Received: 17 January 2023 | Revised: 31 March 2023 | Accepted: 3 April 2023

DOI: 10.1002/ffo2.155

ORIGINAL ARTICLE

WILEY

Facilitating spatial consensus in complex future scenarios through Real-Time Spatial Delphi: A novel web-based open platform

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Funding information
The work carried out in this paper was supported by the project SCORE which has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement, Grant/Award Number: 101003534

Abstract

The Delphi technique is a commonly applied method for (among the various uses) achieving consensus from a group of knowledgeable experts. This approach is frequently employed to generate and prioritize ideas, identify potential solutions, and make decisions in various contexts through a series of iterative rounds. In the Futures Studies (FS) context, the Delphi method is regularly used in combination with the scenario method to explore different futures, implementing strategies in the present with the aim of averting dystopian outcomes and/or facilitating normative scenarios. Nevertheless, assuming that the convergence of opinions can also occur in spatial contexts, a shortcoming of the method is the deficiency of spatial references useful in the planning process. In this paper, we introduce the Real-Time Geo-Spatial Consensus System, a novel web-based open platform useful to develop Delphi-based Spatial Scenarios (DBSS), in an interactive and innovative interface. The platform adopts the Real-Time spatial Delphi technique to obtain a spatial convergence of opinions among experts to offer researchers, decision-makers, policymakers, and local authorities a new tool for complex spatial decisions. The primary innovations of the platform, including its architecture, statistical algorithms, tools, features, and outcomes, are demonstrated through a preliminary application focused on potential future climatic hazards in Dublin, Ireland.

KEYWORDS

Delphi, Delphi-based Spatial Scenarios, future studies, Real-Time Spatial Delphi

1 | INTRODUCTION

Since the early 1950s, the Delphi method is considered one of the most widely used approaches for achieving convergence of opinions among experts, capable of being flexible and adaptable for different contexts of study. From a historical point of view, the invention and the first application of the Delphi method is attributed to the RAND Corporation (Santa Monica) at the end of the 1950s, in a study published by Olaf Helmar, Norman Dalkey, and Nicholas Rescher, 12 years later (Gordon, 1994; Linstone & Turoff, 1975). The objective of the project was to prioritize experts' opinions to identify the optimal US industrial target system and estimate the number of atomic bombs necessary to reduce munitions output (Rowe & Wright, 1999). This demonstrates how the Delphi method has always been linked to future prediction, making it suitable for contexts with strong uncertainty, where traditional forecasting methods (e.g., predictive models based on historical data) may be limited (Sossa et al., 2019).

From the first application, the Delphi method evolved rapidly, so much that we can no longer refer to its classic version of the 1950s, but as a “modified Delphi” (Custer et al. 1999). In the scientific literature, the method is widely adopted and is generally composed of repeated iterative rounds, administering several questionnaires to a panel of experts to receive information, feedback, and judgments (Woudenberg, 1991). Specifically, according to Rowe and Wright (1999), the main characteristics of the method are anonymity, iteration, controlled feedback, and statistical group responses. In fact, the process is valid precisely because it is composed of experts with high competencies on the object of study, combining different opinions. Group decisions are much more accurate than individual judgments (Galton, 1907) because they provide a wider range of perspectives and experiences than any single individual. The anonymity of the experts constitutes a peculiar feature of the Delphi method, as it resolves different biases that could occur during decision-making processes (e.g., confirmation bias, emotional bias, etc.), and eliminate any conflicting situations that could arise during face-to-face meetings.

In the Futures Studies (FS) context, the Delphi method can be combined with other methods in different ways, however, one of the most common combinations is with the scenario method. The development of future scenarios is widely discussed in the literature as a multidisciplinary approach to speculating on long-term outcomes and facilitating effective planning (Becker, 1983). Scenarios cannot be viewed as concrete facts, but rather as imaginative objects to consider potential or plausible futures (Berkhout et al., 2002). Michael Porter (1985) defined this approach as “an internally consistent view of what the future might become—not a forecast, but one potential outcome.” In this context, the future is undefinable and full of unexpected turns and concealed changes, where a single action or shift can alter the pre-established scenario (Kosow & Gaßner, 2008) and the scenario development is a central part of grasping the techniques and technologies for managing future uncertainties.

According to Nowack et al. (2011), the Delphi and the scenario method are combined following a “step-by-step” procedure, and the scenario outputs can be used as inputs for the Delphi, or the outputs of the Delphi are used as scenarios inputs (Di Zio et al., 2021). The method is not intended here to compete with statistical or model-based procedures, which have generally been demonstrated to outperform human judgments, but rather to be utilized in situations where pure model-based statistical methods are infeasible or impractical (Rowe & Wright, 1999). In particular, when the Delphi outputs are used as scenarios inputs, the final scenarios are known as Delphi-based scenarios (DBS). DBS are a form of exploration that combines expert judgments, quantitative analysis, and system dynamics to create a holistic vision of the future state of a complex system. It involves a series of structured and iterative steps that engage experts who provide input on different aspects of a system, such as future trends, potential events, and possible outcomes. The process requires a series of rounds of questioning, during which experts are asked to provide judgments, feedback, and insights. This feedback is finally used to refine the scenarios and create a more realistic vision of the future (von der Gracht, 2008). As such, DBS can be an effective tool for strategic planning in a variety of fields, including public policy, where spatial complexity is increasingly present and when there is a lack of historical/quantitative data. However, from what emerged from the scientific literature, an open challenge is the lack of a spatial component in the process, where opinions, feedback, and judgments could be collected also from a spatial perspective.

The traditional version of the Delphi method is composed of multiple iterative rounds. However, the questionnaires typically rely on open-ended, closed-ended, and scaling questions, not adequate for identifying future projections in the shape of points or polygons on a territory. For this purpose, implementations such as Spatial Delphi (SD) (Di Zio & Pacinelli, 2011) and Real-Time Spatial Delphi (RTSD) (Di Zio et al., 2017) have been developed over the years to overcome this challenge. The Spatial Delphi proposes a structured approach similar to the Delphi method, involving the administration of a spatial survey to a panel of experts, to acquire georeferenced judgments and feedback on the topic. What differs from the traditional method is characteristic of the questionnaire, where instead of textual or scaled judgments, the experts will have to indicate a point (or more) on a geographical map, called opinion point. We can distinguish two main innovations in the approach compared to the traditional version of the Delphi: (1) the first innovation involves replacing the interquartile range (IQR) used in the classical Delphi approach with an area containing a specified percentage of opinions. The size and location of this convergence area are determined by the expert opinions represented as a cloud of points in the study area. To provide room for subsequent iterations, a circle is used as the convergence area shape, with its center located on one of the opinion points. (2) The second innovation involves allowing experts to provide multiple opinion points across several rounds, thus collecting a greater quantity of points and guiding the respondents toward more accurate considerations. The Real-Time Spatial Delphi is a variation of the SD that allows for real-time collaboration and interaction between the expert panel. This approach involves using online platforms or WebGIS digital tools to administer an online survey, where expert panel members provide their opinions and insights on various spatial or geographic issues related to a specific topic in real time. The survey responses are immediately analyzed and summarized, and the results are shared with the expert panel in real time (feedback). This real-time interaction allows for a more dynamic and iterative process, where expert opinions can be refined and updated in response to emerging trends or developments. Overall, the two methods can be particularly useful in situations where there is a need for rapid decision-making, or where there is a high degree of uncertainty or volatility in the area or topic under study. It allows for a more agile and flexible approach to forecasting and decision-making, based on the latest available information and expert insights.

These methods offer unique advantages, such as the incorporation of spatial and temporal information, and can be particularly useful in complex decision-making processes that involve geographic or temporal factors.

Nevertheless, from the first applications, the two methods remained "unexplored," and only a few applications were proposed in the scientific literature (Castillo-Rosas et al., 2017; Diez-Rodríguez et al., 2019), due to different reasons: (1) *SD*: is not widely adopted due to the same limitations of the Delphi method, including the time-intensive nature and the difficulty of statistically summarizing the results, which require the facilitator to expend significant effort. (2) *RTSD*: requires strong programming skills for the development of Web-GIS systems and the creation of new surveys. In addition, the main weakness is the lack of a dedicated system, where the platform originally proposed by Di Zio et al. (2017) is no longer available for use, not allowing for new studies.

To overcome these challenges, in this paper, we present "Real-Time Geo-Spatial Consensus System" (RT-GSCS, https://www.rtgscs.com/), a novel and innovative platform, useful for the development of Delphi-based Spatial Scenarios (DBSS). RT-GSCS is a platform that uses an iterative approach typical of the SD and RTSD to obtain experts' judgments and insights on spatial issues and stimulate a spatial consensus among a panel of experts. The final aim is to identify patterns and trends in delimited areas, obtaining a spatial convergence of opinions (i.e., a small portion of territory suitable for the achievement of a purpose), useful in the consultations for decision and/or forecast purposes.

The platform includes open-access tools for visualization and analysis of the responses in real time, where experts can create and moderate conversations in the panel session, collaborating with each other in real time, allowing for a more in-depth exploration of the issue at hand. Additionally, the platform includes different tools for the experts to track their progress and measure the impact of their input adopting computational algorithms. The main contribution of this paper is to propose a novel and innovative platform useful both in the foresight and decision-making context by implementing the RTSD, to fill the gap related to the unavailability of platforms exploiting the method and to offer a solid tool for researchers, decision-makers, policymakers, and local authorities. Thus, we believe that this platform adds an important piece to the literature on Delphi and Delphi-like methods, taking into consideration the geographical aspects. Furthermore, we implement guidelines for those who want to develop DBSS using RT-GSCS, illustrating the methodology adopted.

This paper is structured in the following sections: in Section 1, we provided an overview of the research context. In Section 2, we outline the theoretical framework, including the Delphi method and the modified versions such as the Real-Time Delphi, Spatial Delphi, and Real-Time Spatial Delphi. We also illustrate the combination of the Delphi and scenario method, outlining the overall process and the recent applications. In Section 3, we present the platform, with a clear definition of the architecture in the front and back end, statistical algorithms used, tools, and implementations. For a practical demonstration, in Section 4. we illustrate the materials and methods used to develop DBSS for a prototype case study in Dublin, in the climate hazard context. In Section 5, we present the results of the study, including the scenarios obtained and the relevant statistical information, adopting GIS analysis. Finally, in Section 6, we discuss the results remarking on the conclusions, limitations of the study, and possible future works.

2 | LITERATURE REVIEW

2.1 | Delphi method and modified versions

The Delphi method is a structured communication approach used to obtain a collective judgment from a group of experts on a particular topic (Dalkey, 1967). It is an iterative process that involves the anonymous collection and consolidation of experts' projections or estimates on a specific research context, with the aim of reducing uncertainty by achieving, most of the time, a consensus. From the first application in the RAND Corporation, the Delphi method is a broadly adopted process to elicit the opinions of experts in a systematic and unbiased manner (intended here as a reduction of cognitive biases with respect to face-to-face decision-making processes), with the aim of improving the accuracy of decision-making processes in complex and uncertain situations (Gupta & Clarke, 1996).

The Delphi method is used in various fields, including planning, policy analysis, management, engineering, social sciences, and medicine (Critcher & Gladstone, 1998; Flostrand et al., 2020; Sourani & Sohail, 2015). Starting from the above-mentioned characteristics listed in the introductory section (Rowe & Wright, 1999, 2011), the process is generally composed of four key features: (1) *Anonymous feedback*: the main feature of the Delphi method is the anonymity of the panel where experts are asked to provide their responses in the iterative rounds anonymously, to prevent bias and groupthink. In addition, compared to other decision-making processes (e.g., workshops, face-to-face meetings, team meetings, etc.) anonymity allows experts to express their opinions freely and without social pressure. (2) *Questionnaire administration*: the questionnaires are developed and administered to the panel of experts following the classic statistical guidelines of writing and administering a survey, thus avoiding direct questions or too broad questions. The questionnaire may contain open-ended or closed-ended questions or a combination of both and should be carefully crafted to elicit relevant and valuable information from the experts (Beiderbeck et al., 2021b). (3) *Consolidation of responses*: the experts' judgments are consolidated and analyzed, and the results are reported back to the experts in the form of statistical summaries. They typically include measures of the central tendency, such as the mean or median, as well as measures of dispersion, such as the standard deviation or the IQR. These statistical measures are used to summarize the responses of the experts and help to identify any consensus or agreement among them. In this way, experts can revise their responses based on the collective feedback. (4) *Iteration*: the purpose of iteration is to gather more detailed and refined estimates or predictions from the experts over time, as they allow to review and consider the responses of their peers in each subsequent round. The number of iterations can vary, but typically two to three rounds are sufficient to achieve a reasonable level of consensus and/or stability (Dajani et al., 1979; Keeney et al., 2006). From the previous key features, emerges the necessity to identify a group of knowledgeable witnesses in the process. The experts' selection is one of the main open challenges in the Delphi method (but generally in all the participatory decision-making processes), to the extent that is currently difficult to objectively quantify the degree of expertise. The experts may be chosen from a variety of fields and may be located in different geographical regions, and since the Delphi process is a creative process, it should involve different experts with different types of expertise.

The Delphi method has several advantages over other methods in the acquisition of expert opinions, it allows for the aggregation of a diverse range of perspectives, and it reduces the influence of any one expert on the final decision (Belton et al., 2022). However, one weakness of the Delphi method is that it can be very time-consuming for several reasons. One of the main reasons is that it involves multiple rounds of questionnaires or surveys, which can take time to administer, analyze, and report on (Windle, 2004). In addition, the process of reaching a consensus among the panelists may also take time, as it may require extensive discussion and debate to resolve any differences in opinions. Finally, as stated before, the Delphi method may involve additional time for recruiting and selecting a suitable panel of experts, as well as for training and orienting them to the process. This can be a lengthy process, especially if the experts are located in different geographical regions, as it may take time to coordinate and communicate with all of them.

To overcome this issue, over the years, a real-time version of the method has been implemented. The Real-Time Delphi is a variant of the Delphi method (fully implemented on a web page), which aims to obtain a reliable group of judgments from a panel of experts in a shorter time frame compared to traditional Delphi (Gnatzy et al., 2011). It is particularly useful for forecasting and decision-making in situations where time is a critical factor or when there is coordination difficulty or a lack of sufficient expert engagement. Gordon and Pease (2006) introduced this method to address the time-consuming nature of the classical Delphi method, which can take several rounds of questionnaire iteration to reach a consensus or stability. The RTD aims to achieve a group consensus in a single round of questionnaire iteration (named by the authors as "round-less") by allowing for real-time communication and feedback among experts. Each expert can provide subjective opinions and written arguments for each question and can revise the opinions at any time. If other experts have responded in the meantime, some group statistics (such as the number of responses, average, median, or IQR) are displayed next to each question, and the experts can provide new judgments and comments based on the statistical synthesis of the group responses and the arguments. In contrast to the traditional Delphi method, experts are not required to respond a fixed number of times at predetermined intervals, and they do not need to complete the questionnaire all at once. Furthermore, RTD can be conducted with a diverse group of participants from various locations, and the questionnaire can include attachments and reference material to help respondents find supporting information online. Several studies have demonstrated the effectiveness of the RTD in various fields, including technology forecasting, policy analysis, and disaster management (Aengenheyster et al., 2017; Gnatzy et al., 2011; Gordon & Pease, 2006; Meyer et al., 2022). However, it is important to note that the RTD may be subject to some of the same limitations as the traditional Delphi method, including subjective choices in the response scales and high dropout rates. In addition, must be taken into consideration the strong programming skills requested by the research group and the possibility that experts may have problems accessing and using the web interface.

In our context, the main disadvantage of the RTD (as well as of the classic Delphi) is its nonsuitability for spatial problems, intended here as a visualization of spatial information, in the form of maps or geographic data. RTD surveys, although they may concern geographic-spatial applicative contexts, typically involve open or closed-scale questions, precluding the possibility of aggregating experts' judgments with a purely geographical perspective. Therefore, while all the methods of the Delphi family are typically "non-geographic" when dealing with decision problems or future issues that involve a geographical component, the classic methods can be supported by different methods, to manage all matters of a spatial nature more easily.

To overcome this last limitation, Di Zio and Pacinelli (2011) provided a useful implementation in the scientific literature, with the introduction of a spatial version of the Delphi method. The S is a variant of the Delphi method, specifically designed to involve spatial and geographic aspects in the decision and forecasting process. It is particularly useful for forecasting issues that have a strong spatial dimension, such as land use, environmental degradation, and urban planning.

The SD involves a series of questionnaire rounds, like traditional Delphi studies, with a focus on spatial and geographic issues. In the SD, experts are invited to participate in the study following the traditional steps of the Delphi method, providing their opinions on a topic, by considering the spatial and geographic components. Specifically, since the logic of the SD, is considered to perform the platform algorithm, we outline here the procedure described by the authors: (1) *Experts engagement and questionnaire administration*: the experts are engaged based on their knowledge and their competencies. In this case, the questionnaire proposed to the experts differs from the traditional version of the Delphi method because it includes a digital map, with attachments to explore the research context. (2) *Submission of the first questionnaire*: the experts are called to answer different questions indicating three points on the map based on their opinions. The authors introduced the concept of "opinion point," where each expert is asked to place a point on the map, representing the location more suitable for the specific decision problem or where the occurrence of a future event is more likely, according to their opinions. (3) *First statistical summary*: it requires a calculation (dimension and geographical location) of the minimum circle containing 50% of the total opinions on the map (called "circle of convergence"). This circle corresponds to the IQR in the classical Delphi. (4) *Submission of the second questionnaire*: the experts are invited to place two points on the map inside the first circle of convergence. If the points are placed outside the circle, the decision must be motivated. (5) *Second statistical summary*: calculation of a second circle of convergence, containing now 50% of the points of the second questionnaire. (6) *Submission of the third questionnaire*: where experts are asked to insert one point, referring to the previous guidelines. (7) *Third statistical summary*: calculation of the third circle of convergence, containing 50% of the last answers. (8) *Iteration*: at this point, the process continues until a spatial convergence or stability is achieved. The spatial convergence is considered achieved when the final circle is sufficiently small with respect to the study area and/or the problem dealt with. As indicated in the first version of the SD (Di Zio & Pacinelli, 2011), the spatially-based challenges are varied and multifaceted. These include determining the ideal location for goods or services, predicting the site of future events, locating invisible materials, and identifying high-risk areas. In essence, decision-making and future-oriented issues frequently involve geographical considerations. However, the geographical dimension (and georeferenced opinions) remains relatively underexplored within the realm of Delphi and Delphi derivative methods (and more generally in FS), while it is highly developed in many other disciplines, such as statistics, sociology, engineering, environment, transports, and so on. It is important to underline that SD and RTSD, are to be considered complementary to other methods and not alternatives.

From what emerged, this methodological implementation has led to interesting insights for the development of geo-spatial questionnaires using the Delphi logic, however, a few applications have been proposed in the scientific literature for some limitations of the method. The SD method, like the traditional version of the Delphi method, involves a series of iterative rounds requiring a significant amount of time to complete the process. Participants are required to provide their judgments in each round within predetermined time intervals, leading to high dropout rates. The presence of a static map, designed and proposed by the research team, lead to the impossibility to alter the map or interact with it in any way during the survey. Furthermore, the statistical summaries facilitated by the research team can be intensive and time-consuming and require specific geographical skills. Overall, the limitations of the SD can be attributed to the lack of dedicated online and real-time tools, which could perform the process by reducing the time-consuming and effort for the facilitators. With this paper, we intend to give a contribution in this direction.

Starting from this assumption, Di Zio et al. (2017), developed a new version of the SD, namely the Real-Time Spatial Delphi. The RTSD is a combination of the RTD and the SD specifically designed for use in forecasting and decision-making processes. It involves the use of Geographic Information Systems (GIS) and multiple spatial technologies to facilitate the communication and collaboration of experts in a virtual environment. The RTSD follows the same logic of the SD but is implemented in a real-time platform and has several advantages over traditional Delphi methods, as it allows for the integration of spatial data and the use of spatial visualization tools to better understand and communicate the spatial dimensions of the problem.

The application of the RTSD represents a methodological innovation that could lead to essential benefits for decision-makers and local authorities because it allows a round-less and cost-less process, enhancing the number of experts in the panel by having spatial statistics information in real time. Nevertheless, as listed in Table 1, the main weakness of the method is the need for advanced programming skills to construct each survey, where the administrator is responsible for creating and administering all the surveys and multiple surveys cannot be created simultaneously by users. Finally, in light of the unavailability of the platform proposed by Di Zio et al. (2017), few studies have been promoted leading to a serious lack in the scientific literature.

As explained in the following sections, we start from the study proposed by Di Zio et al. (2017), to improve it in an innovative and open system, enhancing the quality of the method by allowing users and researchers to create their own survey in an efficient way.

2.2 | Delphi-based scenarios

In the FS context, the Delphi method is used in combination with different methods, however, one of the most widespread combinations is with the scenario method, leading to the so-called DBS (Nowack et al., 2011). Scenarios are descriptions of potential future situations and the paths of development leading to them (Kosow & Gaßner, 2008). They are hypothetical constructs that illustrate a range of possible futures and the key factors that may influence their development (Schoemaker, 1995), and similar to the Delphi method, it arose in the military sector during the 1950s.

Since it is not possible to predict the long-term future, we must refer to the term "futures," because the future is inherently uncertain, and it is impossible to accurately predict with certainty what will happen. Therefore, it is more useful to consider a range of potential future outcomes and the factors that may influence their development. Starting from that, the study of the different futures has shifted from the use of forecasting techniques to the use of foresight (Martin, 1995), because the final aim is not to elaborate a detailed idea of the future, but rather to "orient towards the future" (Nurmi, 1989). By considering multiple futures, it is possible to be more prepared for a variety of potential outcomes and to make more informed decisions in the present. In fact, De Finetti (1968), states that:

> "We must think that things will go as we will be able to make them go and that, therefore, the problem is a problem of decision, not of forecasting the future."

TABLE 1 Strengths and weaknesses of the Delphi, Real-time Delphi, Spatial Delphi, and Real-Time Spatial Delphi.

Method	Strengths	Weaknesses
Delphi	• Direct confrontations without face-to-face meetings • Anonymity, reducing cognitive biases • Controlled feedback process • Reduction of effect noise • Flexible methodology • Revisions of responses over the rounds	• Nonsuitable for spatial contexts • No interactive interface • Time-consuming • Multiple iterative rounds • Predetermined intervals • Materials are attached separately • Efforts for the statistical summary • Incurs costs for implementation
Real-time Delphi	• Round-less and cost-less process • Interactive interface • Large sample of panelists • Real-time participant responses and statistical summaries • Materials attached (e.g., documents) • No predetermined intervals	• Not suitable for spatial contexts • Requires programming skills for each application and survey • Involves subjective choices in the response scales • May result in high dropout rates
Spatial Delphi	• Well-suited for spatial contexts • Simple to provide judgments on an interactive map • Clear interpretation of responses • Low dropout rate • No specific skills are required • No subjective choices in the response scales	• Not suitable for nonspatial contexts • No interactive interface • Time-consuming • Multiple iterative rounds • Predetermined intervals • Materials are attached separately • Efforts for the statistical summary • Incurs costs for implementation
Real-Time Spatial Delphi	• Well-suited for spatial contexts • Round-less and cost-less process • Interactive interface • Large sample of panelists • Real-time participant responses and statistical summaries • Materials attached (e.g., documents) • No predetermined intervals • Simple to provide judgments on a map • Clear interpretation of responses • No subjective choices in the response scales	• Not suitable for nonspatial contexts • Requires programming skills for each application and survey • No platforms are currently available • The survey can only be developed by administrators • The system is not able to identify clusters in real time, splitting the geo-consensus radius • No real-time data are displayed on the map (e.g., weather forecasts, air quality, etc.)

The scenario method is composed of different steps and the Delphi can enter into one or more phases enhancing the quality of the process (Nowack et al., 2011). In the scientific literature, there is no consensus on the methodology used for the development of DBS and it may vary depending on the objectives of the research project. Nevertheless, a widely used approach is suggested by Bishop et al. (2007), in strategic foresight, but frequently used in scenario development, and involves six steps: Framing, Scanning, Forecasting, Visioning, Planning, and Acting. (1) *Framing*: where the purpose and objectives of the process are established. This includes defining the scope of the scenario analysis, identifying the experts involved, and establishing the timeline for the process. The framing phase also involves developing a set of questions or hypotheses that the scenarios will seek to answer or explore. During this phase, it is important to clearly articulate the assumptions and limitations of the scenario analysis. This will help to ensure that the developed scenarios are relevant and useful for the intended purpose. The framing phase is also an opportunity to gather any necessary data or information that will be needed to inform the development of the scenarios. (2) *Scanning*: it involves gathering and analyzing information about the topic that may influence the future and include different research activities such as literature review, expert interviews, and workshops or focus groups. During the scanning phase, the goal is to identify the key trends, drivers, and uncertainties that are likely to shape the future of the system or situation. This may include external factors such as technological, economic, social, and political developments, as well as internal factors such as organizational culture, policies, and decision-making processes. The information gathered during the scanning phase is used to develop a list of potential Delphi projections that could significantly unfold in the future. This list is then refined and prioritized by the panel of experts based on relevance, plausibility, and so on. The output of the scanning phase is a set of potential Delphi projections ready for further development in the next phase of the Delphi survey (von der Gracht & Darkow, 2010).

However, this phase is one of the most time-consuming, specifically for the retracement of the literature, adopting creative workshops and desk research, the formulation of a draft list of projections and the iterative refinement of the Delphi projections useful for the questionnaire. To streamline the process and address this challenge, Kayser and Shala (2020) introduced a new approach by extracting a data set of tweets related to the technology context. This method utilizes concept mapping and topic modeling to provide experts with a clear overview of the topic and valuable starting points by extracting a first draft list of key factors. Furthermore, Calleo and Di Zio (2021) adopted unsupervised spatial data mining and topic modeling to extract a list of key factors from a corpus of tweets including textual and spatial distributions. (3) *Forecasting*: in the forecasting phase, the panel of experts is asked to use the information gathered in the scanning phase in combination with their expertise to make judgments about future events or developments in the research context. This may involve generating a range of future scenarios or estimating future states of the key factors according to specific variables, such as plausibility of occurrence, impact, desirability, and so on. In this case, the Delphi survey can be adopted by administering multiple questionnaires to achieve a consensus and develop future scenarios with the panel. (4) *Visioning*: once the future scenarios have been validated by the panel, in the visioning phase, the experts are asked to consider the implications of the various scenarios that were developed in the forecasting phase. They may be asked to consider how different scenarios would impact the context, the long-term consequences of each scenario, and what actions might be taken to mitigate any negative impacts. (5) *Planning*: in the planning phase, the panelists (not necessarily the same as Delphi) are asked to develop a plan of action based on the scenarios. This may involve identifying specific strategies, policies, and resources that will be needed to implement the plan. (6) *Acting*: concrete actions are required in the acting phase, to shape the future. This may involve taking specific actions or making recommendations to experts, decision-makers, and local and governmental authorities. According to Nowack et al. (2011), the integration of the Delphi method into the Scanning, Forecasting, and/or Visioning phase, can enhance the quality of the scenarios.

In recent years, different authors have conducted studies developing DBS in various contexts, including environmental issues, technology, and transport, following different steps in the process (Calleo & Pilla, 2023; von der Gracht & Darkow, 2010). In a study examining the future of manufacturing, Culot et al. (2020) utilized a Delphi-based survey, dividing the process into four stages. The first stage involved developing projections using a conceptual model technique for then selecting a panel of experts based on an analysis of the Scopus data base and consideration of individuals with managerial positions in relevant industries or employment with digital companies. The Delphi survey was administered in the third stage adopting two iterative rounds to achieve convergence by identifying drivers and trends. In a study on last-mile delivery in 2040, Peppel et al. (2022) developed scenarios by first conducting a literature review and formulating projections, to then be validated through an expert workshop. The Delphi survey was here administered in two iterative rounds to achieve convergence of opinions, and the results were used to create future scenarios through narrative-descriptive analysis and clustering, considering variables such as plausibility and consistency. To investigate the impact of Covid-19 on the European football ecosystem, Beiderbeck et al. (2021a) conducted a DBS following the approach of Roßmann et al. (2018) and divided their study into three phases. The first phase involved developing projections through workshops, desk research, expert interviews, and formulation sessions. The second phase involved selecting a diverse group of experts with various backgrounds, countries of origin, genders, and ages. The third phase involved analyzing the results through descriptive statistics and both qualitative (e.g. content analysis) and quantitative (mean values, IQRs, mode, cross-impact analysis, etc.) methods.

From what emerged, DBS could be useful for grasping future events with collective judgments. However, the limits assumed in the Delphi method regarding a lack of spatial components, emerge equally in the combination with the scenario method. FS would benefit from the addition of a spatial context, developed, and organized, in a way that everyone can benefit from it, through public tools and systems for researchers who aim to develop decision-making strategies in the present.

2.3 | Spatial scenarios

In this context, spatial complexity is an element to be considered in the planning of today's strategies where spatial scenarios can offer numerous advantages. Spatial scenarios can be defined as a set of hypothetical conditions or situations that describe how a particular spatial phenomenon might change in the future (Hossard et al., 2013). They are based on a set of assumptions about future conditions, depicting different possible futures and exploring the potential consequences of different policy decisions or development plans.

The development of spatial scenarios has been applied in different contexts, including land use (Gharbia et al., 2016), climate change (Moss et al., 2010), and behavior tendency (Malet et al., 2005), adopting spatial analysis such as a map or 3D model. In fact, most of the time, when we talk about spatial scenarios, we refer to the forecasting context, where a simulated representation of the future is often obtained using GIS and spatial modeling techniques to inform decision-making and planning in the present. Nevertheless, we must consider that there is no single method, and as far as we are concerned, we can distinguish three lines of research, quantitative, qualitative, and mixed methods.

(1) *Quantitative methods* (Forecasting): the predictive models used to develop spatial scenarios are multiple, in this classification, we refer to the "quantitative" models, intended as the use of data to perform prediction analysis (e.g., historical data, spatial statistics, geostatistics, etc.). One of the most used computer systems is GIS, widely adopted for the use of spatial data and analysis tools to create visual representations of scenarios. GIS can be used to analyze and map data and this information can be adopted to evaluate the potential impacts of different scenarios and identify potential issues or opportunities (Gimpel et al., 2015). In addition, a valid tool is agent-

based modeling (ABM), frequently used to model the interactions and behaviors of agents in a specific environment to explore different scenarios and evaluate the potential impacts of different policies or interventions (Fagnant & Kockelman, 2014). ABM can be adopted to model the behavior and interactions of individuals or groups within a specific geographic area, by simulating the behavior of agents in a virtual environment, we can test different scenarios and observe the outcomes. Furthermore, another broader field is remote sensing, useful to develop spatial scenarios by providing accurate and up-to-date information about the current conditions of an area or region. Remote sensing usually uses satellite imagery and aerial photography to evaluate land use, land cover, and other different parameters. The outputs can be used as a baseline for developing spatial scenarios and can also be used to assess the potential impacts of different land use, vegetation, and topography changes (Jurado et al., 2022). Finally, different mathematical modeling and computational techniques are used in spatial optimization to identify the best location for certain activities or infrastructure. Spatial optimization can be used to identify the most efficient locations for housing, transportation, and commercial development. The aim is to identify the most efficient and sustainable locations that meet the desired objectives (Liu et al., 2019).

The above list of methods is not exhaustive since spatial statistics and related analysis techniques are multiple (e.g., spatial autocorrelation, cluster analysis, spatial regression, land use change modeling, etc.) and differ in relation to the research objectives. However, a common feature of quantitative models is the need to have substantial data sets to perform the analyses. However, often spatial data are not available for specific areas or are not enough to perform predictive analysis. At this point, further methods can be found in the (2) *Qualitative methods*. Although for quantitative methods, predictive analysis techniques are well defined in the spatial context, qualitative methods refer to the general techniques of scenario planning such as scenario workshops, storytelling, backcasting, and mind mapping where different spatial scenarios are visually represented, showing the relationships and connections between different variables and factors. In this case, the main feature of qualitative methods is exactly the participation by involving stakeholders and members of the community in the scenarios' constructions. This can include holding workshops, meetings, and focus groups to gather input and feedback on proposed plans and ideas (Capitani et al., 2016).

From what emerged, it would appear that—in our context—there is a continuous line between quantitative and qualitative models (and not quite distinct) where they can be combined to enhance the overall quality of the outputs. As we will outline in the following sections, the combination of methods in the study of the futures (in a proactive meaning) can perform the process to develop useful strategies (Aspinwall, 2011; Varho & Tapio, 2013). (3) *Mixed methods*: represents a valid solution for the development of spatial scenarios. The combination of predictive-quantitative analysis and qualitative techniques has been widely applied in the scientific literature, also with the Delphi method (Jun et al., 2013; Kim et al., 2016; Ribeiro et al., 2021). In particular, RTSD constitutes a novelty implementation for the development of DBSS. DBSS are not to be intended as single outputs, but as a support to other methods from which to start. They can be efficiently combined with predictive model analysis in two different ways: initially in the desk research stage, to narrow the study area, and identify possible drivers by gathering experts' judgments or afterward implementing strategies based on the outputs obtained both from predictive analysis and experts' judgments (Kim & Chung, 2013). Finally, quantitative techniques can be used to generate maps that can be used as input to initiate a DBSS study.

3 | REAL-TIME GEO-SPATIAL CONSENSUS SYSTEM

In this section, we present the "Real-Time Geo-Spatial Consensus System" (v1.0) (https://www.rtgscs.com/), a novel platform adopting the RTSD in an innovative version which solves most of the weaknesses while keeping the strengths, to offer decision-makers an efficient tool both for decisions and forecasts.

3.1 | Architecture

The RT-GSCS (v1.0) is connected to a web server through a host (WordPress in this case) to ensure the proper functioning and make the system accessible on various browsers and smartphones while map servers (Wms, Wfs, Wcs, etc.) are used to display spatial elements on the interface. One of the novel capabilities of this platform (*beta*) is the ability for any user to create and administer a survey by augmenting the current system and integrating it with the existing app, thereby addressing one of the primary weaknesses of the RTSD, by offering users the ability to generate new surveys adopting open access tools.

In the platform, there are two distinct roles, the administrator, and the contributor. (1) *Administrator*: has the access to the control panel and can modify the system's source files and codes at any time. (2) *Contributor*: can create a new survey, add questions, see the spatial references, upload any attachments, and view the statistical summaries, but is not authorized to modify the source files.

A panel session begins when the contributor is given permission by the administrator to start one. Afterward, they can upload an introduction, questions with (x,y) coordinates, and attachments to the platform. From this moment, invited experts can have access to the panel session in relation to two options taken a priori:

- Only registered experts will have access to the session. The contributor will invite identified experts to register on the platform and accept them as "Subscribers," to prevent the presence of additional or previously registered experts on the platform.
- Everyone can have access to the session. The registration process may be inconvenient for experts, leading to a high dropout rate. To address this, we have implemented the option of making the

session accessible to anyone having the link. However, this poses a risk of allowing people outside the panel to contribute to the study. This option is intended for those who want to conduct a general survey using RTSD and involving a huge audience, similar to the Public Delphi (Glenn, 2009).

For the panel session, we use Mapbox, a provider of custom online maps for websites and applications. It provides building blocks for developers to add maps, search, and navigation to their applications. Mapbox offers both a JavaScript library for displaying maps on web pages, as well as a suite of APIs for retrieving and manipulating data. It is based on an open-source map rendering library, Mapnik, and can be used to create interactive maps that can be integrated into websites and mobile applications. This provider gives us also the possibility to show different layers based on the research objectives (e.g., the map can be used to highlight specific areas, display the presence of services in a particular area, or incorporate the opinions gathered during the workshops). In this case, we believe that the addition of layers within the map can support the panel and for this, we implement using APIs multiple layers to display real-time data such as weather layers (temperature, clouds, pressure, wind, precipitation, and rain) and air pollution (using Open Weather APIs). The implementation of layers directly on the map can be very useful for experts as they can access additional real-time information relevant to the study's research objectives (think perhaps of information obtained during desk research or reference spatial data). A flowchart of the RT-GSCS architecture is depicted in Figure 1.

Once the experts start to work in the panel session adding points on the map, all data are recorded and displayed in the back end and collected in a matrix (CSV), easily exportable for further GIS and statistical analysis. In particular, the main output variables are listed below:

- Pin ID. They represent the singular judgments of the experts ($n_1, n_2, n_3, \ldots, n_N$) and are collected in order of time and displayed overall without distinction from the question, or specifically for each question.
- Coordinates (x,y), expressed in latitude and longitude, of each opinion point.
- Radius (R_i) in km and Area (A_i) in km^2 of the circle of convergence, for each question and for each judgment, based on the statistical algorithm illustrated in the following paragraph. In this case, only for the first judgment of each question we set the radius $R_i = 50$ km^2, since it is not possible to calculate it for a single point.
- User email. The emails of the panelists used at the time of the registration are acquired after each response only if the survey has been set up as "closed" and, therefore, accessible after registration. If the survey is open and accessible using the appropriate link, the variable will show the term "anonymous expert."
- Plausibility of the choice (1–5). After each answer, we ask the expert to rate the plausibility of their response on a scale from 1 to 5, where 1 means minimum plausibility and 5, maximum plausibility. This request may be modified based on the objectives

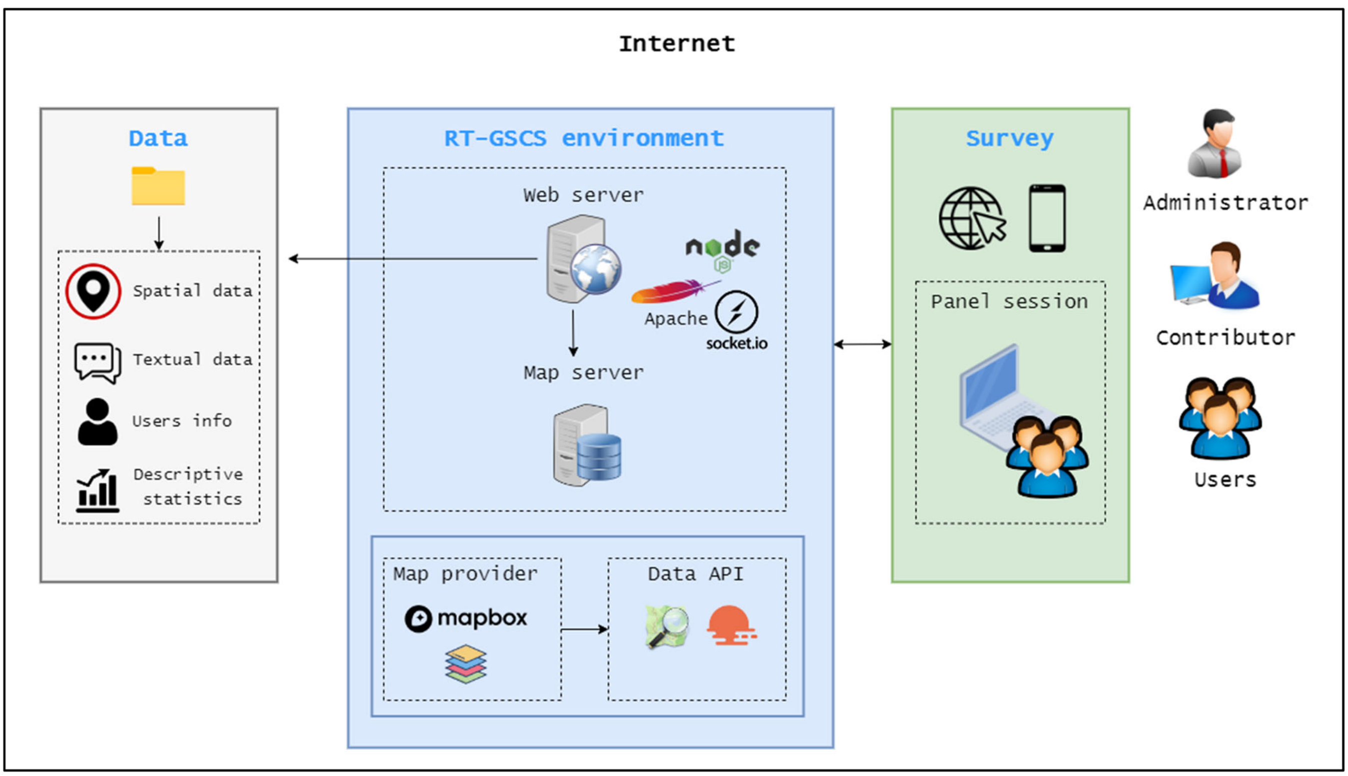

FIGURE 1 The RT-GSCS architecture.

of the survey to evaluate factors such as probability, efficiency, preferability, or urgency.

- Date and time, in the local time, of each opinion point.
- Comments. The comments are shown both in the front end and in the back end, for possible postsurvey textual analysis.

3.2 | Interface and statistical algorithm

One of the major weaknesses of many of the decision support platforms available on the web is the complexity of use for those who are not familiar with the use of WebGIS systems. For this reason, the RT-GSCS platform interface was thoughtfully designed to be "user-friendly," and its central feature is a map where all the necessary information is displayed in a left-hand sidebar, allowing experts to access attachments, questions, comments, and real-time data with ease. In the "attachments" section, experts can preliminarily consult all the documents preloaded by the research team, to understand the current scenario of the research context, possible guidelines, and further updates regarding the session.

Afterward, a box containing a description is included (e.g., Thinking about 2050…), and the expert can select a question based on their expertise (e.g., What area will be most at risk of flooding?). Within the session, it is possible to change at any time layers and maps, activating real-time data or preimplemented layers above-mentioned. Once the experts have read the documents and selected the related question, they can add their own judgments on the map by inserting one or more opinion points. Automatically, a window will open asking them to choose the plausibility in relation to what is expressed (e.g., from 1 to 5 how plausible is your choice?). This prompt can be disabled or changed and is provided to all users when creating a new survey.

Upon entering their responses, judgments will be synthesized through a circle on the map, which will change size and position in real time. The expert can as well consult the size of the circle in km^2 on the sidebar at any time, offering the possibility of a real-time statistical summary. The smaller the circle, the greater the degree of consensus achieved up to that point. A representation of the main interface of the panel session is depicted in Figure 2.

The circle of convergence is obtained following the logic expressed by Di Zio and Pacinelli (2011). If each judgment is represented by x,y coordinates, the spatial convergence is achieved through the use of a geometric element identified in a circle C, which is the smallest, among all possible circles, and contains 50% of the opinions of the panelists which until then have provided opinion points. Including 50% of the judgments, is the analogue—in space—of the IQR of the classical Delphi.

Since the circles containing 50% of N points are infinite, the constraint to make the problem tractable is that the circle must be centered on one of the N points (Di Zio & Pacinelli, 2011). Thus, there are only N circles containing 50% of the N points. On the basis of what has been obtained, for each question composed of the vector of judgments (i.e., points) $n_1, n_2, n_3, \ldots, n_N$, we find a vector $A = A_1, A_2, A_3, \ldots, A_N$ where each element A_i is the area of a circle centered on point n_i and including 50% of nearby points. For the vector A, the minimum corresponds to the geo-consensus, because is the smallest circle—with radius R_i and area A_i—containing the 50% of the N judgments with center n_i (Castillo Rosas et al. 2015; Di Zio & Pacinelli, 2011). Like in the classic Delphi, if the participants continue to place points inside the circle, it will shrink (meaning consensus), while if the points are mostly placed outside, the circle will remain

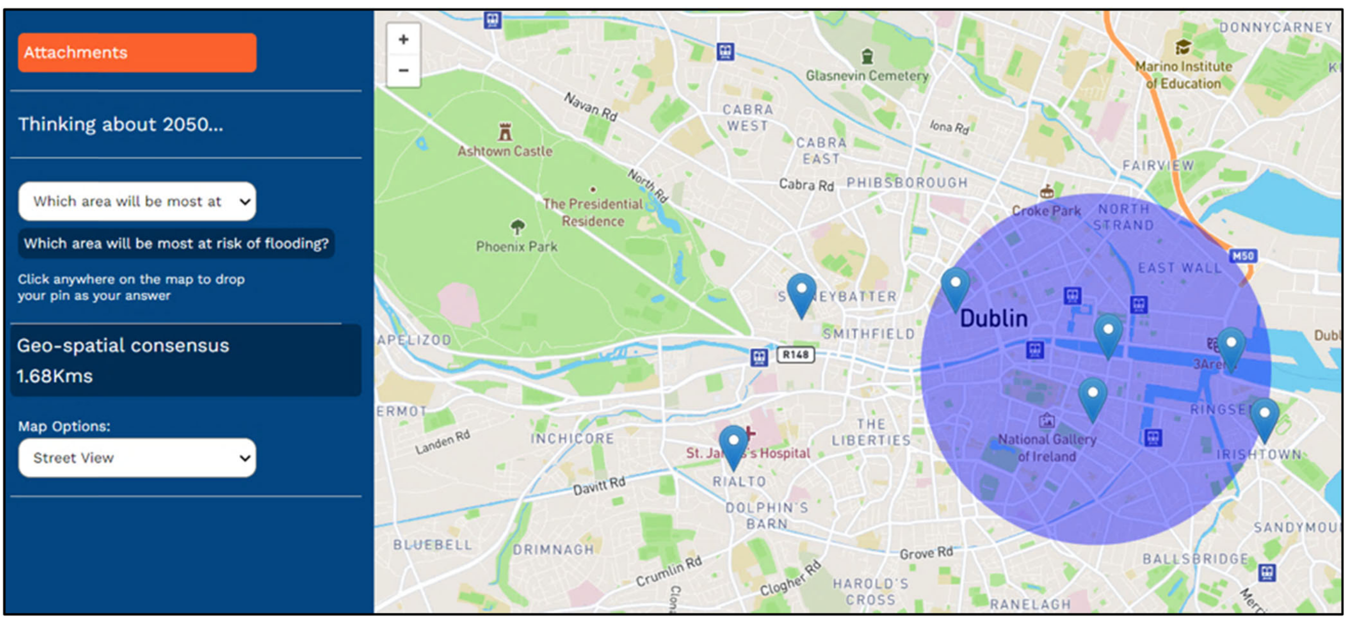

FIGURE 2 Panel session interface.

large (no consensus achieved). Following the Delphi logic, every time the experts add a new point outside the geo consensus range, they are invited to motivate their judgment, precisely to allow others to be able to understand the reason and possibly modify the previous judgment. In this version, we have implemented a further feature which can be enabled in relation to the research objectives, always allowing participants to comment on the judgments of other experts. This feature is intended to encourage proactive engagement and facilitate a more efficient and effective procedure.

Currently, the platform is being examined in various contexts, including the potential future climate hazards in 10 European coastal cities, sustainable mobility, climate change impacts on public health, and the identification of suitable locations for parcel lockers and loading bays in Dublin.

4 | MATERIALS AND METHODS

To pursue the aim of this paper, we propose a new study adopting the RT-GSCS platform to develop DBSS in the context of future climatic hazards in Dublin by 2050. DBSS are the final outputs coming from the combination of the RTSD and scenario method by gathering expert opinions and generating consensus-based outcomes of possible future developments in specific geographic areas. To perform our analysis, we consider a modified DBS process taking into account the approach suggested by Bishop et al. (2007), with the following phases: Framing, Scanning, Forecasting, Visioning, Planning, and Acting (Figure 3).

4.1 | Territorial framework and research design

In spatial contexts, is essential to consider the territorial framework when conducting a study, as it allows for the identification of potential drivers, trends, or general projections. This is important to accurately understand the context in which the study is taking place. The study is conducted in the climate change adaptation and mitigation context for the "Smart control of the climate resilience in European coastal cities" (SCORE H2020) project where the Coastal City Living Lab of Dublin is located.

Coastal flooding is expected to have significant impacts on Dublin in the coming years due to the limited defences in place and a lack of public support for necessary improvements, such as higher flood walls. In 2002, Dublin experienced significant flooding that disrupted the transportation network, including roads, commuter rail, and tourist areas. The flooding was believed to have been caused by a combination of extreme rainfall and other factors. The combined-drainage system, which can become blocked during floods, is also a cause for concern. In addition to these impacts, coastal flooding and erosion have had significant consequences, including reduced property values for homes located in floodplains. Droughts and heat-attributable deaths have also been issues in Dublin. The Office of Public Works is responsible for flood management in Ireland and has developed Flood Plans and provides information on flood risk. The Climate Change Action Plan, which was developed by the four Dublin local authorities, aims to reduce greenhouse gas emissions, increase energy efficiency, and improve the climate resilience of the city region with support from the Climate Action Regional Offices. There is a multitude of stakeholders who are actively engaged in various initiatives aimed at ameliorating flood risk; as such, there exists a significant challenge, particularly with regard to the availability of efficacious decision-making tools that can assist these stakeholders in this endeavor.

After establishing the territorial boundaries for our study, we select a time horizon appropriate for our research objectives, in this case, 2050. In general, it is a good idea to choose a time horizon that is long enough to be meaningful for decision-making, but not so long that it becomes impractical to make accurate predictions (Kosow & Gaßner, 2008). Furthermore, in this phase, we develop the methodology depicted previously in Figure 3, useful for the development of DBSS for climate hazards by 2050, testing the platform efficiency with a group of experts from the Spatial Dynamics Lab at University College Dublin to gather possible concerns and feedback.

4.2 | Key drivers and experts' engagement

From the previous framing of the territorial framework, multiple concerns emerged. However, to find the possible key drivers, intended here as plausible future climate hazards, the research team conducts desk research and analyses available data to identify pre-existing hazards that are likely to have the greatest impact on the future of Dublin. The main drivers are identified and acquired in the project proposal of the SCORE EU project, reducing the time process of formulating, and drafting the drivers. This has led to a speeding up of the procedure since the related part of organizing workshops, formulating a draft list of projections and iterative refinement with the experts until a suitable number of drivers would have been obtained was already available.

From the project proposal, the list of drivers threatening the Dublin coastal area includes six elements depicted in Table 2, leading to dangerous impacts, including tourism loss, cultural heritage, commercial and residential buildings, energy networks, and transport networks.

From the six drivers, we identify three different clusters of topics including flood risk, coastal erosion, and possible extreme events. The three clusters are used to craft the following questions:

- **Q1**: Thinking about 2050, what area will be most at risk of flooding?
- **Q2**: Thinking about 2050, what area will be most at risk of erosion?
- **Q3**: Thinking about 2050, what area will be most affected by extreme events?

At this point, the questions are validated by the research team and uploaded into the platform, along with any relevant attachments, including the scanning of the literature (i.e., hazard data and hazard

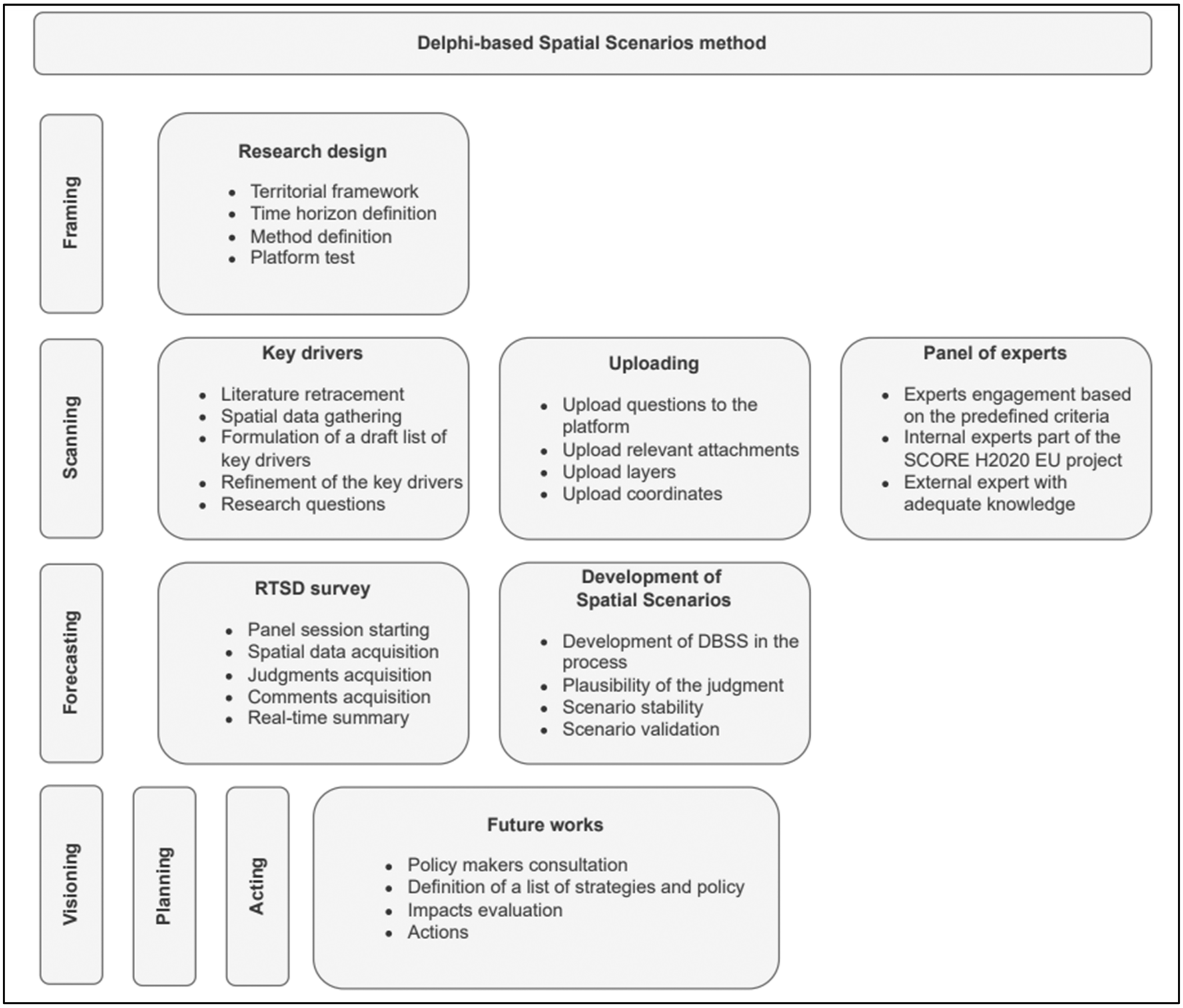

FIGURE 3 Delphi-based Spatial Scenarios for climate hazards by 2050.

TABLE 2 Drivers that can affect the climate future of Dublin until 2050.

Id	Key drivers
1	Coastal flooding
2	Land flooding
3	Landslide
4	Heatwave
5	Storm surge
6	Coastal erosion

explanation with the relative possible impacts included in the project documents).

Meantime, for the purposes of our study, we decide to consider two types of experts (Table 3): (1) *Internal experts*: intended here as people having adequate knowledge of the research context part of the SCORE H2020 project. (2) *External experts*: who have a strong background and expertise in the topic but are not part of the project. They include academic experts with a strong level of experience in the sector, stakeholders, members of companies, ONG, local authorities, and governmental bodies. This decision was made for two primary reasons: first, to ensure a diverse range of expertise among the panel of experts, and second, to test the performance of the platform by conducting a simultaneous survey with many participants.

Upon identifying the experts, we send an initial email introducing the research and requesting their participation on the panel. We contacted 12 internal panelists and 50 external panelists, where only 26 experts accepted to participate in the study (specifically 6 internal and 20 external).

After that, we sent a formal and detailed email to each panelist, including relevant technical information such as registration/login to the platform RT-GSCS, deadlines, and guidelines on the use of the platform.

4.3 | RTSD survey and future scenarios development

Once all the panelists have their personal credentials to access the platform, we start the exercise.

Before answering the questions, in the guideline's documents, we suggest to the experts—especially the external experts—to consider the documents attached by the team, to have a detailed perspective of the research. In relation to personal knowledge, we ask them to select the question to then answer on the map adding new points based on their judgment(s). In this study, we have not established a minimum and a maximum number of points to be entered to avoid possible dropouts by the experts, we give to the experts the possibility to add different points in the session. For each point added, a pop-up window appears asking on a scale from 1 to 5 for the plausibility of the judgment (Figure 4). This is useful in our context to have a map composed of different points and the plausibility of the events to have a weighted system of responses, useful to perform further GIS analysis postprocessing.

Immediately after, an automatically generated circle will appear on the map, and based on the responses of other participants and the computational process, will be modified in real time in terms of movement, reduction, or expansion (the process is completely anonymous, and participants cannot identify the other members of the panel). One choice is asking the participants to motivate their judgment only if they are outside of the circle of convergence; however, in this application, we have enabled the experts to comment at any time on the others' points with the aim of initiating discussions that will enhance the quality of the study. At the end of the exercise, we obtain three main results: geographical, nongeographical (i.e., numerical), and textual data. The geographical result is a final circle which contains $\frac{N}{2}$ opinion points, easily comprehensible and useful for decision support without any further processing. All the other data, including the statistical data, and the comments of the experts are part of the nongeographical and textual results.

As measures of spatial consensus, we use the three measures proposed by Di Zio et al. (2017), called respectively M_1, M_2, and M_3. The first—M_1—is the area of the final circle obtained for the identification of the DBSS. However, this is an absolute measure, which does not take into account the extension of the study area and the size of the initial circle, therefore, cannot be enough to measure the spatial consensus. To overcome this challenge, we consider also a second indicator, obtained as the ratio between the final circle's area (*FC*) and the surface (*S*) of Dublin city ($S = 117.8\,\text{km}^2$):

$$M_2 = 1 - \frac{\text{FC}}{S}.$$

This indicator shows the degree of geo-consensus where the more the measure is close to 1, the more the circle is small compared to the surface area. To perform our analysis, we also consider the third indicator which gives information on the dynamic process of spatial convergence:

$$M_3 = \frac{\text{FC}}{\text{IC}} \cdot 100,$$

where IC is the initial circle area. In this case, the essential premise is that the initial area of the circle is not determined by the first point inserted by the first expert, as it is set a priori as: $\text{IC} = 50\ \ \text{km}^2$, but from the second point. This indicator shows the metric of consensus among participants, and the more the value is higher (close to 100%) and more we have a lower convergence of opinions among the panelists. The more the percentage is close to zero, the higher the spatial consensus.

TABLE 3 Panelists involved.

	Contacted panelists	Participating panelists
Internal	12	6
External	50	20
Total	62	26

FIGURE 4 Entering an opinion point.

Before concluding the session, we consider what is expressed by von der Gracht (2012) in relation to the consensus criterion. The consensus criterion should be not used as a singular factor for stopping the exercise, but we must refer more to the stability of the responses. In Delphi, group stability is achieved when the results of two subsequent Delphi rounds are not significantly different (von der Gracht, 2012).

In our study, we consider the nongeographical results (time and dates) and the related radius of the circle, performing time series, to assess stability. When the last few points (a rule of thumb are 5% of *N*) do not produce any significant change in the size of the circle, we have a clear situation of stability. Nevertheless, since our process differs from the traditional Delphi due to its "roundless" nature, the stability is checked twice. This is because different reasons could lead to stability including the forgetfulness of the experts after adding several opinions or drop-out after entering initial points. In fact, once stability has been achieved for each question, we sent a final email regarding the validation of the scenarios. We ask the panelists to validate the scenarios by adding new points and justifying their decisions if outside of the geo-consensus radius. In this case, participants are requested to access the platform one final time, examine the geo consensus radius and, thus, the region in which the responses were concentrated, and either identify a new area within the circle or, if satisfied, not identify any such area, or identify an area outside the circle and provide a justification for this choice. At this point, we check for the second time the stability, concluding the exercise obtain three main scenarios for the questions, ready for immediate decisions.

5 | RESULTS

The present study was designed to investigate the future climate hazards by 2050 in the city of Dublin, testing the RT-GSCS platform and developing DBSS in three different research contexts: flood risk, coastal erosion, and extreme weather events. The panel session began on November 1, 2022, and concluded on December 5, 2022, reaching two times the stability in all the questions uploaded to the platform.

Out of the 62 experts approached to participate in the survey, 26 accepted to participate and provided judgments by inserting at least one point on the map. For Q1, a total of 58 expert judgments were obtained, along with 13 comments that may be useful for future qualitative analysis and to highlight some not emerged trends. Regarding the question on the plausible future coastal erosion risk (Q2), 54 judgments were recorded, and 16 general comments were provided. Finally, 50 points were recorded in response to Q3, with 11 comments. In Figure 5, we depicted a spatial representation of these results developed and validated by the panelists.

With regard to *Q*1: "Thinking about 2050, what area will be most at risk of flooding?," Figure 5a, shows the area that, according to the opinions expressed by the panel, may be vulnerable to flooding in 2050. The area is located in Dublin city center, between the two ends separated by the River Liffey, which runs through the center of the city and empties into Dublin Bay. From the experts' comments, the significant impacts on this area could lead to significant consequences, as it can damage or destroy buildings and infrastructure, disrupt essential services, lead to the loss of cause environmental damage, and potentially result in loss of life. The city has experienced several instances of flooding, with the most recent major flood occurring in 1993 and 2008. Heavy rain caused the River Liffey to overflow its banks during this event, leading to widespread flooding in the city center.

With regard to the *Q*2: "Thinking about 2050, what area will be most at risk of erosion?," Figure 5b represents the eastern coastal areas of Dublin. For the experts, coastal erosion can have significant impacts on the city of Dublin. It can lead to the loss of valuable real estate and infrastructure, including roads, buildings, and homes. It can also pose a risk to public safety, as erosion can destabilize cliffs and make them prone to collapse. In addition, coastal erosion can result in the loss of recreational areas and habitats for plants and animals. It can also affect the local economy, as businesses that rely on the coast for tourism or fishing may be adversely affected. Finally, in Dublin, coastal erosion can contribute to the overall degradation of the coastal environment, which can have long-term consequences for the health of the ecosystem. Finally, in *Q3*: "Thinking about 2050, what area will be most affected by extreme events?" (Figure 5c) the participants identified the central area of Dublin as the most plausible area to be affected by extreme events in 2050. For the experts, this area is identified in particular for the plausibility that in the future extreme events, such as storms, floods, and heatwaves, can have a range of impacts on the city of Dublin. They can damage or destroy buildings, infrastructure, and public facilities, which can disrupt the daily lives of residents and visitors. Extreme events can also pose a risk to public safety, as they can cause power outages, landslides, and other hazards. Based on the textual results, extreme events can also have social impacts, as they can increase the demand for emergency services and create additional strain on the healthcare system. Finally, extreme events can have environmental impacts, as they can alter the local ecosystem and contribute to the degradation of natural habitats.

What emerged from the three outputs is a clearly limited area plausibly vulnerable to future climate hazards in 2050. The outputs that emerge must not be seen as a single vision of the future, but rather are to be considered as a point of the congregation to different methods. As pointed out in Section 2.3, RTSD was born as a useful method when combined with other methods and in this case, the outputs, which in this paper we have defined as DBSS, are to be combined with possible statistical models if quantitative data are available to enhance the efficiency of the method, developing strategies that help mitigate possible future impacts. In other words, the outputs of this system can be considered draft spatial scenarios.

Once the geographical data that emerged from our study have been illustrated, in Table 4, we highlight the results of the indicators, important to understand how the spatial convergence was achieved. Each question is composed of different variables including the area in km^2 of Dublin city, the initial circle, the final circle (M_1), and the

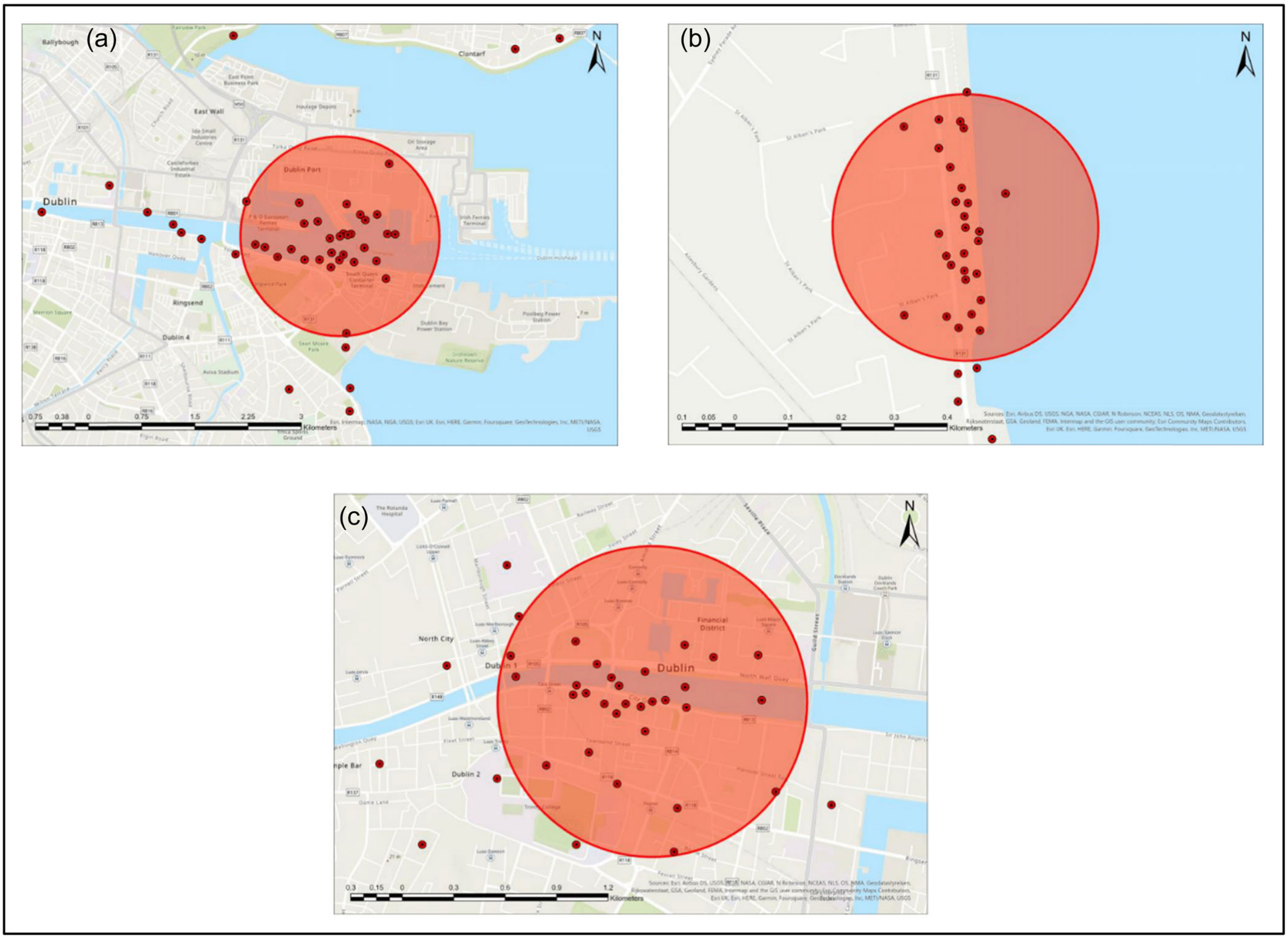

FIGURE 5 The circles of geo-consensus.

TABLE 4 Measures of spatial consensus and descriptive statistics.

	Study area (km^2)	Initial circle (km^2)	Final circle (km^2)M_1	M_2	M_3(%)	Pins	Comments
S1	117.8	8.24	0.77	0.993	9.34	58	13
S2	117.8	3.25	0.15	0.999	4.61	54	16
S3	117.8	2.92	0.54	0.995	18.49	50	11
Total						162	34

convergence measures M_2 and M_3. Finally, we depict the number of pins for each question and the number of comments inserted by the panelists.

In all the final outputs, we obtained a delimited area lower than the initial circle, with a reduction >98% (see M_2 in Table 4). This is significant, as it means that the experts have reached a degree of convergence which has led to a huge reduction of the initial circles.

In particular, for scenarios S1 and S2, we obtained a strong reduction of the initial circle (respectively $M_2 = 0.993$ and $M_2 = 0.999$). The initial circle expressed in km^2 was 8.24 for scenario 1 and 3.25 for scenario 2, with a final circle of $M_1 = 0.77$ for scenario 1 and $M_1 = 0.15$ for scenario 2. Finally, for scenario 3, the initial circle was the smallest (2.92 km^2) and the final circle was $M_1 = 0.54$, with a reduction of the circle based on the area of the city $M_2 = 0.995$.

While M_2 is an indicator of the efficacy of the solution with regard to the specific area under investigation, M_3, as seen above, is a metric of consensus among participants. In the classical Delphi there is no general rule to measure consensus, however, one of the most common measures is the IQR and most authors consider a good consensus when the IQR is <20% of the measurement scale used (von der Gracht, 2012). For analogy, in the SD we can consider reached the consensus when $M_3 \leq 20\%$. In our case, for the three research questions, having respectively $M_3 = 9.34\%$, $M_3 = 4.61\%$, and $M_3 = 18.49\%$, we can say that the experts reached a consensus on all the three areas, very high for S1 and S2 and slightly lower for S3.

In Figure 6, we highlight the circle history of the three scenarios obtaining relevant information about the spatial convergence process.

In all the scenarios, we have a substantial decrease in size, but in the same way also a different shift. Specifically, with regard to S3

FIGURE 6 Circle history.

(illustrated in Figure 6c), it is discernible that the consensus established by the experts in the central Dublin region is evident, however, it is also apparent that over time, the focus of the consensus has shifted to various locations while maintaining a consistent approximate radius. These are all relevant outputs, useful for the refinement of the draft spatial scenarios.

From the dates and the corresponding radius, we can perform time series to check the stability in order stop the process, after the scenario validation. In Figure 7, we depict three time series one for each scenario, where the horizontal axis, displays the number of days from the beginning of the exercise and the vertical axis the radius of the circle. In this case, as the circle becomes smaller, the closer the sequence of points approaches the horizontal axis, resulting in a greater geo-consensus.

In scenario 1, the radius changed multiple times obtaining a stability from the 18th day to the 20th day. This result is interesting, as it also highlights how consensus has been achieved over time, and once we sent the email asking for a validation of the scenarios, three more changes occurred.

For scenario 2, the consensus obtained is strongest, easily visible in the figure by the significant drop, reaching a stability from the tenth day, changing for the validation only two times. This is also visible from Figure 6b, where the experts have reached a fast convergence over the days (it is possible to notice this from the red-colored circles). Finally, for scenario 3, as it was possible to see from the previous statistical results, the circle underwent a significant change over the course of 0–15 days, reaching a stability after 18 days. Overall, for all the scenarios we obtained a situation of stability after the validation of the scenarios, where no further changes were made.

In conclusion, we perform a GIS analysis, considering at this time, all the points and the related plausibility of occurrence expressed by the experts. This analysis had the aim of finding a presumed correlation between the final circles of convergence and the plausibility of occurrence in the judgments of the experts. Figure 8 depicts the tree scenarios, this time analyzed using the heatmap technique.

The previously stated assumptions fully respond to the results obtained from the analysis, in fact there is a visible correlation between the high plausibility of occurrence and the final circle obtained. For scenario 1, the main cluster of points identified is exactly concentrated in the geo-consensus radius, in

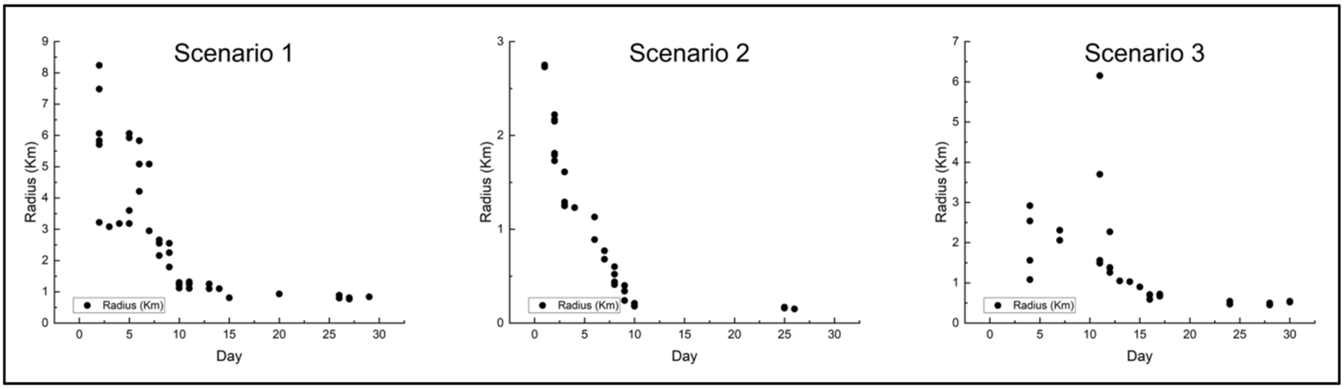

FIGURE 7 Time series of the radius.

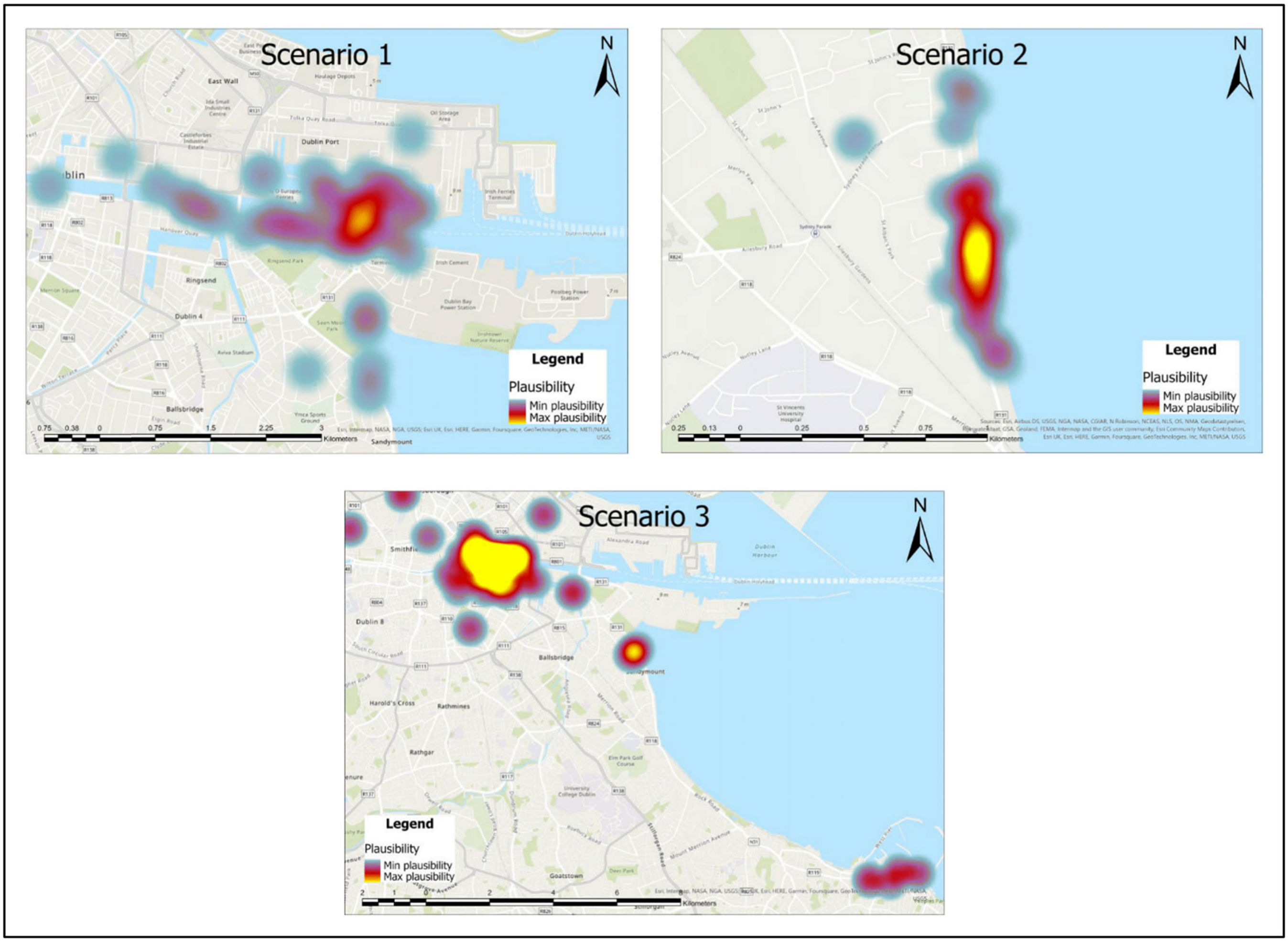

FIGURE 8 Heatmap based on plausibility.

exception for some small cluster composed of 2–3 points outside of the radius. In this case, the average plausibility of the points expressed by the experts is 3.86. Likewise, in scenario 2, a strong plausibility of occurrence is located inside the geo-consensus radius with an average of 4.27, useful to depict an even more framework of the area, managing to underline even better the chosen areas.

Finally, in the last scenario, it is possible to depict greater uncertainty among the experts. In fact, although the strong plausibility of occurrence is located inside the final circle (4.20), we can highlight an important cluster composed of 11 points in the Dún Laoghaire coastal city. This explains why the M_3 measure is close to 20%, because the experts identified two different areas plausible for extreme events.

6 | CONCLUSIONS AND FUTURE WORKS

We presented the "RT-GSCS," a novel web-based open platform adopting the RTSD to obtain a consensus among experts. This platform has the objective of becoming a strategic tool in the family of interactive systems adopting the Delphi techniques, to offer researchers, decision-makers, policymakers, and local and governmental bodies a valid tool for the analysis of complex spatial scenarios. It utilizes an iterative approach to obtain a spatial consensus among a panel of experts, with the aim of identifying patterns and trends in delimited areas. The platform includes open tools for visualizing and analyzing responses in real time, as well as features for experts to track their progress and measure the impact of their input. In this paper, we have assessed the performance of our platform and it has responded very well to each of the parameters, such as scalability, reliability, security, speed, and flexibility. Our platform is designed to be highly effective and efficient and can be adapted to meet the needs of a wide variety of users, including the possibility to participate in the survey using personal smartphones.

The major innovation, compared to previous platforms, is that of enabling users to create personal surveys without the administrator setting up the survey, to make the process more fluid, dynamic and reproducible for future works. Furthermore, we have implemented the platform through the possibility of inserting possible layers or real-time data from atmospheric sensors to facilitate the choice of experts. In fact, it is possible that the panel may not consult the attached documents in the appropriate section and in this way all the (spatial) elements are located directly on the map.

In this paper, we showed the functioning of the platform through a case study in the context of future climate hazards in the city of Dublin, by introducing the concept of DBSS and providing guidelines on how to develop DBSS adopting the RT-GSCS platform. DBSS represents an innovative approach for contributing to the field of FS by identifying specific areas of focus. However, it is important to note that these scenarios should not be considered an exclusive representation of the future. As articulated in the present study, it is recommended that DBSS will be integrated with other methodologies (such as quantitative analysis), to develop a more comprehensive framework for strategy implementation.

In particular, the strengths of our platform are summed in the following key features: (1) *Speed*: it allows for a rapid exchange of ideas and information among experts. This can be particularly useful in situations where time is of the essence, such as during emergency response situations. (2) *Consensus building*: the platform allows experts to engage in a real-time discussion, which can help to further refine and clarify their views and reach a more robust consensus. (3) *Flexibility*: it can be adapted to a wide range of situations and contexts, making it a highly flexible tool for consensus-building. (4) *Anonymity*: it secures anonymity among participants. This can be particularly useful in situations where experts may be reluctant to express their views openly for fear of backlash or criticism. (5) *Remote participation*: the process can be conducted remotely, which makes it possible for experts from different locations to participate and contribute to the process. On the other hand, the platform has some limitations to consider. At the moment, although it solves an important lack of the classical Delphi method (i.e., spatial issues), it fails to cover some of the still present open challenges that exist (i.e., subjectivity in the construction of the panel, drop-out). In both the Delphi method and the SD, methodological rigor should not be ignored, to understand what is behind a choice of a criterion (Hasson & Keeney, 2011). Furthermore, in our paper, we have frequently emphasized that our method addresses one of the Delphi method's limitations, specifically the absence of spatial references. However, in this way, our approach deviates from the fundamental characteristic of the Delphi method, which is centered on textual questioning. To overcome these challenges, in future works, one of the main methodological improvements will be the implementation of a combined version of the RTD and RTSD in the same platform, where both the spatial part and the textual part will be integrated. In this way, the experts will have both textual questions (i.e., with Likert scale, open questions, etc.) and spatial questions where they will be able to identify areas in the territory based on their own judgments.

With regard to the platform, some implementations will be developed, including a clustering-based real-time analysis to solve the choice of different locations by the experts, leading to a difficult obtaining of a convergence. In addition, new real-time data will be implemented in the platform, with the use of APIs and the possibility to allow users to upload personal layers on the map. Furthermore, with regard to the statistical algorithm, weighted-based points will be a useful implementation, meaning that opinion points could be weighted in the convergence process to have different importance based, for example, on their probability of occurrence and/or, when available, on the level of expertise of the respondents. Finally, a possible further implementation could be the incorporation of real-time textual analysis of experts' judgments and comments. This could be achieved by using natural language processing techniques to analyze the written responses and comments of experts during the process. The real-time analysis could be presented to the facilitator in a user-friendly interface, such as a dashboard, to quickly identify areas of consensus and divergence. Additionally, the real-time analysis could also be shared with the experts, allowing them to see the collective opinion and feedback on their own contributions in real time, which might encourage them to revise their judgments and comments accordingly or to validate the scenarios obtained. Finally, a number of future developments will concern a series of practical solutions, including different ways of communicating feedback (e.g., word clouds, topic analysis, interactive buttons, etc.), the geographical-participatory aspect (which will allow the experts to also place several geographical objects on the map, e.g., polygons).

We believe that these implementations will solve, at least in part, the drop-out problem by making the system more participatory.

ACKNOWLEDGMENTS

The work carried out in this paper was supported by the project SCORE, which has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 101003534. Open access funding provided by IReL.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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How to cite this article: Calleo, Y., Di Zio, S., & Pilla, F. (2023). Facilitating spatial consensus in complex future scenarios through Real-Time Spatial Delphi: A novel web-based open platform. *Futures & Foresight Science*, e155. https://doi.org/10.1002/ffo2.155