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Research Article

Introducing Unmanned Aerial Vehicles to multi-criteria performance assessment of inspection techniques for port concrete infrastructure

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Abstract

Port infrastructure plays an important role in the economic and social activities of the regions they serve. Pressures induced by the corrosive marine environment and weather conditions, unexpected events associated with climate change, the usually high freight and vehicle loading conditions, the dynamic load of the equipment, and insufficient maintenance and rehabilitation measures that sometimes are not enough to repair an in-service facility, increase the susceptibility of port structures to rapid aging and deterioration. To ensure port infrastructure safety and reliability, and to maintain operational efficiency, port managers are tasked with forming successful inspection schemes for structural condition monitoring. Within this context, identifying the capabilities and prioritizing existing inspection techniques allow for optimizing resources (cost, time, personnel). The issue of performance assessment for commonly used Non-Destructive Testing techniques has received significant research interest. However, state-of-the-art Unmanned Aerial Vehicle techniques have not been previously involved in studies that assess the performance of various inspection techniques. Hence, the present research seeks to introduce Unmanned Aerial Vehicles techniques into multi-criteria performance assessment practices of inspection techniques for port concrete infrastructure. Three Non-Destructive Techniques: a) Infrared Thermography, b) Ground Penetrating Radar, and c) Impact-Echo, are compared to camera-based Unmanned Aerial Vehicle techniques linked to Close Range Photogrammetry applications. A qualitative approach, including a literature review and expert judgment, is applied to acquire data required for Multi-Criteria Decision Analysis practices with the Preference Ranking Organization METHod for Enrichment Evaluation methodology. The ranking output of the applied model is validated with other multi-criteria methods to ensure the robustness of the results. The obtained results for the specific set of criteria will assist decision-makers in selecting the most suitable technique for inspecting surface or sub-surface defects in port concrete infrastructure.

1. Introduction

Ports serve as major economic catalysts that intend to systematically manage a variety of products and activities (ASCE, 2021; Mehmood et al., 2023). They constitute capital-intensive infrastructures that require the investment of large sums of money to produce high-quality services

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and ensure a high percentage of fixed assets (Rodrigue & Notteboom, 2022). However, corrosive conditions, neglected maintenance planning, environmental factors, climate change impacts, and physical degradation related to infrastructure aging imperil asset availability and service lifetime (Lauritzen et al., 2019; O'Byrne et al., 2018).

Port managers are tasked with applying an effective asset management program to ensure and improve the integrity of an asset while prioritizing and scheduling intervention treatments (Heffron, 2015). Condition monitoring of port infrastructure is a strategic pillar for supporting decision-making in optimizing maintenance, repair, and upgrade actions (Lauritzen et al., 2019). The synergy of condition monitoring practices and maintenance or recovery planning increases the reliability of port infrastructure, and generally of infrastructure assets (Srinivasan & Parlikad, 2013). On the other hand, intervention schemes can be effectively improved by integrating condition monitoring data into reliability assessment approaches and damage prediction. The primary basis of the three inherently linked aspects of condition monitoring, intervention planning, and reliability assessment is the conduction of in-situ inspections to acquire monitoring data. A successful inspection plan involves optimization over time (inspection frequency) and space by estimating the expected benefit of an inspection strategy to support decision-making (Vereecken et al., 2020). Except for investigating the time intervals and the necessity of inspections, integrating the optimum technique for condition monitoring of the examined infrastructure is also crucial to support resources' management (i.e., time, budget, manpower).

Structural Health Monitoring (SHM) of port concrete infrastructure can be supported by employing contact-based and non-contact-based sensors, including Non-Destructive Testing (NDT) equipment (Al Hamaydeh & Ghazal Aswad, 2022). NDT techniques are widely used for inspection purposes since they ensure the reliability, efficiency, and high quality of in-situ inspections without affecting or destroying the structure (Kušar et al., 2018; Lauritzen et al., 2019). NDT in-situ inspections are part of condition-based monitoring and maintenance strategies, as illustrated in several studies (Verma et al., 2013; Dabous & Feroz, 2020; Ali & Abdelhadi, 2022). Nevertheless, their application has some limitations regarding the frequency of the inspections, the suitability of the NDT technique for assessing the different structural elements, the availability of standards to ensure reliable results, and the requirement for properly qualified personnel. A comprehensive evaluation of the capabilities of each NDT technique can provide useful information to infrastructure managers to identify strengths and weaknesses and to plan an effective inspection program (Abdelkhalek & Zayed, 2020).

Commonly to other types of infrastructure, the inspection of port concrete infrastructure relies upon the employment of various NDT techniques, including Infrared Thermography (IRT), Ground Penetrating Radar (GPR), Impact-Echo (IE), Acoustic Emission (AE), Ultrasonic Testing (UT), Chloride Ion Testing (CIT), etc. (Heffron, 2015). Performance assessment of such NDT techniques, considering a variety of criteria (e.g., speed, duration, reliability, cost of inspections etc.), has already taken place for different types of civil infrastructure with similar construction aspects to port structures (e.g., reinforced concrete structures), with a primary focus on bridges (Abdelkhalek & Zayed, 2021; Gucunski et al., 2014; Hesse et al., 2017; Kušar et al., 2018; Lee & Kalos, 2015; Oh et al., 2013; Omar & Nehdi, 2016; Omar et al., 2017; Yehia et al., 2007). Within the port industry, limited research interest has been shown in assessing inspection techniques (e.g., Lauritzen et al., 2019). Current research (Chelioti et al., 2023) has introduced a theoretical background for examining the variations in the performance of the IRT, GPR, camera, and Light Detection and Ranging (LiDAR) techniques for port concrete infrastructure, after fostering a remote sensing-based approach that included the employment of Unmanned Aerial Vehicles (UAVs). As was concluded, the employment of UAVs improved the speed and capability of both IRT and LiDAR techniques, while not significantly affecting the performance of GPR and camera techniques.

Remote sensing with UAVs has gained momentum for inspecting civil infrastructure, as indicated in several recent studies (e.g., Feroz & Abu Dabous, 2021; Greenwood et al., 2019;

Shakhatreh et al., 2019) to support non-destructive inspections (Nooralishahi et al., 2021). Within the maritime sector, UAVs have been used for the structural assessment of vessels (Johansson et al., 2021) and port structures such as breakwaters and port concrete pavements (Tsaimou et al., 2023). Their usage supports the conceptualization of digital maritime (Alexandropoulou et al., 2021) and port smartness (Johansson et al., 2021). Cameras mounted on UAVs provide a large number of captured images. Their further analysis assists in advancing SHM practices by conducting Close Range Photogrammetry (CRP) to reconstruct a structure's replicas with Building Information Modeling (BIM) (Jofré-Briceño et al., 2021) or to map structural conditions with Geographic Information System (GIS) tools (Tsaimou et al., 2023). The effectiveness of a UAV-based SHM program in inspecting the condition of in-service port infrastructure has been recently investigated and contextualized (Tsaimou et al., 2023). Except for the promising practical applicability of UAVs for collecting in-situ structural data, it is also interesting to examine the performance of UAV-driven techniques, compared to other inspection techniques, and to gain a deep insight into the merits and shortcomings of applying UAVs for SHM.

Based on the above, the objective of this research is to initiate a performance assessment approach between NDT techniques that are usually applied conventionally (e.g., IRT, GPR, and IE) and UAV-driven NDT techniques (e.g., camera-based) for inspecting port concrete infrastructure. Seeking to contribute to the existing body of knowledge regarding which inspection technique is optimal, the present paper focuses on extending NDT ranking and prioritizing that has taken place in related work (e.g., Abdelkhalek & Zayed, 2021; Gucunski et al., 2014; Hesse et al., 2017; Kušar et al., 2018; Lee & Kalos, 2015; O'Byrne et al., 2018; Oh et al., 2013; Omar & Nehdi, 2016; Omar et al., 2017; Yehia et al., 2007) by understanding whether, and how, the UAV trends may alter current practices in managing inspection issues.

Following related work that is summarized in Section 2, three (3) NDT techniques that are commonly used for marine concrete structures (Heffron, 2015; Ibrahim, 2016), and which usually score higher than others (e.g. Abdelkhalek & Zayed, 2021): a) IRT, b) GPR, and c) IE, are compared to one (1) camera-based UAV technique. In Section 3, a brief presentation of the four considered techniques is included. Section 4 encompasses the methodology approach followed in the current research for a Multi-Criteria Decision Analysis (MCDA) on the performance of the four techniques. The investigation is based on the Preference Ranking Organization METHod for Enrichment of Evaluations (PROMETHEE) aiming to comprehensively determine the hierarchy of the inspection techniques. The performance criteria required to build the PROMETHEE model are selected by the related work of Kušar et al. (2018) in which inspection techniques were assessed for a set of six criteria. The techniques' performance for each criterion is estimated with qualitative approaches (literature review and questionnaire survey). Three (3) weighting methods are implemented: 1) Mean Weighting (MW), 2) Shannon's Entropy (SE), and 3) Standard Deviation (SD), to eliminate the impact of assigning criteria weights on the stability of the ranking results. A sensitivity analysis is carried out to examine the PROMETHEE model's validity and to justify the outcome's robustness. The results of the PROMETHEE model, as analyzed in Section 5, are compared with two other MCDA methods: a) the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), and b) the Multiple Attribute Utility Theory (MAUT). The most important points of the research are discussed in Section 6, while Section 7 includes the main findings of the multi-criteria assessment. Overall, this study is valuable for supporting decision-making in terms of effective resource management (cost, time, human resources), thus optimizing inspection and monitoring planning for port concrete infrastructure such as jetties, wharves, floating concrete structures, boat ramps, etc.

2. Related work

NDT applications have been widely used for the inspection of conventional, reinforced, or strengthened with advanced materials (e.g., Fiber Reinforced Polymers) concrete infrastructure (Khedmatgozar Dolati et al., 2023), among other types of structures. NDT techniques allow for detecting anomalies during all stages of a structure's lifetime by conducting different types of inspections, such as routine, structural repair or upgrade design, new construction, baseline, or post-event inspections (Heffron, 2015), while reducing the time required to identify structural defects, including cracking, internal voids, steel corrosion, etc. (Lee & Kalos, 2015; Zanini et al., 2019). In the last decades, several studies have focused on assessing the performance of common inspection techniques for concrete infrastructure, especially for bridges (Abdelkhalek & Zayed, 2021; Gucunski et al., 2014; Hesse et al., 2017; Kušar et al., 2018; Lee & Kalos, 2015; O'Byrne et al., 2018; Oh et al., 2013; Omar & Nehdi, 2016; Omar et al., 2017; Yehia et al., 2007). Given the similarities in the structural material, the corrosive environment, and the pressing conditions under which bridges usually operate (O'Byrne et al., 2018), the information provided by a literature review is useful for examining the strengths and weaknesses of inspection techniques for port concrete infrastructure. Such information includes performance criteria, scoring of the techniques for each criterion, methodologies built to prioritize techniques, etc.

Table 1 Summary of criteria for assessing the performance of NDT techniques (Source: Own work).

Criteria	Literature
Capability of distress detection	(Abdelkhalek & Zayed, 2021; Omar & Nehdi, 2016; Yehia et al., 2007)
Speed-duration	(Abdelkhalek & Zayed, 2021; Gucunski et al., 2014; Kušar et al., 2018; O'Byrne et al., 2018; Oh et al., 2013; Omar & Nehdi, 2016; Yehia et al., 2007)
Cost	(Abdelkhalek & Zayed, 2021; Gucunski et al., 2014; Hesse et al., 2017; Kušar et al., 2018; O'Byrne et al., 2018; Oh et al., 2013; Omar & Nehdi, 2016; Yehia et al., 2007)
Precision- Accuracy for distress detection	(Gucunski et al., 2014; Hesse et al., 2017; Oh et al., 2013; Omar & Nehdi, 2016; Yehia et al., 2007)
Ease of use	(Abdelkhalek & Zayed, 2021; Gucunski et al., 2014; Kušar et al., 2018; Lee & Kalos, 2015; O'Byrne et al., 2018)
Simplicity	(O'Byrne et al., 2018; Oh et al., 2013; Omar & Nehdi, 2016)
Reliability	(Hesse et al., 2017; Kušar et al., 2018; O'Byrne et al., 2018)
Repeatability	(Gucunski et al., 2014; Oh et al., 2013)
Performance under different conditions	(Abdelkhalek & Zayed, 2021; O'Byrne et al., 2018)
Surface preparation	(Oh et al., 2013; Yehia et al., 2007)
Functionality interruption	(Oh et al., 2013; Yehia et al., 2007)
Standardization	(Kušar et al., 2018)
Utility	(Kušar et al., 2018)
Portability	(O'Byrne et al., 2018)
Coverage	(O'Byrne et al., 2018)
Versatility	(O'Byrne et al., 2018)
Safety	(O'Byrne et al., 2018)
Effectiveness	(Lee & Kalos, 2015)
Efficiency	(Lee & Kalos, 2015)
Equipment characteristics	(Lee & Kalos, 2015)

A summary of the performance criteria examined in related work is presented in **Table 1**. These criteria were used for the investigation of various NDT techniques. As indicated in **Table 1**, eleven (11) out of the twenty (20) presented criteria are common in more than one study related to the assessment of NDT techniques for collecting in-situ structural data for concrete structures. These criteria are the following: 1) capability of distress detection, 2) speed, 3) duration, 4) cost, 5) precision, 6) accuracy for destress detection, 7) ease of use, 8) simplicity, 9) reliability, 10) repeatability, and 11) performance under different conditions. The criteria of speed-duration, cost, precision-accuracy, and ease of use have attracted considerable attention, based on the number of studies that have used them for assessment purposes.

The performance of the techniques for each criterion can be estimated either qualitatively or quantitatively (Abdelkhalek & Zayed, 2021). For example, Lee and Kalos (2015) and Omar et al. (2017) achieved criteria scoring with a questionnaire survey (qualitative approach), while Gucunski et al. (2014) conducted field and laboratory evaluations (quantitative approach). One more difference observed in the criteria scoring is the number and the characteristics of the participants that were involved in the questionnaire survey. Indicatively, the research of Lee and Kalos (2015) was based on participants working at state agencies, while Kušar et al. (2018) utilized data acquired by experts from the COST Action TU1406 and a literature survey.

The methodologies developed to assess the performance of the inspection techniques and determine their hierarchy involve mainly MCDA applications. Abdelkhalek and Zayed (2021) used a comprehensive approach for NDT ranking by combining the Analytic Network Process (ANP) and the TOPSIS approaches, while Omar et al. (2017) applied the Fuzzy Analytical Hierarchy Process (FAHP). On the other hand, Hesse et al. (2017) conducted a performance assessment of the NDT techniques separately for each criterion by employing the Delphi method.

Table 2 Summary of the three indicative studies for the performance assessment of IRT, GPR, and IE methods under significant criteria. All scoring results were adjusted to a scale of 1 to 5 to facilitate comparison (Source: Own work).

Study	Criteria	IRT	GPR	IE
Kušar et al. (2018)	Results' reliability	3	3	5
	Test duration	3	3	3
	Results' interpretation complexity	1	1	1
	Cost	3	1	3
	Usability	5	5	5
	Standardization	1	3	3
Omar et al. (2017)	Capability	1	3	5
	Speed	4	4	3
	Simplicity	4	4	3
	Accuracy	1	3	5
	Cost	4	4	2
Gucunski et al. (2014)	Accuracy	2	2	3
	Repeatability	2	5	5
	Speed	5	5	3
	Ease of use	5	2	2
	Cost	5	4	4

Despite the significant number of studies focusing on performance assessment of inspection techniques, the absence of UAVs in ranking applications is evident. Therefore, the present research integrates a UAV-based technique into prioritization approaches. The related work presented herein acts as a base to examine which criteria and methodology will be considered, as well as which inspection techniques will be compared with the UAV-based one. Previous studies (e.g., Abdelkhalek & Zayed, 2021) indicated that the IRT, GPR, and IE techniques usually score higher than the others. Hence, these techniques are included in the performance assessment approach of the current work along with a camera-based UAV technique. For the previously examined three techniques, raw data (scoring results) before the ranking can be found indicatively in the studies of Kušar et al. (2018), Omar et al. (2017), and Gucunski et al. (2014) (**Table 2**). As shown in **Table 2**, the IRT scores higher in the criteria of usability (Kušar et al., 2018), simplicity (Omar et al., 2017), ease of use (Gucunski et al., 2014), and speed and cost (Gucunski et al., 2014; Omar et al., 2017). The GPR has better performance in the criteria of usability (Kušar et al., 2018), simplicity, cost (Omar et al., 2017), repeatability (Gucunski et al., 2014) and speed (Gucunski et al., 2014; Omar et al., 2017). The IE scores higher in the criteria of results' reliability, usability (Kušar et al., 2018), capability, accuracy (Omar et al., 2017) and repeatability (Gucunski et al., 2014). In the following, the three inspection techniques of IRT, GPR, and IE are compared with a camera-based UAV technique in terms of performance assessment.

3. Summary of inspection techniques

As mentioned above, at the end of Section 2, the current investigation focuses on the IRT, GPR, IE, and UAVs equipped with cameras. Further details regarding the principles of each technique can be obtained from relevant literature (e.g., Heffron, 2015; Harris et al., 2016; Ibrahim, 2016; Abdelkhalek & Zayed, 2019; Abu Dabous & Feroz, 2020; Tsaimou et al., 2021), while a summary of these techniques is provided below.

The IRT technique enables real-time condition visualization by generating instant thermal images (Bauer et al., 2018; Omar et al., 2018). It is based on three principles: a) all objects with a temperature above 0 °C emit radiant energy, b) all objects emit a specific amount of radiation depending on their temperature, and c) the presence of surface or near-the-surface defects interrupts the thermal flow, thus affecting the quantity of emitted radiation (Abdelkhalek & Zayed, 2019). IRT evaluation is performed by analyzing data collected with high-resolution portable or mounted cameras (Heffron, 2015) to identify defects at the structure surface or at a few centimeters' depth (Oh et al., 2013; Lu et al., 2017). The material captured within the distressed areas refers to different thermal inertia, compared to the non-defected concrete, thus increasing the heat of these areas when exposed to augmented environment temperatures or emitted radiation (Sultan & Washer, 2018). In general, the reliability of IRT testing is subject to boundary conditions (i.e., the conditions beyond the edge of the examined area) and ambient temperatures (Oh et al., 2013). Cracks captured in a concrete slab with an infrared thermal camera are shown in **Figure 1**.

As far as the GPR technique is concerned, electromagnetic waves are transmitted by GPR antennas through the structure and return at the GPR receiver to detect subsurface structural properties and anomalies. GPR wave propagation is a function of the dielectric permittivity (ε), the electric conductivity (σ), and the magnetic permeability (μ) of the encountered material (Alani & Tosti, 2018). During testing, in the case where an internal anomaly is detected, the GPR signal partially travels back to the receiver (Tosti et al., 2020). The typical range of wave frequencies is between 1 to 3 Hz (Ibrahim, 2016), thus enabling defect detection at a centimeter scale (Tosti et al., 2020). The main defects that are identified by applying GPR techniques include moisture presence, voids, chloride intrusion, debonding, and steel corrosion (Abdelkhalek & Zayed, 2019; Abu Dabous & Feroz, 2020). In **Figure 2**, an example of deterioration adjacent to reinforcement of a concrete deck is shown. One of the most challenging issues that should be addressed when analyzing GPR data is engaging surveyors with advanced experience and expertise to comprehensively interpret measurements (Tosti et al., 2020; Solla et al., 2021).

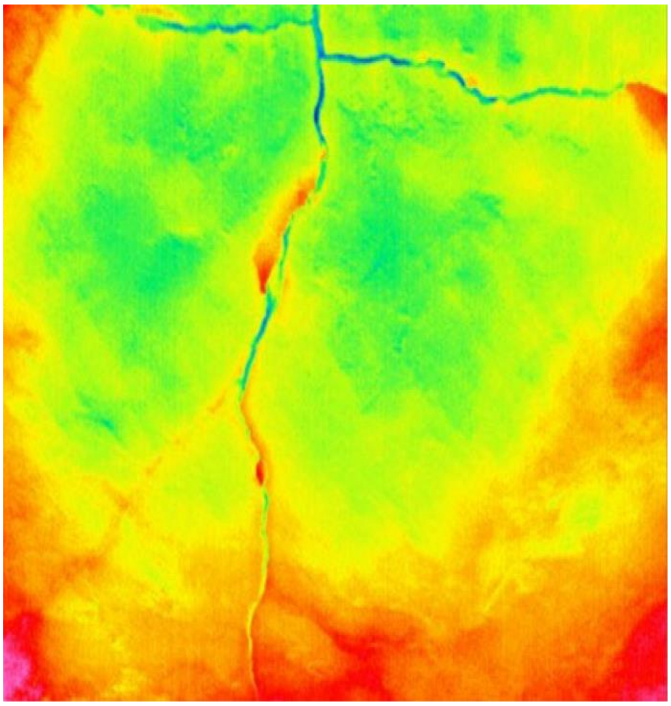

Figure 1 Crack detection and illustration in a concrete slab through an IRT-based inspection (Abu Dabous & Feroz, 2020).

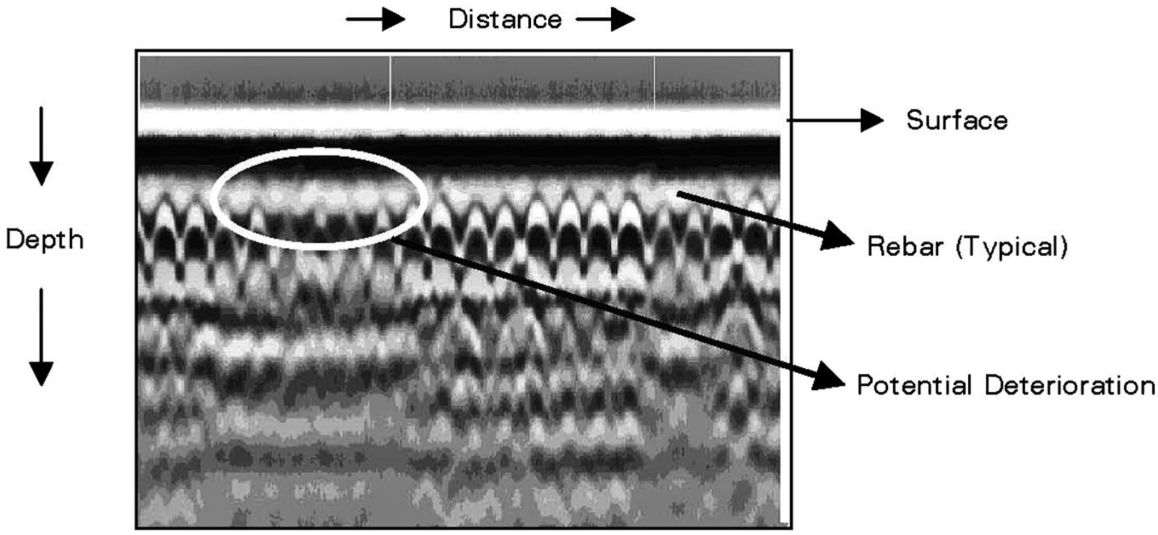

Figure 2 Potential defect (deterioration) detected at a concrete deck through a GPR-based inspection (Heffron, 2015).

The IE techniques used for detecting subsurface discontinuities rely upon creating, transmitting, and reflecting press waves (Abdelkhalek & Zayed, 2019). Transient press waves are produced by a metallic ball that hits the concrete surface. The reflected waves are received by a transducer adjacent to the tested area and transformed within the frequency spectrum (**Figure 3**). Considering the arrival time and the amplitude of the received wave, the type of discontinuities can be identified. IE techniques enable the detection of delamination, cracks, and other sub-surface anomalies, as well as the homogeneity and thickness of the concrete surface (Yehia et al., 2007; Omar & Nehdi, 2018).

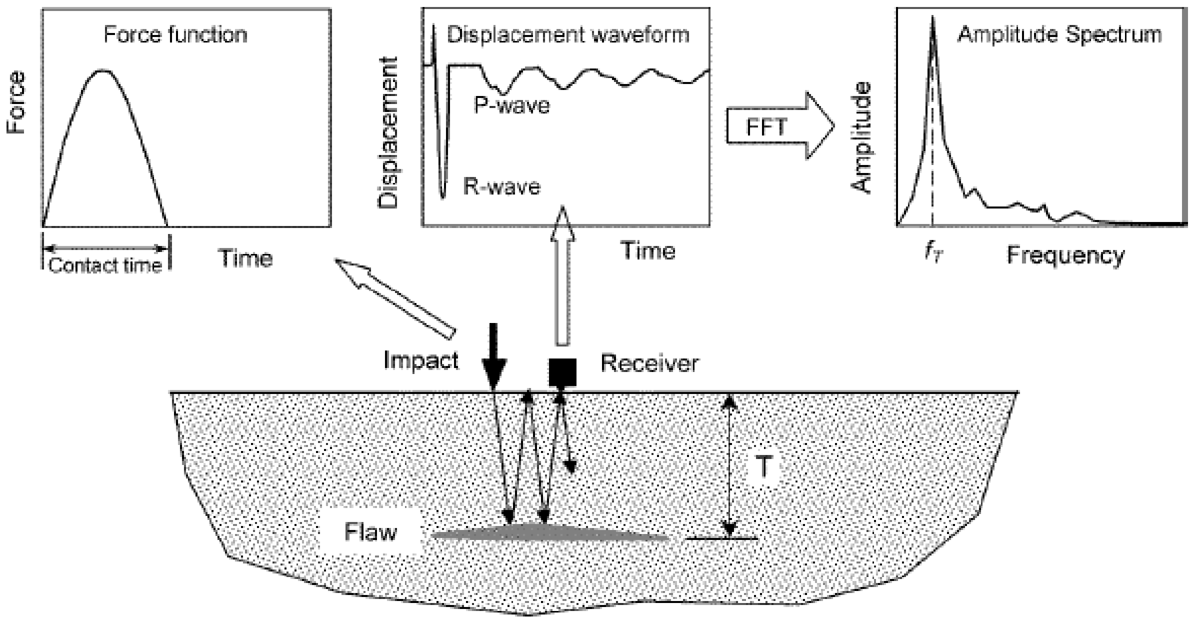

Figure 3 Defect (flaw) detection through an IE-based inspection (Carino, 2015).

Camera-based UAV techniques enable capturing images that include geospatial information (i.e., the latitude, longitude, and elevation required to describe positions) (Tsaimou et al., 2023). An advanced practice of analyzing UAV-captured images includes CRP approaches that generate surface profiles of 3D objects or terrains permitting the identification of their physical dimensions (Harris et al., 2016). The use of CRP assists in recording distresses on the structure's surface (Harris et al., 2016) by generating orthophotos, i.e., georeferenced image output (Tsaimou et al., 2021). CRP is performed by building dense clouds from the tie points identified in the overlapped images (Harris et al., 2016). UAV-driven CRP data reliability is highly affected by flight characteristics and in-situ conditions (Tsaimou et al., 2021). CRP output can be further analyzed with Geographic Information System (GIS) tools to advance defects' detection and quantification, as shown in **Figure 4** produced by Tsaimou et al. (2023).

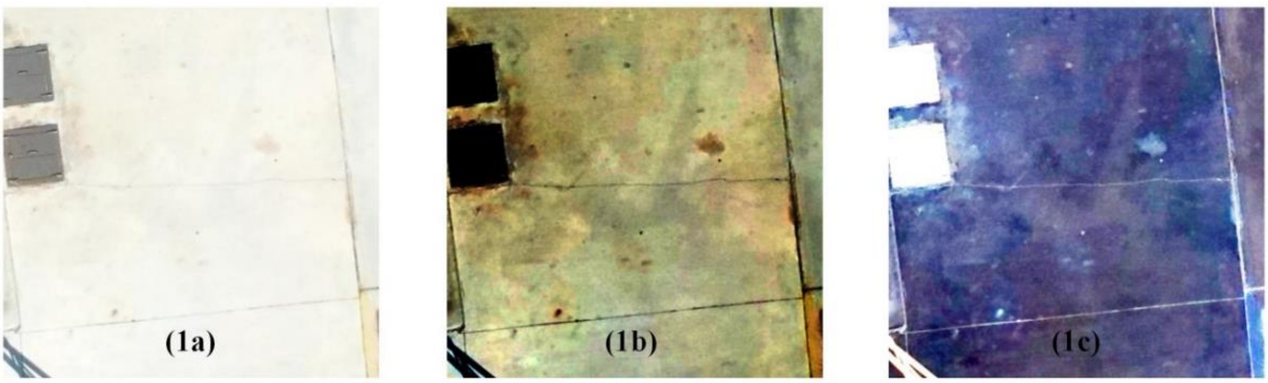

Figure 4 Crack detection (a) and further analysis (b and c) with GIS tools in a Greek port based in UAV-driven inspections (Tsaimou et al., 2023).

4. Materials and methods

4.1 Research methodology

MDCA approaches have been employed by several researchers (e.g., Omar et al., 2017; Abdelkhalek & Zayed, 2021) to scientifically support decision-making (Spronk et al., 2016) and manage the complexity of the factors (e.g., conflicting criteria) that influence the prioritizing procedure of inspection techniques. For the present research, MCDA approaches are implemented based on data collected with the qualitative approach (questionnaires and a literature review). This information was used to assign values to each considered criterion for all four techniques.

On the one hand, the conducted literature review allowed for obtaining the scores of the three previously examined techniques (i.e., IRT, GPR, and IE). Given that the purpose of this work did not include an original performance assessment of all four inspection techniques, the scoring results of current related work were considered as granted. Scoring values were assigned based on the most recent study that includes the unprocessed scoring results for these techniques in its published work. Hence, the scoring data, as well as the relevant criteria of the study of Kušar et al. (2018), were used. The scope of this study was to examine the performance of various NDTs, including the three (3) techniques of interest (i.e., IRT, GPR, and IE), within the context of inspecting concrete infrastructure, such as bridges. The criteria and the scoring of the NDT techniques on these criteria were derived from an investigation conducted on relevant previous studies and assessments by members of the European scientific program COST Action TU1406. The examined criteria were: results' reliability, test duration, results interpretation complexity, cost, usability, and standardization.

On the other hand, data collection with questionnaires assisted in assigning scoring values for the camera-based UAV technique that is linked to CRP applications. The sample included only academic experts to eliminate bias in the outcome. Other potential participants, such as employers in companies that are focused on specific inspection techniques, were not involved, considering that they may be inclined to favor their practices. Moreover, it was a prerequisite that all participants should have applied at least the UAV technique for inspecting the condition of similar concrete structures (e.g., bridges). These conditions limited the size of the sample to 30 academic experts. During the survey, all participants had access to the scoring values for the other three techniques, so that their answers for the UAV technique were given accordingly. Although the survey involved 30 academic experts, only 12 participants delivered a final scoring output (e.g., they were willing to comment on UAV-based CRP, but not compare it with other techniques they were not familiar with, or they did not agree with the given scoring results of the other techniques). During the present research, some significant contributions to the issue of the required number of interviewees were examined (e.g., Galvin, 2015) and, given the homogeneity of the sample (i.e., academic experts that have been exposed to this cutting-edge technology), the number of 12 participants was considered adequate for the specific task of performance assessment.

Once scoring data for all four techniques were acquired, an MCDA approach was conducted to examine the influence of integrating a state-of-the-art UAV technique into performance assessment practices and understand whether the ranking results are consistent with its practical effectiveness, contextualized in the work of Tsaimou et al. (2023). For the application of the MCDA approach, two steps were required: Step 1 and Step 2. In Step 1, a review of existing studies examining the performance of the three (3) NDT inspection techniques (i.e., IRT, GPR, and IE) on concrete structures was conducted. The studies that included unprocessed scoring data were sorted. Thereafter, the criteria and the scoring values for these three techniques were finalized. In Step 2, UAV-based CRP was integrated into the comparative evaluation. A questionnaire survey was conducted based on academic experts' opinions. A decision matrix was constructed with the scoring values for the examined inspection techniques, i.e., IRT, GPR, IE, and UAV-based CRP, followed by assigning weights to the selected criteria. Finally, the multicriteria PROMETHEE model was applied and validated. The steps of the applied MDCA approach are included in **Figure 5**.

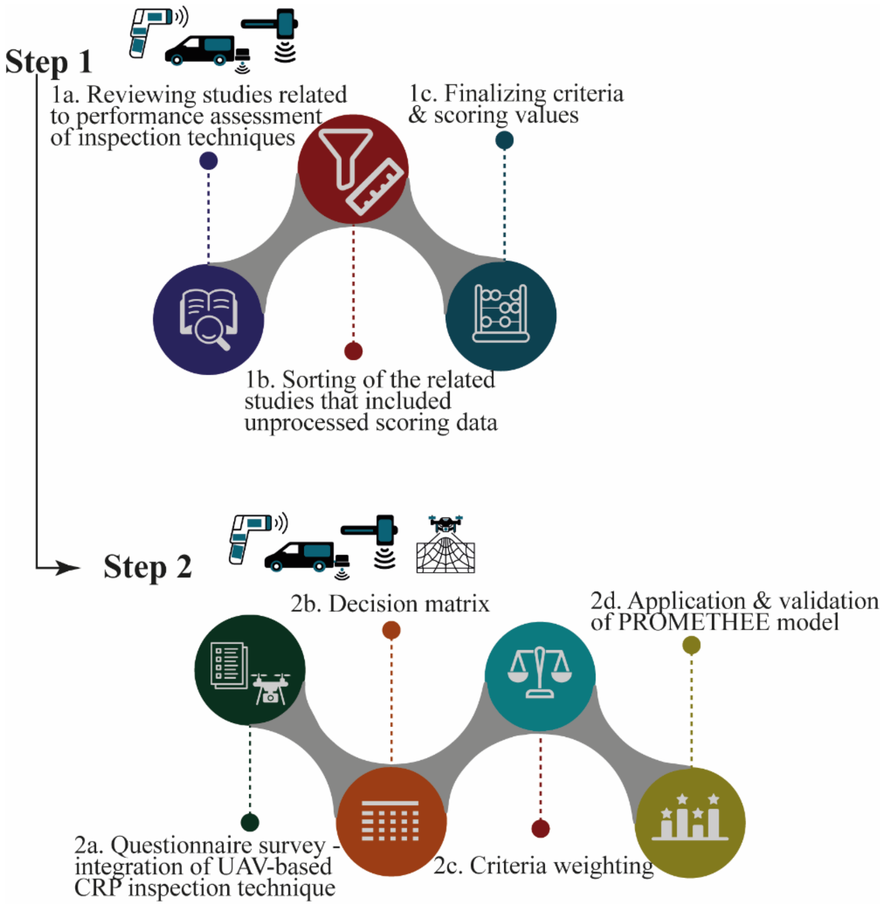

Figure 5 MCDA approach for assessing the performance of a state-of-the-art UAV technique in comparison with other NDT inspection techniques for port infrastructure (Source: Own work).

Table 3 Techniques-Criteria matrix to implement the PROMETHEE methodology for the MCDA, based on (Brans & Mareschal, 2005).

Techniques	**Criteria**					
	$\mathbf{g_1}$	$\mathbf{g_2}$	...	$\mathbf{g_j}$	...	$\mathbf{g_m}$
a_1	$g_1(a_1)$	$g_2(a_1)$	...	$g_j(a_1)$	...	$g_m(a_1)$
a_2	$g_1(a_2)$	$g_2(a_2)$	...	$g_j(a_2)$	...	$g_m(a_2)$
a_3	$g_1(a_3)$	$g_2(a_3)$	...	$g_j(a_3)$	...	$g_m(a_3)$
a_4	$g_1(a_4)$	$g_2(a_4)$	...	$g_j(a_4)$	...	$g_m(a_4)$

Note: $A=\{a_1,a_2,a_3,a_4\}$ is the set of the four inspection techniques, IRT, GPR, IE, and UAV-based CRP techniques for MCDA; $G=\left\{g_1,\dots,g_j,\dots,g_m\right\}$ is the set of the m criteria (j=1,…,m); and $g_j(a_i)$ is the scoring value of each technique a_i under each criterion j.

4.2 The PROMETHEE model

Decision-making in the field of infrastructure management has been applied with various MCDA methodologies, including the PROMETHEE approach (Kabir et al., 2014). PROMETHEE is an outranking method for prioritizing alternatives with a compromising ranking and selecting the optimal one based on predefined conflicting criteria. To solve the ranking problem of the present investigation, an MCDA matrix is defined, as shown in **Table 3** (Brans & Mareschal, 2005), where for each technique a_i a scoring value is assigned for each criterion g_j.

Thereafter, the difference d_{g_j} between the scoring of each pair of the inspection techniques (a_i,a_k) for a specific criterion g_j is calculated Eq. (1), followed by the estimation of the preference between these two techniques P_{g_j} Eqs. (2) and (3).

$$d_j(a_i,a_k)=g_j(a_i)-g_j(a_k),\ j=1,2,\ldots,m \tag{1}$$

$$P_j(a_i,a_k)=F_j\left[d_j(a_i,a_k)\right],\ j=1,2,\ldots,m \text{ (maximizing criterion)} \tag{2}$$

$$P_j(a_i,a_k)=F_j\left[-d_j(a_i,a_k)\right],\ j=1,2,\ldots,m \text{ (minimizing criterion)} \tag{3}$$

With $0\leq P_j(a_i,a_k)\leq 1$

Furthermore, the preference degree π is calculated Eq. (4) by applying weights w_j to each criterion ($\sum_{j=1}^{m} w_j=1,\ w_j\geq 0$):

$$\pi(a_i,a_k)=\sum_{j=1}^{m} w_j\times P_j(a_i,a_k)\in[0,1] \tag{4}$$

Two outranking flows are estimated with Eqs. (5) and (6) for the positive outranking flow $\varphi^+(\alpha_i)$ that indicates how the technique a_i is outranking, compared to the remaining techniques, and the negative outranking flow $\varphi^-(a_i)$ that indicates how the technique a_i is outranked by the other techniques, respectively.

$$\varphi^+(a_i)=\frac{1}{n-1}\sum_{x\in A}\pi(a_i,x) \tag{5}$$

$$\varphi^-(a_i)=\frac{1}{n-1}\sum_{x\in A}\pi(a_i,x) \tag{6}$$

PROMETHEE II (complete ranking) is implemented to estimate the optimal technique by calculating the net outranking flow $\varphi(a_i)$ for each technique Eq. (7). The net outranking flow expresses the total performance of each technique under the selected criteria.

$$\varphi(a_i)=\varphi^+(a_i)-\varphi^-(a_i) \tag{7}$$

4.3 Weight assignment

Weights' assignment is an important step for decision-making actions. The procedure includes either subjective methods that are based on the participants' opinions, or objective ones that involve analyses of the scoring values of the alternatives (Şahin, 2021). During the present investigation, no weighting values or criteria pairwise comparisons were defined by the participants. Hence, objective weighting methods were used for the MCDA. Current studies have combined the PROMETHEE II methodology with various objective weighting methods (e.g., Balali et al., 2014; Şahin, 2021). Following this, PROMETHEE II was implemented with MW, SE, and SD to ensure the results' reliability. In particular:

- With the MW method, all criteria are considered equally important Eq. (8):

$$w_j=\frac{1}{m} \tag{8}$$

- The SE method is suitable for the cases of inadequate or absent preferences of the decision-makers (Monghasemi et al., 2015). For each criterion g_j the entropy value E_j is estimated Eq. (9).

$$E_j=-k\times \sum_{i=1}^{n} p_j(a_i)\times \ln g_j(a_i), \quad j=1,2,\ldots m \tag{9}$$

Where: $k=\frac{1}{\ln n}$ is a constant, n is the number of the techniques (i.e., n=4 for MCDA), and $p_{ij}=\frac{g_j(a_i)}{\sum_{i=1}^{n} g_j(a_i)}$ is the normalized value of the $g_j(a_i)$ scoring of each technique.

The degree of diversity D_j for each criterion g_j is calculated by Eq. (10) to result in the assigned weights w_j for each criterion g_j Eq. (11).

$$D_j=1-E_j \tag{10}$$

$$w_j=\frac{D_j}{\sum_{j=1}^{m} D_j} \tag{11}$$

- The SD method is based on the standard deviation of the collected information σ_j (Eq. (12):

$$\sigma_j=\sqrt{\frac{\sum_{i=1}^{n}[g_j(a_i)-\bar{g}_j]^2}{n}} \tag{12}$$

Where: $\bar{g}_j$ is the mean of $g_j(a_i)$ scoring of each criterion for the total of the n techniques (i.e., n=4 for MCDA).

The weighting values are estimated by Eq. (13):

$$w_j=\frac{\sigma_j}{\sum_{j=1}^{m} \sigma_j} \tag{13}$$

4.4 Model validation

To justify the stability and robustness of the results of the PROMETHEE model, it was important to perform a sensitivity analysis with other MCDA methods. Two more MCDA methods: a) the TOPSIS, and b) the MAUT, were used to enhance the reliability of the findings.

TOPSIS is a utility-based MCDA that determines the optimal alternative by the distance of this alternative from the positive ideal solution (PIS) and the negative ideal solution (NIS). The PIS and the NIS are acquired by Eqs. (14) - (17) (Ishizaka & Nemery, 2013).

$$A^+=\{v_1^+,v_2^+,\ldots,v_m^+\} \tag{14}$$

$$v^+=\{(\max_i v_{ij}\,|j\in J_b),\ (\min_i v_{ij}\,|j\in J_{nb})\ |\ \in[1,\ldots,n]\} \tag{15}$$

$$A^-=\{v_1^-,v_2^-,\ldots,v_m^-\} \tag{16}$$

$$v^-=\{(\min_i v_{ij}\,|j\in J_b),\ (\max_i v_{ij}\,|j\in J_{nb})\ |\ \in[1,\ldots,n]\} \tag{17}$$

Where: $v_{ij}=w_j\times p_{ij}$ is the weighted normalized value of the $g_j(a_i)$ scoring of each technique, $p_{ij}=\frac{g_j(a_i)}{\sum_{i=1}^{n} g_j(a_i)}$ is the normalized value, J_b is associated with beneficial criteria, and J_{nb} is associated with non-beneficial criteria.

Euclidean distances of each alternative technique from PIS and NIS are estimated by Eqs. (18) and (19), respectively. The final ranking of the alternatives is determined by Eq. (20).

$$D_i^+=\sqrt{\sum_{j=1}^{n}(v_{ij}-v_j^+)^2} \quad (18)$$

$$D_i^-=\sqrt{\sum_{j=1}^{n}(v_{ij}-v_j^-)^2} \quad (19)$$

$$C_i=\frac{D_i^-}{D_i^+ + D_i^-} \quad (20)$$

The MAUT method is based on the assumption that a utility function exists for a decision problem that has to be maximized (Ishizaka & Nemery, 2013). The performance of alternatives depends on the utility values U_i (Eq. (21)).

$$U_i=\sum_{j=1}^{m} w_j \times p_{ij} \quad (21)$$

Where: $p_{ij}=\frac{g_j(a_i)-\min\{g_j(a_i)\}}{\max\{g_j(a_i)\}-\min\{g_j(a_i)\}}$ is the normalized value of the $g_j(a_i)$ scoring of each technique for beneficial criteria, and $p_{ij}=\frac{\max\{g_j(a_i)\}-g_j(a_i)}{\max\{g_j(a_i)\}-\min\{g_j(a_i)\}}$ is the normalized value of the $g_j(a_i)$ scoring of each technique for the non-beneficial criteria.

5. Results

5.1 MCDA PROMETHEE ranking

The results of the questionnaire survey regarding the scoring of the camera-based UAV technique (CRP) are presented in **Table 4**. The participants were asked to score the technique for the six (6) criteria included in the study of Kušar et al. (Kušar et al., 2018) by taking into account the scoring results for IRT, GPR, and IE. A new decision matrix was formed with the scoring values for all four inspection techniques. The three weighting methods (MW, SE, and SD) were applied to assign weights to the criteria (**Table 5**). The implementation of the SE method indicated that the cost was the most significant criterion, successively followed by standardization, results' interpretation complexity, test duration, and results' reliability. The usability of each inspection technique was the least important factor. Similar to the SE method, the SD method suggested the cost as the most significant criterion, successively followed by test duration, results' reliability, and standardization. The complexity of the results' interpretation and the usability were considered the less important criteria.

The implementation of the PROMETHEE II model for all four inspection techniques showed that ranking results were the same for all three weighting methods (**Tables 6 - 8**). In particular, the camera-based UAV (CRP) was found to be the optimal one, followed by IE. GPR was placed third in the ranking order, while IRT was the least preferable technique.

Table 4 Scoring for the camera-based UAV technique (CRP), based on the questionnaire survey.

Results reliability	Test duration	Results int. complexity	Cost	Usability	Standardization
4	5	2	4	4	2

Table 5 Criteria weights (%) estimated with MW, SE, and SD.

Weighting technique	Results reliability	Test duration	Results int. complexity	Cost	Usability	Standardization
MW	16.67	16.67	16.67	16.67	16.67	16.67
SE	8.58	10.18	19.48	33.02	1.55	27.18
SD	18.51	19.33	9.67	24.32	9.67	18.51

Table 6 Performance assessment of the inspection techniques with PROMETHEE and MW.

Inspection technique	$\varphi(a_i)$	$\varphi^+(a_i)$	$\varphi^-(a_i)$	Ranking
IRT	-0.3333	0.1111	0.4444	4
GPR	-0.2222	0.1667	0.3889	3
IE	0.2222	0.3889	0.1667	2
UAV camera	0.3333	0.6667	0.3333	1

Table 7 Performance assessment of the inspection techniques with PROMETHEE and SE.

Inspection technique	$\varphi(a_i)$	$\varphi^+(a_i)$	$\varphi^-(a_i)$	Ranking
IRT	-0.4227	0.1152	0.5380	4
GPR	-0.2999	0.1864	0.4863	3
IE	0.1733	0.3823	0.2090	2
UAV camera	0.5494	0.7747	0.2253	1

Table 8 Performance assessment of the inspection techniques with PROMETHEE and SD.

Inspection technique	$\varphi(a_i)$	$\varphi^+(a_i)$	$\varphi^-(a_i)$	Ranking
IRT	-0.3729	0.1133	0.4862	4
GPR	-0.3076	0.1556	0.4632	3
IE	0.2440	0.4218	0.1777	2
UAV camera	0.4365	0.7182	0.2818	1

5.2 PROMETHEE model testing

To validate the robustness of the ranking results of the PROMETHEE II model, a sensitivity analysis was performed with two MCDA methods, i.e., the TOPSIS and the MAUT. The results of the TOPSIS method for the MW, SE, and SD weighting methods are included in **Tables 9 - 11**. It was noticed that, regardless of the weighting method, the optimal inspection technique remained the camera-based UAV (CRP), while IE was found to be the second most preferable one. However, the ranking order changed for the remaining two techniques (IRT and GPR). The MW method indicated IRT as the least preferable technique, while SE and SD methods resulted in GPR occupying the last place.

Table 9 Performance assessment of the inspection techniques with TOPSIS and MW.

Inspection technique	D_i^+	D_i^-	C_i	Ranking
IRT	0.1167	0.0590	0.3358	4
GPR	0.1230	0.0717	0.3681	3
IE	0.0831	0.1010	0.5487	2
UAV camera	0.0445	0.1222	0.7328	1

Table 10 Performance assessment of the inspection techniques with TOPSIS and SE.

Inspection technique	D_i^+	D_i^-	C_i	Ranking
IRT	0.1506	0.1117	0.4257	3
GPR	0.1864	0.1134	0.3781	4
IE	0.0966	0.1607	0.6245	2
UAV camera	0.0578	0.1939	0.7704	1

Table 11 Performance assessment of the inspection techniques with TOPSIS and SD.

Inspection technique	D_i^+	D_i^-	C_i	Ranking
IRT	0.1191	0.0829	0.4103	3
GPR	0.1475	0.0778	0.3455	4
IE	0.0768	0.1231	0.6157	2
UAV camera	0.0466	0.1466	0.7588	1

Regarding the results of the MAUT method (**Table 12**), it was found that the camera-based UAV technique (CRP) was once again the most preferable inspection technique for all three weighting methods. The second place was occupied by IE, the third place by GPR, and the last one by IRT. Moreover, only a small difference was observed in the values of U_i between the camera-based UAV technique (CRP) and the IE for the MW method, thus implying that both inspection techniques are close in the preference order. On the contrary, this difference is higher for the SE and SD methods and, consequently, the camera-based UAV technique (CRP) is by far the most preferable one.

Considering the above, both the PROMETHEE II and TOPSIS approaches revealed that the camera-based UAV technique (CRP) is the optimal one, followed by IE regardless of the weighting method. The ranking order for IRT and GPR was different depending on the assigned weights.

Moreover, both the PROMETHEE II and MAUT approaches resulted in the same ranking order for all weighting methods.

Table 12 Performance assessment of the inspection techniques with MAUT for the three weighting techniques: MW, SE, and SD.

Inspection technique	MW		SE		SD	
	U_i	Ranking	U_i	Ranking	U_i	Ranking
IRT	0.2778	4	0.2357	4	0.2588	4
GPR	0.3333	3	0.2873	3	0.2817	3
IE	0.6111	2	0.5933	2	0.6290	2
UAV camera	0.6667	1	0.8057	1	0.7183	1

6. Discussion

The selected set of techniques was based on the assessment results of related work (e.g., Abdelkhalek & Zayed, 2021) combined with current trends. Due to the limitations presented in Subsection 4.1, "Research methodology", the investigation was performed following previous practices (e.g., Kušar et al., 2018) for simultaneously assessing the performance of techniques that target surface (UAV camera and IRT) (Harris et al., 2016; Khedmatgozar Dolati et al., 2023) or sub-surface defects (IE and GPR) (Khedmatgozar Dolati et al., 2023). However, to support decision-making for building effective SHM programs, it is essential to distinguish assessment results based on the defects that are required to be detected. Considering the existing condition of port infrastructure and the absence or presence of defects, inspections can be focused on surface or sub-surface distress detection. Moreover, depending on the reliability assessment and prediction model used for intervention planning, the required monitoring data should be acquired by the most suitable inspection technique.

Before further analyzing the results for the PROMETHEE ranking, the examination of the scoring data for the camera-based UAV technique (CRP) (**Table 3**) compared to the ones for the other three techniques (IRT, GPR and IE), based on the study of Kušar et al. (2018), indicated that the UAV technique scores higher in the criterion of test duration. This can possibly be attributed to the ease of hovering and maneuvering a UAV, leading to the reduction in data collection time. Furthermore, the performance of the UAV-based CRP technique in the criterion of cost is better than the one of the other inspection techniques. The fact that there is a wide range of affordable UAVs on the market leads to the reduction of a significant part of the expenses required to acquire equipment for inspections.

PROMETHEE ranking analysis indicated that UAV camera (CRP) and IE are the most preferable techniques. By default, the camera-based UAV technique (CRP) is mainly applied to identify surface distresses of concrete infrastructure (e.g., surface cracking, corrosion, etc.), while IE is used for internal defects (subsurface cracking, voids, etc.). The camera-based UAV technique (CRP) can be employed for surface distresses detected during routine visual inspections to achieve detailed mapping and quantifying. IE can be employed in cases where preventive inspections are required to detect potential sub-surface defects that have not yet propagated up to the surface. Hence, although the camera-based UAV technique (CRP) ranks first in the preference order, it may be not universally better compared to all considered inspection techniques. UAV-based CRP is preferable for detecting surface defects. Similarly, IE is preferable for detecting non-surface defects.

7. Conclusions

The integration of UAV trends into current performance assessment practices for inspection techniques affects the ranking order. Before examining the camera-based UAV technique, the qualitative approach of Kušar et al. (2018) revealed that techniques for inspecting sub-surface defects are the most preferable (i.e., IE). Once UAV camera (CRP) was integrated into the qualitative-based approach of this research, the ranking preference was altered toward distinguishing a technique for inspecting surface defects. This technique was found to improve the practical part of inspections and provide flexibility since it scores higher in the criteria of test duration, complexity of interpreting the results, and cost. Moreover, it is concluded that the camera-based UAV technique is the optimal inspection technique for detecting surface defects, while IE is preferred for sub-surface defects.

The above findings are significant for managing condition monitoring practices and, subsequently, planning maintenance actions of port concrete infrastructure. The limitations of this research regarding the sample size can be handled by seeking a wider sample size beyond academic context. Further research is also encouraged to employ different weighting methods for incorporating the relationships and the importance of the criteria as defined by the participants (e.g., Analytical Network Process (ANP)). Moreover, a quantitative approach that includes experimental testing for performance assessment would lead to interesting conclusions.

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