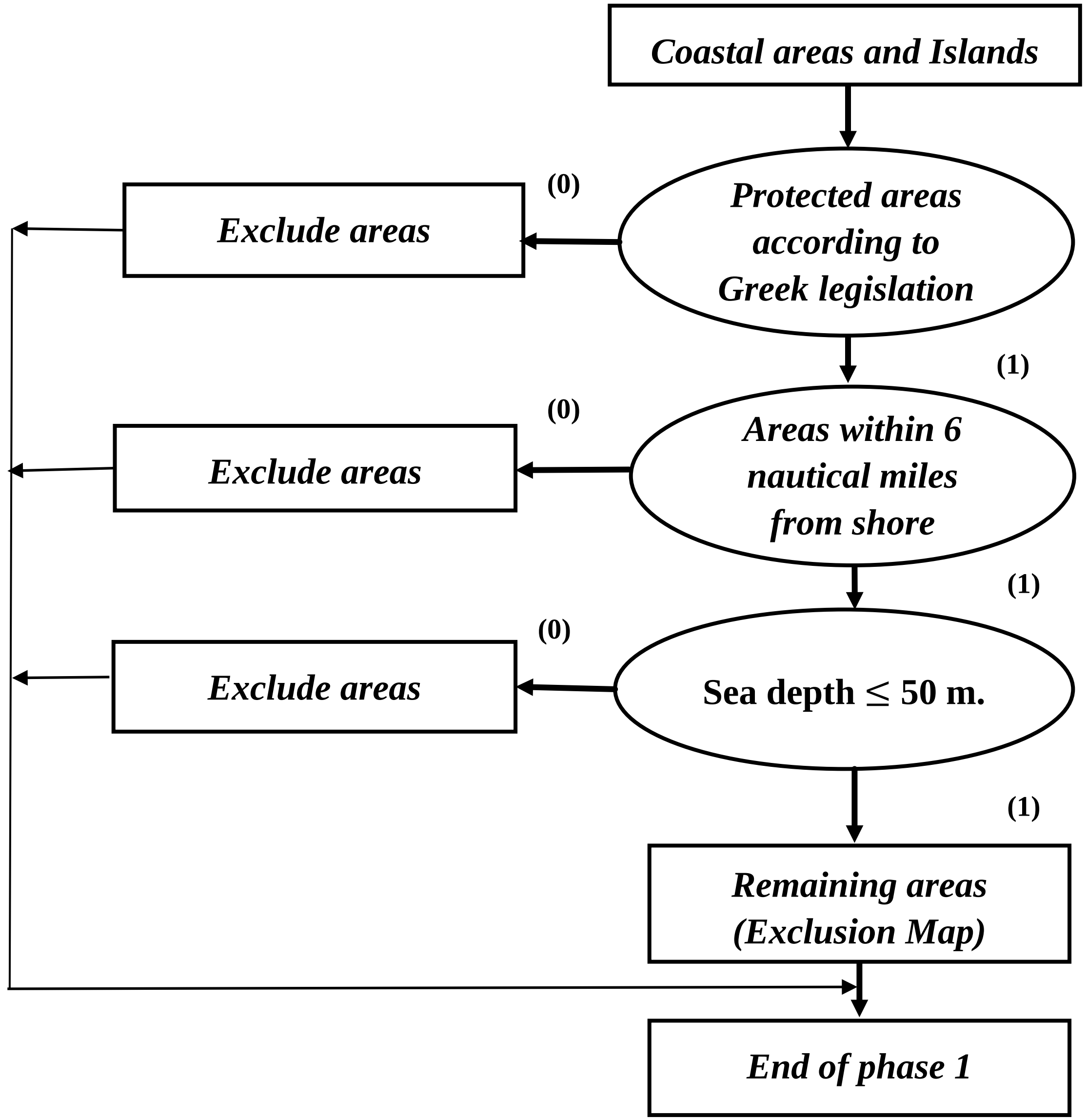
Description of the methodology cont.

- The Spatial Analysis at this phase is based on **Boolean Overlay**
- 3 constraint layers (CLs) will be produced according to the above constraints.

1st stage: Spatial Analysis

1. A binary GIS grid is expected to be created for each constraint, with cells falling within a constraint area assigned (0) and the rest of them assigned (1).
2. By multiplying all constraint layers, the final Excusion map is calculated. Only the cells with value (1) in each input layer will have non zero value in the Exclusion map, meaning these cells meet all constraints and are eligible for further consideration.

Methodological Framework Stage 1.



Description of the methodology cont.

- The second stage of the methodological framework identifies the best suitable sites that derived from the first stage based on social environmental and economic criteria.
- The economic criteria are based on expected cash-flows of the investment, which are estimated by Discounted Cash-Flows Method (DCF) and are evaluated with the use of financial key figures like:
  - Internal Rate of Return (IRR)
  - Debt Service Cover Ratio (DSCR)
  - Loan Life Cover Ratio (LLCR)

This can be achieved by the use of criteria from 3 major cost & revenue categories that are spatially dependent:

1. Revenue from generated electricity
2. Costs that are generated due to distance of wind farm from electricity grid & coastal facilities

Description of the methodology cont.

Evaluation criteria:
Are based on literature review, experts' judgments and personal experience,

2nd stage: Evaluation phase

1. ***Wind resource***: The most important factor that plays a role in economic feasibility is the local wind resource.
2. ***Distance from electricity grid***: Grid connection costs are calculated in this model as a function of distance to the nearest electricity line or substation.
3. ***Distance from coastal facilities***: The easy accessibility to coastal facilities indicates fewer installation, maintenance and decommissioning costs of a wind farm. And at this criterion, these costs are calculated as a function of distance to the nearest coastal facilities.
4. ***Distance from residential areas:*** The adoption of long distances from residential and urban areas ensures limited visual and noise disturbances.
5. ***Distance from ship routes:*** An extremely important factor for an offshore wind farm due to the risk of collision that may arise.
6. ***Distances from underwater cables*:** A possible interaction of an offshore wind farm to the existing underwater cables could result in significant adverse effects on the telecommunication and electricity network.
7. ***Distance from protected areas:*** Keeping sufficient distances from protected areas we ensure their preservation.

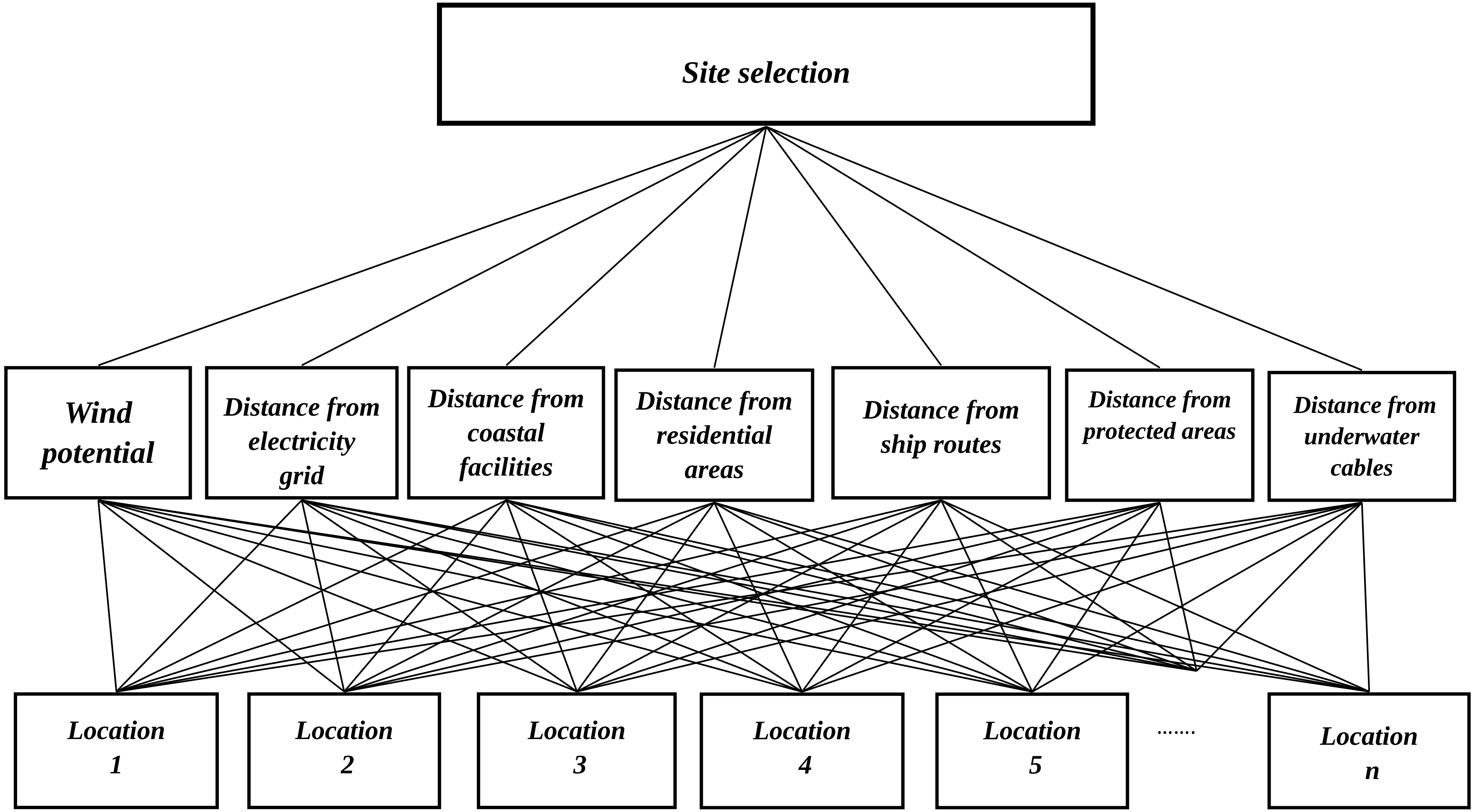
Description of the methodology cont.

- The Spatial Analysis at this phase is based on **Weighted Overlay**
- In Weighted Overlay Analysis the seven steps of Overlay Analysis are followed:

2st stage: Spatial Analysis

1. Define the problem
2. Break the problem into submodels
3. Determine significant layers
4. Reclassify or transform the data within a layer
5. Weight the input layers
6. Add or combine the layers
7. Analyze

Hierarchical Structure of the Problem



Description of the methodology cont.

- Given that the 7 input levels correspond to different numbering systems with different scales, should be set to a common preference scale. Common scales can be predetermined, such as 1 to 9, or a 1 to 10 scale, with the higher value being more favorable.

Reclassify (4th step of Overlay Analysis)

- The criteria of accessibility to the electricity grid and the proximity of coastal facilities **will have degrees of suitability, which will reduce as we move away from them, until they reach the limit in which the degree is zero** (economically inappropriate).
- For the other four criteria (i.e. distances from residential areas, ship routes, undersea cables and protected areas) the degrees of suitability **will increase as we move away from them.**
- For the criterion of wind potential, the class with the highest degree of suitability **will correspond to highest average annual wind speed**

Description of the methodology cont.

The rationale behind the particular criteria weighting used here, based on the on literature review, experts' judgments and personal experience,

- Also, **not all evaluation criteria are equally important**. So, the most important criteria should be heavier weighted than the others. The **AHP method** is used to assign weights to the criteria.

Weight the input layers (5th step of Overlay Analysis)

1. The wind potential is considered to be the most important criterion since it determines the output of the wind turbine.
2. The ship routes and the underwater cables criteria are comes next, since the already use of the sea by other users might hinder the wind farm installation and/or licensing.
3. The distance from the electricity grid and coastal facilities are thought to be less important as they affect mainly the final cost of installation, maintenance and decommission and the grid losses.
4. Sixth in the order of priorities is the distance from residential areas. The adoption of sufficient distances from residential areas can minimize possible reactions from local communities.
5. Finally, the distance from protected areas is placed last in order of importance, since the protected areas have already been excluded from the first stage.

Description of the methodology cont.

- After the criteria weights have been estimated, a weighted sum aggregation function is used in order to compute an overall suitability index for each cell of the study area.

Add or combine the layers
(6th step of Overlay Analysis)

1. More specifically, the cell values of each input layer are multiplied by the raster's (criterion) weight (or percent influence). The resulting cell values are added to produce an overall suitability index for each cell.
2. The map cells are ranked from the highest to the lowest score
3. In GIS, this technique results in an overall evaluation map.

Description of the methodology cont.

- Given that the areas of interest are considered only those, which resulted from the first stage, the exclusion map is used like a "mask" so the final results to be attributed only to interest areas. The results of overlay, except of interest areas, are not taken into account.

Analyze:
(7th step of Overlay Analysis)

1. The tool Extract by mask is used.
2. Product of this process is the final suitability map.
3. In the final suitability map the suitable locations will be presented and ranked based on NPV, IRR, DSCR and LLCR.

Methodological Framework Stage 2

Exclusion map

↓

Evaluation criteria

(Common Preference scale)

$E_1, E_2, \ldots\ldots E_7$

↓

Analytic Hierarchy Process

*(*weights*)*

$W_1, W_2, \ldots\ldots W_7$

↓

Weighted Overlay

$E_1 * W_1 + E_2 * W_2 + \ldots + E_7 * W_7$

↓

Evaluation Map

↓

Final suitability map

(Extract by Mask)

↓

End of phase 2

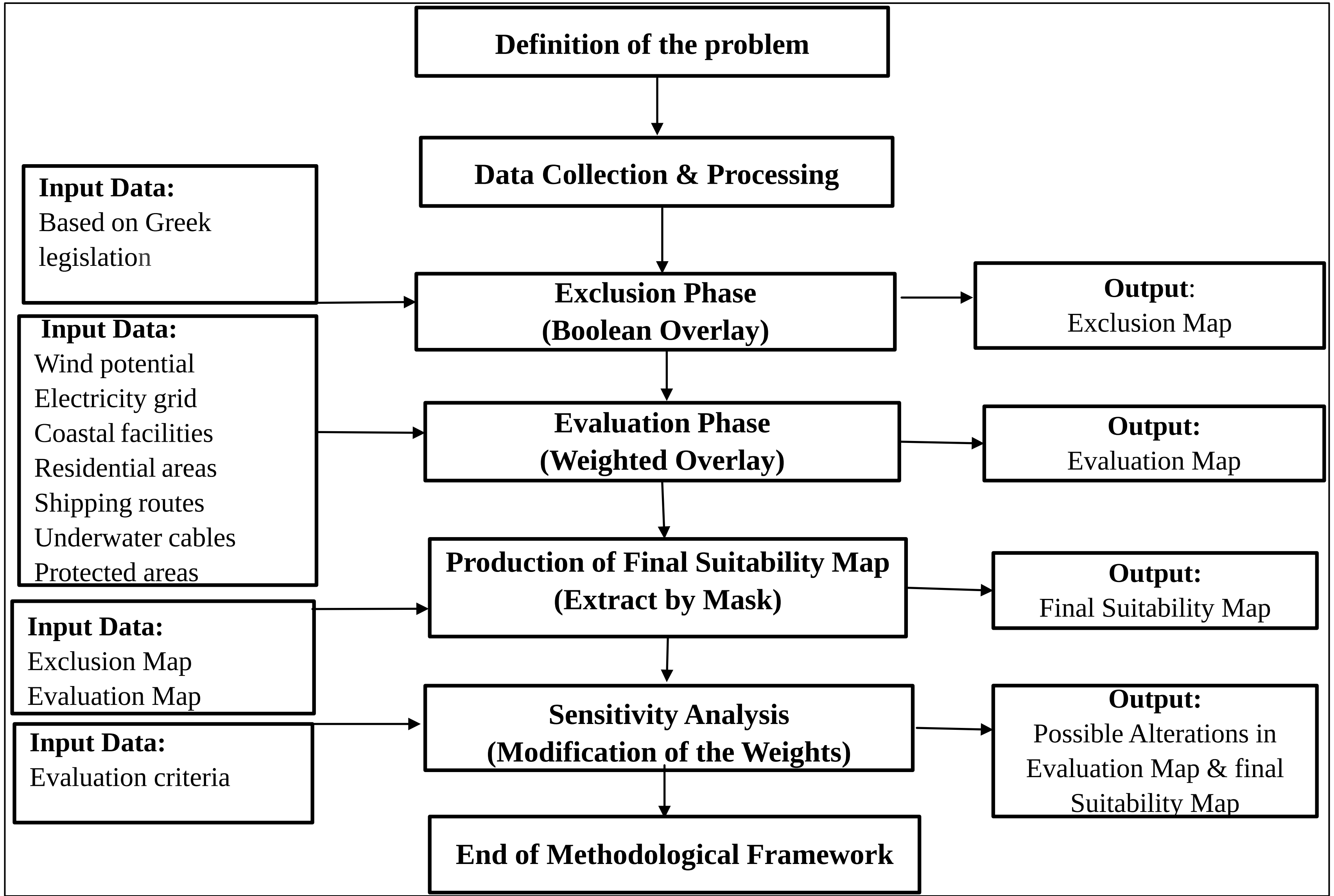
Description of the methodology cont.

- In multi-criteria exercises a “*what if*” sensitivity analysis is recommended as a means of checking the stability of the results against the subjectivity of the experts judgments.
- In this paper, the sensitivity analysis considers the effect of criteria weights changes upon the overall suitability index. To that aim, the following two cases are examined:

Sensitivity Analysis

1. All criteria have the same weights
2. The weights of the criteria “distance from residential areas” and “distance from protected areas” are zero.

Integrated Multi-Criteria Decision Support Framework



Conclusions

- The objective of the study was to develop an integrated multi-criteria decision support framework for offshore floating wind farm installation.
  - The pair-wise comparison method in the context of the AHP is used to assign the relative weights to the evaluation criteria.
  - The GIS establishes the spatial dimension of constraints and evaluation criteria in order to produce the overall suitability map.
  - A sensitivity analysis on the weights of the evaluation criteria is used in order to examine the influence of each criterion in the evaluation of the suitability of site.

This paper proves the reliability and the strength of multi-criteria analysis as a means to serve energy planners a clear tool for decision making. Energy planners and scholars may use this methodological framework to determine locations for feasible offshore floating wind farm installation or to use this as a useful guidance.


THANK
YOU
GRACIAS
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TASHAKKUR ATU
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