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Enhancing Flood Resilience in Coastal Areas by Investigating Issues and Countermeasures Using Digital Twin Technology

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Abstract

The impact of flooding requires innovative solutions for enhancing flood preparedness and reducing societal and economic losses. This study explores the potential of digital twin technology as an innovative tool for flood predictions, enabling real-time monitoring and data integration, contributing to developing more resilient communities and reducing flood risks. This study aims to enhance coastal flood resilience in Malaysia by examining challenges and strategies by applying digital twin technology. The objectives of the study are (1) to identify issues and countermeasures of flood in coastal areas (2) to compare the most relevant issues and countermeasures of flood in the coastal area for different organizations for application in digital twin technology and (3) to analyses the interrelationship among organization for application in digital twin technology in Malaysia. The survey gathered collaboration data from 122 participants, comprising clients, consultants, and contractors. Finally, the data were analysed using each criterion's mean score ranking, normalization techniques, Kruskal-Wallis's, spearman correlation, and overlap analysis. The top 4 critical issues are F05, F07, F06, and F02. The high cost of implementation due to the increased amount of sensor and computational resources needed is considered the most critical. While for the top 3 countermeasures are S04, S06, and S07. Improved planning and prediction for floods are considered the highest rank among the countermeasures. The findings of this study will provide practical insights for organizational practitioners in identifying critical elements and countermeasures when implementing digital twin technology in Malaysia. Future industry studies can build on the strong foundation laid by this research, deepening the understanding of digital twin applications in flood management and risk reduction.

Keywords: Flood Monitoring System, Resilience, Issues, Strategies, Digital Twin

Introduction

Floods, caused by climate change, are the top global risk and one of the top five worldwide hazards. The World Economic Forum has identified them as a major issue, with future risks increasing due to urbanization, deteriorating infrastructure, and stressed drainage systems [1]. Even worse, severe flooding frequently worsens people's health and results in fatalities. It is estimated that these natural disasters affected 1.4 billion people globally and claimed about 100,000 lives during the last decade of the 20th century. Besides, floods in Europe in 2005, 2007 and 2010 resulted in economic damages that were greater than EUR 1 billion. Floods in Europe in 2002 resulted in material damage worth EUR 20 billion [2].

Flooding can be caused by a variety of sources. This deluge cannot be traced solely to natural sources. When a flood happens, it can inflict severe damage to public structures, agricultural products, human lives, and other things. Many past studies have been conducted including using geographic information system (GIS) technology, flood forecasting, and warning systems, especially in flood risk management. For the past few years. However, hard work yields effective results only when it is used in the right way. As a result, research is needed to determine the real cause and reduce the effects of flooding in coastal areas. The method is fundamentally difficult to monitor because it is not real-time.

The digital twin is a game-changing technology for future smart cities and industrial metaverses. A virtual representation of a real-world entity, system, process, or other abstraction that can be recreated by a computer-programmed or closed software model that interacts and synchronizes with its physical counterpart is referred to as a digital twin. This gadget not only monitors for floods, but it may also assist the surrounding area in preparing because its speed decreases the possibility of property and life damage [1]. A digital twin (DT) is a representation of a physical object that includes a dynamic two-way mapping between a real-time object and its digital model. According to findings of this investigation, the process of developing digital twins for smart cities has evolved from static 3D modelling to the digital twin stage, which combines dynamic digital technology with static 3D models. Users can use digital twins to visualize assets, check status, perform analysis and generate insights [3]. The digital twin is a solution that can be used. However, research related to digital twins in solving the flood problem in Malaysia is still new.

In addition, there are 3 objectives which are (1) to identify issues and countermeasures of flood in coastal areas (2) to compare the most relevant issues and countermeasures of flood in the coastal area for different organizations for application in digital twin technology and (3) to analyses the interrelationship among organization for application in digital twin technology in Malaysia.

Literature Review

Limitations of Digital Twin Technology for Climate Resilience Implementation

The digital twin is a flood monitoring and early warning system that uses real-time sensors as one of the flood management tactics. A digital twin is a digital representation of a physical asset, process, or system, along with the engineering information that allows people to understand and model its performance. Digital twin technology is a promising solution to coastal flooding, but it faces several issues (Table 1), Data-related issues include large-scale data collection, monitoring, governance, privacy, cybersecurity, and trust. Social conflict, socio-political issues, social inequity, and environmental sustainability also pose challenges. The lack of adoption of digital twin structures, standards, and laws also hinders widespread use. Literature surveys and reviews can help spread awareness of these issues. Implementation costs are high due to the need for more sensors and processing resources, often in developing countries. Big data and AI are essential for long-term data analysis. Communication networks, such as 5G, are also obstacles. The need for further research and development is highlighted, as well as the need for improved data management and standardization. However, existing city digital twin models are not complete or comprehensive due to flaws in precision, errors, and integration of human interactions, socioeconomic and political aspects.

Table 1. Issues of digital twin technology

No	Issues	Explanation	References
1.	Lack of framework	Previous studies lack a clear framework, indicating a need for systematic guidelines in future research.	[4], [5]
2.	Trust, privacy, cybersecurity, convergence and governance, data gathering, and extensive analysis-related issues.	These important issues are often overlooked, requiring more in-depth research and better solutions.	[6], [7], [8]
3.	Lack of standards	There is a lack of consistent standards, highlighting the need for widely accepted guidelines.	[5], [9], [10]
4.	Lack of implementations of standards, protocols, and rules for digital twins.	Although standards exist, their implementation is inadequate, requiring more detailed studies.	[9], [11], [12]
5.	High cost due to the increased number of sensors and computational resources required.	The high cost of sensors and computational resources is a major challenge that needs cost-reducing solutions.	[13]
6.	Lack of communication network-related obstacles	Communication network issues hinder performance, needing more research to overcome these obstacles.	[7], [12], [14]
7.	The use of AI and big data to satisfy long-term and large-scale.	AI and big data applications for long-term, large-scale needs are underexplored, presenting opportunities for future research.	[6], [8], [11], [15]

Method to minimize potentials of the city using digital twin

Data administration, visualization, situational awareness, planning and prediction, and integration and collaboration were found as five topics by thematic analysis of city digital twin papers (Table 2). The realized and perceived potentials and use cases of utilizing the city digital twin may be comprehended, and a research agenda can be offered to further maximize the benefits of the city digital twin.

Table 2. Countermeasure of digital twin technology

No	Themes	Application	Explanation	References
1.	Data management	• Data processing • Interoperability • Software fusion • Open-source software	Efficient handling and organization of data to improve processing, interoperability, and use of software tools	[16], [17]
2.	Visualization	• 3D real-time experience • Multi-spatial and temporal scales • Unified platform • Behavior modelling • Network dynamics • Personalized information system	Utilization of advanced techniques to create detailed and interactive visual representations, covering various scales and integrating data for better insights.	[16], [17], [18], [19]
3.	Situational awareness	• Monitoring • Tracking • Localization • Analysis	Gaining a thorough understanding of real-time conditions through effective monitoring, tracking, and analysis to enhance decision-making.	[4], [6], [7], [8], [20], [21]
4.	Planning and prediction	• Policy evaluation • Simulation	Developing accurate forecasts and strategic plans by evaluating policies and simulating various scenarios to anticipate future outcomes.	[11], [15], [22]
5.	Integration and collaboration	• Citizen's engagement • Open platform • Stakeholder participation	Enhancing teamwork and stakeholder engagement by using open platforms and encouraging active participation to achieve common goals.	[3], [4], [7]

Research gap

Digital twin technology is able to assist communities in high-risk areas in overcoming obstacles and enhancing their climate resilience, according to earlier research. There are several research gaps concerning the implementation and use of a bidirectional data flow in an actual digital twin. Unfortunately, little information about the effects of various flood-related variables using digital twin technologies is available in the literature [23]. In the first example of a digital twin, this technology is commonly used in Canada and Europe. The focus of this inquiry will be Malaysia's circumstances. Aside from that, the causes and techniques for enhancing flood-employing digital twin technology were identified in order to close the knowledge gap.

Methodology

Figure 1 illustrates the methodology used in this study, which involves literature reviews (LR) and questionnaire surveys. Quantitative results from the questionnaire survey give an in-depth understanding of the interrelationship between Digital twins adoption in flood prevention.

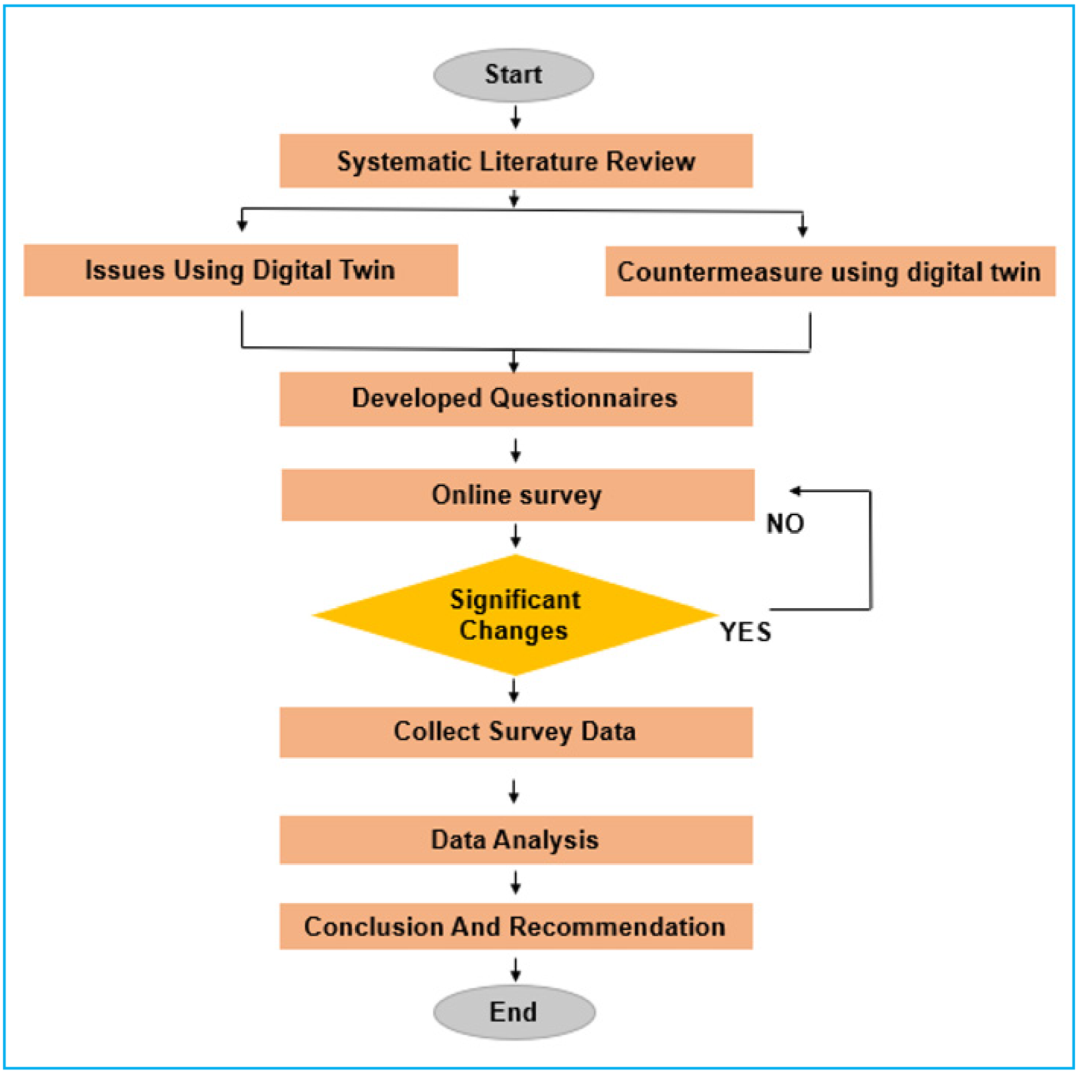

Figure 1. Flowchart of the methodology

Data collection

The literature review (LR) approach is used in this study to conduct a comprehensive assessment of the existing literature to develop a list of potential strategies and capability factors. Journals and research articles from Scopus, Web of Science, and Google Scholar were used as sources for the literature review. Several factors and strategies related to digital twins, specifically on flood resilience were discovered and combined into a questionnaire survey to be distributed.

In this study, the online questionnaire was used and distributed to contractors, consultants, and owners in Malaysia using Google Forms. The data was then, analyzed using Statistical Package for the Social Sciences (SPSS) software. Out of 160 online questionnaires distributed, only 122 respondents answered and filled accordingly. The section of the questionnaire was divided into 3 categories which are part A provides a general profile of respondents such as gender, position in current company, years of experience in construction, etc. Meanwhile, for part B, several questions related to issues using digital twin technology, and part C is a countermeasure for reducing the issues of digital twin technology in the survey, the following question was linked to the study's dependent variable: "On a scale of 1 to 5, please rate the level of agreement based on the issues and countermeasures. The answers for issues will be recorded by using a Likert scale with 1 = not critical, 2 = slightly critical, 3 = moderate critical, 4 = critical, and 5 = very critical. meanwhile, for countermeasure which is 1= not effective, 2= slightly effective, 3= effective, 4= very effective, and 5= extremely effective.

Respondent profile

A total of 122 responses were gathered during the data collection phase, providing valuable insights into the organizational landscape, and experience levels with digital twins. The results are presented in tabular form (Table 3), highlighting the distribution of responses across different categories.

Data analysis

The gathered data is qualitatively analyzed, resulting in numerical data or findings to quantify the information. The information can also be displayed in the form of useable data, tables, or graphs that can be numerically analyzed. The acquired data was analyzed using five different methods: mean ranking analysis, Kruskal-Wallis's method, normalization method, overlap analysis, and correlation analysis. The goal of mean ranking analysis in a questionnaire survey is to find the most common answer among all respondents. Normalization, on the other hand, helps in decreasing data redundancy and identifying the most important variables. These two methods aim to achieve objective one to identify issues and countermeasures of flood in the coastal area as well as to compare the most relevant issues and countermeasures of flood in the coastal area for different organization using digital twin technology. After that, determine the relationship between the crucial variable and the mean ranking and normalization analysis results. Thus, this method targeted to solve objectives two and three. This research aims to analyse the interrelationship among organizations using digital twin technology in Malaysia.

Table 3. Respondent demographics

Characteristic	Categories	Frequency	Percent (%)
Gender	Male	59	48.4
	Female	63	51.6
Age group	24 years old and below	30	24.6
	25 to 29 years old	70	57.4
	30 to 34 years old	10	8.2
	35 to 39 years old	7	5.7
	40 to 44 years old	3	2.5
	45 to 49 years old	2	1.6
Academic qualification	High School	1	0.8
	Diploma	21	17.2
	Polytechnic	1	0.8
	Bachelor's Degree	91	74.6
	Master's Degree	6	4.9
	Doctoral Degree	2	1.6
Type of organization	Contractors	35	28.7
	Consultants	62	50.8
	Owners	25	20.5
Year of experience in industry	Below 2 years	46	37.7
	2-5 years	48	39.3
	6-10 years	23	18.9
	11-15 years	2	1.6
	16-20 years	1	.8
	More than 20 years	2	1.6
Experience with digital twins	No project	74	60.7
	Less than 2 project	19	15.6
	2-5 project	18	14.8
	6-10 project	8	6.6
	11-15 project	1	.8
	More than 20 project	2	1.6

Mean score ranking

The average scores of the factors were used to rank them in relation to one another. The mean score ranking approach was used to determine the criticalities of the components in this investigation. Equation 1 shows the normalization strategy was used after ranking the factors. In this study, a strategy was used to minimize the minimum mean. In contrast, the maximum mean value was modified to a number equal to 1. Following that, decimal values ranging from 0 to 1 were assigned to the remaining mean values. The normalized value was calculated using the following Equation 1 [24].

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$$X_{new} = \frac{X - \min(X)}{\max(X) - \min(X)}$$

X_{new} = The new value from the normalized results

X = Old value

Max (X) = Maximum value in the dataset

Min (X) = Minimum value in the dataset

Normalisation is a step in the pre-processing, scaling, or mapping process. It is capable of generating a new range from an existing one.

Kruskal Wallis test

Within the organization, disagreements may emerge between clients, consultants, and contractors. Kruskal-Wallis's test is utilized to analyze any inconsistencies between expert feedback from the deployment of digital twin technology in coastal areas due to its adaptability for non-parametric data. To identify group differences, a test can compare two or more groups with comparable or dissimilar sample sizes. When p 0.05, the difference in opinion between groups is statistically significant at the 95% confidence level. P > 0.05 implies that the tested groups share the same opinion [25].

Overlap analysis

The overlap analysis method was used to pinpoint the overlaps between digital twin technology and other approaches and problems. The overlap analysis is a method of decision-making that compares two or more groups to find similarities and differences. The best variables are simply combined via the overlap analysis, which also gets rid of the non-explanatory variables [26]. This method is frequently used to recognize the overlap between the variables. This method made use of circles to depict a collection of visibly overlapping edges [27].

Correlation analysis

Correlation analysis is a rigorous approach used in research to determine the relationship between two components and gauge the potency of their direct connection [27]. It establishes the extent to which the change in one variable has benefited the other. A low correlation highlights a weak relationship between the two elements, whereas a high correlation highlights a strong relationship between the two factors.

Results and Discussion

Result mean score ranking, normalization value

Tables 4 and 5 show the mean, standard deviation (STD), and normalized values (NV) of collected data from respondents' collaboration issues selection in using digital twin technology: a perspective through a registered contractor, consultant, and owner view. this result displays the rank of each variable from highest to lowest values based on the amount of data for each variable.

Table 4. Result issues mean score ranking, normalization and Kruskal-Wallis

Code	All responses			Owners			Consultants			Contractor			Kruskall-Wallis
	Mean	STD	NV	Mean	STD	NV	Mean	STD	NV	Mean	STD	NV	P-Value
F05	3.893	1.162	1.000	3.482	1.326	0.400	4.096	1.193	1.000	3.983	1.000	1.000	0.102
F07	3.827	1.901	0.777	3.517	1.325	0.500	4.032	1.139	0.333	3.87	1.123	0.766	0.228
F06	3.819	1.253	0.750	3.655	1.421	0.900	4.000	1.238	0.000	3.806	1.185	0.633	0.571
F02	3.745	1.23	0.500	3.689	1.284	1.000	4.000	1.095	0.000	3.645	1.268	0.299	0.461
F01	3.663	1.27	0.222	3.551	1.325	0.600	4.000	0.211	0.000	3.548	1.263	0.100	0.221
F03	3.639	1.24	0.138	3.517	1.352	0.500	4.032	0.333	0.333	3.500	1.238	0.000	0.119
F04	3.598	1.289	0.000	3.344	1.395	0.000	4.032	1.110	0.333	3.500	1.289	0.000	0.900

Table 5. Result strategy mean score ranking, normalization and Kruskal-Wallis

Code	All responses			Owners			Consultants			Contractor			Kruskall-Wallis
	Mean	STD	NV	Mean	STD	NV	Mean	STD	NV	Mean	STD	NV	P-Value
S04	4.254	0.867	1.000	4.137	1.000	1.000	4.258	0.841	0.916	4.306	1.000	1.000	0.530
S06	4.237	0.881	0.944	4.068	0.750	0.750	4.290	0.956	1.000	4.290	0.958	0.958	0.305
S07	4.131	1.995	0.583	4.137	1.000	1.000	4.225	1.000	0.833	4.080	0.146	0.416	0.862
S02	4.065	1.023	0.361	3.862	0.000	0.000	4.129	1.099	0.583	4.129	0.541	0.541	0.343
S03	4.040	1.023	0.277	3.896	0.976	0.125	4.258	0.914	0.916	4.000	0.208	0.208	0.407
S05	4.016	1.003	0.194	3.896	0.939	0.125	3.903	1.088	0.000	4.129	0.983	4.129	0.309
S01	3.959	3.959	0.000	4.000	0.963	0.500	4.000	1.163	0.250	3.919	0.000	0.000	0.985

Based on normalized values, seven issues (F05: High cost of implementation due to the increased amount of sensors and computational resources needed, F07: Lack of regulation for digital twin implementations, F02: Issues related to data (trust, privacy, cybersecurity, convergence and governance, acquisition and large-scale analysis), F06: Lack of communication network-related obstacles) have normalized values ≥ 0.5 were considered significant. Conversely, issues such as F01 (Lack of framework), F03 (Lack of standards), and F04 (Organizational issues) had normalized values less than 0.5, indicating they were not deemed as critical by the respondents.

Similarly, the analysis of countermeasures highlighted that seven strategies, particularly (S04: Improved planning and prediction for flood, S06: Provide real-time sensor for flood, S07: Increase the use of AI to satisfy the requirements for data analysis for digital twin technology) were prioritized by the respondents with normalized valued ≥ 0.5. These strategies had normalized values equal to or greater than 0.5, signifying their effectiveness in addressing the identified issues. while (S02: Provide 3D simulation of flood, F03: Expand situational awareness on flood and S01: Increase secure data management for data processing and software) is not critical.

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Result agreement analysis on issues and countermeasures using digital twin technology

Table 4 and Table 5 show the p-value for four factors was larger than 0.05 for Kruskal-Wallis, although the p-values for F01, F03, and F04 were statistically significant (p 0.05), indicating no statistically significant difference among the groups. The decision criteria associated with the critical factors are as follows: (F05), (F04), (F01), and (F07), demonstrating a significant difference in opinions across the different groups.

For countermeasures, the p-value is greater than 0.05: (S01), (S04), and (S07) expand the usage of AI to meet the data analysis needs for digital twin technology. Indicating these strategies were generally agreed upon across different groups. While p-values for (S02), (S06), and (S05), (S03) were less than ($p \leq 0.05$), reflecting significant differences in their perceived effectiveness among the respondents. The decision criteria linked with the important strategies are as follows: (S06), and (S05).

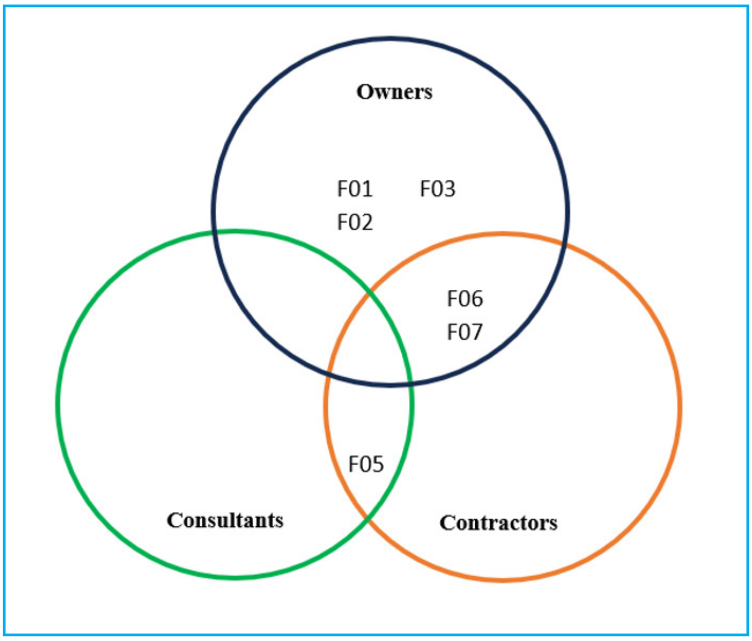


Figure 2. Issues overlapping analysis using a digital twin analysis

Result from overlap analysis

Figures 2 and 3 show the findings of the analysis for the various categories of concerns and strategies, which include owners, consultants, and contractors. The unique overlapping aspect for improved planning and prediction for floods and provides real-time sensors for floods.

The overlapping of issues between contractor and consultant is a high cost of implementation due to the increased amount of sensors and computational resources needed. The overlapping between owners and contractors is a lack of communication network-related obstacles and a lack of regulation for digital twin implementations. Other issues for owners are lack of framework, and Issues related to data (trust, privacy, cybersecurity, convergence and governance, acquisition, and large-scale analysis) and, lack of standards.

Based on Figure 3 the overlapping between owners, contractors, and consultants improves planning and prediction for floods and provides a real-time sensor for floods, next overlapping between consultants and owners Increases the use of AI to satisfy the requirements for data analysis for digital twin technology. lastly, the overlapping between consultants and contractors is to provide the 3D simulation of the flood.

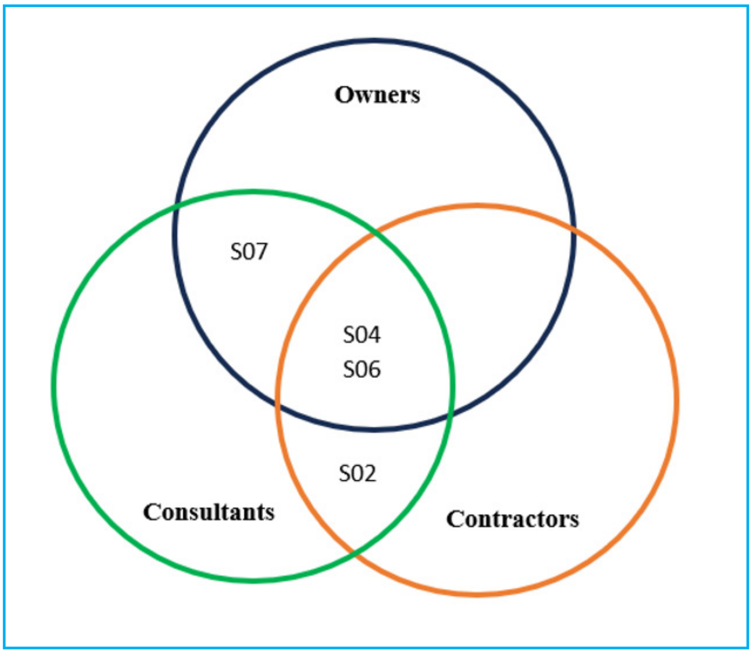


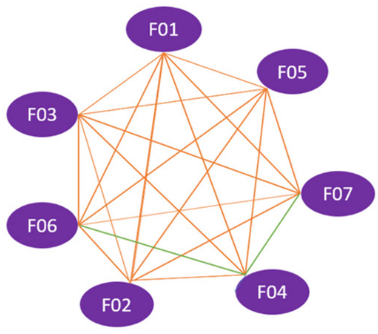
Figure 3. Countermeasure overlapping analysis using digital twin analysis

Result correlation analysis

Figure 4, Figure 5, and Figure 6 along with Table 6 and Table 7 represent Spearmen's correlation coefficients between issues and countermeasures utilising digital twin technology in Malaysia's coastal area. The approach computes the values of the variables' relationships. Some of the variables, however, exhibit a moderate connection that is all significant at 0.05.

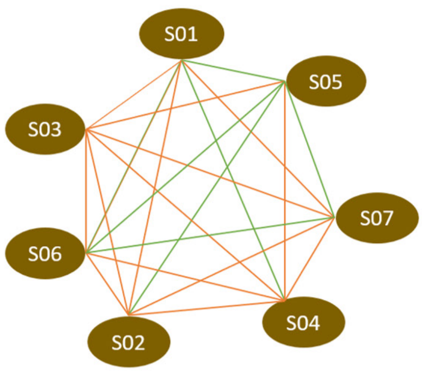
Spearmen's correlation coefficients (r) between two collaboration issues elements and the findings show that several of the consequences have a moderate association. Figure 4 the findings show that several of the consequences have a moderate association as are Organization issues and lack of regulation for digital twin implementations. Meanwhile based on Figure 5, the findings show that several of the consequences have a moderate association. The moderately associated effects are as follows, improved planning and prediction for floods, increased integration and collaboration for engagement and participation, provided real-time sensors for floods, and an increase in the use of AI to satisfy the requirements for data analysis for digital twin technology. Figure 6 analyses the interrelationship among organisations for the application of digital twins in

Malaysia. the high correlation is 168 and 12 for the moderate correlation. These results indicate that there are some associations between the collaboration strategies of owners and contractors.



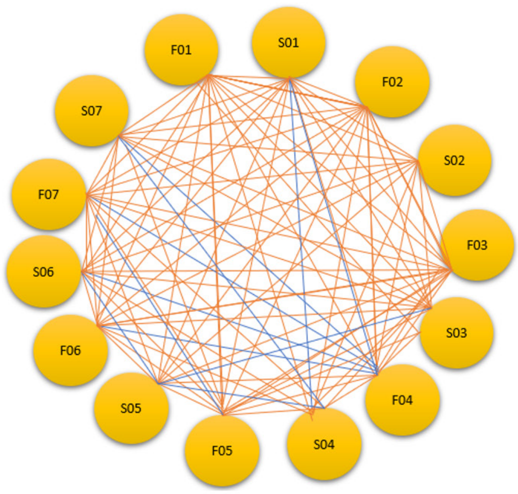
High correlation	38
Moderate correlation	2

Figure 4. Issues/Factor correlation analysis



High correlation	39
Moderate correlation	4

Figure 5. Countermeasure correlation analysis



High correlation	168
Moderate correlation	12

Figure 6. Interrelationship between issues and countermeasure

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Table 6. Result issues correlation analysis

Code	Issues	F01	F02	F03	F04	F05	F07	F08
F01	Lack of framework	1						
F02	Issues related to data (trust, privacy, cybersecurity, convergence and governance, acquisition and large-scale analysis)	0.869**	1					
F03	Lack of standards	0.798**	0.763**	1				
F04	Organization issues	0.796**	0.764**	0.786**	1			
F05	High cost of implementation due to the increased amount of sensors and computational resources needed	0.731**	0.746**	0.720**	0.705**	1		
F06	Lack of communication network-related obstacles	0.905**	0.782**	0.712**	0.662**	0.754**	1	
F07	Lack of regulation for digital twin implementations	0.793**	0.750**	0.789**	0.680**	0.738**	0.763**	1

Notes *represents issues with correlation significant at the 0.05 level (two-tailed); **Represents issues with correlation significant at 0.01 level (two-tailed)

Table 7. Result countermeasure correlation analysis

Code	Countermeasure	S01	S02	S03	S04	S05	S06	S07
S01	Increase secure data management for data processing and software.	1						
S02	Provide 3D simulation of flood.	0.772**	1					
C03	Expand situational awareness on flood	0.715**	0.768**	1				
C04	Improved planning and prediction for flood.	0.647**	0.715**	0.805**	1			
C05	Increase integration and collaboration for engagement and participation.	0.694**	0.642**	0.722**	0.768**	1		
C06	Provide real-time sensor for flood.	0.711**	0.741**	0.790**	0.732**	0.695**	1	
C07	Increase the use of AI to satisfy the requirements for data analysis for digital twin technology.	0.698**	0.705**	0.761**	0.741**	0.662**	0.696**	1

Notes *represents Strategies with correlation significant at the 0.05 level (two-tailed); **Represents strategies with correlation significant at 0.01 level (two-tailed)

Conclusion

In conclusion, the research on organizational interrelationships for the implementation of digital twin technology in Malaysia revealed some critical conclusions. To effectively use digital twin technology, the study identified the issues and significance of collaborative networks and information sharing among organizations to enhance the successful adoption of digital twin technology in flood management. The critical issue is F05 which is, the high cost of implementation due to the increased amount of sensor and computational resources needed are considered the most critical. While the countermeasures are S04, improved planning and prediction for flood is considered the highest rank among the countermeasures. It also emphasized improved flood planning and prediction, as well as providing real-time sensing for flood mutual support, to maximize the potential benefits of this technology. The study also emphasized the importance of a collaborative approach to data management and security to ensure the successful integration of digital twin systems across organizations. These findings highlight the importance of inter-organizational interactions in the successful adoption and use of digital twin technology in Malaysia.

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Conflicts of Interest

The authors declare no competing interest.

Author Contributions

Nur Arina Amirah Azlan: writing, original draft preparation. **Rahimi Abdul Rahman:** writing, reviewing and editing. **Bala Ishiyaku:** reviewing and editing. **Ahmad Rizal Alias:** funding and reviewing.

Data Availability Statement

The data used to support the findings of this study are included within the article.

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