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Fermatean Fuzzy DEMATEL and MMDE Algorithm for Modelling the Barriers of Implementing Education 4.0: Insights from the Philippines

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Citation: Gonzales, G.; Costan, F.; Suladay, D.; Gonzales, R.; Enriquez, L.; Costan, E.; Atibing, N.M.; Aro, J.L.; Evangelista, S.S.; Maturan, F.; et al. Fermatean Fuzzy DEMATEL and MMDE Algorithm for Modelling the Barriers of Implementing Education 4.0: Insights from the Philippines. *Appl. Sci.* **2022**, *12*, 689. https://doi.org/10.3390/app12020689

Academic Editor: Hong-Zhong Huang

Received: 15 November 2021
Accepted: 21 December 2021
Published: 11 January 2022

Abstract: Technological transitions in the education sector of developing economies are faced with a range of barriers, involving resource scarcity, socio-cultural concerns, and issues related to management and policy. The popularity of Industry 4.0 has prompted Education 4.0 (EDUC4), an approach to learning that involves transformation using advanced technologies. While a recent work reported a comprehensive list of barriers to EDUC4 implementation, particularly in developing economies, further analysis to identify those priority barriers remains a gap. Thus, this work addresses this gap by introducing a novel methodological extension of the decision-making trial and evaluation laboratory (DEMATEL) method following the integration of Fermatean fuzzy sets (FFS). The FFS, compared to other fuzzy environments, could capture higher levels of uncertainties that are associated when eliciting judgments necessary for the DEMATEL. Such integration is aided by the maximum mean de-entropy (MMDE) algorithm, which analytically determines the threshold value crucial for constructing the prominence-relation map of the DEMATEL. Following its application in evaluating the implementation of EDUC4 in Philippine universities, the critical barriers are the lack of training resources, costs, insufficiency of available technologies, skills gap of human resources, knowledge gap, and the complexity of the learning platforms. Among this set, barriers related to cost and lack of training resources are deemed the most prominent ones. The statistical test on the impact of addressing the two prominent barriers shows that addressing the barrier related to costs yields statistically more favorable results regarding the mitigation of other EDUC4 implementation barriers. Although these insights may contain idiosyncrasies, they can serve as starting points of discussion in other relevant developing economies. These methodological and practical contributions advance the development of analytical tools under uncertainty that can handle pressing problems such as the EDUC4 implementation.

Keywords: Fermatean fuzzy sets; DEMATEL; maximum mean de-entropy; Education 4.0; developing economies

1. Introduction

The use of big data, IoT, virtual and augmented reality, machine learning, and other IT paradigms laid the basis for the fourth industrial revolution (4IR) [1]. The transformation brought about by the 4IR has led the education sector to adopt Education 4.0 (EDUC4), which aims to utilize technologies in the 4IR for education [2]. Such transition prompted the development of technology-based pedagogical approaches. The central idea of EDUC4 is to integrate information and communications technology into the curricula to prepare learners for the 4IR. However, several EDUC4 implementation barriers have recently become obvious. In the context of human resources, the necessary realignment of competencies of various stakeholders is among the factors that lag EDUC4 implementation [3]. Arguably, the most noticeable aspect of EDUC4 is the potential displacement of human intellectual capital due to the emergence of artificial intellectual capital [4]. Previous works (i.e., Ref. [4]) have illustrated that 85% of the higher education system can be automated with artificial intelligence (AI) in EDUC4. This issue warrants the identification of crucial learning characteristics to synergize human and artificial intellectual capital [5].

A foremost challenge to adopting EDUC4 lies with how educational leaders can successfully evaluate and frame its necessary changes [6]. Educational leaders and policymakers play a vital role in this respect. Specifically, they are role players in the augmentation of financial deficiencies surrounding the execution of EDUC4 [7]. The financial barrier is also embedded in the infrastructure-related challenges in EDUC4. Furthermore, the technological requirements of 4IR entail a mandatory institutionalization of modern equipment in universities [8], as infrastructure is closely linked to EDUC4 implementation. These practical observations show the interrelatedness of barriers to EDUC4 implementation, encompassing human resource, financial, technological, and infrastructure transition aspects.

Although the developed world may face various issues at scale, investigating EDUC4 barriers becomes increasingly important in developing economies for the following reasons: First, developing economies are characterized by resource scarcity, i.e., limited financial resources to build infrastructures required for EDUC4 implementation. Second, educational politics in developing economies are not sharply differentiated from the spheres of social and personal relations, making them susceptible to monopolistic markets and corruption. This dilemma ripples to other management difficulties (i.e., difficulties in project implementation) in the education sector. Lastly, the cultural aspect in developing economies has been found to hamper technological transitions [9]. In developing countries, the relatively low socio-economic status of people makes them more accustomed to outdated pedagogical methods [10], which can impede crucial transitions towards EDUC4.

For the developing economies, Thorell et al. [11] underlined the necessary alignment of the strategies for implementing EDUC4 not just in infrastructure for universities but also in the inherent incapability of the students and parents to provide the needed technology at home. To this end, a recent work reported by Costan et al. [10] comprehensively identifies a set of 12 barriers to implementing EDUC4 among higher education institutions (HEIs) in developing economies through a systematic literature review. They provided essential insights into how these barriers interplay within HEIs, particularly in developing economies, and offered possible interlinkages among these barriers to aid educational leaders in carrying out crucial decision-making processes. This work intends to respond to their call to identify priority EDUC4 implementation barriers. Narrowing the focus to those priority barriers is necessary for planning, resource allocation decisions, and strategy development for the effective, efficient, and sustainable transition to EDUC4. To this end, three research questions are highlighted in this work: (1) How can EDUC4 barriers be prioritized while accounting for their interrelationships? (2) What strategies can be employed to address priority EDUC4 barriers? (3) What are the effects of addressing priority EDUC4 barriers?

Building on the previous work of Costan et al. [10], an expert elicitation-based analytic approach using the decision-making trial and evaluation laboratory (DEMATEL) [12,13] is adopted in this work. The DEMATEL is used to evaluate the intertwined causal relationships among EDUC4 barriers. The output of the DEMATEL is a subset of barriers that are crucial for EDUC4 implementation. However, the expert elicitation inputs of the DEMATEL are subject to epistemic uncertainties, which may yield counterintuitive insights when not addressed. While various extensions of the DEMATEL were introduced to address the uncertainties in eliciting judgments, this work integrates the notion of Fermatean fuzzy sets (FFS) [14] into the DEMATEL analysis, along with the maximum mean de-entropy (MMDE) algorithm [15] to discriminate less critical EDUC4 barriers from the most critical ones. The use of the FFS provided an expanded space of membership grades, which offers a platform for capturing a higher degree of uncertainty. A case study in Philippine universities demonstrates the application of such an approach and offers some strategic insights that can be extended to other developing economies. Aside from introducing the Fermatean fuzzy DEMATEL, which formed the methodological contribution of this work, the main departure of this work is in evaluating the barriers of implementing EDUC4, effectively contributing to the domain literature in gaining crucial insights not just for Philippine universities but for comparable HEIs in other developing regions.

The remainder of this paper is arranged as follows: Section 2 provides a brief literature review about EDUC4 and the background of the methodology adopted in this work, while Section 3 details some preliminaries to FFS, the DEMATEL, and the MDDE algorithm, and details the proposed approach for prioritizing EDUC4 barriers, along with the details of the post-analysis employed to analyze the results further. The case in the Philippines is adopted as the specific environment of this work. Discussions of the findings are offered in Section 4, which ends with some concluding remarks and future works in Section 5.

2. Literature Review

Halim et al. [16] characterized 4IR with new industries and modes of production powered by innovations in mechanical, biological, environmental, and digital domains. The 4IR augments the demand for technologically inclined graduates in the labor market [16]. This increase has compelled HEIs to incorporate various technologies in redesigning curriculums. The employability of graduates determines the success of HEI programs [8,17]. The transition from higher education towards employment is a challenge that could be more easily addressed through the efforts of both universities and employers as strategic partners. The graduate employment rate also supported the importance of employer–university relationships as a key performance indicator for universities [17]. It is also deemed essential to implement EDUC4 in HEIs through the specification of needs and sharing technological knowledge from private institutions [10].

On the other hand, the World Economic Forum [18] emphasized that the rapid shift in industrial processes from work performed by humans to those performed by machines and algorithms results in significant transformations of the labor market [19]. In response, the education sector is expected to lead the reconfiguration of the workforce by ensuring that competencies developed among its learners are responsive to the demands of the changing landscape of work. Since education embeds skills and competencies in the labor force [20], it is crucial to balance the impact of technological advances on economic and social infrastructure. This suggests that HEIs need to reconceive their programs, especially in STEAM education [21], to ensure that graduates possess the skills necessary in the 4IR [19].

In response to the needed technological competency, new effective educational programs will have to be improved or developed, and the existing academic curricula will have to be restructured [17]. According to Manyika et al. [22], workers who are skilled at developing and deploying industrial IoT (IIoT) systems will find themselves in greater demand. Digital competencies and innovation are widely considered to be some of the key drivers to boost the competitiveness of industrial firms within the IIoT context [17]. Thus, the education sector must produce a human workforce base that can demonstrate skills that machines cannot perform [19].

With the 4IR being the backbone of the labor market, the need for HEIs to adapt to its complementary EDUC4 principle is integral. The concept of EDUC4 includes using digital literacy and skills in critical thinking and problem-solving in an educational setting [8]. EDUC4 has become the basis for recent educational reforms globally [23]. In Asia, countries such as Vietnam, Malaysia, and Thailand have framed their version of EDUC4 to provide their workforce with the skills for 4IR [24]. Malaysia's Ministry of Education recognized the need for changes in response to EDUC4, including adapting to new learning environments and utilizing new technologies [25]. In its Thailand 4.0, Thailand recognizes the importance of its people by forging "Thai people 4.0" as the prime focus of its blueprint. The initiative intends future generations to aspire to be knowledgeable, highly-skilled, socially responsible, and maintain their Thai identity and capability of using technology. Related to these desirable characteristics are new teaching and learning paradigms, including purposeful learning, generative learning, mindful learning, and result-based learning [26].

Despite the need for EDUC4, crucial barriers in its implementation hinder HEIs. Some insights were reported in the current literature. For instance, in the domain of IIoT, reports revealed that the biggest challenge of its supporters is primarily associated with the people rather than the technology. While digital technologies are rapidly becoming a commodity, success largely depends on an organization's digital IQ [27]. The current IIoT education and training approaches fail to meet the required changes [28]. Moreover, with the changes necessary to integrate EDUC4, their implementation may not be straightforward. Turcu and Turcu [17] emphasized that changes in higher education take time. Retraining human resources to meet the market's needs takes at least two to four years, on the condition that the educational system exists for this purpose [29].

On the other hand, the current faculty professors may lack the pedagogy needed to teach in this "digitalized" world, and therefore are not competent enough to guide learners into the new era of technology-driven experiences [8]. There is a lack of knowledge and expertise in using and adapting them to the requirements of various educational activities [1]. On the other hand, some technologies might be too complex or demanding to use for some professors or learners [30]. As a case in point, Suhaimi [31] revealed that 75% of the learners failed to identify the computer system's main components correctly. The lack of knowledge in using technology due to the unfamiliarity of learners and professors with the tools that support virtual environments is another relevant barrier [8]. This condition may be even more amplified when a massive scale of implementation is considered.

While extensive use of technology must be associated with the implementation of EDUC4, there are limited tools to understand the effect of these technologies on education practices [32]. For instance, Hrastinski [33] found that the main problems faced in facilitating hybrid–synchronous learning designs of lessons were related to communication and cognitive overload caused by dividing attention. Cultural differences, background, awareness, and digital inclusion of the students may play a role in their acceptance of distance learning in education [34].

The 4IR signals a substantial shift for the global workforce. Highly qualified and professional workers will move more to developed countries, unskilled workers will move to less-developed ones [35]. Thus, the determinant of the country's workforce depends on the availability of the opportunity to learn to respond to the changing need relevant in 4IR. In the Philippines, for instance, the 4IR transforms the landscapes of Philippine higher education. Such a transformation ushers in need to adopt paradigms aligned to EDUC4 [36], as the education sector is required to produce a creative, innovative, and competitive generation. As the Philippines entered the global economy, the demand for a globalized higher education also prompted the dramatic and challenging shift in learners' environment that characterizes networked, virtualized, and flexible learning [37].

The outset of the transformation steered a pedagogical interference in the conventional perception of schooling—the learners in the new generation of teaching and learning associated with EDUC4 are tech-savvy and hyperconnectivity-dependent and are ready to thrive in 4D simulated and augmented reality environments. Alakrash and Razak [25] called this "becoming the norm" to include initiatives related to cyber-physical systems, big data, automation, data exchanges, cloud, robots, AI, IoT, and (semi)autonomous industrial techniques. Along this line, the report from the 2020 Global Connectivity Index (GCI) confirmed that the Philippines scored positively in three of four technology enablers: broadband, cloud, AI, and IoT [38].

Despite the interests in contextualizing and bridging the gap between EDUC4 vis-à-vis 4IR, there exist the discrepancy, accessibility, and preparedness of modern educational facilities among HEIs for the required transformation. Thus, there is a need to better understand the barriers that hinder HEIs from implementing EDUC4. This agenda is crucial for developing collective initiatives to advance their capabilities in addressing the necessary components of EDUC4. Costan et al. [10] recently reported such an agenda by systematically reviewing the available EDUC4 literature. In addition, as an input to resource allocation decisions, determining the degree of relevance of these barriers would help HEIs efficiently transition to an environment that facilitates EDUC4. To this end, the DEMATEL is employed in this work.

The DEMATEL, developed by Gabus and Fontela [12] and Gabus and Fontela [13], is a tool based on graph theory that considers the set of elements (e.g., barriers) as vertices and the causal relationships between elements as directed edges. Based on the direct relationships among elements elicited by expert decision-makers, the DEMATEL attempts to achieve two objectives: (1) examining the total relationships among elements brought about by indirect (transitive) relationships; and (2) clustering these barriers into a net cause or net effect. These objectives provide powerful decision support in analyzing complex problems that humans can hardly understand. Due to its straightforward computational characteristics, the DEMATEL is used in various domain applications [39]. Some applications include some domains in education, such as sustainability in management education [40], performance evaluation [41], mobile learning [42], and e-learning in the COVID-19 pandemic [43], among others. Si et al. [44] put forward a review of its applications.

Due to the uncertainty inherent in eliciting judgments within the DEMATEL, the integration of modelling approaches that capture fuzziness has become a popular approach. The introduction of fuzzy set theory [45] revolutionized an array of analytic tools that address vagueness and uncertainty in computing information. The fuzzy set extension of DEMATEL was popularized by Lin and Wu [46] and colleagues and its application has been widespread, even in handling recent issues in the education sector; e.g., Çelikbilek and Adıgüzel Tüylü [47], Thavi et al. [48], Tooranloo et al. [49]. With the limitation of the fuzzy set theory in better handling uncertainty by introducing non-membership functions, the development of fuzzy environments associated with intuitionistic fuzzy sets [50], Pythagorean fuzzy sets [51], and Fermatean fuzzy sets [14] forms a class of q-rung orthopair fuzzy sets [52]. Following these developments, computational platforms based on the DEMATEL were offered, including some variations of intuitionistic fuzzy DEMATEL [53–55] and Pythagorean fuzzy sets [56,57].

While the Pythagorean fuzzy sets offer a distinct advantage over the intuitionistic fuzzy sets and Zadeh's fuzzy sets, expert decision-makers eliciting judgments within the DEMATEL may be limited to express uncertainty under a few conditions. Thus, the introduction of FFS is deemed more applicable in handling such conditions. Despite its advantages, current literature has not offered a computational platform in integrating FFS within the DEMATEL. This work addresses such a gap by developing a Fermatean fuzzy DEMATEL model. In addition, following the required systematic approach for computing threshold values that would identify significant directed relationships among elements in the DEMATEL, the MMDE algorithm proposed by Li and Tzeng [15] is adopted in this work. The MMDE algorithm applies the concept of entropy to identify the adequate information of the influence matrix and draws a threshold to filter the unnecessary information in the influence matrix [15]. Entropy is a physical measurement of thermal dynamics and has become an essential concept in the social sciences [58,59]. In information theory, entropy is used to measure the expected information content of specific messages and is a criterion for the amount of "uncertainty" represented by a discrete probability distribution. Entropy is affected by the probabilities of the elements in a system. The larger the entropy, the more the uncertainty of single events, which implies that the system is more unstable.

3. Method

3.1. Preliminaries for the Computational Framework

Fermatean Fuzzy Sets

The conventional approach to computing is performed using real or "crisp" numbers. In dealing with systems with epistemic uncertainties, such an approach is deemed inadequate because quantities in such systems lie on a "fuzzy" spectrum rather than on a fixed value, which crisp numbers suggest. This problem was addressed by Zadeh [45] by proposing the fuzzy set theory. Since then, various extensions have been introduced for the past decades. Among the recent advances is the notion of Fermatean fuzzy set (FFS) theory, which corresponds to the fuzzy environment adopted in this work. Some useful definitions of the FFS are presented as follows:

Definition 1 ([14])**.** *Let X be a universe of discourse. The general form of an FFS, $\mathcal{F}$, in X can be presented as*:

$$\mathcal{F} = \left\{ \left(x,\ \mu^F_{\mathcal{F}}(x), \nu^F_{\mathcal{F}}(x) \right) : x \in X \right\} \tag{1}$$

where $\mu^F_{\mathcal{F}}(x) : X \to [0,1]$ and $\nu^F_{\mathcal{F}}(x) : X \to [0,1]$, such that $0 \le \left(\mu^F_{\mathcal{F}}(x)\right)^3 + \left(\nu^F_{\mathcal{F}}(x)\right)^3 \le 1$ for all $x \in X$. Furthermore, $\mu^F_{\mathcal{F}}(x)$ and $\nu^F_{\mathcal{F}}(x)$ refer to the degree of membership and non-membership of the element x in the set $\mathcal{F}$, respectively [14]. *Meanwhile, the degree of indeterminacy, $\pi^F_{\mathcal{F}}(x)$ is obtained through:*

$$\pi^F_{\mathcal{F}}(x) = \sqrt[3]{1 - \left(\mu^F_{\mathcal{F}}(x)\right)^3 - \left(\nu^F_{\mathcal{F}}(x)\right)^3} \tag{2}$$

Definition 2 ([14])**.** *Let $\mathcal{F}_i = \left(\mu^F_{\mathcal{F}_i}, \nu^F_{\mathcal{F}_i}\right) (i = 1, 2, \ldots, n)$ be a set of FFS, and $w = (w_1, w_2, \ldots, w_n)^T$ be the corresponding weight vector such that $\sum\limits_i w_i = 1$. Then, the Fermatean fuzzy weighted average (FFWA) aggregation operator is defined by*:

$$FFWA(\mathcal{F}_1, \mathcal{F}_2, \ldots \mathcal{F}_n) = \left(\textstyle\sum_{i=1}^n w_i \mu^F_{\mathcal{F}_i}, \sum_{i=1}^n w_i \nu^F_{\mathcal{F}_i} \right) \tag{3}$$

Definition 3 ([60])**.** *Let $\mathcal{F} = \left(\mu^F_{\mathcal{F}}, \nu^F_{\mathcal{F}}\right)$ be an FFS. The score function S^F for $\mathcal{F}$ is defined as*:

$$S^F(\mathcal{F}) = \frac{1}{2}\left[\left(\left(\mu^F_{\mathcal{F}}\right)^3 - \left(\nu^F_{\mathcal{F}}\right)^3 - ln\left(1 + \left(\pi^F_{\mathcal{F}}\right)^3\right) \right) + 1 \right] \tag{4}$$

where $S^F : \mathcal{F} \to \mathbb{R}$.

Decision-Making Trial and Evaluation Laboratory

Let $i \in \{1, \ldots, n\}$ be an element of the system under study. First, generate the direct-relation matrix. An expert group of K members performs pairwise comparisons of the causal relationships between n elements. The response from the expert group generates a direct-relation matrix $X^k = \left(x^k_{ij}\right)_{n\times n}$, where x^k_{ij} represents the causal influence of the element i on element j as perceived by the k^{th} member, $k \in \{1, 2, \ldots, K\}$, of the group. An evaluation scale of 0, 1, 2, 3, and 4 is used for the causal influence, representing "no influence", "medium influence", "high influence", and "very high influence", respectively. Second, aggregate X^k, considering that $w_k > 0$ ($\sum_k w_k = 1$) is assigned to the importance of the k^{th} member, as described in Equation (5):

$$X = \left(x_{ij}\right)_{n\times n} = \left(\textstyle\sum_k w_k\, x^k_{ij} \right)_{n\times n} \tag{5}$$

Third, normalize the aggregate direct-relation matrix X. The normalized direct-relation matrix is calculated using Equations (6) and (7):

$$G = g^{-1}\ X \tag{6}$$

$$g = \max\left(\max_{1\le i\le n} \sum_{j=1}^{n} x_{ij}, \max_{1\le j\le n} \sum_{i=1}^{n} x_{ij}\right) \tag{7}$$

Fourth, calculate the total relation matrix $T = \left(t_{ij}\right)_{n\times n}$ as follows:

$$T = G\ (I - G)^{-1} \tag{8}$$

Fifth, categorize the elements into a net cause and net effect by calculating for D and R as follows:

$$D = \left(\sum_{j=1}^{n} t_{ij}\right)_{n\times 1} = (t_i)_{n\times 1} \tag{9}$$

$$R = \left(\sum_{i=1}^{n} t_{ij}\right)_{1\times n} = (t_j)_{1\times n} \tag{10}$$

The $\left(D + R^T\right)$ vector (also known as the "prominence" vector) represents the relative importance of each element. Those elements in the $\left(D - R^T\right)$ (also known as the "relation" vector) having $t_i - t_j\ > 0, i = j$ belong to the net cause group, while those elements with $t_i - t_j\ < 0, i = j$ belong to the net effect group.

Lastly, create a prominence-relation map. This map illustrates the $\left(D + R^T,\ D - R^T\right)$ mapping of the elements, as shown in Figure 1. The directed relationships of the elements of the prominence-relation map are defined by t_{ij}. However, some of these total relationships are insignificant, either in theory or practice. A threshold value λ is set to filter out these insignificant relations. For $t_{ij} > \lambda$, then a directed edge from element i to element j is drawn in the prominence-relation map. Otherwise, such a directed edge does not exist. The calculation for λ is critical since having a low value implies that most of the relationships are significant while having a high value suggests that only a few relationships are significant. A handful of approaches has been put forward in determining λ within the context of the DEMATEL. One systematic approach is the MMDE algorithm proposed by Li and Tzeng [15].

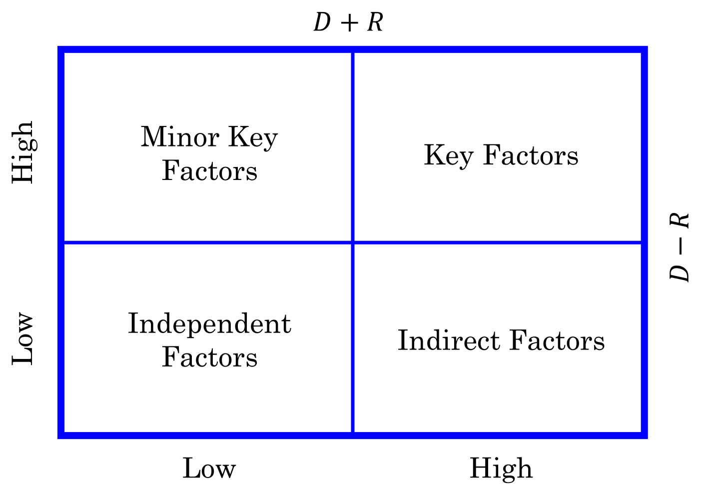


Figure 1. The prominence-relation map.

Maximum Mean De-Entropy Algorithm

The total relation matrix T in Equation (8) can be considered as a set (set T) with n^2 pair ordered elements. There are ordered dispatch-node set T^{Di} and ordered receive-node set T^{Re} in the set T. If the number of the variables in T^{Di} or T^{Re} is m, and the frequency of variables i or j is k, the probability of the variable is $p_i = \frac{k}{m}$. Thus, the probability of each variable can be defined as:

$$H(p_1, p_2, \ldots, p_n) = -\sum p_i \log p_i \tag{11}$$

where $\sum_{i=1}^{n} p_i = 1$ and $p_i \log p_i = 0$ if $p_i = 0$.

By this definition, $H(p_1, p_2, \ldots, p_n)$ is the largest when $p_1 = p_2 = \cdots = p_n$, and the largest entropy is denoted as $H\left(\frac{1}{n}, \frac{1}{n}, \ldots, \frac{1}{n}\right)$. In addition, the de-entropy is denoted as H^D, and is defined as:

$$H^D = H\left(\frac{1}{n}, \frac{1}{n}, \ldots, \frac{1}{n}\right) - H(p_1, p_2, \ldots, p_n) \tag{12}$$

In the following description, $C(T^{Di})$ or $C(T^{Re})$ represents the cardinality of set T, and $N(T^{Di})$ or $N(T^{Re})$ represents the cardinality of the different elements in set T. With the total relation matrix T of the DEMATEL and the definitions mentioned above, the steps of finding the threshold value λ using the MMDE are described as follows: First, transform the $n \times n$ total relation matrix T into an ordered set $T = \{t_{11}, t_{12}, \ldots, t_{21} t_{22}, \ldots, t_{nn}\}$, rearrange the element order in set T from large to small, and then transform to a corresponding ordered triplets set (t_{ij}, i, j) denoted as T^*. Second, take the second and third element from the ordered triplets of the set T and then obtain a new ordered dispatch-node set (T^{Di}) and receive-node set (T^{Re}). These two sets can be defined as follows:

$$T^{Di} = \{i : i \in \{1, \ldots, n\}\} \tag{13}$$

$$T^{Re} = \{j : j \in \{1, \ldots, n\}\} \tag{14}$$

Third, take the first t elements of T^{Di} and T^{Re} as a new set T_t^{Di} and T_t^{Re}, where $t = 1, 2, \ldots, C(T_t^{Di})$ or $C(T_t^{Re})$. Owing to the dispatch node and receive node appearing one time, $N(T^{Di})$ or $N(T^{Re})$ should be used to calculate the probabilities of different elements and calculate the H^{Di} and H^{Re} of the set T_t^{Di} and T_t^{Re}. Then, H_t^{Di}, H_t^{Re}, MDE_t^{Di}, and MDE_t^{Re} can be calculated using the following equations:

$$H_t^{Di} = H\left[\frac{1}{C(T_t^{Di})}, \frac{1}{C(T_t^{Di})}, \ldots, \frac{1}{C(T_t^{Di})}\right] - H\left[\frac{k_1}{N(T_t^{Di})}, \frac{k_2}{N(T_t^{Di})}, \ldots, \frac{k_t}{N(T_t^{Di})}\right] \tag{15}$$

$$H_t^{Re} = H\left[\frac{1}{C(T_t^{Re})}, \frac{1}{C(T_t^{Re})}, \ldots, \frac{1}{C(T_t^{Re})}\right] - H\left[\frac{k_1}{N(T_t^{Re})}, \frac{k_2}{N(T_t^{Re})}, \ldots, \frac{k_t}{N(T_t^{Re})}\right] \tag{16}$$

$$MDE_t^{Di} = \frac{H_t^{Di}}{N(T_t^{Di})} \tag{17}$$

$$MDE_t^{Re} = \frac{H_t^{Re}}{N(T_t^{Re})} \tag{18}$$

Fourth, select the maximum MDE_t^{Di} and MDE_t^{Di} and their corresponding T_t^{Di} and T_t^{Re}. These are denoted as T_{max}^{Di} and T_{max}^{Re}, and are defined as:

$$T_{max}^{Di} = \max\left(MDE_t^{Di}\right) = \{1, 2, \ldots, t^{max}\} \tag{19}$$

$$T_{max}^{Re} = \max\left(MDE_t^{Re}\right) = \{1, 2, \ldots, t^{max}\} \tag{20}$$

Lastly, fifth, the union set T^* is formed by taking all elements of T_{max}^{Di} in the dispatch-node and T_{max}^{Re} in the receive-node. The minimum value in T^* is the threshold value denoted as $T^{Th} = \lambda$.

3.2. Process Flow of the Proposed Computational Framework

Step 1: Identify the barriers to EDUC4 implementation. A list of barriers to implementing EDUC4 in HEIs can be constructed using a literature survey, interview with experts, or a focus group discussion.

Step 2: Set up the initial direct relation in FFS. From the list of barriers, decision-makers or experts are asked to elicit judgment on the degree of the causal relationship of each barrier to other barriers of EDUC4 implementation using a predefined scale. To capture the uncertainty and ambiguity within the dataset, a 5-point scale is provided with an equivalent linguistic evaluation scale and corresponding FFS values, as shown in Table 1.

Table 1. Linguistic evaluation scale.

Linguistic Variables	Influence Score	Equivalent FFSs
No Influence (NO)	0	(0, 1)
Very Low (VL)	1	(0.1, 0.75)
Low (L)	2	(0.4, 0.5)
High (H)	3	(0.7, 0.2)
Very High (VH)	4	(0.9, 0.1)

Step 3: Aggregate the initial direct-relation matrices in FFS. To aggregate the initial direct-relation matrices, Equation (3) is used.

Step 4: Construct the corresponding crisp values of the initial direct-relation matrix. The initial direct-relation matrix in crisp values is calculated using Equation (4).

Step 5: Generate the normalized direct-relation matrix. The normalized direct-relation matrix is obtained using Equation (5) to Equation (7).

Step 6: Obtain the total relation matrix. The total relation matrix is obtained using Equation (8).

Step 7: Calculate the threshold value λ. The threshold value is determined via the MMDE algorithm detailed in Section 3.1.

Step 8: Construct the prominence-relation map using $\left(D + R^T,\ D - R^T\right)$ coordinates, the components of which are obtained using Equations (9) and (10). The calculated threshold value λ is used to filter out significant relationships among the barriers of EDUC4 implementation, and then a directed edge is drawn in the map.

The process flow diagram of the adopted computation framework is presented in Figure 2.

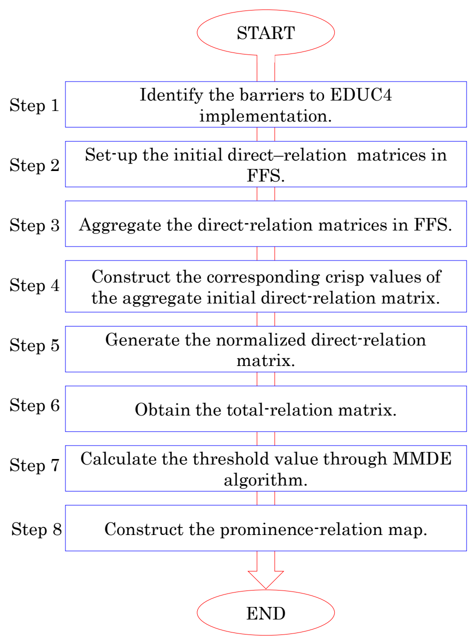


Figure 2. Process flow.

3.3. Case Study Background

The proposed methodology was applied to identify priority barriers to implementing EDUC4 in HEIs. The Philippine scenario was taken here as a case in point. The Philippines is a developing economy in the ASEAN characterized by various educational challenges. For instance, Filipino students ranked last in reading proficiency among all countries/territories in the PISA 2018, with only 19% meeting the minimum (Level 2) standard [61]. The provision of educational resources such as information technologies, among other things, is essential in addressing this concern [62]. Several works have attempted to investigate the supplementation of such technologies in the Philippine context [63,64]. An overarching theme in the future work suggestions provided in these studies involves understanding the barriers that impede the implementation of EDUC4. The recent work reported by Costan et al. [10], which preceded this study, identifies the barriers to EDUC4 implementation in developing economies through a systematic literature review. The importance of addressing these barriers is magnified by the various social and economic implications of the COVID-19 pandemic. This study, built on the findings of Costan et al. [10], hopes to examine the causality of the barriers, with an end goal of identifying policy insights from the analysis for developing economies.

3.4. Data Gathering

This study utilizes the list of barriers to EDUC4 implementation identified by Costan et al. [10]. Twelve (12) barriers were obtained, and their summary, the corresponding codes, and their brief descriptions are shown in Appendix A. The required expert elicitations for the pairwise comparisons of the 12 barriers were obtained through an online survey. An online survey was selected due to strict COVID-19 lockdown restrictions in the Philippines. Thirty-seven (37) expert respondents participated in the online survey. They were chosen in such a way that satisfies the following qualifications: (1) must be affiliated with a private or public HEI; (2) must have a PhD degree; (3) must have at least five years of experience in a supervisory or administrative function; and (4) must have at least five years of experience working at a public or private HEI. The experts came from multiple universities located throughout the Philippines. Their elicitation on the degree of the causal relationship of the barriers to one another attempts to answer the following specific question: "To what extent does [insert barrier *i*] influence [insert barrier *j*]?" This question is standard for all pairwise comparisons. During the survey, the barriers were clearly presented and explained to the experts. In addition, the researchers provided clarification whenever requested.

4. Results and Discussion

4.1. Baseline Results

For tractability, detailed documentation of the computations and all the matrices involved in the proposed computational framework is presented as Supplementary Materials. For brevity, only the key results are presented. The prominence and relation vectors are presented in Table 2. Results show that six, or 50%, of the barriers identified in the systematic review of Costan et al. [10] are dispatchers (net cause), and six, or 50%, are receivers (net effect). The net cause group contains barriers with positive $\left(D - R^T\right)$, implying that they had a lower influenced impact (R) than the influencer (D); otherwise, net effect. The barriers belonging to the net cause group (arranged from the most influential to least) are costly (B2), lack of training resources (B5), lack of collaboration (B6), apprehensive stakeholders (B4), cybersecurity threat (B1), and insufficient foundation of basic education (B12). These barriers impact the identified system of barriers in implementing EDUC4 from a developing economy perspective. On the other hand, the net effect group consists of the insufficient available technologies (B8), skills gap of human capital (B3), knowledge gap for the customization of curriculum design (B7), time constraints for material preparation (B10), health issues (B9), and complexity of learning platforms (B11). These barriers are the most easily influenced ones by other barriers.

Table 2. The prominence and relation vectors.

Code	Barrier	D	R^T	$(D{+}R^T)$	Rank $(D{+}R^T)$	$(D{-}R^T)$	Rank $(D{-}R^T)$	Category
B1	Cybersecurity threat	6.35	6.00	12.35	10	0.35	5	Net cause
B2	Costly	7.06	6.38	13.43	5	0.68	1	Net cause
B3	Skills gap of the human capital	6.89	7.03	13.92	2	−0.14	8	Net effect
B4	Apprehensive stakeholders	6.78	6.36	13.14	7	0.42	4	Net cause
B5	Lack of training resources	7.50	6.85	14.35	1	0.65	2	Net cause
B6	Lack of collaboration	6.77	6.19	12.95	9	0.58	3	Net cause
B7	Knowledge gap for the customization of curriculum design	6.43	6.90	13.33	6	−0.47	9	Net effect
B8	Insufficient available technologies	6.93	6.97	13.90	3	−0.03	7	Net effect
B9	Health issues	5.19	5.80	10.98	12	−0.61	11	Net effect
B10	Time constraint for material preparation	6.26	6.80	13.06	8	−0.54	10	Net effect
B11	Complexity of learning platforms	6.30	7.43	13.73	4	−1.14	12	Net effect
B12	Insufficient foundation in basic education	6.29	6.03	12.32	11	0.26	6	Net cause

As to the prominence, the lack of training resources (B5), skills gap of the human capital (B3), insufficient available technologies (B8), the complexity of learning platforms (B11), and costly (B2) are considered the topmost prominent barriers. The prominence of the barriers is associated with the measure of $\left(D + R^T\right)$. Identifying the most prominent barriers only highlights relative significance, not the most significant. The ranking of barriers based on $\left(D + R^T\right)$ measures is as follows: (B5) $\succ$ (B3) $\succ$ (B8) $\succ$ (B11) $\succ$ (B2) $\succ$ (B7) $\succ$ (B4) $\succ$ (B10) $\succ$ (B6) $\succ$ (B1) $\succ$ (B12) $\succ$ (B9). On the other hand, the results of the MMDE algorithm are presented in Table 3.

Table 3. Results of MMDE algorithm.

Item	Data
The ordered triplet set, T^*	$\left\{ \begin{array}{c} (0.71, 5, 11), (0.68, 5, 8), (0.67, 5, 3), (0.67, 2, 11), (0.66, 8, 11), \\ (0.66, 3, 11), (0.66, 5, 7), (0.66, 5, 10), (0.65, 6, 11), \ldots, (0.34, 9, 9) \end{array} \right\}$
Dispatch − node set, T^{Di}	$\{5, 5, 5, 2, 8, 3, 5, 5, 6, \ldots, 9\}$
T_i^{Di} sets and MDE_i^{Di} values	$T_1^{Di} = \{5\}, MDE_1^{Di} = 0; T_2^{Di} = \{5, 5\}, MDE_2^{Di} = 0; T_3^{Di} = \{5, 5, 5\},$ $MDE_3^{Di} = 0; T_4^{Di} = \{5, 5, 5, 2\}, MDE_4^{Di} = 0.028; \ldots$
Set of MDE_i^{Di} values	$\{0, 0, 0, 0.028, 0.021, 0.016, 0.025, 0.034, 0.027, \ldots, 0\}$
Maximum MDE_i^{Di}	0.034
Dispatch − node set of the maximum MDE_i^{Di}	$\{5, 2, 8, 3\}$
Receive − node set, T^{Re}	$\{11, 8, 3, 11, 11, 11, 7, 10, 11, \ldots, 9\}$
Set of MDE_i^{Re} values	$\{0, 0, 0, 0.009, 0.021, 0.033, 0.025, 0.019, 0.027, \ldots, 0\}$
Maximum MDE_i^{Re}	0.033
Receive − node set of the maximum MDE_i^{Re}	$\{11, 8, 3\}$
T_{max}^{Di}	$\{(0.71, 5, 11), (0.67, 2, 11), (0.66, 8, 11), (0.66, 3, 11)\}$
T_{max}^{Re}	$\{(0.71, 11, 5), (0.68, 8, 5), (0.67, 3, 5)\}$
T^{Th}	$\left\{ \begin{array}{c} (0.71, 5, 11), (0.67, 2, 11), (0.66, 8, 11), (0.66, 3, 11), \\ (0.71, 11, 5), (0.68, 8, 5), (0.67, 3, 5) \end{array} \right\}$
Threshold value (λ)	0.66

The obtained threshold value discriminates less critical/crucial total causal relationships from the crucial ones. Figure 3 categorizes all barriers into four distinct categories: minor key barriers (low prominence, high relation), key barriers (high prominence, high relation), indirect barriers (high prominence, low relation), and independent barriers (low prominence, low relation). It also presents the crucial barriers and their relationships. Based on Figure 3, the minor key barriers comprise cybersecurity threat (B1) and insufficient foundation of basic education (B12). The key barriers include costly (B2), skills gap of human capital (B3), apprehensive stakeholders (B4), lack of training resources (B5), lack of collaboration (B6), and insufficient available technologies (B8). The indirect factors category is composed of knowledge gap for the customization of curriculum design (B7), time constraints for material preparation (B10), and complexity of learning platforms (B11). The independent factor consists of health issues (B9). We focus our attention on the key factors category and identify the crucial barriers. The lack of training resources (B5) yields the most significant barrier in this category. It influences the skills gap of human capital (B3), insufficient available technologies (B8), time constraints for material preparation (B10), and complexity of learning platforms (B11). It implies that the lack of training materials affected the nexus of human and technological requirements essential to the implementation of EDUC4. Thus, government and HEIs must concentrate their resources and efforts to ensure that the lack of training resources must be addressed for the benefit of the stakeholders. This finding is consistent with the observations of Ishak and Mansor [65]. The rank order of the key barriers is as follows: (B5) $\succ$ (B11) $\succ$ (B2) $\succ$ (B8) $\succ$ (B3) $\succ$ (B7).

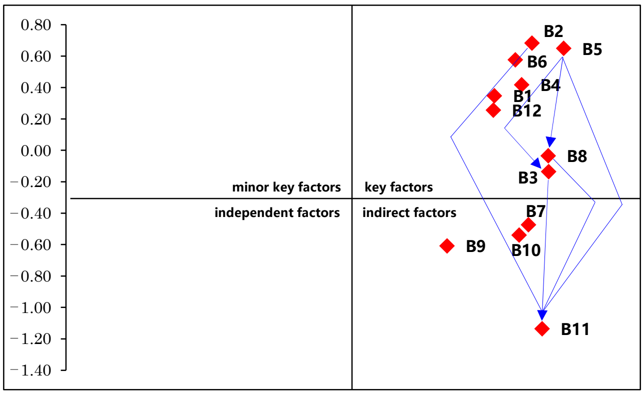


Figure 3. Prominence-relation map of the barriers to EDUC4 implementation.

The proposed Fermatean fuzzy DEMATEL classifies five key barriers from among those identified by Costan et al. [10]: lack of training resources (B5), skills gap of the human capital (B3), insufficient available technologies (B8), the complexity of learning platforms (B11), and costly (B2). The critical relationships that characterize the identified barriers can be seen through the heatmap of the total relation matrix in Figure 4. The critical relationships are indicated by the dark blue sections of the heatmap. It is important to note that the relationships made the barriers critical. In this regard, in prioritizing critical barriers, the priority should be provided to the source of the influence (rows). A way to understand interrelationships of the barriers is to think of the values in the matrix as dimensionless quantities that describe how much a barrier influences (i.e., magnifies) the other barrier. Hence, a lower value made a relationship less critical, while a higher value made the source barrier (i.e., the barrier where the influence emanates) a critical barrier that must be given priority over the others. For instance, the 0.4588 influence of B9 to B8 is relatively less critical than the massive 0.7134 influence of B5 to B11.

	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11	B12
B1	0.4250	0.5300	0.5672	0.5275	0.5535	0.5041	0.5539	0.5639	0.4775	0.5429	0.6163	0.4869
B2	0.5480	0.5017	0.6357	0.5719	0.6204	0.5611	0.6227	0.6401	0.5302	0.6144	0.6695	0.5420
B3	0.5309	0.5603	0.5399	0.5601	0.6065	0.5458	0.6141	0.6140	0.5151	0.6044	0.6605	0.5399
B4	0.5203	0.5518	0.6082	0.4806	0.6029	0.5477	0.6020	0.6121	0.5036	0.5889	0.6386	0.5199
B5	0.5763	0.6187	0.6746	0.6180	0.5726	0.5954	0.6590	0.6750	0.5580	0.6562	0.7134	0.5806
B6	0.5177	0.5506	0.6151	0.5489	0.5986	0.4670	0.6054	0.6095	0.4924	0.5974	0.6454	0.5175
B7	0.4911	0.5270	0.5815	0.5280	0.5680	0.5163	0.4948	0.5756	0.4702	0.5602	0.6142	0.5004
B8	0.5313	0.5650	0.6312	0.5681	0.6113	0.5522	0.6158	0.5391	0.5075	0.6176	0.6643	0.5307
B9	0.4043	0.4277	0.4615	0.4178	0.4539	0.4094	0.4583	0.4588	0.3352	0.4555	0.4995	0.4061
B10	0.4740	0.5107	0.5673	0.5126	0.5610	0.4940	0.5551	0.5631	0.4610	0.4749	0.5968	0.4898
B11	0.4948	0.5184	0.5688	0.5098	0.5474	0.4973	0.5561	0.5645	0.4793	0.5426	0.5214	0.4947
B12	0.4876	0.5145	0.5767	0.5159	0.5533	0.4985	0.5637	0.5532	0.4657	0.5441	0.5915	0.4230

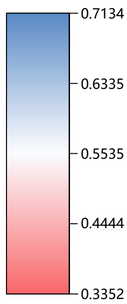


Figure 4. Heatmap of the total relation matrix.

4.2. Policy Insights

The impact of these critical (key) barriers shall be alleviated if not averted by engaging in active educational reforms and measures to meet national-level economic goals. The case environment (i.e., Philippines) may proactively address these barriers to compete in the emerging innovation in education. Addressing these barriers would substantially inform the design of initiatives in improving the economic performance yardsticks of developing countries. These identified crucial barriers require concerted overarching efforts at different institutional levels, ranging from HEIs to the national or country levels. On the national level (top-down), the government may incentivize academic and industry linkages. Such a policy is essential for technology transfer and information exchange. The skills gap of human capital may be addressed by redesigning the curriculum, transforming pedagogies, training for technologies, and matching labor market signals to the competencies and teaching practices. The impact of heightened collaborations among the stakeholders may ascertain confidence among HEIs by adopting rigorous program orientation; cascading performance review; the highlighting impact of EDUC4 in the implementation goals; personnel hiring, training, retention, promotions, accountability and monitoring; and performance management. The administrators of HEIs may review the commitment to mainstream the synchronization of technology infrastructure with human resource training build-up. On the national level, the best combination of low-cost, high-impact strategies may bridge the gap by aligning strategic plans with infrastructure and human resource development through more responsive R&D programs for equitable and sustainable development. The issue of cost may be addressed by heightening international linkages. Such linkages are essential because various international organizations support the development of lower-income economies. Such a strategy facilitates the acquisition of cheap but valuable digital technologies. The preceding strategies may likewise address the complexity of the EDUC4 platform. As the availability of technologies increases and more stakeholders become competent at using the EDUC4 platform, the negative interpretation of the "complexity" of such platforms should be averted.

4.3. Scenario Analysis

On top of the baseline analysis performed previously, a scenario analysis was performed as a post-analysis to demonstrate how the prioritization of barriers changes when some of the critical barriers become fully addressed due to the extensive implementation of available alternative strategies. In the first scenario (a), the influence of the cost barrier (B2) on all other barriers is assumed to be near zero, while the influence of other barriers is assumed to be as is. In the second scenario (b), the influence of the barrier on lack of training resources (B5) on all other barriers is assumed to be near zero, while the influence of the other barriers is assumed to be as is. Simultaneous implementation of the computational framework for both cases was performed, and the resulting prominence relation maps are presented in Figure 5. The heatmaps of the total relation matrix for both scenarios are also presented in Figure 6.

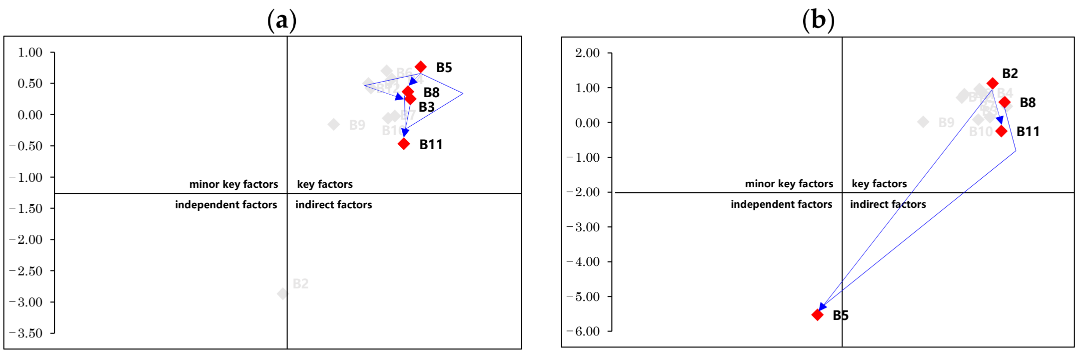
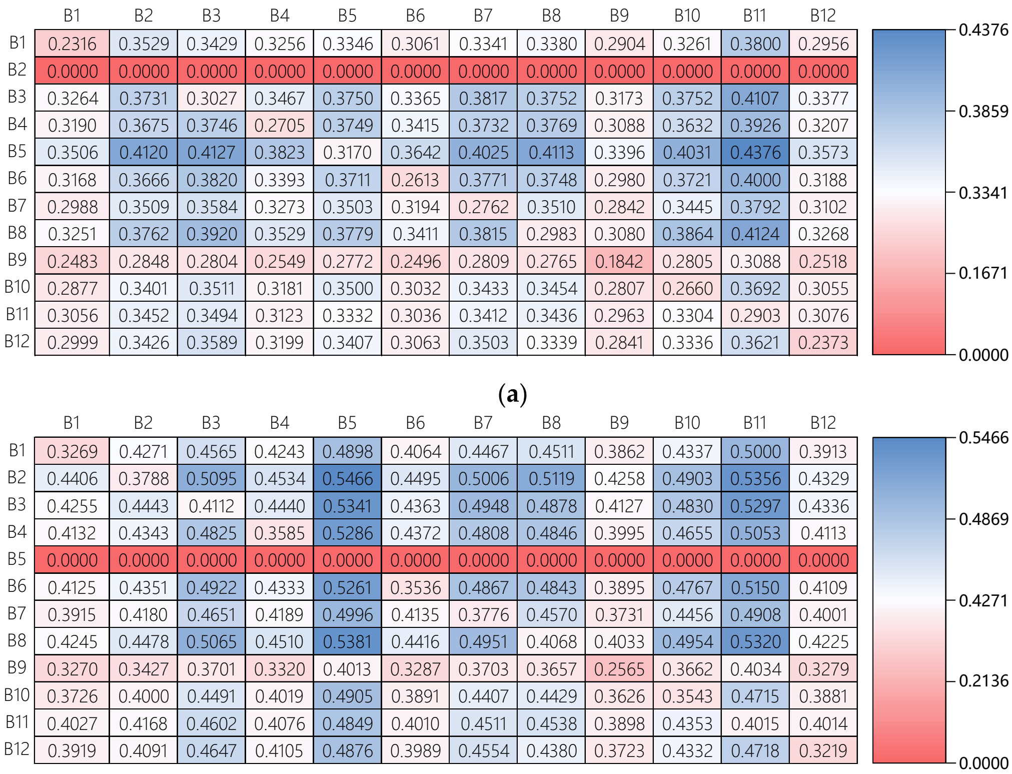


Figure 5. Prominence-relation maps for scenario (**a**) and scenario (**b**).



(**b**)

Figure 6. Heatmaps of the total relation matrix for scenario (**a**) and scenario (**b**).

The critical barriers identified in the baseline analysis remain critical for both post-analysis scenarios. For scenario (a), the cost barrier is no longer classified as critical. This result is expected because its initial influence on other barriers is reconfigured to near zero. The result for scenario (b) presents a more interesting finding. In scenario (b), the lack of training resources remains a critical barrier regardless of its initially near-zero influences on other barriers. These results can be easily explained by zooming into the heatmaps in Figure 5. The relationships involving the cost barrier in scenario (a) are not sufficiently significant to be considered critical. However, the opposite is observed for the barrier on lack of training resources in scenario (b). It should be noted that in the baseline case (see Figure 3), the majority of the critical relationships are influences of other barriers towards the complexity of learning platforms (B11), while the majority of the critical relationships have the barrier on lack of training resources (B5) as the source of influence.

On the other hand, scenario (b) demonstrates that addressing the barrier on lack of training resources (B) eliminates almost all critical relationships of other barriers towards the complexity of learning platforms (B11). This result is both intuitive and demonstrative of the effects of strategic planning. By focusing attention on the most critical barrier, in the case of the baseline case/results—B5, all other barrier relationships are also addressed. Comparing the heatmaps in Figures 4 and 6, it is also clear that addressing the critical barriers significantly reduces the overall barrier influences in the system. This result is indicative of the general alleviation of the EDUC4 implementation barriers in the system, which is deemed ideal. The reduction in the mean influence of barriers to one another (in matrix T) for the baseline, scenario (a), and scenario (b) while omitting the row with all zeros (to avoid bias) yields statistically significant results (see Table 4). The statistical results reveal that, although the lack of training resources (B5) has the most significant relationship with other critical barriers in the baseline case, addressing it does not yield a better result. Instead, addressing the cost barrier (B2), which only has one critical relationship in the baseline case, yields a statistically better abatement of mean influence in the total relation matrix. These results demonstrate that the quantity/frequency of critical relationships may not be a direct indicator of priority. Instead, the quality of critical relationships may be seen as a better measure for prioritizing EDUC4 implementation barriers.

Table 4. The t-test assuming unequal variances of comparisons of the mean of the total relation matrices for the baseline, scenario (a), and scenario (b).

	Baseline	Scenario (a)	Baseline	Scenario (b)	Scenario (a)	Scenario (b)
Mean	0.5430	0.3338	0.5273	0.4333	0.3338	0.4333
Variance	0.0042	0.0019	0.0057	0.0030	0.0019	0.0030
Observations	132	132	132	132	132	132
df	230		238		251	
t Stat	30.7897		11.5844		−16.3662	
p-value (two-tail)	0.0000 *		0.0000 *		0.0000 *	
t Critical (two-tail)	1.9703		1.9700		1.9695	

* Significantly different at $\alpha = 0.01$.

5. Conclusions and Future Work

This study analyzes the causality of the barriers that impede EDUC4 implementation using the DEMATEL. This work extended the conventional DEMATEL analysis by integrating the notion of Fermatean fuzzy sets into the analysis. Such an approach is novel in the domain literature and is considered the primary methodological contribution of this work. The threshold parameter for the DEMATEL analysis is also analytically determined via the application of the MMDE algorithm. A post-analysis of the results of the proposed computational framework is also reported. The analysis yielded the following findings:

- The critical EDUC4 barriers in the baseline case are identified to be related to the lack of training resources (B5), costs (B2), insufficiency of available technologies (B8), skills gap of human resources (B3), knowledge gap (B7), and the complexity of the learning platforms (B11);
- The lack of training resources (B5) for implementing EDUC4 has the most influence on the other barriers, making it the most prominent dispatcher (in terms of frequency) in the baseline case;
- The complexity of learning platforms (B11) for EDUC4 implementation receives the most influence from the dispatchers, making it the most prominent receiver in the baseline case;
- The scenario analysis and the subsequent statistical test show that, while B5 is more prominent in terms of frequency of critical relationships with other EDUC4 barriers, addressing the cost barrier (B2) yields statistically more favorable results in terms of the general (mean) reduction of EDUC4 implementation barriers in the system.

Two important observations are made based on these findings. First, the quantity/frequency of critical relationships may not directly imply priority. Rather, the quality of critical relationships may be seen as a more favorable measure for prioritizing EDUC4 implementation barriers. Second, considering the interdependencies of the EDUC4 barriers of implementing EDUC4 is essential in focusing efforts on those barriers that yield the greatest abatement of other barriers, which should further facilitate EDUC4 implementation. For instance, focusing investment on addressing the most significant barriers is comparative to addressing the fundamental issue of implementing EDUC4. Consequently, the prominent barriers (i.e., B2 and B5) should be prioritized by policymakers to efficiently address the EDUC4 implementation. Among the two prominent barriers, the cost barrier (B2) is found to yield significantly greater abatement of aggregate influence of barriers in the system. This insight is essential for the Philippines and other developing economies with limited resources for employing initiatives to implement EDUC4, making prioritization critical, especially in addressing EDUC4 barriers. While the case demonstration is in the Philippines, the developed causal framework can be adopted by other developing economies, especially in the ASEAN, because the variations in the characteristics of the countries in this region are relatively minimal. However, an analyst should factor in cultural factors, which can be more pronounced in other countries. Nevertheless, the generalizability of the results of this work to developing economies is deemed a significant contribution to address EDUC4 implementation in the region.

The results of this study can be further examined by applying statistical analysis, especially for validating the causal relationships of the barriers under consideration. Such an analysis should provide a solid empirical scaffolding of the exploratory work performed here, based on expert elicitation rather than rigorous statistical data. However, for brevity, such an analysis is reserved for future work. Furthermore, scholars may provide a comprehensive comparative analysis of the robustness of the results if other types of techniques for incorporating epistemic uncertainties (e.g., Pythagorean fuzzy sets, neutrosophic set, Picture fuzzy sets) are employed in the causal modelling work. Lastly, developing a means to simulate the impact of addressing critical barriers identified here should be a worthwhile undertaking for directly tracing the impact of policy on EDUC4 implementation.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/app12020689/s1.

Author Contributions: Conceptualization, L.O.; methodology, J.L.A., S.S.E., F.M., E.S.J. and L.O.; software, J.L.A., S.S.E., F.M. and E.S.J.; validation, J.L.A., S.S.E., F.M., E.S.J. and L.O.; investigation, G.G., F.C., D.S., R.G., L.E., E.C., N.M.A., J.L.A., S.S.E., F.M., E.S.J. and L.O.; resources, G.G., F.C., D.S., R.G., L.E. and E.C.; data curation, J.L.A., S.S.E., F.M. and E.S.J.; writing—original draft preparation, G.G., F.C., D.S., R.G., L.E., E.C., N.M.A., J.L.A., S.S.E., F.M., E.S.J. and L.O.; writing—review and editing, J.L.A., S.S.E., F.M., E.S.J. and L.O.; visualization, J.L.A., S.S.E., F.M. and E.S.J.; supervision, G.G. and L.O.; project administration, L.O.; funding acquisition, G.G., F.C., D.S., R.G., L.E. and E.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research is funded by the 2021 CTU-GAA Research Grant entitled "Challenges of Implementing Education 4.0 from a Developing Country Perspective".

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Barriers to EDUC4 (adopted from Ref. [10]).

Code	Barrier	Brief Description
B1	Cybersecurity threat	The threat of information leakage, security attacks, and misusage of technology.
B2	Costly	Implementation of EDUC4 is associated with higher costs (e.g., acquisition of equipment, maintenance).
B3	Skills gap of the human capital	Insufficient knowledge and experience of the human capital in using digital technology for education, including the lack of specific skills (i.e., critical thinking, emotional intelligence).
B4	Apprehensive stakeholders	Apprehension of some stakeholders (i.e., learners, educators, administrators) to EDUC4.
B5	Lack of training resources	The lack of training resources (i.e., facilities, materials) for the professional development of educators.
B6	Lack of collaboration	Lack of collaboration with other sectors (i.e., community, government, other HEIs, industry) is essential in successfully implementing EDUC4.
B7	Knowledge gap for the customization of curriculum design	Current lack of knowledge to create a customized curriculum design to enhance learners' skills (i.e., creativity, critical thinking) and promote skills-based training.
B8	Insufficient available technologies	Due to the rapid advancement of technology, developing countries cannot catch up with the developed ones. Some technologies might be available in some countries, but not in others.

Table A1. *Cont.*

Code	Barrier	Brief Description
B9	Health issues	Prolonged exposure to the technology may cause health issues in the physical and mental well-being of the learners and educators.
B10	Time constraint for material preparation	Preparing and teaching in a virtual learning platform requires more time than the traditional one.
B11	Complexity of learning platforms	The challenge that the users (i.e., learners and educators) face on utilizing the virtual learning platform.
B12	Insufficient foundation in basic education	Quality primary education of learners is essential in the implementation of EDUC4 in HEIs.

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