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Exploring the Barriers to the Advancement of 3D Printing Technology

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Abstract: 3D printing technology is suitable for application in advancing digitization in dentistry. However, the use of this technology in the dental field is not as widespread as expected. The study discusses the barriers to advancing 3D printing technology in dentistry. First, Fuzzy Delphi was used to conduct in-depth interviews with experts to explore what barriers prevent the advancement of 3D printing technology in dentistry. Second, the decision-making and trial assessment laboratory (DEMATEL) was used to identify the cause-and-effect relationship among barriers. Because DEMATEL relies on the expert decision-making system, experts often have different experiences and backgrounds, so judgment results are often uncertain and inconsistent. Therefore, this study proposes using a rough-Z-number to integrate opinions among experts, which can effectively overcome the problems of inconsistency and uncertainty. After analyzing the results, we found that "lack of standard infrastructure" is the most important barrier to the advancement of 3D printing in dentistry, and this study provides improvement strategies based on the results. The results put forward countermeasures for the barriers to the promotion of 3D printing technology in dentistry, which will make the development of dental digitization more effective.

Keywords: 3D Printing; barriers; dentistry; additive manufacturing; Fuzzy Delphi; Rough-Z-DEMATEL

MSC: 90-10

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1. Introduction

Additive manufacturing (also known as 3D printing) is a way to stack materials layer by layer to complete product manufacturing [1]. Unlike traditional manufacturing methods, such as forming, casting, and reduction manufacturing, 3D printing technology can provide design and manufacturing advantages for products with complex structural designs, considerable material savings, flexible and efficient production processes, as well as customization for the customers [2,3] In recent years, the application and development of 3D printing technology have become mature, which can save material consumption and thus reduce production costs [4]. Because digitization accelerates product design and reduces development time, 3D printing can meet the demand for small-batch production and customization [5]. This technology has been widely applied in various fields, such as automotive parts production [6], electronic parts [7], the aerospace industry [8], construction [9], food [10], and agriculture [11].

Although 3D printing technology is one of the most important innovations in various industries, its use in the medical field is still limited. 3D printing technology has the following characteristics for medical applications: (1) the ability to customize for individual patient needs [12], (2) the ability to improve precision and patient comfort through digital devices [13], and (3) the ability to reduce material waste in the manufacturing process [14]. Because of the aforementioned properties, 3D printing has been introduced to dentistry in recent years. Liaw and Guvendiren [15] pointed out that 3D printing technology is characterized by high tunability and complexity and enabling the production of anatomically matched and patient-specific devices. This makes it very suitable for the introduction of digitalization in dentistry. Their study also showed that (1) improving print quality, accuracy, and print speed, (2) developing and integrating more application materials, and (3) eliminating time-consuming and dangerous post-processing procedures will be challenges for 3D printing technology in the future dental field. However, its use in the dental field is not as popular as expected [16]. Past studies have focused on material applications [17] and technological improvements and enhancements [18]. The discussion on the barriers that dentistry encounters when introducing 3D printing is rather limited. Therefore, what are the barriers to the advancement of 3D printing in dentistry will be a research gap. Loges and Tiberius [16] used a Ranking-Type Delphi study to investigate the key barriers to implementing 3D printing technology among dentists, dental technologists, and vendors selling 3D printing equipment. Their results showed that (1) lack of relevant knowledge, (2) lack of re-enhancement of employee education and training, (3) willingness to use only traditional methods, and (4) high investment costs combine to be the challenges. From their study, some barriers to the application of 3D printing technology in dentistry were identified. However, among these barriers, there are often many mutual influence relationships. The objectives of this study include the exploration of what the barriers to the application of 3D printing technology in dentistry are. What are their mutual influence relationships? Which barriers are the key core of the influences? Understanding these issues appears to be a key factor in accelerating the digital transformation of dentistry.

There are many methods to investigate the mutual influence relationships among factors, such as principal component analysis [19] and structural equation modeling (SEM) [20]. In recent years, there have been an increasing number of studies using the decision-making and trial assessment laboratory (DEMATEL) technique to explore the influential relationships among barriers, such as women entrepreneurship [21], green lean practices [22], electric vehicle [23], e-commerce technology in SMEs [24], social banking systems [25], construction program manager selection in China [26], risk analysis of maritime transportation [27], etc. Regarding the food industry, Novel Taguchi scheme-based DEMATEL is applied to discuss the performance index of system maintenance [28]. In addition, during the period of COVID-19 spread, DEMATEL has been used to research the tie between the patient's willingness to employ mobile health treatment and the service quality [29].

DEMATEL has the following advantages: (1) It can effectively analyze the direct or indirect effects among different factors and understand the complex cause-and-effect relationships; (2) It can visualize the mutual relationships among the factors through an Influential Network Relationship Map (INRM), enabling decision-makers to clearly understand which factors influence each other; (3) It can also be used to determine the ranking of alternative solutions and at the same time to identify key assessment criteria and measure the weights of the assessment criteria [30]. So this study uses DEMATEL to explore the cause-and-effect relationships between barriers. However, the decision-making process of DEMATEL relies heavily on an expert decision-making system, so the information for decision-making is uncertain and inconsistent because experts often have different preferences regarding different experiences and backgrounds [31]. To remedy these problems, this study proposes using rough-Z numbers to overcome these drawbacks. The rough set can be used as an effective tool to resolve uncertainty and inconsistency, and the advantage of Z-numbers is the integration of experts' judgments and their confidence in the assessment, which can help resolve the uncertainty in decision-making [13]. The proposed rough-Z-number can integrate opinions among experts and overcome inconsistent and uncertain judgments.

The contributions of this study include:

1. Identify the key barriers to the advancement of 3D printing in dentistry;
2. Overcome the experts' uncertain and inconsistent judgments using the Rough-Z-DEMATEL method;
3. Investigate the mutual influences of key barriers to the advancement of 3D printing in dentistry;
4. Provide recommendations and strategies for dentists, dental technologists, and vendors to accelerate the advancement of 3D printing technology in the dental profession.

2. Literature Review

2.1. Development and Application of 3D Printing

3D printing technology is a manufacturing method that constructs one layer of material at a time and adds multiple layers of material to form the desired object based on demand [32]. According to the Wohler's Report [33], despite the influence of COVID-19 on the global economy in 2020, 3D printing technology grew by 7.5%, reaching a market size of $12.8 billion. After more than 40 years of development, 3D printing technology has been continuously developed and improved. According to the American Society for Testing and Materials (ASTM), there are seven types of additive manufacturing (AM), including VAT Photopolymerization, Material Jetting, Binder Jetting, Material Extrusion, Powder Bed Fusion, Sheet Lamination, and Direct Energy Deposition [4]. In response to the nature of 3D printing technology, there are also innovative developments in the materials already used. For example, composite materials for the aerospace industry are widely used because of their specific strength, high stiffness, resistance to corrosion, and endurance performance [34]. In the construction industry, suitable combinations of additives have been proposed for incorporation into hybrid soils for 3D printing [35]. In the medical industry, composite materials have been developed by combining different types of materials, such as ceramics and metal materials and ceramics and polymer materials for orthopedic treatment [36]. The application of 3D printing technology is becoming more and more widespread in various industries, such as the manufacturing industry for the production of mold-making models and robotic structural parts [4], the food industry for the rapid production of military food in the battlefield [37], the construction industry for new methods using 3D printing technology for concrete [9], and the construction industry for new methods using 3D printing technology [9], and in the textile industry, the production of special textiles with thermal conductivity and intelligence [38], which shows the wide range of applications and importance of 3D printing technology in various industries.

As customers' expectations for products become diverse, companies have moved from large-scale mass production to small-batch orders. The fourth industrial revolution [39], also known as Industry 4.0, is taking shape as network infrastructure becomes widespread and innovations in hardware and software are integrated into the manufacturing industries. With the emergence of digital technologies, such as the Internet of Things [40], robotics [41], 3D printing [4], Artificial Intelligence [42], blockchain [43], and virtual reality [44], and their gradual application in various areas, it has led to the revolutionary development of digital transformation in the global manufacturing industry. It should be noted that the emergence of 3D printing technology has attracted people's attention.

2.2. Development of 3D Printing in the Medical Field

The application of 3D printing technology in the medical field has also been described in recent years, such as the creation of surgical tools and prostheses tailored to individual patient needs [45], bioprinting to create artificial skin for the treatment of burns [46], and the creation of synthetic organs [47]. 3D printing technology has also improved medical education by allowing medical students to learn medical knowledge through human anatomy [48]. Actually, digital 3D simulations created by 3D printing technology can improve the quality and efficiency of learning [49,50]. In the field of dentistry, 3D printing technology is used to create full dentures without the use of traditional manufacturing techniques and tools, such as molds, cutting tools, or tooling fixtures [51]. 3D printing technology provides dental students with digital models of teeth and mouths for clinical dental training [52].

2.3. Barriers to the Advancement of 3D Printing

The development and application of 3D printing technology in various industries are booming, but what are the barriers to its application in the dental field that make it less common than expected? What are the mutual influence relationships among these barriers? In this study, DEMATEL was used to investigate and propose ways to address and improve the situation. From the preliminary literature review, the possible barriers to the advancement of 3D printing technology in dentistry are summarized in Table 1 and Section 3 presents the methodology used to investigate the mutual influence relationships among the factors.

Table 1. Barriers to the advancement of 3D printing in dentistry.

Barrier	References	Barrier	References
Cumbersome processes	[15]	Economic benefits	[15]
Post-processing steps	[15]	Equipment cleaning and disinfection	[15]
Limited clinical cases	[15]	Not familiar with new technology	[16]
Collaboration capability	[16]	Management process responsiveness	[53]
Consensus within the organization	[53]	Technology integration	[53]
Conservative attitude	[53]	Government's attitude	[53]
Managerial support	[53]	High installation cost	[2,53]
Suitability of raw materials	[53,54]	Financial benefit assessment	[55]
Regulations and management	[56]	Intellectual property	[56]
Accuracy improvement	[54]	Education and training	[15,57,58]
Equipment intellectualization	[59]	Technical talents	[60]
Material supply chain	[61]	Hidden costs of new technology	[61]
Protocol standardization	[61]	Corresponding infrastructure	[59,62]
Material limitations	[2,16,63]	Technology optimization	[16,58,63]
Information security	[64]	Technology maturity	[59,64]

3. Methodology

This section first introduces the Fuzzy Delphi method, illustrating the basic concepts and formulas of Z-number and rough set. Second, the procedural steps of the Rough-Z-DEMATEL method are introduced in detail. Subsequently, the influential network relationship map (INRM) describes the mutual influence relationships between the visualized study factors. The proposed research methodology and flowchart are shown in Figure 1 below.

3.1. Constructing an Assessment Framework for Barriers

Since there are many possible barriers to 3D printing technology in dentistry, we must identify the core barriers for analyses. With the Fuzzy Delphi method, expert consensus can be effectively obtained to construct the framework of core indicators. Prior studies have been conducted with fixed semantics in the Delphi method, but this study defines five levels of influences: No influence (NI), Low influence (LI), Moderate influence (MI), High influence (HI), and Very high influence (VHI), and allows the experts to have different cognitions for different semantics. The five levels of influence are determined according to the subjective opinions of the experts, with a full score of 100 points and a total range of 0–100 points. For example, the lowest score for "no influence", according to Expert 1, is 0, the median score is 20, and the highest score is 40; the lowest score for "low influence" is 40, the median score is 45, and the highest score is 50. The establishment of the variable semantic scale is different from the past studies. Although the calculation process is more complicated, it can fully express the real semantics of the experts.

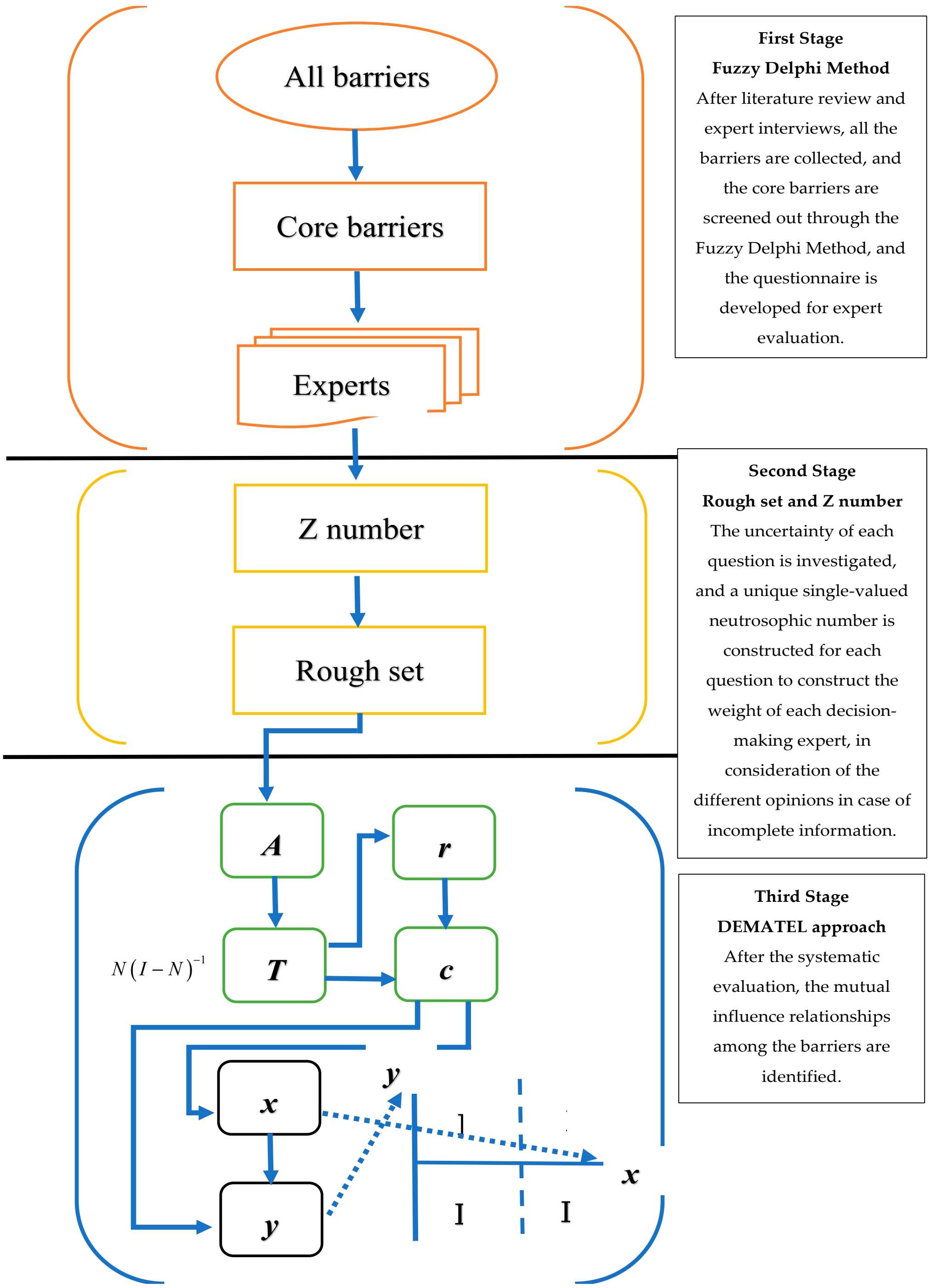

Figure 1. Research methodology and flowchart.

*Step 1. Constructing the assessment matrix **S** of indicator importance.*

According to the investigation of each expert's indicator importance, the indicator importance assessment matrix ***S*** can be formed by collecting the results. s_{ij} is any element in the matrix, where ($i = 1, 2, \ldots, b$; $j = 1, 2, \ldots, k$). The matrix base refers to the assessment results of the b assessment indicators by k experts.

Step 2. Constructing the fuzzy decision matrix ***D***.

According to the initial matrix of expert importance using Equations (1)–(4), a fuzzy decision matrix ***D*** can be constructed. $\widetilde{\boldsymbol{d}}$ refers to the fuzzy number, and this study uses the triangular fuzzy number.

$$\boldsymbol{D} = \left[d_{ij}\right]_{b\times 3} \text{for} \widetilde{\boldsymbol{d}} = \left(d_i^l,\ d_i^m,\ d_i^u\right) \tag{1}$$

$\boldsymbol{d}^l$ is the lowest value of the inter-expert assessment factor j.

$$\boldsymbol{d}^l = \left[d_i^l\right]_{b\times 1} = \min_j\left(d_{ij}\right) \text{ for } j = 1, 2, \ldots, k \tag{2}$$

$\boldsymbol{d}^u$ is the highest value of the importance of the inter-expert assessment factor j.

$$\boldsymbol{d}^u = \left[d_i^u\right]_{b\times 1} = \max_j\left(d_{ij}\right) \text{ for } j = 1, 2, \ldots, k \tag{3}$$

$\boldsymbol{d}^m$ is the geometric mean among k experts.

$$\boldsymbol{d}^m = \left[d_i^m\right]_{b\times 1} = \sqrt[k]{\prod_{j=1}^{k} d_{ij}} \text{ for } j = 1,\ 2,\ \ldots,\ k \tag{4}$$

Step 3. Obtaining the explicit value p_i.

The explicit value p_i is obtained by defuzzifying the fuzzy decision matrix ***D*** using the center of gravity method, as shown in Equation (5).

$$\boldsymbol{p} = p_i = \left(d_i^l + d_i^m + d_i^u\right)/3 \tag{5}$$

Step 4. Determining the threshold value based on the demand.

In this study, the inter-quartile range (IQR) technique is used to assess the threshold value to avoid the influence of extreme values. The smaller the value, the more concentrated the data in the middle; the larger the value, the more dispersed the data in the middle. If p_i < threshold, the indicator is labeled as "Delete". If p_i > threshold, the indicator is labeled as "KEEP".

3.2. Measurement of Uncertainty and Inconsistent Information

The rough-Z-number collected uncertainty and inconsistency information, eventually leading to an integrated expert decision.

3.2.1. Z Fuzzy Set

Zadeh [65] proposed Z-numbers as a special type of fuzzy approach to increase experts' confidence in the assessment. The calculation procedure of Z-numbers is described as follows. For an explanation of the related formulas of the following steps, please refer to Ahmandi et al. [13].

Step 1. Defining the fuzzy system of assessed values and confidence.

Z-numbers are modeled in consideration of triangular fuzzy triplets, and Z-numbers can be defined as $Z = \left(\widetilde{F},\ q\right) = \left[\left(f^L,\ f^M,\ f^U\right),\ q\right]$, where $\widetilde{F}$ denotes a fuzzy membership function for general assessment, i.e., $\widetilde{F} = \left(f,\ u_{\widetilde{F}}\right)|y \in [0,\ 1]$ and q is the confidence level of the expert in the assessment, which also belongs to a fuzzy membership function, and can be expressed as $q = \left(q,\ u_q\right)|y \in [0,\ 1]$.

Step 2. Transform the fuzzy membership function of confidence to the crisp equivalent.

The confidence q is converted into a crisp value by applying the integral concept shown in Equation (6). The parameter "φ" denotes the confidence weight.

$$\varphi = \frac{\int^{\eta} u_q d_\eta}{\int^{u_q} d_\eta} \tag{6}$$

Step 3. Generating Z-numbers.

The confidence weight φ is added to the assessment value $\widetilde{F}$ using the equation to obtain the weighted Z-fuzzy membership function, as in Equation (7).

$$Z^{\varphi} = \left\{(\eta,\ u_{\widetilde{F}^{\varphi}})\middle|u_{\widetilde{F}^{\varphi}}(\eta)\ = \varphi u_{\widetilde{F}}(\eta),\ \eta \in [0,\ 1]\right\} \tag{7}$$

The final weighted Z-fuzzy membership function can be converted to a regular triangular fuzzy number using Equation (8)

$$\widetilde{Z}^{*} = \left(\sqrt{\varphi}f^{L},\ \sqrt{\varphi}f^{M},\ \sqrt{\varphi}f^{U}\right) \tag{8}$$

3.2.2. Rough Numbers

The judgments of multiple experts should be integrated in a meaningful way to improve the decision outcomes [66]. Zhai et al. [67] developed rough numbers to construct upper and lower approximations of group opinions based on rough set theory. The following is a brief introduction to the operation process of rough numbers. For a detailed explanation of the related formulas of the following steps, please refer to Ahmandi et al. [13].

Step 1. Constructinglower and upper approximations.

If U is a full domain including all objects, where $\aleph$ is a random object from U, a set construction exists where ν classes denote expert preferences $E = \{K_1,\ K_2,\ \ldots,\ K_\nu\}$ where $K_1,\ K_2,\ \ldots,\ K_\nu$. In this definition, if $\forall\aleph \in U,\ K_\delta \in E, 1 \leq \delta \leq \nu$, the two sets of $\underline{A_{pr}}(K_\delta)$ and $\overline{A_{pr}}(K_\delta)$ denote the lower approximation and the upper approximation K_δ, denoted by Equations (9) and (10), respectively. In addition, the boundary interval denoted as $Bnd(K_\delta)$ can be determined using Equation (11).

$$\underline{A_{pr}}(K_\delta) = \{\aleph \in U/E(\aleph) \leq K_\delta\},\ \text{the lower approximation;} \tag{9}$$

$$\overline{A_{pr}}(K_\delta) = \{\aleph \in U/E(\aleph) \geq K_\delta\},\ \text{the upper approximation;} \tag{10}$$

$$\begin{aligned} &Bnd(K_\delta) = \{\aleph \in U/E(\aleph) \neq K_\delta\} \\ &= \{\aleph \in U/E(\aleph) > K_\delta\} \cup \{\aleph \in U/E(\aleph) < K_\delta\} \end{aligned} \tag{11}$$

Step 2. Defining the rough of lower and upper limits.

The expert opinions can be aggregated using rough numbers with lower and upper limits, i.e., $\underline{Lim}(K_\delta)$ and $\overline{Lim}(K_\delta)$. These limits are calculated using the arithmetic mean of the elements in the lower and upper approximations expressed in Equations (12) and (13), respectively.

$$\underline{Lim}(K_\delta) = \sum\nolimits_{i=1}^{N_L} E(\aleph)/N_L\ \middle|\aleph \in \underline{A_{pr}}(K_\delta) \tag{12}$$

$$\overline{Lim}(K_\delta) = \sum\nolimits_{i=1}^{N_L} E(\aleph)/N_U\ \middle|\aleph \in \underline{A_{pr}}(K_\delta) \tag{13}$$

In N_L and N_U denote the total number of objects K_δ included in the lower and upper approximation, respectively, and the rough boundary $R_{Bnd}(K_\delta)$ denotes the interval K_δ between the upper and lower limits of the objects, as expressed in Equation (14).

$$R_{Bnd}(K_\delta) = \overline{Lim}(K_\delta) - \underline{Lim}(K_\delta) \tag{14}$$

$R_{Bnd}(K_\delta)$ represents the calculated value of the experts' consensus. When the value is higher, there are differences in the experts' opinions, and the smaller the value $\mathrm{R_{Bnd}}(K_\delta)$ means that the experts agree that there is no significant conflict in their judgment.

Step 3. Determining the interval value of the rough numbers.

Finally, a set of expert opinions should be converted into a set of rough numbers, as shown in Equation (15). For a detailed description of the rough number calculation, see Chang et al. [68,69].

$$RN(K_\delta) = \left[\underline{Lim}(K_\delta),\ \overline{Lim}(K_\delta)\right] \tag{15}$$

3.3. Barrier Influence Relationship Assessment

The steps for DEMATEL analysis are described as the following steps. For an explanation of the related formulas of the following steps, please refer to the research of Hung et al. [70].

Step 1. Obtaining normalized direct influence relationship matrix.

After the direct influence matrix $\boldsymbol{A}$ is obtained from the survey, it is normalized. The normalized direct influence matrix $\boldsymbol{N}$ is obtained by using Equations (16) and (17), where ϖ is the maximum of summed rows and columns, and a_{ij} is each element of the matrix $\boldsymbol{A}$.

$$\boldsymbol{A} = \left[a_{ij}\right]_{\psi\times\psi} = \begin{bmatrix} a_{11} & \cdots & a_{1j} & \cdots & a_{1\psi} \\ \vdots & & \vdots & & \vdots \\ a_{i1} & \cdots & a_{ij} & \cdots & a_{i\psi} \\ \vdots & & \vdots & & \vdots \\ a_{\psi 1} & \cdots & a_{\psi j} & \cdots & a_{\psi\psi} \end{bmatrix}_{\psi\times\psi} \tag{16}$$

$$\boldsymbol{N} = {}^{\boldsymbol{A}}\!/_{\Omega} \tag{17}$$

$$\text{where } \Omega = \max\left\{\max_i \sum\nolimits_{j=1}^{n} a_{ij},\ \max_j \sum\nolimits_{i=1}^{n} a_{ij}\right\}$$

Step 2. Generating total influence relation matrix.

Using the principle of Markov training convergence, the total influence relation matrix can be generated after an infinite number of interactions of influence relations, as in Equation (18).

$$\begin{aligned} \boldsymbol{T} &= \boldsymbol{N} + \boldsymbol{N}^2 + \boldsymbol{N}^3 + \ldots + \boldsymbol{N}^k \\ &= \boldsymbol{N}(\boldsymbol{I} + \boldsymbol{N} + \boldsymbol{N}^2 + \ldots + \boldsymbol{N}^{k-1})[(\boldsymbol{I} - \boldsymbol{N})(\boldsymbol{I} - \boldsymbol{N})^{-1}] \\ &= \boldsymbol{N}(\boldsymbol{I} - \boldsymbol{N}^k)(\boldsymbol{I} - \boldsymbol{N})^{-1} \\ &= \boldsymbol{N}(\boldsymbol{I} - \boldsymbol{N})^{-1},\ \text{when } k \to \infty,\ \boldsymbol{N}^k = [0]_{m\times m} \end{aligned} \tag{18}$$

Step 3. Counting influence relationships.

The influence relationships of an indicator include the degree of influence, the degree of being influenced, the degree of total influence, and the degree of net influence ($\boldsymbol{r}, \boldsymbol{c}, \boldsymbol{x}, \boldsymbol{y}$).

The degree of influence refers to the degree of influence of the indicator on the other indicators, which is summed to produce the "degree of influence", expressed as a vector $\boldsymbol{r}$ in this study, as shown in Equation (19).

$$\boldsymbol{r} = (r_1, r_2, \ldots, r_\psi) = (r_i)_{\psi\times 1} = \left[\sum_{j=1}^{n} r_{ij}\right]_{\psi\times 1} \quad \text{for } i, j = 1, 2, \ldots, \psi \tag{19}$$

The degree of being influenced refers to the degree of being influenced by other indicators. This is summed to produce the "degree of being influenced", expressed as vector $\boldsymbol{c}$ in this study, as shown in Equation (20).

$$\boldsymbol{c} = (c_i)_{\psi\times 1} = (c_1, c_2, \cdots, c_\psi)\prime = (c_j)\prime_{1\times\psi} = \left[\sum_{i=1}^{\psi} c_{ij}\right]'_{1\times\psi} \quad \text{for } i, j = 1, 2, \ldots, \psi \tag{20}$$

The degree of net effect is the degree of influence of the indication minus the degree of being influenced to produce the "degree of net effect", which is represented by the vector $\boldsymbol{y}$, meaning the "relation" of the indicator. A positive value of y_i is the cause, and a negative value of y_i is the effect, as shown in Equation (21).

$$\boldsymbol{y} = y_i = r_i - c_i, \text{ for } i = 1, 2, \ldots, \psi \tag{21}$$

The influence of the total degree is the total of the degree of influence of the indicator and the degree of being influenced to produce the "total degree of influence", which is represented by the vector $\boldsymbol{x}$, meaning the "prominence" of the indicator, as shown in Equation (22).

$$\boldsymbol{x} = x_i = r_i + c_i, \text{ for } i = 1, 2, \ldots, \psi \tag{22}$$

Step 4. Drawing influential network relationship map (INRM).

Based on the calculation in the previous stage, the influence relationships ($\boldsymbol{T}$, $\boldsymbol{r}$, $\boldsymbol{c}$, $\boldsymbol{x}$, $\boldsymbol{y}$) among the whole assessment indicators can be obtained, and the influence network relationship map can be drawn based on the influence relationships.

4. Case Description and Results

The case chosen in the paper is to explore the barrier factors to the advancement of 3D printing technology in the field of dentistry in Taiwan and the mutual influence relationships among the barriers. To make the research results more representative, dentists, dental technologists, and medical device manufacturers with experience working with 3D printing devices were selected as the main members of the expert team in this study. In this section, the background of the experts, the emergence of core barriers, the method of investigation, the process of analysis, and the results are described.

4.1. Identifying the Core Barriers to the Advancement of 3D Printing in Dentistry

A total of 15 experts from the field of dentistry, medical information system integration, and 3D printing equipment vendors were invited to participate in this study. These experts have extensive experience working in the relevant fields and were able to provide input and discussion in this study. Table 2 summarizes the background of the experts who participated in this study. The experts included dentists, dental technologists, and medical device managers with many years of experience in their field of expertise. We used the Fuzzy Delphi Method, as described in Section 3.1, to start collecting the expert's evaluation opinions. All of the experts' data are filled in this order and compiled as shown in Table 3.

Table 2. List of experts.

Expert	Gender	Job Title	Prof. Experience	Job Duty
1	M	Dental technologist	>10 years	Dental mold production
2	F	Sales Manager	5–10 years	3D printing equipment sales
3	F	Sales Associate	5–10 years	3D printing equipment sales
4	M	General Manager	>10 years	Medical information equipment integration
5	M	Dental technologist	>10 years	Dental mold production
6	F	Dentist	5–10 years	Oral therapy
7	M	Dentist	>10 years	Oral therapy
8	M	Dental technologist	5–10 years	Dental mold production
9	M	Dental technologist	5–10 years	Dental mold production
10	M	Dental technologist	5–10 years	Dental mold production
11	F	Dental technologist	5–10 years	Dental mold production
12	F	Dental technologist	<5 years	Dental mold production
13	F	Dental technologist	<5 years	Dental mold production
14	F	Dental technologist	<5 years	Dental mold production
15	F	Dental technologist	<5 years	Dental mold production

Table 3. The variable semantic scale of all experts.

	NI			LI			MI			HI			VHI		
	L	**M**	**U**	**L**	**M**	**U**	**L**	**M**	**U**	**L**	**M**	**U**	**L**	**M**	**U**
EXP_1	0	20	40	40	45	50	50	55	60	60	70	80	80	90	100
EXP_2	0	20	40	40	40	40	50	55	60	60	65	70	70	85	100
EXP_3	0	15	30	30	45	60	60	65	70	70	80	90	90	95	100
EXP_4	0	25	50	50	55	60	60	65	70	70	75	80	80	90	100
EXP_5	0	0	0	0	15	30	30	55	80	80	85	90	90	95	100
EXP_6	0	10	20	20	30	40	40	50	60	60	70	80	80	90	100
EXP_7	0	0	0	0	20	40	40	50	60	60	70	80	80	90	100
EXP_8	0	5	10	10	15	20	20	40	60	60	70	80	80	90	100
EXP_9	0	0	0	0	20	40	40	45	50	50	65	80	80	90	100
EXP_{10}	0	0	0	0	20	40	40	50	60	60	70	80	80	90	100
EXP_{11}	0	5	10	10	20	30	30	40	50	50	60	70	70	85	100
EXP_{12}	0	5	10	10	20	30	30	40	50	50	60	70	70	85	100
EXP_{13}	0	15	30	30	40	50	50	60	70	70	80	90	90	95	100
EXP_{14}	0	10	20	20	30	40	40	50	60	60	70	80	80	90	100
EXP_{15}	0	5	10	10	25	40	40	50	60	60	70	80	80	90	100

After the initial barriers were generated from the literature (Table 1), a survey designed using Fuzzy Delphi as the research method was provided to the experts for review. The experts responded to each of the barriers based on their individual experience and knowledge in the manner described in Section 3.1. To make the study results more informative and complete, the experts were also asked to suggest other factors identified as barriers to advancing 3D printing technology in dentistry based on their work experience. The experts were also allowed to adjust the semantics of the barriers, including “inheritance of experience”, “government subsidies”, “data management”, and “responding backup plans”. The barriers, such as “inheritance of experience”, “government subsidies”, “data management”, and “corresponding backup plans”, were raised by the experts during the discussion. To reduce the uncertainty of the expert’s answers, each barrier was converted into a fuzzy number by converting the linguistic variable into a fuzzy number, and then the results were calculated and defuzzied by using Equations (1)–(5) as shown in Table 4. After the experts reviewed the barriers and the survey results, the experts decided to keep the barriers with an importance coefficient > 4.45. After constructing the initial indicator framework using the Fuzzy Delphi method, the expert team revised or merged the semantically and practically close barriers to make the subsequent analysis more definite. The nine barriers were finally identified as the core indicators for the final assessment stage, and the core indicators were renumbered from C_1 to C_9 for ease of labeling, as shown in Table 5.

4.2. Date Collection and Integration for the Direct Influence Matrix

After using the Fuzzy Delphi method to define the key barriers, the experts were invited to use semantic variables to assess the degree of mutual influence relationship among the barriers and their confidence level in this degree of influence. In the case of Expert 1, as shown in Table 6, he considers the degree of influence of C_1 on C_2 as “High Influence (HI)” with a confidence level of 90%, which is then calculated according to the Z-number proposed by Zadeh [66], which contains two types of fuzzy information, namely, the assessed value and the confidence level. The degree of certainty of a fuzzy event can be measured by probability and reliability, and the Z-number can transform the information of both into a set of fuzzy numbers. Unlike previous studies that used fixed semantic tables, the semantic variables in this study were transformed into triangular fuzzy numbers based on the definitions of individual experts. According to the method in Section 3.2, after the Z-number of each expert was transformed, the pairwise comparisons of all key factors were completed, as shown in Table 7. Finally, the Z-number membership function was defuzzified to obtain the direct influence matrix of Expert 1, as Table 8 shows. The data was assessed considering the uncertainty and confidence of the expert, and the data of other experts were all calculated similarly.

Table 4. Assessment of the barriers constructed by the Fuzzy Delphi method.

NO	Barrier	d^l	d^m	d^u	p_i	Q3
B_1	Consensus within the organization	3	3.949	5	3.983	Delete
B_2	Managerial support	4	4.573	5	4.524	KEEP
B_3	Management process responsiveness	4	4.373	5	4.458	KEEP
B_4	Conservative attitude	3	3.949	5	3.983	Delete
B_5	Lack of understanding of new technologies	3	3.949	5	3.983	Delete
B_6	Collaboration capability	4	4.373	5	4.458	KEEP
B_7	Government attitude	3	3.898	5	3.966	Delete
B_8	Financial efficiency assessment	4	4.782	5	4.594	KEEP
B_9	Inheritance of experience	3	3.776	4	3.592	Delete
B_{10}	Government subsidies	3	3.728	5	3.909	Delete
B_{11}	Regulations and management	3	4.317	5	4.106	Delete
B_{12}	Intellectual property	4	4.373	5	4.458	KEEP
B_{13}	Limited clinical cases	4	4.373	5	4.458	KEEP
B_{14}	Accuracy improvement	4	4.782	5	4.594	KEEP
B_{15}	High construction costs	3	4.317	5	4.106	Delete
B_{16}	Suitability of raw materials	4	4.573	5	4.524	KEEP
B_{17}	Education and training	4	4.573	5	4.524	KEEP
B_{18}	Economic benefits	3	4.317	5	4.106	Delete
B_{19}	Technical talents	4	4.373	5	4.458	KEEP
B_{20}	Hidden costs of new technology	4	4.373	5	4.458	KEEP
B_{21}	Corresponding infrastructure	4	4.373	5	4.458	KEEP
B_{22}	Technology integration	3	4.129	5	4.043	Delete
B_{23}	Material limitations	4	4.573	5	4.524	KEEP
B_{24}	Material supply chain	4	4.373	5	4.458	KEEP
B_{25}	Equipment cleaning and disinfection	3	3.949	5	3.983	Delete
B_{26}	Technology maturity	3	4.514	5	4.171	Delete
B_{27}	Cumbersome processes	4	4.183	5	4.394	Delete
B_{28}	Post-processing steps	4	4.373	5	4.458	KEEP
B_{29}	Information security	3	3.949	5	3.983	Delete
B_{30}	Protocol standardization	4	4.373	5	4.458	KEEP
B_{31}	Equipment intelligence	3	3.898	5	3.966	Delete
B_{32}	Data management	3	3.949	5	3.983	Delete
B_{33}	Technology optimization	4	4.183	5	4.394	Delete
B_{34}	Corresponding backup plans	4	4.373	5	4.458	KEEP

Note: The threshold values are Q1: 3.98, Q2: 4.43, and Q3: 4.46 (Inter Quartile Range, IQR).

4.3. Exploring the Mutual Influence Relationships among Core Barriers

All 15 experts had different initial direct influence matrices on the key factors. Previous studies mainly used averages to integrate group judgments, which are likely to lead to the shortcoming of missing information. For example, the extreme opinions of experts may be ignored when we use the averaging method. According to Equations (12)–(15), the concept of a rough set is used to structure the upper and lower limit approximation matrix, and the integration of the 15 experts' opinions produces an approximate matrix of direct influences, as in Table 9. For example, the lower limit of the direct effect of C1 on C2 is 63.58, and the upper limit is 84.94 after we integrated the opinions of the 15 experts.

Table 5. Core barriers.

Code	Assessment Criteria	Criteria Definition
C_1	Unable to assess financial benefits with certainty	Will the investment in new technology and equipment balance the financial position of revenue and expenses? Can future hidden costs be estimated and managed? The control of operational risk will affect the willingness to invest in new technologies and equipment.
C_2	Cumbersome post-processing due to poor accuracy	There is still room to improve the precision and yield of the finished product with existing 3D printing technology, and the post-processing process of 3D printing technology not only complicates the workflow, increasing production time and cost but also poses potential risks to user safety and product quality.
C_3	Managerial support and change in workflow	The support and recognition of the responsible person or manager for the new technology will influence the decision of whether to introduce and implement the new technology or equipment, and the advancement of the new technology or equipment will change the workflow in the original organization, and if the management mechanism and process are not adjusted accordingly, it will affect the effectiveness of the implementation.
C_4	Insufficient technical personnel and training	The advancement of new technology or equipment without adequately trained and skilled personnel will affect the effectiveness of implementation.
C_5	Limited use and availability of materials	The choice of materials for filling in 3D printing is already limited, and the choice of materials for dental applications is very limited because of the need for human safety. 3D printing materials are different from those used in existing technologies, and the availability and cost of new materials affect the willingness of those involved. The existing material supply system is very limited regarding the safety of materials and the determination of quality standards.
C_6	Limited clinical cases	3D printing technology still has a limited number of clinical cases in dentistry. While new technologies and materials continue to be introduced and used, the accuracy and safety of the products must be tracked over time to be validated.
C_7	Lack of standard infrastructure	3D printing equipment requires a complete set of hardware and software to operate. For example, network equipment, computer equipment, computer-aided design software, scanning input equipment, etc.
C_8	No backup plans	Failure of the 3D printing equipment to function for any reason without a backup plan will affect the ongoing printing process and the promised product delivery time.
C_9	Insufficient collaborative skills	Collaboration between dentists and dental technicians requires a high degree of synergy. Lack of effective communication and consistent knowledge background can affect the efficiency, quality, stability, and reliability of 3D printing output.

Table 6. Response of Expert 1 based on semantic variables.

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9
C_1	0	(HI, 90%)	(LI, 100%)	(MI, 20%)	(LI, 100%)	(LI, 100%)	(HI, 90%)	(LI, 90%)	(HI, 90%)
C_2	(LI, 90%)	0	(HI, 90%)	(HI, 90%)	(HI, 100%)	(LI, 90%)	(VHI, 100%)	(VHI, 100%)	(VHI, 100%)
C_3	(HI, 100%)	(HI, 100%)	0	(LI, 100%)	(VHI, 100%)	(VHI, 100%)	(VHI, 100%)	(VHI, 100%)	(MI, 100%)
C_4	(HI, 100%)	(MI, 50%)	(VHI, 100%)	0	(VHI, 100%)	(VHI, 100%)	(VHI, 100%)	(VHI, 100%)	(VHI, 100%)
C_5	(LI, 100%)	(VHI, 100%)	(VHI, 100%)	(LI, 100%)	0	(VHI, 100%)	(VHI, 100%)	(VHI, 100%)	(VHI, 100%)
C_6	(VHI, 100%)	(HI, 100%)	(VHI, 100%)	(VHI, 100%)	(VHI, 100%)	0	(VHI, 100%)	(HI, 100%)	(VHI, 100%)
C_7	(VHI, 100%)	(VHI, 100%)	(VHI, 100%)	(VHI, 100%)	(VHI, 100%)	(VHI, 100%)	0	(VHI, 100%)	(VHI, 100%)
C_8	(HI, 70%)	(VHI, 100%)	(HI, 100%)	(HI, 90%)	(VHI, 90%)	(VHI, 100%)	(VHI, 100%)	0	(VHI, 100%)
C_9	(VHI, 100%)	(VHI, 100%)	(VHI, 100%)	(VHI, 100%)	(VHI, 100%)	(VHI, 100%)	(VHI, 100%)	(MI, 100%)	0

Based on the aforementioned survey and integrating experts' opinions, this study used DEMATEL to investigate the cause-and-effect relationships among the barriers. Because of the different subjective perceptions and backgrounds of the experts, this study combined the rough-Z-number to integrate the opinions of the experts and the uncertainty considerations of the group to obtain the explicit values of the direct influence relationship matrix $\boldsymbol{A}$ (Table 10) through Equations (16)–(18). The matrix is obtained by an infinite number of interactions to obtain the total influence relationship matrix $\boldsymbol{T}$, as Table 11 shows. From the matrix $\boldsymbol{T}$, we can see that the influence relationship of C_7 on C_3 is the largest at 1.54, followed by the influence relationship of C_2 on C_3 at 1.53.

Table 7. Z direct influence matrix of Expert 1.

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9
C_1	(0, 0, 0) 0	(80, 90, 100) 90%	(80, 90, 100) 100%	(80, 90, 100) 20%	(60, 70, 80) 100%	(40, 50, 60) 100%	(60, 70, 80) 90%	(60, 70, 80) 90%	(40, 50, 60) 90%
C_2	(80, 90, 100) 90%	(0, 0, 0) 0	(80, 90, 100) 90%	(80, 90, 100) 90%	(40, 50, 60) 100%	(80, 90, 100) 90%	(80, 90, 100) 100%	(40, 50, 60) 100%	(80, 90, 100) 100%
C_3	(80, 90, 100) 100%	(60, 70, 80) 100%	(0, 0, 0) 0	(80, 90, 100) 100%	(40, 50, 60) 100%	(60, 70, 80) 100%	(40, 50, 60) 100%	(60, 70, 80) 100%	(60, 70, 80) 100%
C_4	(60, 70, 80) 100%	(60, 70, 80) 50%	(60, 70, 80) 100%	(0, 0, 0) 0	(60, 70, 80) 100%	(80, 90, 100) 100%	(80, 90, 100) 100%	(60, 70, 80) 100%	(80, 90, 100) 100%
C_5	(40, 50, 60) 100%	(80, 90, 100) 100%	(40, 50, 60) 100%	(40, 50, 60) 100%	(0, 0, 0) 0	(80, 90, 100) 100%	(60, 70, 80) 100%	(80, 90, 100) 100%	(60, 70, 80) 100%
C_6	(60, 70, 80) 100%	(80, 90, 100) 100%	(80, 90, 100) 100%	(80, 90, 100) 100%	(80, 90, 100) 100%	(0, 0, 0) 0	(80, 90, 100) 100%	(80, 90, 100) 100%	(80, 90, 100) 100%
C_7	(40, 50, 60) 100%	(80, 90, 100) 100%	(80, 90, 100) 100%	(80, 90, 100) 100%	(80, 90, 100) 100%	(80, 90, 100) 100%	(0, 0, 0) 0	(80, 90, 100) 100%	(80, 90, 100) 100%
C_8	(40, 50, 60) 70%	(40, 50, 60) 100%	(60, 70, 80) 100%	(60, 70, 80) 90%	(60, 70, 80) 90%	(60, 70, 80) 100%	(60, 70, 80) 100%	(0, 0, 0) 0	(80, 90, 100) 100%
C_9	(80, 90, 100) 100%	(80, 90, 100) 100%	(80, 90, 100) 100%	(80, 90, 100) 100%	(80, 90, 100) 100%	(80, 90, 100) 100%	(80, 90, 100) 100%	(80, 90, 100) 100%	(0, 0, 0) 0

Table 8. Defuzzied direct influence matrix of Expert 1.

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9
C_1	0.00	85.38	90.00	40.25	70.00	50.00	66.41	66.41	47.43
C_2	85.38	0.00	85.38	85.38	50.00	85.38	90.00	50.00	90.00
C_3	90.00	70.00	0.00	90.00	50.00	70.00	50.00	70.00	70.00
C_4	70.00	49.50	70.00	0.00	70.00	90.00	90.00	70.00	90.00
C_5	50.00	90.00	50.00	50.00	0.00	90.00	70.00	90.00	70.00
C_6	70.00	90.00	90.00	90.00	90.00	0.00	90.00	90.00	90.00
C_7	50.00	90.00	90.00	90.00	90.00	90.00	0.00	90.00	90.00
C_8	41.83	50.00	70.00	66.41	66.41	70.00	70.00	0.00	90.00
C_9	90.00	90.00	90.00	90.00	90.00	90.00	90.00	90.00	0.00

Table 9. Matrix of approximate upper and lower limits.

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9
C_1	[0, 0]	[63.58, 84.94]	[63.84, 85.27]	[54.98, 80.73]	[53.54, 71.39]	[39.05, 61.09]	[51.14, 68.83]	[49.07, 68.64]	[34.42, 54.39]
C_2	[64.89, 84.30]	[0, 0]	[65.98, 84.30]	[65.14, 85.92]	[41.18, 85.40]	[67.90, 60.51]	[67.59, 84.96]	[44.81, 86.67]	[63.64, 56.64]
C_3	[52.22, 87.30]	[69.21, 85.65]	[0, 0]	[39.60, 70.64]	[54.70, 87.29]	[35.64, 55.21]	[49.15, 68.39]	[51.14, 54.16]	[56.42, 68.94]
C_4	[39.60, 71.50]	[54.70, 70.29]	[35.64, 70.70]	[0, 0]	[49.15, 73.84]	[51.14, 73.27]	[56.42, 87.55]	[55.23, 87.35]	[56.46, 71.75]
C_5	[59.85, 86.17]	[68.84, 57.45]	[69.76, 86.89]	[52.16, 57.98]	[0, 0]	[62.88, 56.59]	[38.78, 86.29]	[69.98, 72.12]	[38.61, 85.00]
C_6	[62.88, 70.55]	[38.78, 72.66]	[69.98, 85.03]	[38.61, 87.25]	[37.18, 88.39]	[0, 0]	[67.99, 85.67]	[57.90, 85.85]	[62.39, 85.09]
C_7	[44.33, 85.67]	[48.40, 85.85]	[57.74, 85.09]	[64.72, 85.14]	[70.64, 56.81]	[60.33, 86.78]	[0, 0]	[61.80, 86.24]	[57.46, 85.59]
C_8	[60.85, 85.91]	[34.28, 84.78]	[69.70, 86.02]	[61.49, 56.30]	[63.42, 56.47]	[64.94, 71.56]	[67.22, 71.25]	[0, 0]	[60.45, 70.12]
C_9	[64.55, 70.48]	[32.85, 70.51]	[34.31, 84.55]	[50.13, 84.80]	[53.29, 86.74]	[49.36, 86.09]	[48.03, 85.72]	[51.53, 86.06]	[0, 0]

Table 10. Initial direct-influence relationship matrix $\boldsymbol{A}$.

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9
C_1	0.00	74.26	74.56	67.85	62.47	50.07	59.98	58.86	44.40
C_2	74.59	0.00	75.14	75.53	63.29	64.21	76.28	65.74	60.14
C_3	69.76	77.43	0.00	55.12	70.99	45.43	58.77	52.65	62.68
C_4	55.55	62.49	53.17	0.00	61.50	62.21	71.98	71.29	64.10
C_5	73.01	63.15	78.32	55.07	0.00	59.74	62.54	71.05	61.80
C_6	66.72	55.72	77.50	62.93	62.78	0.00	76.83	71.87	73.74
C_7	65.00	67.13	71.42	74.93	63.72	73.55	0.00	74.02	71.52
C_8	73.38	59.53	77.86	58.90	59.95	68.25	69.24	0.00	65.29
C_9	67.52	51.68	59.43	67.47	70.02	67.72	66.88	68.80	0.00

Table 11. Total Influence Matrix $\boldsymbol{T}$.

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9
C_1	1.22	1.28	1.38	1.27	1.26	1.19	1.31	1.29	1.21
C_2	1.48	1.29	1.53	1.42	1.39	1.34	1.47	1.44	1.36
C_3	1.34	1.28	1.27	1.26	1.28	1.19	1.31	1.28	1.24
C_4	1.34	1.28	1.38	1.19	1.29	1.24	1.35	1.34	1.26
C_5	1.41	1.33	1.46	1.32	1.23	1.27	1.38	1.38	1.30
C_6	1.45	1.37	1.52	1.39	1.38	1.22	1.46	1.43	1.37
C_7	1.48	1.41	1.54	1.43	1.41	1.37	1.37	1.46	1.39
C_8	1.43	1.34	1.48	1.35	1.34	1.30	1.41	1.28	1.32
C_9	1.39	1.30	1.43	1.33	1.33	1.27	1.38	1.37	1.19

After the total influence matrix $\boldsymbol{T}$ is obtained, the net influence ($\boldsymbol{r_i} - \boldsymbol{c_i}$) and centrality ($\boldsymbol{r_i} + \boldsymbol{c_i}$) of each barrier can be calculated according to Equations (20)–(22), and the overall assessment of each influence relationship in the system is obtained according to the total influence matrix. Table 12 shows that the top three barriers affecting other barriers are lack of standard infrastructure (C_7) > (C_2)cumbersome post-processing due to poor accuracy (C_2) > limited clinical cases (C_6). And the top three barriers that are influenced by other barriers are managerial support and change in workflow (C_3) > unable to assess financial benefits with certainty (C_1) > lack of standard infrastructure (C_7). In descending order of the total influence of the indicators, lack of standard infrastructure (C_7) > cumbersome post-processing due to poor accuracy (C_2) > no backup plans (C_8) > managerial support and change in workflow (C_3) > limited use and availability of materials (C_5) > limited clinical cases (C_6) > unable to assess financial benefits with certainty (C_1) > inadequate collaboration (C_9) > lack of financial benefits (C_4). This would mean that "lack of standard infrastructure (C_7)" has the largest total influence on the system, followed by "cumbersome post-processing due to poor accuracy (C_2)".

Table 12. Core barrier affecting relationships.

Code	Barrier	r	c	$r + c$	$r - c$	Rank
C_1	Unable to assess financial benefits with certainty	11.42	12.54	23.96	−1.12	9
C_2	Cumbersome post-processing due to poor accuracy	12.72	11.88	24.60	0.84	2
C_3	Managerial support and change in workflow	11.44	12.99	24.43	−1.55	8
C_4	Insufficient technical personnel and training	11.67	11.96	23.63	−0.28	7
C_5	Limited use and availability of materials	12.09	11.91	23.99	0.18	5
C_6	Limited clinical cases	12.58	11.38	23.97	1.20	3
C_7	Lack of standard infrastructure	12.86	12.45	25.31	0.42	1
C_8	No backup plans	12.25	12.28	24.53	−0.02	4
C_9	Insufficient collaborative skills	12.00	11.65	23.65	0.34	6

By projecting the total influence ($\boldsymbol{x}$) and net influence ($\boldsymbol{y}$) of each evaluation indicator into the coordinate axis, the INRM of the entire system can be obtained, as shown in Figure 2. The yellow squares at the top of the figure represent the system causes, while the red solid lines at the bottom represent the effects. The upper right area of the chart shows that the total influence of the indicators is higher, and the lower left area indicates the total influence is lower. In this study, to make the effect presented by INRM clear and more definite, the influence flow is drawn according to the larger influence relationship. From the figure, it can be found that C_7 (lack of standard infrastructure) is the role of "cause" in the entire assessment system and has a high-level degree of total influence. This means that C_7 (lack of standard infrastructure) is the fundamental cause and key factor in the assessment system.

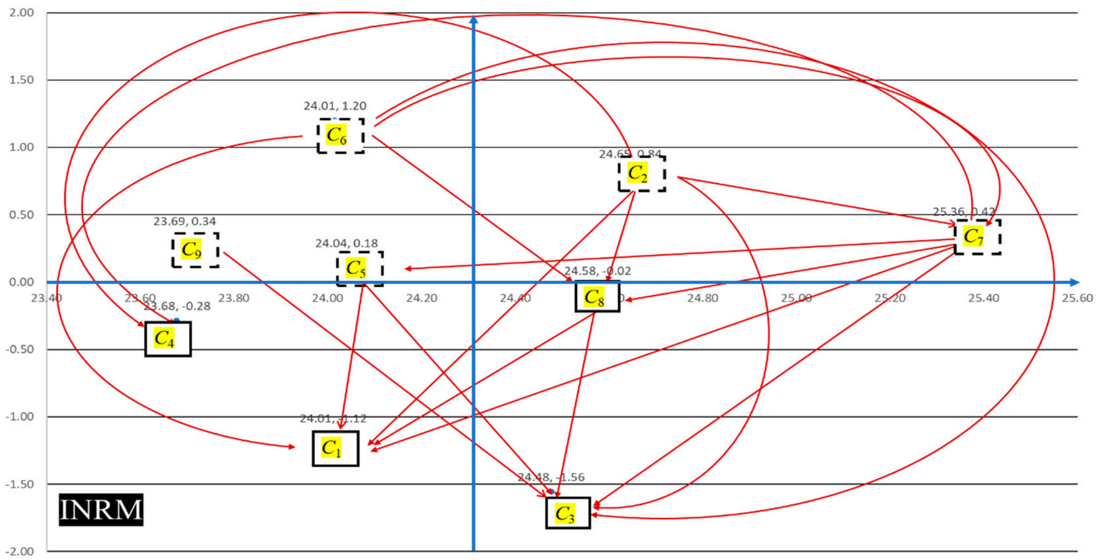

Figure 2. Influence network relationship map of the indicator assessment system.

5. Discussion

This section presents the analysis of the study's results with the management implications suggested and the theoretical implications explored.

5.1. Management Implications

After in-depth interviews with the experts using Fuzzy Delphi, nine key barriers to the advancement of 3D printing in dentistry were identified out of 34 barriers, and the mutual influence relationships among the key barriers were further investigated using a rough−Z−number combined with DEMATEL. In the total influence relationship, "lack of standard infrastructure (C7)" was ranked the highest and, therefore, could be considered the most influential barrier to advancing 3D printing technology in the dental field. This top-ranked barrier is similar to the findings of Shan et al. (2023) [45]. Interviews with the experts revealed that 3D printing devices are not stand-alone devices, so they must be equipped with computers that can perform computer-aided design (CAD) and legal software to store images of the patient's oral cavity. The CAD electronic data storage device and the internal network architecture and devices that link the 3D printing device, the computer, and the storage device are installed and integrated before they can operate smoothly. Stornelli et al. [60] also pointed out that the infrastructure and capabilities needed to support the operation of 3D printing devices are unnecessary for the traditional dental technician's workflow. Therefore, dental technologists or dentists who want to use 3D printing equipment must consider adding the aforementioned inadequate equipment and learning the skills to use it. The lack of consistent standards and criteria for the specification and integration of these hardware and software devices makes it necessary and urgent for the dental technician or dentist to consider adopting 3D printing technology. Therefore, it is recommended that school education should include courses and training to familiarize users, such as dentists or dental technologists, with the use of related hardware and software and that vendors selling equipment should be transformed into total solution providers to enable users to adopt 3D printing technology with confidence. For a dentist or dental technologist, it is a heavy financial burden to prepare a backup plan to prevent the risk of equipment failure, which will result in not delivering products on time.

The second barrier in the total influence study results is "cumbersome post-processing due to poor accuracy (C2)". Currently, the products produced by 3D printing are not immediately usable. They must undergo subsequent reprocessing, such as adjustment of the shape and angle of the product, curing of the product surface, and other adjustments necessary for the actual condition of the patient's mouth. Therefore, the future of 3D printing equipment and materials should be accelerated so that the finished product need not undergo the tedious post-processing process to reduce production costs and time. From the net influence relationship results, "limited clinical cases (C6)" is the top-ranked item. Clinical research is used in the medical field to verify the safety and efficacy of new drugs, medical devices, and innovative therapeutic techniques. The study by Liaw and Guvendiren [15] mentions the need for long-term clinical case studies to validate the safety and accuracy of 3D printing devices used in the dental field. It is recommended that a project should be conducted to manage and track the products and users of 3D printing devices for dental use so that the relevant data can be properly managed to enable the developers of related products to have better research results based on the existing clinical studies.

Of the nine core barriers, "No backup plans (C8)" is at the center of INRM and has been a lesser−mentioned barrier in previous studies. The implementation can be affected by unforeseen circumstances, such as power outages that stop the computer system and 3D printing equipment. Without backup plans in place, scheduled product interruptions can lead to delays in delivery or quality changes that must be discarded. In the manufacturing industry, it is common to have more than two sets of 3D printing equipment in case one 3D printing device fails and one is still functional. For a dentist or dental technologist, it is a heavy financial burden to prepare a backup plan to prevent the risk of equipment failure, which will result in not delivering products on time. It is recommended that the installation of an uninterruptible power supply and the establishment of cooperative mechanisms with industry partners are the ways to reduce the risk of disruptions. For "limited use and availability of materials (C5)", clinicians and technicians will not have the opportunity to rely on a huge portfolio of dental printable materials for permanent restorations, and 3D−printed dental technology will hardly further develop. Furthermore, current permanent 3D−printed materials still have lower mechanical properties when compared to conventional or milled ones [71].

5.2. Theoretical Implication

This study uses the Fuzzy Delphi method to identify the core barriers from a review of relevant literature and interviews with experts. The Fuzzy Delphi Method is formed by adding fuzzy theory, which maintains the advantages of the Delphi method while we reduce the provision number and cost of the questionnaire using the traditional Delphi method. Although the Delphi method has been widely used in many management areas, the traditional Delphi method has been criticized for the low convergence of generated results, the lengthy review process, and the omission of valuable information from expert opinions [70]. This study further defines fuzzy upper and lower limits by the experts. And it is more flexible than the original Fuzzy Delphi and reflects the difference in subjective expert perceptions.

This study used Z−numbers to measure incomplete and uncertain decision information rather than fuzzy numbers. Previous studies using Z−numbers measured the degree of influence and confidence level using fixed semantic scales [72]. Such a result will significantly limit the applications of the Z−number. The proposed novel approach develops a semantic scale specific to each expert's semantic meaning and simplifies the confidence level scale. The results will better account for the semantic differences among experts and more accurately reflect decision-making opinions. The new process and execution steps improve the traditional Z−number and will increase the Z−number's usefulness. In addition, although experts have consensus in real decision-making, they still have different opinions in detailed discussions. Most prior studies aggregated information using averages [22], which ignores the variability of each expert's opinion. This study uses a rough number for information fusion, which can fully consider each expert's opinion and present more useful information. In summary, the academic contributions of this study include improving the limitations of using Fuzzy Delphi and Z−numbers in the proposed assessment model, extending the application of traditional DEMATEL by combining the inconsistency of information integration with a rough set, which can reduce the uncertainty and inconsistency in group decision-making, and integrating the subjective opinions of experts from different working experience and backgrounds.

The results of the original DEMATEL are compared with the results of this study, as shown in Table 13. "C_2", "C_4", "C_6", and "C_9" are all classified as causes in this study, while they are categorized as effects in the original DEMATEL analysis. In addition, the ranks of the total influence degrees are also different. Using the rough−Z−number to integrate expert opinions in this study can more effectively overcome the problem of inconsistency and uncertainty of expert opinions and improve the shortcomings of the original DEMATEL. This is indeed another important theoretical contribution of this study.

Table 13. Comparisons between R-Z-DEMATEL and Orignal DEMATEL.

	R–Z Number DEMATEL						Original DEMATEL					
	r	c	$r + c$	Rank	$r - c$		r	c	$r + c$	Rank	$r - c$	
C_1	11.45	12.57	24.01	7	−1.12	Effect	7.24	7.42	14.66	8	−0.18	Effect
C_2	12.74	11.90	24.65	2	0.84	Cause	7.85	7.97	15.82	2	−0.12	Effect
C_3	11.46	13.02	24.48	4	−1.56	Effect	7.60	7.89	15.49	4	−0.30	Effect
C_4	11.70	11.98	23.68	9	−0.28	Effect	8.29	7.81	16.09	1	0.48	Cause
C_5	12.11	11.93	24.04	5	0.18	Cause	7.88	7.57	15.45	5	0.31	Cause
C_6	12.61	11.41	24.01	6	1.20	Cause	7.75	7.91	15.66	3	−0.16	Effect
C_7	12.89	12.47	25.36	1	0.42	Cause	7.85	7.55	15.40	6	0.30	Cause
C_8	12.28	12.30	24.58	3	−0.02	Effect	7.03	7.29	14.32	9	−0.26	Effect
C_9	12.02	11.68	23.69	8	0.34	Cause	7.59	7.65	15.24	7	−0.07	Effect

6. Conclusions

This study uses the Rough-Z-DEMATEL research framework to examine the key barriers to advancing 3D printing technology in the dental field. The research procedure of the study includes (1) exploring 34 barriers to the advancement of 3D printing technology into dentistry based on a literature review, (2) using the Fuzzy Delphi method to explore the core barriers to the advancement of 3D printing technology into dentistry, (3) using R-Z-number to fully consider the integration of expert opinions that are uncertain and inconsistent information, (4) exploring the key factors of the core barriers based on the interactions. Through this research procedure, it is found that the top three of the nine most critical barriers were found to be "lack of standard infrastructure (C_7)", "cumbersome post-processing due to poor accuracy (C_2)", and "limited clinical cases (C_6)", It is recommended that dentists or dental technologists should first consider receiving educational training or courses on digital transformation to be fully prepared to learn the use of 3D printing equipment before using it. Suppliers of 3D printing equipment should be able to integrate the system to increase the willingness of users to adopt the new technology and the possibility of increasing the number of patients applying 3D printing products. Improving these three most significant barriers would help accelerate the advancement of 3D printing in the dental field. Based on the interaction between the evaluation systems, DEMATEL can effectively explore the cause-and-effect relationships in the evaluation system. However, this methodology cannot effectively distinguish the level of relation of the evaluation system. Controlling the level relationship of the evaluation system can enhance and improve the evaluation system. It is suggested that future research should consider how to effectively construct the level relation of the evaluation system based on the interaction relations.

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