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A Choquet Integral with DEMATEL-based Method for Coastal Erosion Decision Problem

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Abstract

Background/Objectives: This study aims to investigate the cause-effect relationship risk factors associated to coastal erosion decision problem using a decision model based on Choquet integral and Decision-making Trial and Evaluation Laboratory (DEMATEL) method. **Methods/Statistical Analysis:** In this study, DEMATEL method is used to determine the cause-effect diagram of the risk factor. DEMATEL is known as one of the tools in dealing with digraph visualization of the degree importance for factor influence. Meanwhile, a Choquet integral is used to yield the aggregation among the subjective preference judgement made by the decision makers based on normal capacity. The process of combining a several preference values into a single value is called as an aggregation process. **Findings**: The Choquet integral DEMATEL-based approach is applied to coastal erosion decision problem to evaluate both interactive and causal relationship of the risk factors. There are two phases involve in this method. The first phase is to illustrate the relationship digraphs of selected risk factors and the implementation of weighted eigenvector matrix comparison in DEMATEL-based method. The second phase takes into aggregation of the multi-criteria decision risk factors by fuzzy measure and Choquet integral to obtain the integrated weights value. From the study, it is indicated that shoreline changes has the highest score of Choquet integral by 1.8198 that contribute the most to the coastal erosion followed by relative sea level rise (1.5791), climate change (1.1917) and wave condition (0.9315). **Application/Improvements**: The feasibility of the developed method can be used to improve the risk factors of coastal erosion management and assessment.

Keywords: Cause-effect Relationship, Choquet Integral, Coastal Erosion, DEMATEL Method, Risk Factors

1. Introduction

Coastal erosion is one of the environmental issues that lead the authorities to prevent this problem from getting worse in order to protect the variety of natural resources and population biodiversity in the coastline area. Coastal erosion can be induced by both natural effects and human-factors activities. The natural factors such as wind, waves and continuous wave height leads to the unstable waves and severe some dangerous storm that reaches the shoreline. The sea level rise and the changes of climate may also cause the coastal erosion by water flooding and increase the depth of the water[1]. In addition, the human-induced factors and coastal developments also tends to expose the coastline to the erosion from construction of navigation channels, dredging, reclamation, water extraction, artificial islands/artificial lagoon and also ports and harbours[1]. The sediment movement from the development and construction lead to cause wave shadow area and causing the acceleration of sediment transport on the down-drift coastline which lead to coastal erosion[1].

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The rapid development and economic monopoly, town planning nowadays were too many illogical aspects rather than healthy and sanitary environment conditions[2]. The rivalry between dynamic ecosystems and human activities on the coastal zones results in inducing a negative impact on the societal value of the coastline and environmental issues[3]. Thus, it is compulsory to investigate and evaluate how much this risk factor related to coastal erosion to overcome the coastal erosion. A risk assessment is needed to provide a set of policy recommendation, erosion planning and coastal hazard protection and local information for decision making system. Besides, the previous studies only focus on the general coastal erosion problem without capability on demonstrated the knowledge of decision making toward causal-relationships between factors and the interaction between the information provided by the decision maker.

Hence, this study intends to investigate the influence risks factor related to coastal erosion problems using Decision Making Trial and Evaluation Laboratory (DEMATEL)-based method and Choquet integral as fuzzy measurement. The direct and indirect risk factors are evaluated using DEMATEL-based method and illustrate the causal relationship diagrams for coastal erosion decision problem as the first phase of the Choquet integral DEMATEL-based method. The DEMATEL method was introduced by the Science and Human Affairs Program at the Battelle Memorial Institute's Geneva research Centre[4], as a structural modelling approach about complex problems in scientific fields[5]. The DEMATEL is used to visualize the causal relationship between the criteria and indicate the degree of factor influence to each other[6]. Upon the increases attention to the real decision problems, DEMATEL method has widely been used in various applications such as environmental sciences[7], technology[8] and management[9,10]. The DEMATEL method gathers collective information to capture the causal relationship between potential criteria and basically visualize them into digraphs[11].

The DEMATEL-based method is extended by the implementation of one step involving the calculation of the weighted eigenvector matrix comparison to be proceeding for the next phase of Choquet integral. The Choquet integral is used to calculate an aggregation of decision maker judgement. In recent years, lots of study investigates a Multi-Criteria Decision Making (MCDM) problems as an evaluation toward the real implementation of complicated situation. Meanwhile, working on MCDM problems need an essential important step to aggregate the information provided by decision makers since the performing criteria is independent or lacks of interactive measure. The aggregation operator used by many authors in the decision making process is mostly do not consider the interaction between the information provided by decision makers[12]. To tackle this problem, the concept of fuzzy measure (monotonicity) which introduced by Sugeno[13] instead of additivity property is used to model the interaction of interdependent decision criteria in MCDM problems[14,15]. One of the main characteristics of Choquet integral is a wide range of circumstances and approaches can be considered in the closest accordance of the interests can be selected.

This paper is organized as follows. In Section 2 describes an overview of DEMATEL-based method and the Choquet integral definitions. Section 3 demonstrates the methodology of the Choquet integral DEMATEL-based method as one of tools in dealing with MCDM problems. Section 4 implements the coastal erosion decision problem using Choquet integral DEMATEL-based method. Section 5 discusses the results and some implication of the case study. Finally, a simple conclusion with future recommendations is represented in Section 6.

1.1 DEMATEL Method and Choquet Integral

This section describes the details on DEMATEL method and Choquet integral concept.

1.2 DEMATEL Method as Modelling the Causal Relationship

The DEMATEL technique has widely used to determine the critical point of the risk assessment in the decision process. To details, the DEMATEL method can be summarized by the succeeding steps:

Step 1: Calculate the average matrix, A of the expert,

H and n factors are considered for the investigate problem. Each expert is required to indicate the measure, for a considerable of a criteria, i, affects criteria j. The comparison matrix between any two criteria are denoted by

Table 1. The linguistic scale of DEMATEL method[16]

Linguistic Number	Linguistic preference
0	No influence
1	Low influence
2	Medium influence
3	High influence
4	Very high influence

x_{ij}^{k} and the linguistic scale is given an integer score 0-4 (see Table 1).

The $n \times n$ averaging score of the H can be computed by Equation (1):

$$A_{ij} = \frac{1}{H}\sum_{k=1}^{H} X_{ij}^{k} \qquad (1)$$

Then, the total average matrix can be defined as:

$$A = \begin{bmatrix} a_{11} & \cdots & a_{1j} & \cdots & a_{1n} \\ \vdots & & \vdots & & \vdots \\ a_{i1} & \cdots & a_{ij} & \cdots & a_{in} \\ \vdots & & \vdots & & \vdots \\ a_{n1} & \cdots & a_{nj} & \cdots & a_{nn} \end{bmatrix} \qquad (2)$$

Step 2: Calculate the initial direct-influence matrix, D by normalizing the average matrix A as follows:

$$D = \frac{A}{s} \qquad (3)$$

where $s = \max\left(\max_{1\le i\le n} \sum_{j=1}^{n} a_{ij}, \max_{1\le i\le n} \sum_{i=1}^{n} a_{ij}, \right) \qquad (4)$

Since that the sum of each row j of matrix A has represented the direct effects that factor exerts on the other factors, $\max_{1\le i\le n} \sum_{j=1}^{n} a_{ij}$ represent the factor of the highest direct influence on the other factors. Likewise, since the sum of each column i of the matrix A represents the direct effects by a factor i, $\max_{1\le i\le n} \sum_{j=1}^{n} a_{ij}$ represents the factor which is the most influenced factor by the other factors. The positive scalar s is equal to the bigger of two extreme sums. The matrix D is obtained by dividing each element of A by the scalar. Note that each element d_{ij} of the matrix D is between 0 and 1.

Step 3: Compute the total relation matrix T by Equation (5):

$$T = D(I - D)^{-1} \qquad (5)$$

where I is the identity matrix. Denote r_i be the sum of i row in matrix T, then r_i summarizes both direct and indirect effects given by factor i to the other factors. The sum $(r_i + c_j)$ shows the total effects given and received by factor i and indicates the degree of importance for factor i in the entire system. In contrast, the difference $(r_i - c_j)$ represents the net effect that factor i contributes to the system. If $(r_i - c_j)$ is positive, factor i

is a net cause, while factor i is a net receiver or result if $(r_i - c_j)$ is negative.

Step 4: Set up a threshold value to illustrate the causal relationship diagram. The threshold value can be set up by figuring the average of the elements in the matrix T.

The digraph can be acquired by mapping the data set of $(r+c, r-c)$.

Step 5: Calculate the weighted matrix eigenvector, W_{ij} for each matrix comparison by Equation (6);

$$W_{ij} = \frac{\left(\sum_{i=1} T_i\right)^{1/n}}{\sum\left(\left(\sum_{i=1} T_i\right)^{1/n}\right)} \quad (6)$$

where n is sum of elements.

2. The Choquet Integral as Aggregation Measure

The Choquet integral takes into account the interaction of fuzzy measure. The definition of fuzzy measure is given as below;

Definition 2.2.1: Let $X = \{x_1, x_2, \ldots, x_N\}$ be a non-empty finite set and $g: 2^X \rightarrow [0,1]$, be a fuzzy measure with the following properties[17,18]:

$g(\phi) = 0, g(X) = 1$ (boundary conditions)

If $A \subseteq B \subseteq X$ then $g(A) \leq g(B) \leq 1$ (g is non-decreasing)

The measure g is the confidence or worth of each subset information source that tells property (1) has the worth of no sources, the ϕ is 0 and the worth of *all* sources, is 1 to the universal set of X. Property (2) follows that the two sources are worth at least as much as one, three sources are worth at least as much as two and so on.

Definition 2.2.2[19–21]: Let $X = \{x_1, x_2, \ldots, x_n\}$ be a non-empty finite set, the Choquet integral of $f: X \rightarrow [0,1]$ with respect to non-monotonic fuzzy measure g can be denoted by:

$$C_g(f) = \sum_{i=1}^{N} f(x_{\pi(i)})\left(g(A_{\pi(i)}) - g(A_{\pi(i+1)})\right)$$

where π is permutation of X, such that $f(x_{\pi(1)}) \leq f(x_{\pi(2)}) \leq \ldots \leq f(x_{\pi(N)})$, $A_{\pi(i)} = \{x_{\pi(i)}, \ldots, x_{\pi(N)}\}$, and $g(A_{\pi(N+1)}) = 0$.

Definition 2.2.3[20,21]: The Choquet integral $\int f \, d\mu$ is said to be monotonic with respect to integrand f, if $f_1 \leq f_2$ implies $\int f_1 \, d\mu \leq \int f_2 \, d\mu$.

2.1 Methodology of the Choquet Integral DEMATEL-based Method

The Choquet integral DEMATEL-based method is divided into two main phase which is the first phase is determining the causal relationship of the selected criteria using DEMATEL method. The second phase of the method takes into aggregated of multiplicity of criteria by using weighted eigenvector matrix comparison calculated on the first phase. To demonstrate the main idea of this method, Figure 1 is constructed to illustrate the method.

The framework of Choquet integral DEMATEL-based Method is implemented to the coastal erosion decision problem to test the feasibility of the approaches in dealing with MCDM problems.

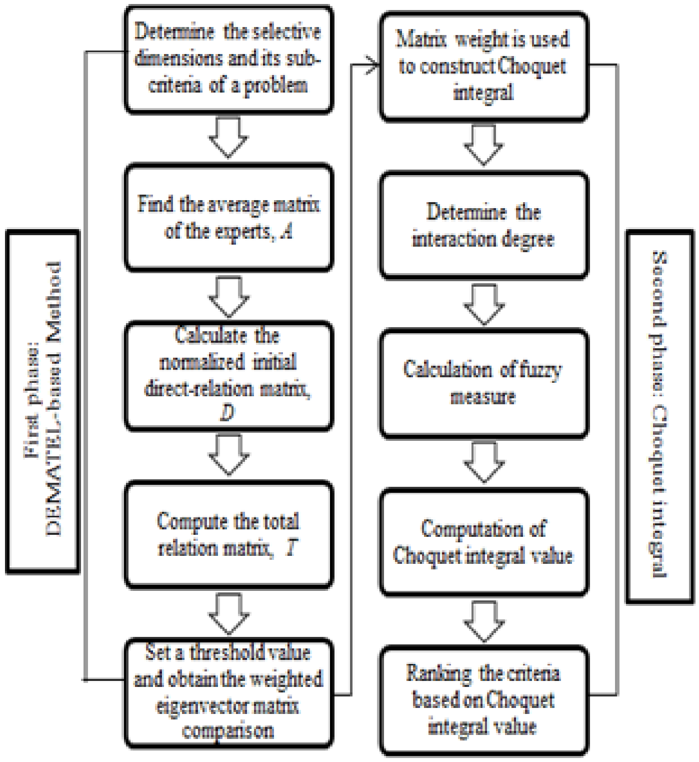

Figure 1. Framework of Choquet integral DEMATEL-based method.

Table 2. Four Dimensions with fourteen critical criteria

Dimension	Critical Criteria
Shoreline changes/evolution, D_1	Population density, C_1 Hydrodynamic pattern, C_2 Longshore sediment transport, C_3
Relative sea level rise, D_2	High intensity of current longshore, C_4 Tidal range, C_5 Sea area class, C_6
Wave condition, D_3	High significant wave, C_7 Maximum wave height, C_8 Wave acceleration/gusts, C_9 Wave pattern, C_{10}
Climate change, D_4	Wave climate, C_{11} Seasonal climate (e.g.: Heavy rain), C_{12} Storm surge, C_{13} Wind speed, C_{14}

2.2 Implementation of the Method to Coastal Erosion Decision Problem

The main four dimensions and fourteen criteria had been identified from the pointed literature review and consultation with the expert to demonstrate the net causes of the erosion. The experts need to judge the relative measurement between the dimensions and its critical criteria criterion using comparison matrix. The dimensions and its critical criteria contribute to coastal erosion problems are shown in Table 2.

Phase 1: The DEMATEL-based Method

The causal relationship between the four dimensions of Shoreline changes/evolution (D_1), Relative sea level rise (D_2), Wave condition (D_3) and Climate changes (D_4) using DEMATEL method is developed as below. The computation is based on the three experts (X^1, X^2, X^3) and their linguistic influence factor scale.

$$X^1 = \begin{pmatrix} 0 & 4 & 2 & 1 \\ 0 & 0 & 3 & 3 \\ 0 & 1 & 0 & 4 \\ 0 & 0 & 0 & 0 \end{pmatrix} \qquad X^2 = \begin{pmatrix} 0 & 4 & 2 & 1 \\ 1 & 0 & 3 & 3 \\ 4 & 1 & 0 & 4 \\ 4 & 1 & 1 & 0 \end{pmatrix}$$

$$X^3 = \begin{pmatrix} 0 & 1 & 3 & 4 \\ 4 & 0 & 1 & 1 \\ 2 & 3 & 0 & 4 \\ 1 & 3 & 14 & 0 \end{pmatrix}$$

The average matrix, A of four dimensions is calculated by Equation (1).

$$A = \begin{pmatrix} 0 & 3.0000 & 2.3333 & 2.0000 \\ 1.6667 & 0 & 2.3333 & 2.3333 \\ 2.0000 & 1.6667 & 0 & 4.0000 \\ 1.6667 & 1.3333 & 1.6667 & 0 \end{pmatrix}$$

Next, the normalized initial direct influence matrix D is computed using Equation (3).

$$D = \frac{1}{8.3333}\begin{pmatrix} 0 & 3.0000 & 2.3333 & 2.0000 \\ 1.6667 & 0 & 2.3333 & 2.3333 \\ 2.0000 & 1.6667 & 0 & 4.0000 \\ 1.6667 & 1.3333 & 1.6667 & 0 \end{pmatrix}$$
$$= \begin{pmatrix} 0 & 0.36 & 0.28 & 0.24 \\ 0.20 & 0 & 0.28 & 0.28 \\ 0.24 & 0.20 & 0 & 0.48 \\ 0.20 & 0.16 & 0.20 & 0 \end{pmatrix}$$

Equation (5) is computed to obtain the total relation matrix T of the four dimensions.

$$T = D(I - D)^{-1}$$
$$= \begin{pmatrix} 0 & 0.36 & 0.28 & 0.24 \\ 0.20 & 0 & 0.28 & 0.28 \\ 0.24 & 0.20 & 0 & 0.48 \\ 0.20 & 0.16 & 0.20 & 0 \end{pmatrix} \bullet \left(\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} - \begin{pmatrix} 0 & 0.36 & 0.28 & 0.24 \\ 0.20 & 0 & 0.28 & 0.28 \\ 0.24 & 0.20 & 0 & 0.48 \\ 0.20 & 0.16 & 0.20 & 0 \end{pmatrix} \right)^{-1}$$
$$= \begin{pmatrix} 0.6470 & 0.9639 & 0.9558 & 1.1239 \\ 0.7360 & 0.6040 & 0.8632 & 1.0401 \\ 0.8375 & 0.8494 & 0.7257 & 1.2672 \\ 0.6146 & 0.6193 & 0.6744 & 0.6446 \end{pmatrix}$$

Table 3. Total relation matrix and sum of influence for dimensions

Dimensions	r_i	c_j	$(r_i + c_j)$	$(r_i - c_j)$
Shoreline changes/ evolution, D_1	3.6906	2.8351	6.5257	0.8555
Relative sea level rise, D_2	3.2433	3.0366	6.2799	0.2067
Wave condition, D_3	3.6798	3.2191	6.8989	0.4607
Climate change, D_4	2.5529	4.0758	6.6287	-1.5229

In step 4, the threshold value for these four dimensions is set up to 0.8229 to visualize the digraph of cause-effect relationship diagram and Table 3 is established to represent the total summarized of direct and indirect effects for the four dimensions.

From Table 3, shoreline evolution/changes, relative sea level rise and wave condition are net causes due to the positive value of $\left(r_i - c_j\right)$, while climate change is net receivers because of negative value of $\left(r_i - c_j\right)$.

The Table 3 describes that shoreline changes/evolution (D_1), relative sea level rise (D_2) and wave conditions (D_3) are net causes and have mutual interaction toward each other. That means, if either one of each aspect is going to affect each other. However, wave conditions are the most essential dimension and have influenced the climate change which is net receiver. Since the second highest value of $(r_i + c_j)$, climate change also have an influence toward relative sea level rise.

For the final step in the first phase of DEMATEL-based method, the weighted eigenvector of matrix comparison for dimension is calculated by Equation (6) and Table 4 details the weighted eigenvector matrix comparison for the dimension.

Phase 2: The Choquet Integral

In this phase, the calculation was made by using Fuzzy Measure-Choquet Integral Calculation System software produced by[22].

Table 4 describes the weights of eigenvector matrix comparison for the dimension and the results are used for Choquet integral calculations. Figure 2 shows the input of the weight for dimension of the coastal erosion problems.

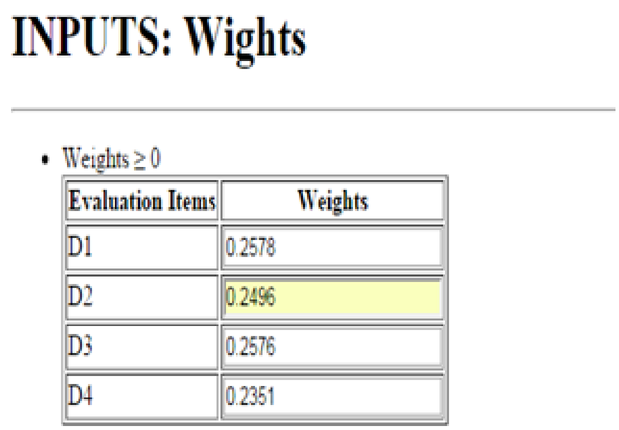

Figure 2. Weight of dimension input.

Next, determine the interaction degree for the evaluation. In this study, the interaction degree is used as 0.5 for weighted sum dimension. Figure 3 shows the input for interaction degree.

Table 4. Weighted eigenvector matrix comparison for dimensions

Dimensions	$\sum r_i$	$\left(\sum_{i=1} T_i\right)^{1/n}$	W_i
Shoreline changes/ evolution, D_1	3.6906	1.3860	0.2578
Relative sea level rise, D_2	3.2433	1.3420	0.2496
Wave condition, D_3	3.6798	1.3850	0.2576
Climate change, D_4	2.5529	1.2640	0.2351

INPUTS: Interaction Degree

$\xi \in [0,1]$ 0.5

- $\xi \in [0,1]$
- $\xi = 0.5$: Weighted Sum
- $\xi \rightarrow 1$: Output $\rightarrow$ Maximum input
- $\xi \rightarrow 0$: Output $\rightarrow$ Minimum input

Figure 3. Interaction degree identification.

Confirmation: Identified Fuzzy Measure

Identified Fuzzy Measure

Sets	Fuzzy Measure
{}	0
{D1}	0.257774
{D2}	0.249575
{D1,D2}	0.507349
{D3}	0.257574
{D1,D3}	0.515348
{D2,D3}	0.507149
{D1,D2,D3}	0.764924
{D4}	0.235076
{D1,D4}	0.492851
{D2,D4}	0.484652
{D1,D2,D4}	0.742426
{D3,D4}	0.492651
{D1,D3,D4}	0.750425
{D2,D3,D4}	0.742226
{D1,D2,D3,D4}	1

Figure 4. Calculated fuzzy measure for sets of dimensions.

After identification of interaction degree, the process is continue by calculating the fuzzy measure for the sets of dimensions. Figure 4 describes the fuzzy measures for the dimensions.

Then, after receiving the fuzzy measures of each sets, the process is continue by computation of Choquet integral values. The average matrix, A of decision makers calculated by Equation (1) is used as a data input to obtain

Display: Choquet Integrated Values

Display: Input Values and those Choquet Integrated Values

No.	D1	D2	D3	D4	Choquet Integrated Values
1	0	3	2.3333	2	1.81988
2	1.6667	0	2.3333	2.3333	1.57913
3	2	1.6667	0	0	0.931515
4	1.6667	1.3333	1.6667	0	1.19169

Figure 5. The Choquet integrated value of the dimension.

the Choquet integral value. Figure 5 illustrate the Choquet integrated value of the dimensions.

From the Figure 5, it can be seen that the ranking of the dimension based on Choquet integral value shows that shoreline changes, D_1 has the highest score by 1.8198 that contribute the most toward the coastal erosion followed by relative sea level rise, D_2 and climate change, D_4. Wave condition, D_3 has the lowest score indicate by 0.9315.

3. Result and Discussion

The procedures of Choquet integral DEMATEL-based method is proceed in a similar fashion to compute the Choquet integral value and demonstrate the cause-effect relationship of the critical criteria of each dimension. Figure 6 shows a diagram relation of the critical criteria.

Table 5 describes the Choquet integrated value for the critical criteria. From Table 5, the finding suggest that Population density, C_1 has the highest value that contribute to shoreline changes/evolution compared to long shore sediment transport, C_3 and Hydrodynamic pattern, C_2 respectively. For relative sea level rise, the most contributed criteria is a high density of current long shore, C_4 by 2.6307 followed by tidal range, C_5 and sea area class, C_6. Meanwhile, wave acceleration/gusts, C_9 is influential criteria to wave conditions of the shoreline. However, for climate changes, the wave climate, C_{11} is happen to effect the most with the highest score compared to seasonal cli-

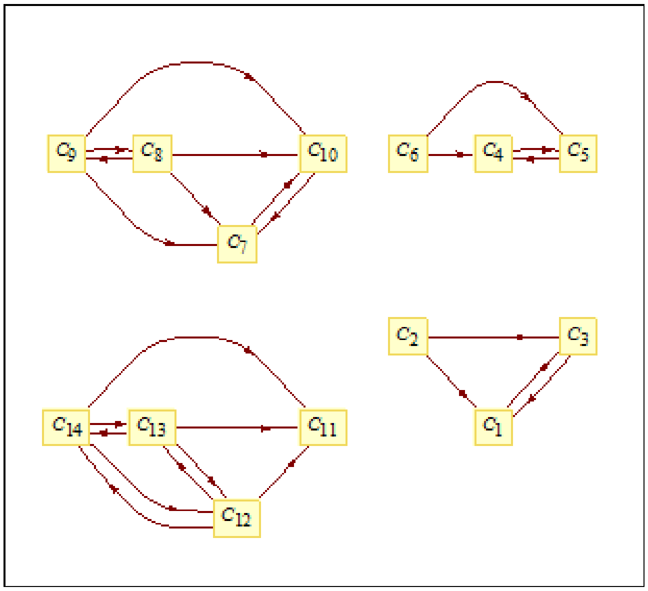

Figure 6. Cause-effect relationship diagram of critical criteria.

Table 5. Choquet integrated value for critical criteria

Critical Criteria	Choquet Integrated value
Choquet integrated value for critical criteria of shoreline changes/evolution	
Population density, C_1	2.5603
Hydrodynamic pattern, C_2	0.9397
Long shore sediment transport, C_3	2.1288
Choquet integrated value for critical criteria of relative sea level rise	
High density of current long shore, C_4	2.6307
Tidal range, C_5	1.8775
Sea area class, C_6	1.3736
Choquet integrated value for critical criteria of wave condition	
High significant wave, C_7	2.2487
Maximum wave height, C_8	2.1733
Wave acceleration/gusts, C_9	2.3282
Wave pattern, C_{10}	2.2500

Choquet integrated value for critical criteria of climate changes	
Wave climate, C_{11}	2.6788
Seasonal climate (e.g.: Heavy rain), C_{12}	1.3598
Storm surge, C_{13}	1.5584
Wind speed, C_{14}	2.0830

mate (e.g.: Heavy rain), C_{12}, storm surge, C_{13} and wind speed, C_{14}.

4. Conclusion

This study investigates the selected dimensions and its critical criteria as the main character that contributes the coastal erosion decision problems using Choquet integral DEMATEL-based method. The main innovation of this paper is to demonstrate both the relation and interaction of the criteria and information provided by the decision maker in one approach. The Choquet integral DEMATEL-based method consists two main phases which are the modelling the causal relationship of the selected dimensions and its critical criteria and proceed by the interaction of the knowledge information by the Choquet integral. From the modelling of cause-effect relationship, it can be described that the shoreline changes/evolution (D_1), relative sea level rise (D_2) and wave conditions (D_3) are net causes and have mutual interaction toward each other. That means, if either one of each aspect is going to affect each other. However, wave conditions are the most essential dimension and have influenced the climate change which is net receiver. In the term of interaction by Choquet integral, the most influential risk factor that contributing to the coastal erosion is shoreline changes followed by relative sea level rise, and climate change and wave condition. For the extension of the study, it is recommended to test the feasibility of the results approach by sensitivity analysis. Besides, instead of using the crisp value, it can be also to apply fuzzy approach to illustrate the linguistic information of the decision maker.

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