A web-based participatory GIS (PGIS) for offshore wind farm suitability within Lake Erie, Ohio

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PGIS for Offshore Wind Farm Suitability

Keywords: PGIS, spatial decision support system, offshore wind farm suitability, Borda method, decision alternatives, and multiple criteria evaluation

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Abstract

This study presents the design and implementation of a web-based Participatory Geographic Information System (PGIS) framework intended for offshore wind suitability analysis. The PGIS prototype presented here integrates GIS and decision-making tools that are intended to involve different stakeholders and the public for solving complex planning problems and building consensus. Public involvement from the early planning stage of projects with a spatial nature is very important for future legitimacy and acceptance of these projects. Therefore, developing and executing a system that facilitates effective public involvement for resolving contentious issues can help in fostering long-lasting agreements. The prototype here is a distributed and asynchronous PGIS that combines a discussion forum, a mapping tool and a decision tool. The potential strengths and benefits of this PGIS are demonstrated in a hypothetical case study in Lake Erie, northern Ohio. In the hypothetical case study, participants evaluate the importance of three decision alternatives using different evaluation criteria for expressing their individual preferences. The individual preferences are aggregated by Borda Count (BC) method for generating the group solution, which is used for synthesizing the different evaluation aspects such as the importance of criteria, ranking of the decision alternatives and planning issues related to environmental and socio-economic concerns from the participants.

Keywords: PGIS; spatial decision support system; offshore wind farm suitability; Borda method; decision alternatives; multiple criteria evaluation.

1. Introduction

Global warming resulting from human-induced emissions poses important policy challenges that can have significant implications for macroeconomic stability and economic well-being. Today's economy, which is mainly based on depleted fossil fuels, minerals and oil, may not be sustained if technologies remain constant while energy demands increase substantially [1,2,3]. The need to control human-induced atmospheric emissions of greenhouse gases requires development of other clean and renewable sources of energy. Renewable energy sources (RES) include replenishable natural resources such as geothermal, solar, bioenergy, ocean, and wind [3,4,5,6]. Among these RES, currently wind energy is given the most attention due to its widespread distribution, economic viability, significant market value, potential in power generation, and presence of advanced technology [7,8,9,10].

Offshore wind energy in the U.S. represents one of the largest RES. Thus, developing an offshore wind generating capacity is one of the most important steps for reducing global warming. For instance, some of the future plans of the U.S. Department of Energy (USDOE) examine the technical feasibility to generate 20% of the country's electricity demand from wind energy by 2030 [11,12]. Short term implementation of those plans suggests that net generation from wind power increased by 28.1 % from 2009 to 2010, bringing its share of total generation to 2.3% [13]. Offshore wind energy development in the U.S. is in its early stage; however, there are some projects which are in the planning phase. These include the Cape Wind project (Massachusetts), the Bluewater Wind project (Delaware), the LIPA offshore wind park (New York), and the Galveston offshore wind project (Texas) [4,10,14].

Over the last decade, the world's wind power generation capacity has been growing rapidly. This increase is due to implementation of federal policy initiatives promoting the development of offshore wind farms and other advancements achieved by wind turbine

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4 technologies such as efficiency and scalability [1,4,15]. At present, there is an increasing interest
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7 in development of offshore wind farms due to several advantages: stronger and constant offshore
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9 winds that exist in the offshore environment; closeness to coastal urban load centers, where most
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11 electrical energy demand exists and opportunities for wind development on land are limited; and
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13 efficiency of the offshore wind turbines, which can produce more electricity and can maintain
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16 higher levels of electricity generation for longer periods of time [4,7,16,17,18,19,20].
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19 One of the major problems in offshore development is identifying the appropriate site for
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21 wind energy farms. Determining wind farm site suitability is a difficult, complex, and protracted
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23 process that requires evaluation of many different criteria [1,21] since it combines
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25 environmental, economic, and social considerations. Environmental considerations are important
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27 and are routinely carried out for wind farm establishment [4,10]. For example, some
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29 environmental impacts of wind farms include turbine noise, visual effect and aesthetic and other
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31 impacts on humans, and effects on ecosystems, including the killing of wildlife, especially birds
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33 and bats [3,4,17]. Economic considerations in the siting of wind farms include the costs
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35 associated with the acquisition, development, and operation of the site [1,19]. Social and political
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37 considerations are related to acceptance of a proposed offshore wind project by residents along
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39 the shore, other stakeholders from tourism and fishing industries, and policy makers. Their
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41 concerns include fear about harm to the local environment leading to negative impacts on the
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43 fish stocks, and loss of property value and income from tourism [22,23,24]. The differences in
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45 viewpoints among stakeholders and the spatial nature of the information regarding offshore wind
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47 siting problems require a tool that can handle these issues effectively.
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55 In recent years, Geographic Information System (GIS) has become a major tool used to
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57 select the most suitable sites for onshore and offshore wind installation [25]. GIS methods for
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59 wind studies have been used in many countries around the world such as China [26], Vietnam
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[27], Taiwan [28], India [29], Turkey [30], Greece [18,31,32], Spain [33,34], Denmark [35], Netherlands [36], England [37,38], Brazil [39], Australia [40], and U.S. [41,42]. Within this context, the relevance of GIS for decision support systems (DSS) for locating suitable sites was first tested by Voivontas *et al.* [31]. Following this work a study from UK aimed at understanding the factors (decision criteria) necessary to determine site suitability for wind farms [43]. Subsequent DSS studies used predetermined criteria that used different aggregation techniques such as Boolean overlay and weighted linear combination (WLC). The Boolean overlay combines the criteria by logical operators such as intersection (AND) or union (OR) while the WLC applies numeric standardization before the criteria are aggregated by weighted average [42,44,45,46].

For instance, Beacham *et al.* [47] used Boolean overlay analysis in ArcGIS to identify suitable offshore wind sites in South Carolina. In this study, the raster format criteria were reclassified as suitable (1) and non-suitable (0); then they used Boolean multiplication of the reclassified layers to identify suitable sites. Another study accomplished by Schillings *et al.* [48] illustrated the use of a web-based spatial decision support system (SDSS) to locate and assess offshore wind potential at the North Sea. This SDSS tool uses overlay analysis of raster layers weighted by users' inputs to generate the final offshore wind farm suitability map. Similarly, Vagiona and Karanikolas [18] used GIS and multi-criteria decision making (MCDM) to identify offshore wind sites in Greece. In this research, Vagiona and Karanikolas [18] applied constraints to all coastal areas to identify places that did not fulfill a certain set of criteria and excluded them from further analysis. Then they used the Analytical Hierarchy Process (AHP) and pairwise comparison of the evaluation criteria to determine weights that show the importance of each criterion [45]. They also performed pairwise comparisons of the candidate sites with respect to

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4 each criterion, generating weights, and then aggregated the weights for each candidate site from
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6 each criterion to locate the most appropriate sites for an offshore wind farm.
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9 This integration of GIS capabilities and MCDM techniques is also known as the SDSS
10 framework [49,50]. Such frameworks are often extended to accommodate collective group
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12 decision making where individuals involved in the decision making process can articulate their
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14 individual preferences for the decision problems in the process. The potential of this integration
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16 accommodates for Collaborative Spatial Decision Support System (CSDSS) where individuals
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18 are united by a common issue-driven interest that acknowledges the complexity of geographic
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20 realities in the solution process. For example, Gorsevski *et al* [42] demonstrated a prototype for
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22 this collaborative group-based SDSS for wind farm selection for regional planning using
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24 traditional GIS. The framework integrated environmental and economic criteria to develop a
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26 hierarchy for wind farm siting through WLC techniques and GIS functionality. The maps created
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28 by the individual's preferences were aggregated for producing a group solution and subsequent
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30 sensitivity analysis that intended to examine conflicting areas associated with the final solution
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32 from all participants.
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41 Traditional GIS technologies have been used for local and regional planning in the past;
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43 however, their complex nature coupled with a requirement to involve key players (interest
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45 groups) in the planning process limits their uses [51]. According to Jelokhani-Niaraki and
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47 Malczewski [52], these key players are the stakeholders who are affected by the consequences of
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49 the planning decision. Thus, for the planning process to be effective, it is very important to
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51 involve different groups of stakeholders [53]. In recent years, an important GIS trend suggests
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53 the importance of the development of a simplified Graphical User Interface (GUI), which is
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55 capable of engaging different groups of stakeholders as a “community” in the planning process
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60 [51]. This approach, also known as Participatory GIS (PGIS), involves public participation so
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4 that the decision-making process becomes more democratic and unbiased. PGIS is, therefore, an
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6 attempt to simplify and bring GIS from a ‘close’ expert oriented to an ‘open’ user-oriented
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8 environment and utilize its technologies in the context of the needs and capabilities of
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10 communities that will be involved with and affected by development projects and programs
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16 According to Balram and Dragičević [56], PGIS application in community planning has
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18 bridged the gap between planning and geographic information science. The decision-making
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20 process in PGIS also involves information exchange, discussion and negotiation among
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22 stakeholders in order to clarify, refine, and resolve the spatial problem in hand. PGIS integrates
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24 people, geographic information data, exploratory tools and structured discussion in order to use
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26 and maximize the knowledge, expertise, and experience of multiple stakeholders [53,57,58,59].
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31 Trang [54] and Meng and Malczewski [60] explained how PGIS practitioners use a
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33 public participation ladder as the conceptual framework to guide public participation. In this
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35 ladder, non-participation is put at the base of the ladder while higher levels of public
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37 participation at the top. The public participation increases as the ladder level increases, leading to
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39 empowerment of the public with more control of the decision-making process. The advancement
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41 of internet technologies in recent years is leading PGIS implementation in a web-based
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43 environment (Web-PGIS), which provides an easy way for sharing public opinion with decision
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45 makers without any place and/or time limitation by enhancing the level of public involvement
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53 The Web-PGIS framework has addressed one of the problems observed in traditional GIS
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55 by allowing participants to express their views anonymously, without any fear and confrontation
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57 from anyone [60]. Research shows that implementation of web-based PGIS can be achieved in
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59 various application domains such as onshore wind farm planning [37,38], regional social
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4 networking [63] and flood risk analysis [64]. Berry *et al.* [38] developed an application which
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6 integrates wind farm sites visualization mapping tool and a web-based survey tool which
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8 facilitates public participation in wind farm planning. The focus of this research is aimed to
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10 quantify potential visual impacts of proposed wind farm planning using web-based mapping and
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12 digital landscape visualization techniques. The results from the survey are used to evaluate the
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14 effectiveness and dissemination of wind farm visualizations and to enhance public participation
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16 in the wind farm planning process. On the other hand, Simão *et al.* [37] developed a conceptual
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18 system framework for web-based PGIS that combines an information area, a multi-criteria
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20 spatial decision support system (MC-SDSS), and an argumentation map. The PGIS module so
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22 called Web-based Participatory Wind Energy Planning (WePWEPP) supports collaborative and
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24 spatial planning through the information area that facilitates both problem exploration and
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26 discussion of alternative solutions. The MC-SDSS enables interactive and iterative learning
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28 about the nature of the problem through user inputs which are required for setting the relative
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30 importance of the decision criteria that determines the assignment of feasible sites. The
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32 argumentation map supports and stimulates the sharing of opinions associated with the interests
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34 behind the users' preferences. Other research by Jelokhani-Niaraki and Malczewski [52] and
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36 Boroushaki and Malczewski [61] presented web-based prototypes that allow users to set weights
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38 of evaluation criteria for decision alternatives under consideration and generate both individual
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40 and aggregated group solutions. Decision alternatives represent the basic structure of a decision
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42 problem that is used in the selection of a given decision maker's course of action [50]. Yet to
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44 date, little research has been done in the implementation of web-based PGIS decision alternatives
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46 for wind farm site selection applications. Therefore, this limitation has stimulated the current
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48 research; this new line of research supports the evaluation of integrated web-based decision
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alternatives using public participation through web-based PGIS intended for offshore wind farm site selection.

In this research project, a custom-built, web-based PGIS tool was developed and its capabilities are demonstrated using a hypothetical dataset that could be generated in real settings by potential stakeholders. The proposed tool in this research has some similarities to the Simão *et al.* [37] WePWEF framework but it offers distinctive features. While WePWEF determines the assignment of feasible sites by evaluating relative importance of the decision criteria, the proposed approach here evaluates the best alternatives of those feasible sites and further complements this previous work. The evaluation of the decision criteria in the WePWEF tool uses a weighting scale that ranges between 0 and 100, which can be cumbersome, especially for non-expert GIS users, while the approach here is based on ranking that simplifies the weighting scale. In addition, in this approach the results from the group scores from the decision alternatives and the frequency of criteria selection are communicated real-time through simple chart statistics that is comprehensive for common users.

Thus, the potential of the tool is illustrated by evaluating three predefined decision alternatives using various evaluation criteria in the southwestern part of Lake Erie, Ohio. The three main components that are emphasized in the illustrated tool include: discussion forum, mapping tool and decision tool. The discussion forum is used to facilitate communication and debate among users regarding different criteria before they use the decision tool. The map tool is used in conjunction with the discussion forum for exploration and visualization of the decision alternatives associated with different criteria while the decision tool allows participants to make their decisions by ranking the decision alternatives using different sets of criteria and cast their votes. The methodology, the proposed conceptual framework, and the system architecture are discussed in the sections below.

2. Methodology

Implementation of the prototype PGIS tool involves configuration of the client-server environment, development of the database which serves as storage of both spatial and non-spatial data, development of the different components including forums, spatial maps and a decision module, and their integration in the web-based framework. In the next section, the conceptual framework of the proposed web-based PGIS and the system architecture are discussed.

2.1. The Conceptual Framework

The advantage of implementing PGIS in a web-based environment is that it allows a group of people to interact about common interests, tasks and ideas through easy access and integration of different tools [58,65]. Some of the features that are present in an effective PGIS are designed to support communication and collaboration for a community of non-technical users using spatial data visualization and decision analysis modules [66].

In this research, the proposed conceptual framework is a web-based PGIS for ranking decision alternatives associated with offshore wind farm site selection, which contains modules including visualization through mapping, collaboration through discussion forum, and a voting module for decision making purposes through an asynchronous and distributed environment. An asynchronous and distributed environment refers to a system that is designed specifically to facilitate user participation during different-time and different-place environments, which improves turnout and involvement in web-based collaborative decision making [36].

The integration of the mapping and the decision tools in the proposed framework follows a loose coupling (ad hoc linkage) approach in terms of data exchange between different modules. This approach also has the capability to combine functionalities of different tools by sharing data in a web-based environment [49,52]. In the system, the decision tool and mapping tool share the

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4 same data, which is stored in a database while the communication tool runs independently. The
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6 literature suggests different communication tools such as the Argumentation Map (“Argumap”)
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8 that integrates geographically referenced discussions, and a web-based GIS capable of
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10 structuring debates with spatial elements in asynchronous online discussions [67,68]. However,
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12 the prototype in this study uses a communication tool customized by a .NET forum for the
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14 purpose of easy customization and integration with the proposed ASP.NET (Active Server Page)
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16 development environment used here.
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21 The most common way of achieving a distributed and asynchronous environment for
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23 web-based PGIS is through the implementation of a client-server architecture. In this
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25 architecture, the client requests different services such as mapping, communication, decision
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27 analysis, data processing, and data storage, while the server provides the services [51,52,69].
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29 Implementations of a client-server architecture were implemented in different studies including
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31 urban planning [60,70], tourism development [71], transportation improvement program [72],
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33 and watershed management [73,74] where the chief objective of the PGIS is to involve different
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35 grassroots and community-based groups for broadening public involvement in policymaking.
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37 The following section illustrates the system architecture of the proposed prototype which uses
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39 ideas from existing PGIS frameworks.
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46 47 *2.2. System Architecture*

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49 Figure 1 illustrates the conceptual PGIS framework of the thin client-server architecture.
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51 This approach is fully “server-side” processing that facilitates robust management and
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53 deployment of the system with easy data update, integration, and implementation [65]. The
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55 client-server adopted here is a three-tier system configuration, which is the fundamental
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57 framework for the model design that segments the application into three tiers of services. The
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4 advantages of the three-tier system architecture over other systems includes high security,
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6 performance, scalability, and reusability of modules and system services [58,74,75]. In the
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8 current implementation, the three-tier architecture is composed of the Presentation, Business
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10 Logic or Middle, and Data tiers. The Presentation tier is the top-most level of the system and
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12 used by participants to interact with the system using simple web browsing interface. The main
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14 function of the interface is to translate and interpret tasks and results that are comprehensive for
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16 the users. The web server, Internet Information Services (IIS), and ASP or Servlet connectors,
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18 which facilitate the communication between the Presentation client tier and the Data tier, are
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20 under the Business Logic tier. In the prototype, the Business Logic tier integrates different
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22 modules such as the decision tool, .NET classes, ArcGIS server and the communication tool.
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24 This tier coordinates the application processes such as decision making, evaluations and
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26 calculations that are used for data processing between the two adjacent tiers. The third tier is the
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28 Data or Database tier, which is used to store and retrieve both spatial and non-spatial information
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30 that is passed back to the Business Logic tier and then back to the user. In this implementation,
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32 the Data tier includes two main components: PostgreSQL and MS SQL server. The PostgreSQL
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34 uses geodatabase and tables to organize the spatial data related to users' information and their
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36 preferences. A one-to-many relationship is maintained between a user and related tables. The
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38 PostGIS plug-in stores and manages the spatial data in the PostgreSQL database which is
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40 subsequently accessed by ArcGIS Server which is the mapping server. Lastly, the MS SQL
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42 relational database stores the non-spatial information from all debates posted by the participants
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44 associated with the communication tool. Here the data flow between the tool's interface and the
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46 database is handled by the .NET Framework Data Provider for SQL Server connection string.
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58 The ArcGIS Server mapping server is used for creating and managing GIS Web services,
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60 applications, and for accessing spatial data stored in the PostgreSQL database, where ArcGIS
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Viewer for Silverlight is used to deploy robust web applications. The two main components of ArcGIS Server that are involved in the process are server object manager (SOM) and server object container (SOC). The SOC machine hosts the server objects (services) while the SOM manages the set of server objects that are distributed across one or more SOC machines. When the SOC receives a request from the SOM for the mapping service; it processes the request and returns back the result to the SOM. Then, the SOM presents the map to clients through the Representational State Transfer (REST) in the ArcGIS Viewer for Silverlight. REST is a set of system architecture principles that facilitates data transfer between client and server over a network using standard protocols such as Hypertext Transfer Protocol (HTTP).

In the prototype, the decision tool is developed using ASP among different .NET classes. It also uses the .NET Data Provider for a PostgreSQL (Npgsql) connection string to communicate with the database. The decision tool implements Multi Criteria Decision Analysis (MCDA), also referred to as Multi Attribute Decision Analysis (MADA), which deals with decision problems from a number of alternatives. The tool accepts users' preferences, such as criteria and rank of decision alternatives based on the selected criteria, and stores the data in the PostgreSQL database. Moreover, it is also responsible for retrieval of data from the database and presentation of the analysis results to the users.

MCDA is a decision-support process that provides procedures and techniques to structure and evaluate complex problems by assessing a set of alternatives using different criteria. In MCDA, the criteria are evaluated based on their relative importance to assess the problem in hand [50,61,76]. According to Malczewski [49]; Jelokhani-Niaraki and Malczewski [52]; Boroushaki and Malczewski [61], the capabilities of MCDA and GIS can be integrated to facilitate participatory spatial decision making. As a result of this integration, participants can

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4 explore and visualize the location of alternatives, and rank or weight these alternatives based on
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6 the preferred criteria.
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9 Figure 2 shows the relation between three spatial alternatives associated with different
10 site locations and a number of different criteria. In this figure, the matrix of criteria and
11 alternatives illustrates the fundamental flow of the spatial MCDA process, which requires the
12 assignment of a rank/weight to each of the alternatives based on the selected criterion. The
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14 ranking/weighting values in this figure are represented as r_{ij} , where i is the i^{th} alternative and j is
15 the j^{th} criterion. Table 1 shows the calculated scores for the alternatives where the end result of
16 this process represents an ordered ranking of alternatives. In this study, the data values associated
17 with each of the alternatives are used to calculate the scores by implementing the Borda
18 aggregation method [42,77,78,79,80].
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31 Borda's method or Borda Count (BC) was first introduced by a French scientist named
32 Jean Charles de Borda at the end of the 18th century [42,77,78,79,80]. BC represents a social
33 choice method that is generated by a large group of people for decision making purposes; this
34 method expresses properties called anonymity, neutrality, and consistency in the social choice
35 literature [79]. This "positional" method assigns a score corresponding to the positions in which
36 an alternative appears within the ranked list of preferences. For instance, if there are N numbers
37 of alternatives under consideration, then the alternative that is ranked first gets $N-1$ points and the
38 alternative ranked next to the first ranked alternative gets $N-2$ points. This process of assigning
39 scores continues up to the last ranked alternative that gets zero points. Subsequently, the points
40 assigned to each alternative are summed up in order to calculate the total score and identify the
41 ranking order. Thus, the alternative with the highest total score is considered to be the most
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In this study, the decision alternatives are ranked from first to third position in terms of preferred importance. To get a clear understanding, the method is further explained using a numerical example. Using the three alternatives (a-c) and 21 participants as shown in Table 2, alternative 'a' is ranked in first position by eight (8), second position by zero (0), and third position by thirteen (13) participants respectively. The points assigned for each rank range for 0 to 2 where score of 2 is assigned for all first ranked outcomes, a score of 1 for all second ranked outcomes, and 0 for all third ranked outcomes. Hence, the total score for each alternative is summarized below by applying the Borda rule. As shown below, the Borda score for alternative 'c' is higher than all the other alternatives. A careful observation of Table 2 shows that alternative 'a' which has the most first ranked outcomes is also the one with the strongest opposition since 13 outcomes reside in the last position. Therefore, alternative 'c' is the most important and highly favored by the participants.

$$\text{Alternative 'a'} = (2 \times 8) + (1 \times 0) + (0 \times 13) = 16$$

$$\text{Alternative 'b'} = (2 \times 7) + (1 \times 9) + (0 \times 5) = 23$$

$$\text{Alternative 'c'} = (2 \times 6) + (1 \times 12) + (0 \times 3) = 24$$

However, the merit of Borda's method is in the aggregation of participants' scores where individuals collectively make a choice from a set of presented alternatives. Such an approach achieves a consensus solution by preventing contentious participants, who rank some alternatives very high and some very low, from holding dominance while it also promotes a consensual solution.

2.3. Study Area

The hypothetical study area is located in northern Ohio along the western Lake Erie shore (Figure 3). Five counties in Ohio are included in the study area, including Lucas, Ottawa, Sandusky, Erie, and Lorain. According to the US Census Bureau's report [81], the total population in these five counties is more than 0.9 million, which is equal to 8% of the State's total population. Major cities and towns located in the study area are Sandusky, Toledo, Port Clinton, and Monroe.

Lake Erie is a fresh water lake, it is the shallowest of the Great Lakes (averaging only 19 meters), and overall the smallest by volume. Lake Erie is divided into three basins: western, central, and eastern. The study area covers the western and central parts of the lake. The average depth of the western part of the lake is 10 m and the central part is 18.5 m [82,83]. The study area is characterized by strong wind with an annual average speed of 7 to 7.5 m/sec, which is highest in November and lowest in July, and is favorable for offshore wind energy generation. The area is characterized by high ice concentration in mid-December to mid-February, with the ice concentration decreasing from mid-February to mid-April [84,85]. The wetlands of Lake Erie support a variety of plant and bird species. For instance, according to Herdendorf [83], there are over 300 plant species in the aquatic and wetland habitats of western Lake Erie. The Ohio National Wildlife Refuge (ONWR), which is known for its rich biodiversity, is part of the study area. Moreover, birds such as waterfowl, wading birds, shore birds, gulls and terns, raptors and perching birds use Lake Erie wetlands for migration, nesting and feeding.

The U.S. Department of Energy [86] reported that the average annual electric consumption of Ohio is around 154,145 million kWh and it shows a 1.4 % increase annually. In the Great Lakes Region, there is a potential of 700 GW of offshore wind energy production. Of this significant level of potential wind energy from Lake Erie, it would be possible to generate up

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4 to 45GW in Ohio [11]. This energy is equivalent to 98,550 million kWh with a 25% production
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6 capacity. The 25% of production capacity is used to reflect other restrictions that may impede
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8 farm deployment due to competing uses, engineering design, weather conditions, fishery,
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10 environmentally sensitive areas, and migratory birds. It would also be possible to cover around
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12 63.9% of the state's energy consumption with this energy. According to the Lake Erie Energy
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14 Development Corporation [87], Lake Erie is a favorable and cost effective location for offshore
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16 wind farm installations.
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21 In the study area there are three decision alternatives to be assessed by the participants.
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23 As shown in Figure 3, "Site 1" is located near Maumee Bay, "Site 2" is located east of Kelley's
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25 Island, and "Site 3" is located off the far northwestern corner of Lorain County. These decision
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27 alternatives were identified since they fulfill the wind resource required for offshore wind farm
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29 development, which is at least 7 m/s at a turbine height of 90 meters (or 262 ft) above the local
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31 surface [11]. To demonstrate the functionalities of this prototype tool and to illustrate the
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33 potential application for evaluation of alternatives for wind farm selection, the simple
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35 hypothetical scenario uses a total of three sites for ranking of alternatives.
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41 *2.4. Decision Making Alternatives*

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44 SDSS for suitable offshore wind site selection involves ranking of the decision
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46 alternatives based on different evaluation criteria. In this study a total of eight evaluation criteria
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48 were used, including: Population Density (PD), Bird Habitat (BH), Commercial Fishery Effort
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50 (CF), Distance from Shore (DS), Fish Habitat (FH), Navigable Waterways (NW), Sport Fishery
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52 Effort (SF), and Utilities (UT) (Figure 4). The criteria used in this demonstration were identified
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54 based on a detailed literature review, US offshore wind energy siting legislation, and data
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56 availability [7,11,12,88,89]. For instance, the policies that have affected offshore wind
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development in federal waters include the Outer Continental Shelf Lands Act (43 U.S.C. 1337) and the National Environmental Policy Act (NEPA) (42 U.S.C. 4321-4347). In the case of the state's waters that surround the Great Lakes, the Coastal Zone Management Act of 1972 (Pub.L. 92-583) administered by the National Oceanic and Atmospheric Administration (NOAA) is the only policy that is designed to set up a basis for coastal zone management plans for preservation, protection, and restoration of wildlife and natural resources. In addition, in this study the evaluation criteria are intended to address different wind farm development planning issues related to environmental and socio-economic concerns, which can impede the decision making process. The consideration of environmental issues helps to minimize any potential ecological impacts, while socio-economic considerations include minimizing construction, operation and maintenance costs and impacts on the local economy and quality of life affected directly or indirectly due to wind farm installation.

BH and FH are under the environmental consideration and the socio-economic considerations include SP, CF, UT, PD, NW, and DS. In this project, rather than fully accounting for all possible evaluation criteria and concerns, the main objective was to demonstrate the flexibility of this PGIS prototype that could be altered by using different evaluation criteria and concerns for different site specific problems and requirements.

2.4.1. Bird Habitat

Planning of new offshore wind energy site selection should consider the impact on the natural habitat of birds. The study area is known to possess two national wildlife refuges (NWRs), including Cedar Point and Ottawa NWR's, and three Important Birds Areas (IBA) sites which are included in the American Birds Conservancy list of the 500 most important IBAs in the U.S. [90]. According to Audubon Ohio [91], IBA is a conservable site identified on the basis

of its international significance for the conservation of birds at the global, regional or sub-regional level for: threatened, congregatory, assemblages of restricted-range and biome-restricted bird species. As stated by NREL [11]; Baisner *et al.*[92], the major risks from offshore wind turbines to migratory and resting birds are collisions and mortality, physical habitat loss from displacement, and visual stimulus/avoidance response and barrier effects, including fragmentation of the ecological habitat network (e.g., migration pathways, breeding or feeding areas). Therefore, ideally, offshore wind farms should be located out of bird habitat [84]. In this study, the electronic spatial data of IBA's in vector format was collected from Ohio Department of Natural Resources [93] Office of Costal Management and used to show the location and proximity of bird habitats relative to the proposed wind farm sites. Therefore, sites that are farthest away from bird habitat are most suitable for offshore wind farms.

2.4.2. Fish Habitat

The effect of offshore wind installation on fish habitat is one of the main environmental concerns that should be addressed during wind farm site planning. Fish habitat is disturbed and altered during and after installation of wind farms [11,23,84]. Therefore, it is important to know the fish habitat in the water body ahead of making any further decision on the suitable site. The U.S. Fish and Wildlife Service legislation stipulates that offshore wind sites should be away from fish nursery and spawning areas. These areas are habitat for larval and young-of-year fishes [11]. In this study, four classes of fish including walleye nursery, adult walleye, walleye/perch, and dead zone (absence of habitat) represent the fish habitat map [93]. The walleye nursery class is considered as the least suitable, adult walleye and walleye/perch are moderately suitable, while the dead zone class is the most suitable habitat for wind farms.

2.4.3. *Sport Fishery Effort*

The sport fishery effort is a common activity in Lake Erie that is compiled by the average hours targeting walleye and yellow perch using an area of 10-minute quadrangle from 2000 to 2006. According to GLWEC [84], in 2006 alone a total of 1.25 million fishing licenses were sold in Ohio, generating around \$1 billion. Of these licenses, one third was sold in the counties along the Lake Erie shore. From the different fish species that exist in the lake, walleye and yellow perch are most popular for sport fishery. The spatial data layer for this criterion was acquired from ODNR [93], which groups the sport fishery map into four classes as 0-4,000, 4,000-25,000, 25,000-106,000, and 106,000-700,000 hours. The classes are based on the total hours spent by people in the areas. Classes with higher average hours are least suitable and classes with lower average hours are most suitable for wind farm development.

2.4.4. *Commercial Fishery Effort*

This criterion is related to the amount of fish which is utilized for commercial purposes from the study area. This criterion needs careful attention because Lake Erie is known for its largest fresh water commercial fisheries among all of the Great Lakes, especially because of the lake's relatively mild temperatures and abundant plankton supply which is the basic building block of the food chain [84]. Wind turbine development is opposed by the fishing community fearing for their traditional fishing grounds, which are their livelihood. The fish productivity of an area is measured based on the number of fish harvested, which is measured in trap net lift [84]. ODNR [93] provided the vector map showing the total number of commercial fishery effort trap-net lifts by 10-minute quadrangle, from 2000 to 2006. The map was classified into four classes as 0-32, 32-250, 250-600, and 600-2900 trap net lifts. Therefore, suitability decreases from the first class, 0-32 traps, to the last class, 600-2900 traps.

2.4.5. *Utilities (Transmission)*

The third socio-economic factor considered was proximity to utilities or transmission lines.

According to GLWEC [84], cable installation has a significant impact on the cost of offshore wind projects. Cable cost is dependent on the project proximity to existing transmission stations.

The closer the project site is to existing transmission stations, the less the cable installation cost.

Therefore, offshore wind energy developers prefer the closest site to develop so that they may access existing transmission stations easily and deliver energy to customers at a lower cost. In this study, data of existing transmission stations along the shore was collected from ONDR [93].

Thereafter, in GIS using the buffer tool, this distance was calculated from these places in different intervals. The distance was grouped into seven classes as 0-5, 5-10, 10-15, 15-20, 20-25, 25-30, and 30-35 miles. Classes with shorter distances, such as 0-5 and 5-10, are most suitable; classes with medium distances such as 10-15 and 15-20 are moderately suitable; while the other three classes are the least suitable for wind farm installation.

2.4.6. *Population Density*

Population density is assessed based on the number of residents per square kilometer. As stated in HEI [89], when considering population density from an economic point of view, areas suitable for offshore wind energy installation are those which are close to higher population densities. As reported by AWS Truewind [88], these areas are the main consumers of the produced energy. In this study, census tract vector data of the counties, located along the shore, was collected from the US census office to calculate the population density [81]. Then, the population density was calculated in GIS, dividing the total population by the total area of each census tract. The population density layer was classified into five classes as 0-200, 201-500, 501-

900, 901-1400, and 1400-2277. Therefore, sites that are close to a high population density are given higher priority than those which are far away.

2.4.7. *Navigable Waterways*

Offshore wind sites that are located far away from navigable waterways are more suitable sites. These sites will not affect any transportation route in the water body [88,89]. The spatial data for navigable waterways was collected from ODNR [93]. Then, the data was added in GIS to generate buffer zones at 0-1, 1-2, and 2-3 miles intervals. The limitation of the distance into these three zones helps to reduce cost of offshore wind turbine installation and to accommodate concerns related to turbine components transportation to greater distances. Therefore, sites that are in the third zone, which is 2-3 miles, are most suitable, followed by the second zone that is 1-2 miles, leaving sites in the 0-1 mile zone as being deemed least suitable.

2.4.8. *Distance from Shore*

Noise pollution, shadow flickering, and aesthetic influence effects on people living along a shore are important concerns for the acceptance of offshore wind farm projects by affected communities. Some claims are that wind turbines close to the shore diminish quality of life, decrease property value, and affect the local economy supported by income generated from recreation and tourism [3,11,89]. As a result, distance from the shore at which wind turbines are going to be installed should be given more attention. In this study, the shoreline data from ODNR [93] was used to generate buffer distance with three classes: 0-3 miles, 3-6 miles, and 6-9 miles.

3. Results

The intention of the prototype was to provide a simple interface for non-experienced GIS users. The main components that comprise the prototype were organized under different themes, including a discussion forum, a mapping tool and a decision tool. The easy-to-use interface was based on the principles of web usability, such as guided user interface elements that are easy to follow, and elements of the navigation tool that are arranged logically and which are similar to a traditional web site navigation bar.

Figure 5 illustrates the PGIS web interface that is associated with the main page of the project, which can be accessed by web browsers such as Internet Explorer, Chrome or Mozilla Firefox. The default web page is used for navigation between different levels that are used for the development of a thorough understanding of criteria associated with different decision alternatives. The main goal of the default web page is to acquaint the participants with the project and the process of selection alternatives for suitable offshore wind farms. As shown in Figure 5, the default web page contains location map of the case study area and brief description of the main components used in this PGIS.

The “Background” theme presents all the details associated with the project, including the basics of wind energy, the benefits and the concerns associated with wind farms, development of wind projects, the PGIS concept, information regarding the criteria used in the project, and instructions for using the tool. In addition, participants may access a manual which contains a brief explanation of how to utilize the different components in this prototype.

Figure 6 shows the mapping interface where participants can explore individual criterion associated with decision alternatives. The main purpose of this component is for data visualization, which communicates the spatial extent of the criteria and the location of the decision alternatives that will drive the process of the decision making. Here the visualization

helps with the overall understanding of the spatial criteria that provide valuable insights and reasoning behind the ranking of the decision alternative. The background map information is powered by the Google Maps interactive map interface (API) that helps participants to create a better understanding of location while the familiarity and simplicity of Google Maps helps the general public to participate in a complex decision making planning process. In addition, the system allows for displaying different Google Maps as backgrounds, including roadmaps (normal, default 2D map), satellite (photographic) maps, terrain (featuring mountains, rivers, etc.) maps, and hybrid (photographic with roads and city names) maps.

In Figure 6, the easy-to-use mapping interface contains basic mapping functionalities such as zoom and pan shown in the top right corner. Participants can use these tools to manipulate and explore the spatial data associated with different criteria in the case study area. The map content includes a legend display that provides useful narrative and graphic descriptions for understanding what is being viewed in the map. For instance, the figure shows that the “Decision Alternatives” and the “Fish Habitat” layers have been selected in the Map Contents Panel. The “Decision Alternatives” layer shows the location for the proposed wind farm locations that correspond to the displayed attribute table. The data from this attribute table is primarily stored in the PostgreSQL database and the table contains information about different geographic features that are used to find, query, and symbolize information. The “Fish Habitat” layer shows the legend and the distribution of the four main species including walleye nursery, adult walleye, walleye/perch, and dead zone, each of which is separated by different colors. In addition, participants can also display or hide map layers for better visualization of the spatial data.

Figure 7 shows the forum component that is used to facilitate discussion among participants for exchanging views and ideas of spatially-related issues. Specifically, the main objective of this module is to accommodate a diverse array of participants and community

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4 members, enabling them to discuss issues such as impacts on the local community, as influenced
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6 by the selection of different criteria and alternatives; the module also enables users to generate
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8 new ideas based on different feedback. The module allows for an ongoing, asynchronous
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10 discussion, so it can help each participant to better formulate his or her opinion, which may
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12 evolve throughout the discussion process. Such a module is capable of catering to a large group
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14 of participants since it supports various tools such as text, maps, sketches, images and
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16 annotations to express and convey users' opinions. In addition, for better integration of the public
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18 to participate in the ongoing discussion, an impartial facilitator can guide the discussion process.
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20 Some of the tasks for the facilitator may include coordination of the planning process, advising
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22 on the proper use of the tools, providing working materials and nonpartisan information, and
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24 encouraging each participant's full involvement in the discussion.
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31 The discussion and interaction among participants precedes the voting module that is used
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33 for the ranking of the alternatives by individual participants. Participants are required to register
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35 before using the forum and voting module. The registration details from the participants are only
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37 used to help with the identification of participants and to collect the voting preferences for the
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39 inclusion of criteria and ranking of alternatives.
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43 Figure 8 shows the decision tool or the voting module for ranking the decision alternatives
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45 associated with the selection of a given wind farm location. The decision tool is the core part of
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47 the system that is used to collect voting preferences from the participants. Here, the participants
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49 can vote on the importance of criteria and the rank of the alternatives. In this study, the ranking
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51 method was used due to its simplicity and unambiguousness in collaborative and participatory
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53 decision-making [49,52]. For instance, Figure 8 shows that the two selected important criteria
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55 include bird habitat (BH) and commercial fishery (CF). The selection of the criteria activates the
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57 ranking information where participants can select the rank for each of the decision alternatives
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4 that relates to a specific criterion. Rank 1 indicates the most suitable site, rank 2 the second most
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6 suitable, and rank 3 the least suitable location for wind farm installation. For instance, Site 3 is
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8 the most suitable location for a new wind farm in relation to the bird habitat criterion whereas
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10 Site 1 is the least suitable location. Participants can also easily display the mapping module from
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12 the decision tool by using the link 'Display Map.' This helps participants to see the spatial
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14 relationship between criteria and the decision alternatives while using the decision tool.
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19 The flow chart in Figure 9 highlights the data flow process behind the voting tool. After
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21 the participant is logged in, the decision module requires the participant to select the most
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23 important criteria, which are used for the ranking of the decision alternatives. Before the
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25 information is submitted to the database, the system checks for errors such as selection of at least
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27 one criterion and whether the participant already had casted his or her vote earlier. After the
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29 participant submits the vote, the score and voting position of the decision alternatives is
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31 calculated by adding the ranks for each alternative from every voter using the Borda Count
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33 approach.
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39 Participants can also visualize the voting results using a chart display before and after
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41 casting their vote. Figure 10 shows the scores for the decision alternatives and the importance of
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43 the criteria. For instance, Figure 10 shows that Site 1 is the most suitable decision alternative
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45 while Site 3 is the least suitable decision alternative for a wind farm location. Also, the most
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47 preferred criteria for the participants is the fish habitat, while distance from shore and utilities are
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49 the most controversial criteria used for the selection of the wind farm location.
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54 55 **4. Discussion** 56

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58 In development of PGIS, the set of evaluation criteria depends on the problem under
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60 consideration and suggestions of stakeholders who participate in the planning process. These
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4 stakeholders have to be representatives of diverse areas of competence, political and economic
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6 agendas, and social values. This can be achieved by enabling and fostering the most inclusive
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8 participation [57,72]. An inclusive participation approach follows the principle of involving
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10 representatives from the wider general public as participants while utilizing a nonpartisan
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12 facilitator to elicit a well rounded discussion from all participants. Otherwise, if participants and
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14 the facilitators are only activists, interested groups, planners and professionals, then the public
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16 voice will be biased or dominated by certain opinions that may not be widely representative or
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18 wise. Therefore, the public's involvement should be from the earliest stages of the planning
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20 process and should be designed to build mutual understanding and consensus among participants
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22 [53]. Later, once diverse voices have been considered, this also tends to support legitimization
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24 and greater public acceptance of the decision process.
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31 Participants can be informed and empowered about the initial idea through different
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33 mechanisms such as stakeholder workshops, consensus conferences, deliberative opinion polls,
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35 negotiated rulemaking, task forces, and town meetings [94]. However, recently public
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37 participation practices are using information technology (IT) for public involvement other than,
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39 or in addition to, these traditional methods of participation. The mechanisms described above
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41 allow participants to express their concerns and suggest criteria to be considered in the decision-
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43 making process. Based on Malczewski [50], the procedure for identifying the criteria should be a
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45 multistep iterative process. That is, the process should be done repeatedly to accommodate all of
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47 the concerns of the stakeholders.
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53 In this research, the implemented web-based PGIS is flexible and can incorporate different
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55 criteria other than the eight criteria which we had already included in the current version of the
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57 tool. Adding diverse and alternative criteria could be accomplished by public involvement in
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59 discussion forums for selection of goals and criteria that should be considered in the offshore
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4 wind farms planning process [60,69,76,]. For instance, this module can be used for idea
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6 generation, collection and sorting of ideas and improvement of the planning process based on
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8 feedback.
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11 The identification of stakeholders is an important step in developing a PGIS. Determining
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13 truly representative stakeholders will better help to address the general public's issues and
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15 concerns. Furthermore, it will give added confidence to the stakeholders in how to use the
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17 developed system. In this study, the main objective was to demonstrate the potential of web-
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19 based PGIS as a SDSS tool using hypothetical scenario without the involvement of stakeholders'
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21 opinions in the planning phase. Hence, as a starting point, this research consulted relevant studies
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23 to identify some of the criteria that are important in offshore wind farm planning
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25 [9,22,24,61,84,89]. A real scenario of PGIS development for wind farm site selection should
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27 involve a description of concerns to participants, discussion(s) among participants, setting
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29 criteria, and voting on the decision alternatives. During the description of concerns participants
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31 will be informed about the problem and will be provided with background information. Then
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33 participants will express their concerns regarding any proposed wind farm project during the
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35 discussion phase. This stage helps to address NIMBY (Not In My Back Yard) syndrome often
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37 associated with suitable wind farm site selection. The criteria set by participants will serve as a
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39 means to evaluate the decision alternatives. Once common understanding and consensus is
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41 achieved among participants regarding the criteria, the next step will be voting for achieving
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43 group decision making [72].
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53 There are different approaches that can be followed to use the web-based PGIS in order to
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55 achieve group decision making. For instance, nonpartisan facilitators can moderate the forum
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57 discussions and guide the process where the voting goal may include the gathering of additional
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59 data to measure stakeholder attitudes. Other models are also possible, such as an "open access
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poll,” which uses continuous voting (i.e., submitting a voting option on a website), or an “online poll,” which may use a survey in which participants communicate responses via the internet.

5. Conclusions

This study demonstrated the design and implementation of a conceptual framework for distributed and asynchronous web-based PGIS. The PGIS framework integrated three components including a discussion forum, a mapping tool and a decision tool. The potential implementation was illustrated by using a hypothetical case study to show the strengths and the benefits from PGIS in facilitating suitable offshore wind farm site selection in Lake Erie. The hypothetical case study implemented a standard decision-making scenario by ranking three predefined sites or decision alternatives using eight different spatial criteria in a collaborative and transparent way.

The implementation of the proposed framework used a thin client-server environment with three-tier architecture. The final PGIS product of this integration used standard GIS-based multi-criteria evaluation approach that accommodates multi-user environments and supports group decision making. The mapping tool is used for visualization, exploration and comparison of decision alternatives and their corresponding properties such as total score and rank. The decision tool is used to perform ranking of the decision alternatives based on the evaluation criteria using Borda Count (BC) method as a means to calculate the group scores of each decision alternative. Lastly, the discussion forum is used to facilitate communication and debate among participants.

In summary, the intention of this study was to show the potential of a web-based PGIS for offshore wind suitability analysis that integrates alternatives, evaluation criteria, and participants’ input using new technological ideas. The strength of this methodology is the flexibility for

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4 modification and customization when implemented in different study areas or other applications
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6 and problems, which require spatial decision support. Although the system was not fully tested
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8 with real stakeholders, the potential implementation to resolve complex issues of important
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10 public planning problems was demonstrated through the real-world-based data that we
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12 incorporated into the hypothetical scenario that we discussed.
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16 Future recommendations for refinement of this decision-making tool and process include
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18 the addition of more modules for dynamic inclusion and exclusion of decision alternatives,
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20 different voting approaches, aggregation of individual scores to obtain a group solution, and
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22 simplification of the importance of the criteria using sets of linguistic terms such as “low,”
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24 “medium,” and “high.” The use of linguistic terms or quantifiers can help with the conversion of
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26 human language to be formulated mathematically, which can further simplify the system in terms
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28 of its user-friendliness, and encourage wider participation in the spatial decision-making process.
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Fig. 1. System architecture

Fig. 2. Relation between alternatives and criteria

Fig. 3. Location map of the study area

Fig. 4. Evaluation criteria (a) bird habitat, (b) fish habitat, (c) sport fishery effort, (d) commercial fishery effort, (e) distance from utilities, (f) population density, (g) distance from navigable waterways, and (h) distance from shore

Fig. 5. Home page of the prototype PGIS

Fig. 6. Mapping tool interface with map contents dialogue box and attribute table of the decision alternatives

Fig. 7. Interface for the forum module

Vote - Mozilla Firefox

File Edit View History Bookmarks Tools Help

Vote

a048585/wpgis/vote.aspx

☆ Google

BGSU
Bowling Green State University

**LAKE ERIE PARTICIPATORY GIS (PGIS)
FOR
WIND FARM SUITABILITY ANALYSIS**

Welcome, Addisu!
LOGOUT

Voting

Please select at least one criteria in order to participate in the vote

Rank values indicate that 1-most suitable for wind farm, 2-second most suitable, and 3-the least suitable

[Display Map](#)

* Required Field

Voting Information

Criteria	Decision Alternatives		
	Site1	Site2	Site3
☐ Population Density (PD)	select rank ▼	select rank ▼	select rank ▼
☒ Bird Habitat (BH)	3 ▼	2 ▼	1 ▼
☐ Navigable Waterways (NW)	select rank ▼	select rank ▼	select rank ▼
☐ Distance from Shore (DS)	select rank ▼	select rank ▼	select rank ▼
☒ Commercial Fishery (CF)	2 ▼	1 ▼	3 ▼
☐ Fish Habitat (FH)	select rank ▼	select rank ▼	select rank ▼
☐ Sport Fishery (SF)	select rank ▼	select rank ▼	select rank ▼
☐ Utilities (UT)	select rank ▼	select rank ▼	select rank ▼

[View Score](#)

Fig. 8. Decision tool interface

Fig. 9. Data flow in the decision tool

Fig. 10. Charts showing the group score from the decision alternatives and the frequency of criteria selection

Table 1. Calculated scores and ranks after MCDA is performed

	Criterion 1	Criterion 2	...	Criterion n	Score	Rank
Site 1	r_{11}	r_{12}	...	r_{1n}	Score ₁	rank ₁
Site 2	r_{21}	r_{22}	...	r_{2n}	Score ₂	rank ₂
Site 3	r_{31}	r_{32}	...	r_{3n}	Score ₃	rank ₃

Table 2. Numerical example of 3 alternatives and 21 participants

Ranking	Alternatives			Points
	a	b	c	
1 st	8	7	6	2
2 nd	0	9	12	1
3 rd	13	5	3	0
Number of Participants	21	21	21	