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Barriers to the Implementation of Building Information Modeling (BIM) in Late-Adopting Countries in the European Union: The Case of Portugal

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Abstract: Adopting Building Information Modeling (BIM) within the Architecture, Engineering, and Construction (AEC) industry presents an opportunity to address enduring challenges, including chronic productivity deficits and emerging imperatives such as cleaner production and sustainability. However, the pace of BIM implementation (BIMI) across European Union (EU) countries is uneven due to varying contexts and the inherent complexity of BIM adoption. Notably, Portugal lags in BIMI among these countries. Using the Portuguese context, the manuscript endeavours to identify the main barriers to BIMI by the late-adopting countries in the EU and, based on the dynamics of their relationships, design effective mitigation measures to lessen their impact and eventually leverage BIMI. A comprehensive list of barriers was compiled from the literature and ranked by experts through a Delphi survey, resulting in 15 critical barriers. Subsequently, an Interpretive Structural Modelling (ISM) model was constructed to elucidate the hierarchical relationships among these barriers, while a fuzzy Impact Matrix Cross-Reference Multiplication Applied to a Classification (MICMAC) analysis was employed to determine their driving and dependence powers. The resulting main barriers were the lack of evaluation and feedback mechanisms on BIMI, ignorance of BIM capabilities/benefits, scarcity of BIM-capable professionals, lack of experience and cooperation in BIMI, resistance to change, and lack of support from top management. Finally, experts formulated mitigation measures aimed at tackling these main barriers. These measures were designed to not only address each barrier individually but also to have a comprehensive and practical impact on the entire barrier system as a whole. These findings will assist researchers, policymakers, and practitioners in comprehending the barriers and hierarchical structures affecting BIMI in EU late-adopting countries.

Keywords: Building Information Modelling (BIM); barriers; interpretive structural modelling; mitigation measures; fuzzy MICMAC analysis

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1. Introduction

The construction industry is crucial for the global economy and has a significant role in the growth and development of countries. The EU BIM Task Group [1] reports that the construction sector is responsible for about 9% of the European Union's GDP (Gross Domestic Product) and provides employment to 18 million individuals. In Portugal, the construction industry accounts for 6.2% of total jobs and approximately 5% of the country's GDP [2]. Moreover, according to Eurostat [3], the construction sector share of GVA (Gross Value Added) varied between 5 and 6% in the European Union (EU) from 2010 to 2021. These statistics highlight the importance of the construction industry in promoting economic growth and providing employment opportunities. Despite its importance, the construction industry has suffered few changes [4]. This lack of progress means that the age-old problems and challenges associated with the construction industry, such as project delays and cost overruns, are still present, and newer ones, such as cleaner production and sustainability [5], are emerging.

The Architecture, Engineering and Construction industry (AEC) is remarked as slow and hesitant toward innovation and technology, remaining heavily reliant on manual labour and ancient techniques and processes, with minimal use of technology. Investment in research and development (R&D) is minimal compared to other industries, ranging from 0.01% to 0.4% of the construction value-added, compared to 3-4% in manufacturing and 2-3% in general industries [6]. The lack of investment in innovation has been a persistent problem for the industry, with the authors reporting that increasing R&D expenditure could help address the productivity deficit when compared with other industries [7–9]. To address this gap, new technologies and practices are being considered and tested, such as Artificial Intelligence (AI), Sustainability, Lean methodology, Business Process Reengineering (BPR), Total Quality Management (TQM), and Building Information Modelling (BIM), among others.

BIM is a technology and process that provides a collaborative digital environment for the design, planning, construction, and operation of facilities that incorporates all relevant information in a cloud-based model accessible to all entities involved [10]. This technology has recently attracted much interest as it may provide solutions to the problems of the ACE industry. BIM implementation (BIMI) solves several problems: improved clash detection, enhanced and streamlined communication, reduced costs, and improved quality while boosting productivity values [11]. Furthermore, BIM also provides solutions to more modern problems, such as sustainability, cleaner production and safety concerns, while incorporating cost estimation and facility management tools [12].

In the literature, several studies deal with the barriers to BIMI; however, they are scarce in the European context. Moreover, Charef et al. [13] conclude that the adoption of BIM in the European Union (EU) was heterogeneous. If countries such as Finland, Sweden, the Netherlands, France and Italy are early to adopt BIM, Spain and Germany are actively implementing BIM programs, and countries like Belgium, Switzerland and Portugal are among the late adopters [14]. Therefore, there is still a gap in understanding the barriers to BIMI and the inherent mitigation measures, particularly in the context of late-adopting countries, so standardized and unified BIM across the EU can become a reality.

This study uses the Portuguese context to identify the main barriers to BIMI by the EU's late-adopting countries, comprehend how these barriers are interrelated, and design effective mitigation measures to lessen their impact and eventually leverage BIMI in the AEC industry.

This paper is organized as follows: after this introductory section, the literature review is in Section 2; Section 3 shows the research approach; Section 4 presents the results; Section 5 comprises the discussion of the results and the mitigation measures; and Section 6 presents the main conclusions, implications, and limitations.

2. Literature Review

In the short term, BIM involves significant technical knowledge and raises the costs of operations of companies related to implementation and training [15]. These burdens, hampered by the traditional resistance to change in the construction industry [8,9], have generally stalled the BIMI rate. However, several studies have revealed that the benefits associated with BIM compensate for its drawbacks, hence the government's push for adoption in developed countries [16], as is the case of the EU countries [13].

The literature from the last decade and a half has tackled the topic of BIMI in different contexts and with different research methodologies. Literature reviews were always used to obtain secondary data from past studies, namely barriers to BIMI. In this study, the set of literature-based barriers considered is presented in Table 1, in Section 4.1.1. On the contrary, several methodologies were used to acquire the primary data. Focus groups, based on experts' and researchers' opinions, were employed to filter and adapt the barriers found in the literature to the study context or to decide on the importance of the barrier or the relationship between them [17,18]. Questionnaire surveys were used to rank the barriers [19–22] or determine the relationships between barriers by applying statistical analysis such as the Pearson relationship analysis [18], partial least squares structural equation modelling (PLS-SEM) [23], Factor analysis [15] or Principal component analysis [24]. Finally, several authors have recently adopted the ISM combined with the MICMAC analysis [7,25–27].

Table 1. List of Barriers to BIM implementation.

No	Barrier	References
1	Lacking functionalities of BIM tools	[7,8,10,25,28,43,44]
2	Complexity of BIM tools	[9,10,19,21,28,45,46]
3	BIM-related project risks and potential engineering and information defects	[9,21,26,47]
4	Immaturity of BIM technology	[24,45]
5	Interoperability difficulties of the software	[7,9,10,19–23,25–28,45–51]
6	Software acquisition cost	[7–10,18–21,23,25–29,45–49,51,52]
7	IT investment necessary for the transition to BIM	[7,9,10,19–22,25–27,45,47,49–51]
8	Time and capital investment in training	[9,10,20,21,23–25,45,47,51,53,54]
9	Change in work method required	[7,8,10,18–22,24,44]
10	Lack of BIM standards and implementation strategies	[8–10,18–26,50,51]
11	Lack of support and knowledge from top management	[7,9,10,20,21,24–27,44,45,48]
12	Need for corporate restructuring	[8–10,44,49]
13	Lack of internal communication protocols	[8–10,44,49]
14	Current methods provide satisfactory results	[9,22,24,26,27]
15	Weak cooperation in BIM adoption from other stakeholders	[9,19,21,24,25,43–45,49–51]
16	Lack of IT structure in the firm	[10,24,49]
17	Lack of experience within the firm for BIM implementation	[7–9,18,19,21,24,27,44,45,47–49,51]
18	Weak cooperation from other industry partners	[10,44,55]
19	Resistance to change	[7,8,10,19,20,23,26,27,44,45,47,48,50,51,54]
20	Lack of available BIM training	[19–22,24,27,43,49,50]
21	Scarcity of BIM-capable professionals	[7,9,20,22–24,27,50,51]
22	Lack of client demand	[8,9,19–21,23,24,26,44,45,48,49,51]
23	Ignorance of BIM capabilities/benefits	[10,19–21,23,25,26,48,54]
24	Lack of evaluation and feedback for successful BIM implementation	[7–9,19,22,24,25,29,45,50,51]
25	Fragmented nature of the construction industry	[9,10,43,44,47,56]
26	BIM data ownership and rights	[7–10,19,47–49,51]
27	Lack of government regulation	[8,9,18,19,21,23–27,43,44,47–49,51]
28	Concerns related to the safety and insurance framework of BIM	[7,8,10,19,43,47,49,50]

Most studies do not present mitigation measures for the barriers to BIMI or do not explicitly present them [7,15,18,20,23–25,28]. In the cases where measures are presented when the barriers are ranked, the measures are usually designed considering only the best-ranked ones [8,17,19,29]; and when the relationships between barriers and their respective driving and dependence powers are

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determined (ISM-MICMAC analysis), the proposed measures do not adequately explore these results [27,30].

Lastly, context-wise, there are studies in Australia [17,23], the UK [28], the Netherlands [31], China [7,8,24,25,32], Hong Kong [29], Nigeria [15,26], Pakistan [27], Iran [22], Jordania [20], Yemen [21] and Malaysia [19]. These studies are scarce in the EU context.

Thus, the present study looks at the case of Portugal (an EU member country and a late adopter of BIM) and offers a contribution to BIMI knowledge by applying a practitioner-wise methodology to design effective mitigation measures grounded on a combined ISM-fuzzyMICMAC analysis approach to scrutinize the complex hierarchical relationships among barriers and their respective driving and dependence powers from a systematical perspective.

3. Methods

The Mixed Methods Research (MMR) adopted in this study (Figure 1) has four stages: Stage I – Determination of the critical barriers to BIMI; Stage II – ISM Model; Stage III – Fuzzy MICMAC analysis; Stage VI – Development of measures to promote BIMI. A Delphi survey and two focus group discussions were conducted whenever expert opinion was requested.

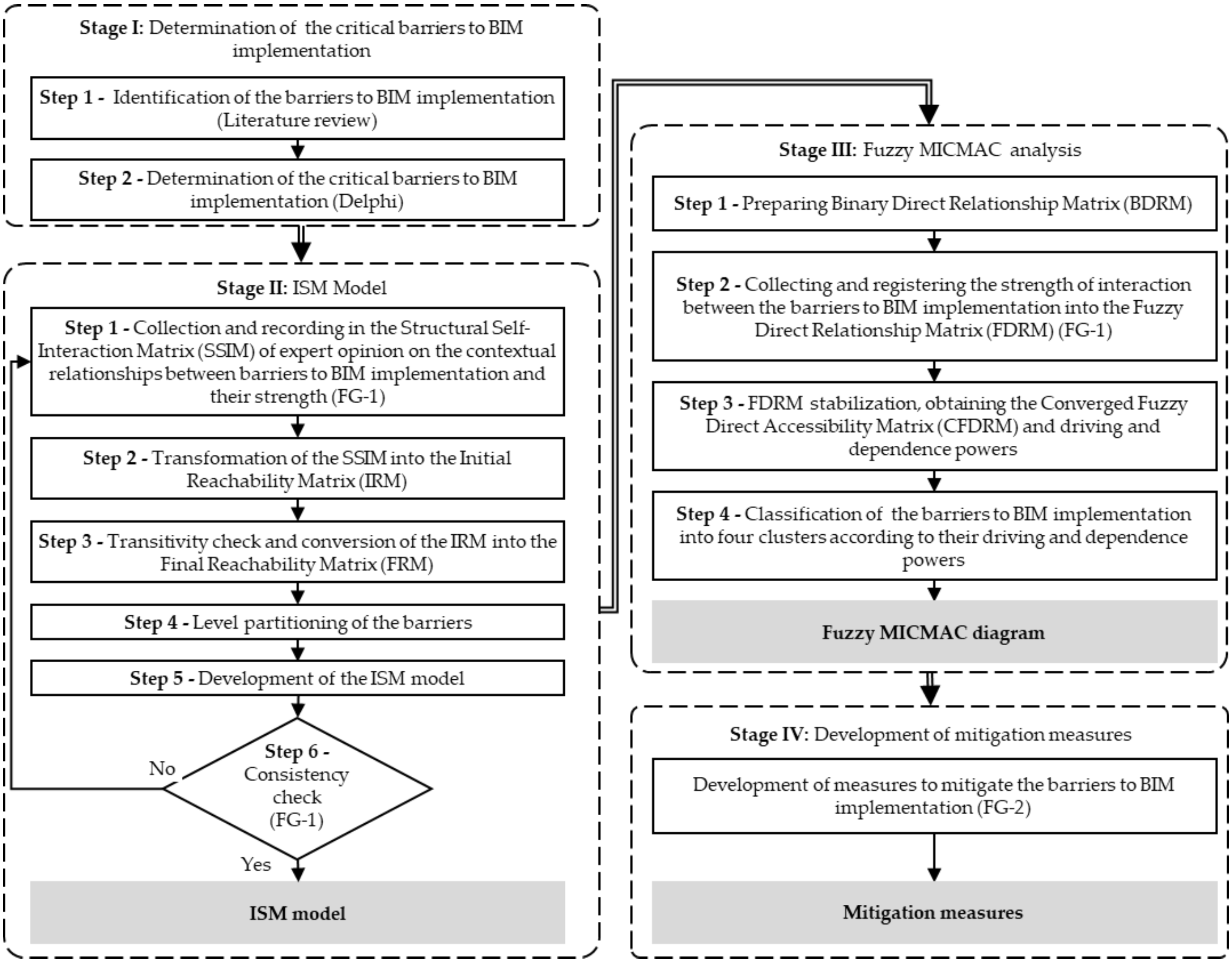

Figure 1. Research methodology.

3.1. Delphi Survey

The Delphi survey produces and refines group judgments [33]. It is grounded on the premise that 'pooled intelligence' enhances individual opinion and captures the collective opinion of a group of experts. It allows experts to communicate their knowledge and opinions anonymously about a

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complex issue of interest, realize how their evaluation of the issue aligns with others, and change their opinion, if desired, after revising and reevaluating the findings of the group's ideas. Following Needham and de Loë [34] recommendations, the panel of participants (hereafter designated "experts") selected for this study was composed of three researchers in Civil Engineering with more than 15 years of experience and nine practitioners with more than ten years of experience in construction each and with extensive knowledge of BIM.

3.2. Focus Group

The FG is a research approach, exploratory by nature, that gathers qualitative data on a subject through group interaction facilitated by a moderator [35]. FG encourages discussion among experts about their perceptions, beliefs, opinions, and attitudes toward a product, concept, or theory. Kitzinger [36] suggested that an FG includes between four and 12 experts. Following Kitzinger's recommendation [36], eight experts were selected for the FGs among the participants in the Delphi survey.

Two FGs were carried out in this study (Figure 1). The moderator of the FGs, one of the authors, helped to reach a consensus, encouraged discussion, and guaranteed the debate advanced from general to specific subjects to promote sincerity and reduce bias [35]. During the FGs, all experts had equal weight in decision-making. However, whenever a consensus was not reached, "the minority gave way to the majority".

3.3. ISM Model

The ISM model was introduced by Warfield (1974), and it is a group learning procedure supported by a computer and employed to research the relationships between various variables regarding a specific topic of a particular dynamic, complex, and multifaceted system [38]. It decodes vague mental models into observable and well-defined systems, expanding the understanding of the system's variables by defining their interrelationships and hierarchy. Moreover, ISM integrates experts' opinions based on their experience and knowledge, permitting review opinions and change judgments. It is suitable for application in real-life circumstances, not requiring too many interactions to evaluate systems with fewer than 15 variables [25].

ISM considers that the top of the hierarchy largely controls the system's behaviour by influencing other variables. Thus, in the present study, the ISM allows the design of mitigation measures for the top-of-the-hierarchy barriers (variables), considered as the root barriers, which will hopefully effectively promote the systematic mitigation of all barriers, thus promoting BIMI. The development of the ISM model followed six steps well-established in the literature [39] (Stage II in Figure 1).

3.4. Fuzzi MICMAC Analysis

Duperrin & Godet (1973) developed MICMAC analysis, based on the multiplication properties of matrices, to distribute and better comprehend a set of system variables according to their driving power (DVP) and dependence power (DEP). The DVP represents the capacity of the variable to influence others, and the DEP shows the level to which others influence it. The MICMAC analysis results in a DEP-DVP diagram with the variables placed in one of four clusters: Independent (strong DVP and weak DEP), Linkage (strong DVP and strong DEP), Dependent (weak DVP and strong DEP), and Autonomous (weak DVP and weak DEP). Variables in the Independent cluster are considered the more influential ones.

However, the original MICMAC analysis was developed to investigate binary relationship strength types between different variables. Hence, to avoid this limitation and improve the sensitivity, the fuzzy set theory was added as an extra input of the strength of the relationship between the variables [40]. Thus, the fuzzy MICMAC analysis allows for a more precise analysis of the relationships between variables compared to the original.

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The development of the MICMAC fuzzy analysis followed a well-established four-step procedure in the literature [41] (Stage III in Figure 1).

3.5. Development of Mitigation Measures

Combining the barriers from the Independent cluster (MICMAC analysis) with the root barriers (ISM model) establishes the main barriers to BIMI [42]. Therefore, when developing the mitigation measures, the focus should be on those main barriers while considering that the measures should be capable of reaching and impacting the remaining barriers according to the hierarchy between them and their DVPs and DEPs. However, specific measures should also be developed, if needed, to mitigate the barriers in the Autonomous cluster (MICMAC analysis) due to their reduced DEPs.

4. Results

This section applies the first three stages of the research methodology (Figure 1) to obtain the ISM model and fuzzy MICMAC analysis.

4.1. Critical Barriers to BIMI

4.1.1. Identification of the Barriers to BIMI

First, a literature review was carried out to find and analyze the most common barriers to BIMI. For that, the Web of Science and Scopus databases were searched with a combination of the following keywords: "BIM", "Building Information Modelling", "implementation", "adoption", "barriers", "critical success factors", and "mitigation measures". After title and abstract analysis, 22 articles were retained for review to determine barriers to BIMI. Then, after merging comparable barriers and adapting them to the Portuguese context by three experts with BIM knowledge, 28 barriers were selected (Table 1). Furthermore, these barriers were grouped into five categories: Technological, Cost, Organisational, External Environment, and Legal.

4.1.2. Determination of the Critical Barriers to BIM

The 12 experts selected to determine the critical barriers received an email explaining the study's objectives and the list of barriers duly presented, asking for misunderstandings, ambiguities, and recurrences. Then, a three-round Delphi survey (comprised of the 28 barriers in Table 1) followed. The experts were requested to score each barrier on a 7-point scale, where: "7" designates that the barrier is highly critical, "4" critical, and "1" slightly or not critical to BIMI [33]. After each round, the geometric mean of the scores, adopted to prevent the impact of extreme values, was calculated. Barriers with a geometric mean greater than or equal to 5 were considered critical [33]. At the end of the first round, nine barriers were scored as critical. In the second round, the experts were informed of the first round results and again requested to score each barrier, resulting in 15 critical barriers. Following the same procedure in the third round, the experts reached a consensus, maintaining the same 15 critical barriers from the previous round (Figure 2 and Table 2). It is interesting to note that none of the barriers from the technological category were considered critical for the BIMI in Portugal, which aligns with the findings of Kassem et al. [28].

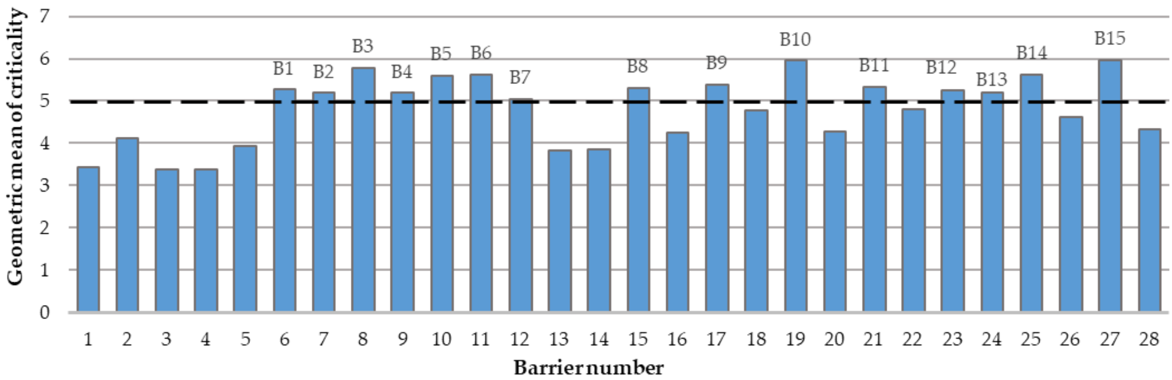

Figure 2. Barrier criticality scores (geometric mean). B1 to B15 are deemed critical.

Table 2. List and description of critical barriers to BIM implementation.

Code	Barrier – description
B1	Software acquisition cost – Decision-makers are often unfamiliar with the possible benefits of BIMI [15], which, when combined with the high cost of software procurement, can result in a perceived negative return on investment (ROI), aggravating the resistance to BIMI [9].
B2	IT investment necessary for the transition to BIM – Since the BIM process requires significant computing power, most businesses will need to upgrade their current hardware, network, and any other infrastructure component that may be inadequate [9].
B3	Time and capital investment in training – For successful BIMIs, companies must provide their employees with adequate training, as BIM tools, workflows, and protocols differ from traditional practices. According to Young et al. [11], receiving adequate training in the early stages of BIMI is the greatest challenge to successful BIM.
B4	Change in working methods required – BIM work procedures do not align with traditional work practices. As Sun et al. [7] confirmed, with BIM, there is a need for change in work processes, with the authors adding that the lack of a defined BIMI procedure makes it a management risk.
B5	Lack of BIM standards and implementation strategies – The lack of documentation regarding BIMI strategies significantly deters companies wishing to transition to BIM [19,50]. These standards should cover all the main aspects of BIM, such as data exchange, best practices, necessary workflows, operation and maintenance requirements, and more [8].
B6	Lack of support and knowledge from top management – The top management is accountable for strategic decisions that affect the company's future success. They are experienced professionals, are deeply familiar with traditional methods and generally have a risk-averse attitude toward BIM. Their perception of BIM as a disruptive and fad technology might harm the BIMI[48].
B7	Need for corporate restructuring – As understood by Dossick and Neff [57], projects become heavily reliant on project managers when BIM is implemented without a proper organizational structure that potentiates collaboration. Chan et al. [50] concluded that companies implementing BIM must reassess their current structure and strategy.
B8	Weak cooperation in BIM adoption from other entities involved – AEC projects require the intervention and collaboration of several entities with vested interests in the correct project development. Due to the multidisciplinary nature, all these entities must interact and cooperate most efficiently. This is one of the main

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	strengths of BIM, as it allows for better collaboration and communication. However, to achieve BIM's full potential, all the parties involved must adopt it and cooperate [8].
B9	Lack of experience within the company for BIMI – As Kassem et al. [28] stated, technology can only be successfully implemented if the workforce is adequately trained and experienced. When there is insufficient team knowledge and experience at the project level to ensure a seamless transition to BIM, extra costs and time spent on corrections and adjustments result [7].
B10	Resistance to change – It can be defined as an attitude or conduct that undermines the objective of change, which can cause the procedure to fail. However, the development of new technologies and new and improved methods is a competitive advantage for those who adopt them. Chan et al. [50] considered cultural resistance to change a significant barrier.
B11	Scarcity of BIM professionals – Rogers et al. [18] found that the lack of BIM skills in newly graduated engineers resulted from BIM-deficient university curricula. This issue was also recognized by university representatives among the experts in the present study.
B12	Ignorance of BIM capabilities/benefits – A lack of understanding of the possible benefits of BIMI undermines its potential for success, as companies and their employees don't see the need for change and what advantages it may bring them [20].
B13	Lack of evaluation and feedback on successful BIM implementations – BIM is still fairly recent compared to traditional construction methods, resulting in a lack of assessment and feedback regarding its implementation [24]. This is worsened by the fact that the construction industry has a notoriously low investment rate in R&D, which is also true in the case of BIM.
B14	Fragmented nature of the construction industry – A fragmented industry is one where knowledge gained by a team or company during a specific project is not retained and shared with other teams or companies to be used in future projects, as in the construction industry. [9]. For effective BIMI, proper collaboration is essential, as it is one of the cornerstones of the BIM process [7].
B15	Lack of government regulation – The immaturity of the contractual and regulatory legislation regarding BIM is a significant obstacle to its implementation [7]. The lack of mandatory BIM policies and government stimulus through incentives, subsidies, or tax incentives means that companies are unwilling to implement BIM [48].

4.2. ISM Model

The development of the ISM model based on the 15 critical barriers includes six steps (stage II of the research methodology in Figure 1). From now on, the "critical barriers" will be referred to as only "barriers" for simplification.

4.2.1. Contextual Relationships

In the FG-1, experts expressed the contextual relationships between pairs (i,j) of barriers, giving the following symbology: V – barrier i influences or leads to achieving the barrier j; A – barrier j influences or leads to achieving the barrier i; X – Barriers i and j influences or leads to achieving each other; O – barriers i and j do not influence each other. The results were placed in the Structural Self-Intersection Matrix (SSIM) (Table 4).

Table 4. Structural Self-Intersection Matrix.

B(*i*/*j*)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**

1		V	O	O	O	A	O	O	O	O	O	O	O	O	O
2			O	O	O	A	O	A	O	O	O	A	O	O	O
3				A	A	A	O	O	A	O	A	O	O	O	O
4					A	A	X	O	A	A	O	O	O	A	O
5						O	V	A	O	O	A	O	A	A	A
6							V	O	O	V	O	A	A	O	O
7								A	A	A	O	O	A	A	O
8									A	A	A	O	O	A	O
9										O	A	O	O	O	O
10											O	A	A	O	O
11												O	O	O	O
12													A	O	O
13														O	O
14															O
15															

Note: B(i/j) – Barrier in line i, or column j.

4.2.2. Transformation of the SSIM into the Initial Reachability Matrix

The SSIM was transformed into the Initial Reachability Matrix (IRM) (a binary matrix, Table S1), by replacing the letters with 1s and 0s: if SSIM(a,b) = V, then IRM(a,b) = 1 and IRM(b,a) = 0; if SSIM(a,b) = A, then IRM(a,b) = 0 and IRM(b,a) = 1; if SSIM(a,b) = X, then IRM(a,b) = IRM(b,a) = 1; if SSIM(a,b) = O, then IRM(a,b) = IRM(b,a) = 0.

4.2.3. Transitivity Check and Conversion of the IRM into the Final Reachability Matrix

The transitivity check converted the IRM into the Final Reachability Matrix (FRM) (Table 5). If barrier i influences barrier j and j influences k, then barrier i indirectly influences k through j, and if (i,k) entry in the IRM is 0, then it has to be changed to 1*. The FRM was obtained through a Boolean operation, which involved self-multiplication of IRMI (IRM plus the identity matrix I) until it reached a stable result, as shown in Equation (1) [58].

$$\mathrm{IRMI} \neq \mathrm{IRMI}^2 \neq \cdots \neq \mathrm{IRMI}^{n-1} \neq \mathrm{IRMI}^n = \mathrm{IRMI}^{n+1} = \mathrm{FRM} \quad (1)$$

Table 5. Final Reachability Matrix.

B(i/j)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	1	1	0	0	1	0	0	0	0	0	0	0	0
5	0	0	1	1	1	0	1	0	0	0	0	0	0	0	0
6	1	1	1	1	1*	1	1	1*	0	1	0	0	0	0	0
7	0	0	1*	1	0	0	1	0	0	0	0	0	0	0	0
8	0	1	1*	1*	1	0	1	1	0	0	0	0	0	0	0
9	0	1*	1	1	1*	0	1	1	1	0	0	0	0	0	0
10	0	1*	1*	1	1*	0	1	1	0	1	0	0	0	0	0
11	0	1*	1	1*	1	0	1*	1	1	0	1	0	0	0	0
12	1*	1	1*	1*	1*	1	1*	1*	0	1	0	1	0	0	0
13	1*	1*	1*	1*	1	1	1	1*	0	1	0	1	1	0	0
14	0	1*	1*	1	1	0	1	1	0	0	0	0	0	1	0
15	0	0	1*	1*	1	0	1*	0	0	0	0	0	0	0	1

Notes: B(i/j) – Barrier in line i, or column j; 1* is a transitive linkage.

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4.2.4. Level Partitioning of the Barriers

In this step, the level partitioning of the barrier was performed using the FRM. To this end, the reachability, the antecedent, and the intersection sets were formed for each barrier. The reachability set of the barrier i comprises all barriers influenced by it. The antecedent set of the barrier i comprises all the barriers that influence it. Finally, the intersection set contains the common barriers to the reachability and antecedent sets. When a particular barrier's intersection and reachability sets are equal, that barrier is assigned to the current iteration (hierarchical level). The barriers assigned to a given level are detached from the remaining reachability and antecedent sets for the following iteration. This procedure is repeated until all the barriers are partitioned into levels. In the present study, all the Barriers were partitioned into levels after eight iterations. Thus, the resulting ISM model has eight hierarchical levels (Table S2).

4.2.5. Development of the ISM Model and Consistency Check

An initial digraph was drawn up by vertically placing the barriers according to their hierarchical levels and linking them through arrows according to the FRM. Then, the indirect links between the barriers were detached to get the ISM model (Figure 2).

Finally, the experts at FG-1 were instructed to check if the ISM model correctly characterizes the “vague” mental model they have of the system of barriers to BIMI. They agree regarding the consistency of the resulting ISM model. Thus, the model was deemed adequate, highlighting both the hierarchical structure and the interrelationships between the barriers.

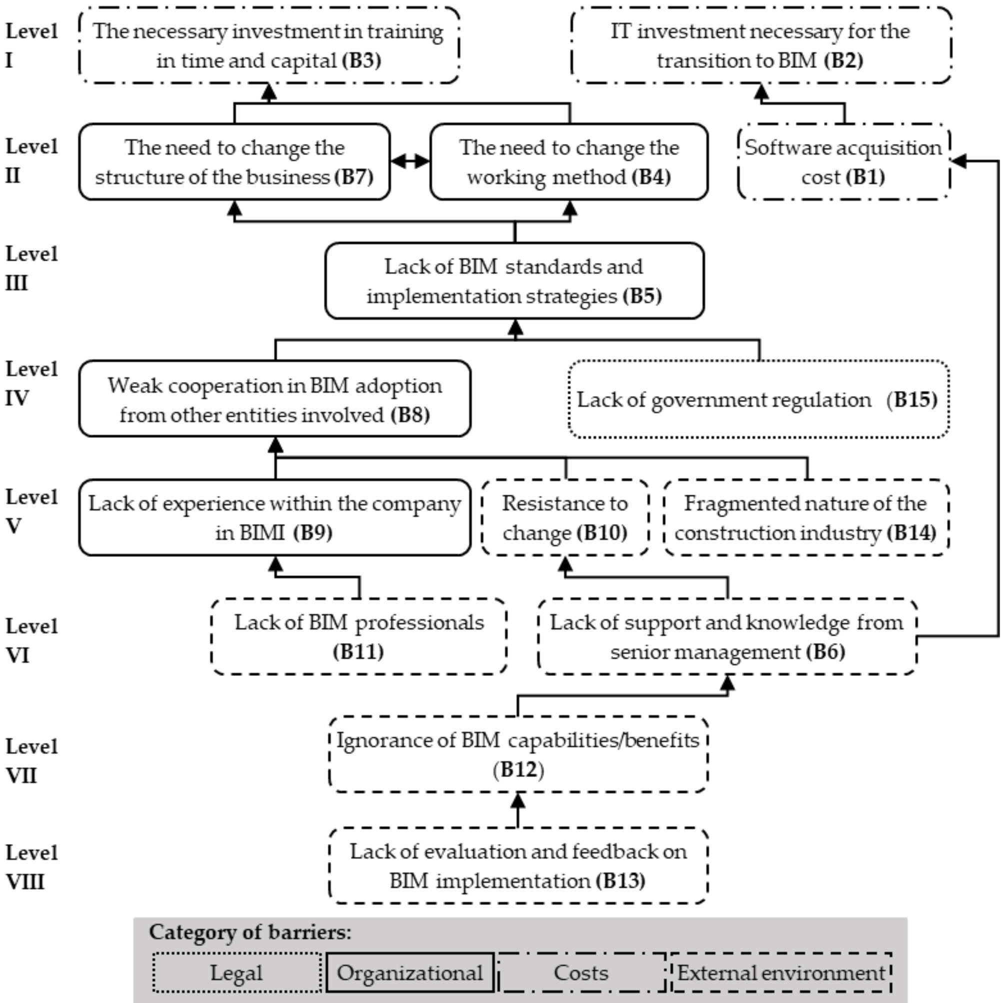

Figure 2. The ISM model of the barriers to BIMI in Portugal.

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4.3. Fuzzy MICMAC Analysis

The development of the fuzzy MICMAC analysis takes four steps (stage III of the research methodology in Figure 1).

4.3.1. Preparing Binary Direct Relationship Matrix

The Binary Direct Relationship Matrix (BDRM) is obtained by substituting all the diagonal entries in the IRM with zeros.

4.3.2. Collecting the Strength of Interaction between Barriers

In step 2, the Fuzzy Direct Relationship Matrix (FDRM) is obtained by replacing the non-zero values in the BDRM with the fuzzy values defined by the experts in FG-1 (Table 6). The judgments of the experts on the strength of relationships among various barriers were expressed on a fuzzy scale (varying from 0 to 1) using seven linguistic terms [40], namely: 0 – no relationship, 0.1 –very weak, 0.3 – weak, 0.5 –medium, 0.7 – strong, 0.9 – very strong, 1 – complete.

Table 6. Fuzzy Direct Reachability Matrix.

B(*i*/*j*)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
1	0	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0.5	0	0	0	0.7	0	0	0	0	0	0	0	0
5	0	0	0.5	0.5	0	0	0.5	0	0	0	0	0	0	0	0
6	0.3	0.5	1	0.7	0	0	0.3	0	0	0.3	0	0	0	0	0
7	0	0	0	0.7	0	0	0	0	0	0	0	0	0	0	0
8	0	0.7	0	0	1	0	0.7	0	0	0	0	0	0	0	0
9	0	0	0.7	0.3	0	0	0.1	0.7	0	0	0	0	0	0	0
10	0	0	0	0.5	0	0	0.7	0.5	0	0	0	0	0	0	0
11	0	0	0.7	0	0.3	0	0	0.9	0.7	0	0	0	0	0	0
12	0	0.7	0	0	0	0.7	0	0	0	0.3	0	0	0	0	0
13	0	0	0	0	0.7	0.3	0.1	0	0	0.1	0	0.7	0	0	0
14	0	0	0	0.3	0.5	0	0.5	0.1	0	0	0	0	0	0	0
15	0	0	0	0	0.9	0	0	0	0	0	0	0	0	0	0

Note: B(i/j) – Barrier in line i, or column j.

4.3.3. Fuzzy Direct Relationship Matrix Stabilization

In this step, the stabilization of the FDRM generates the Converged Fuzzy Direct Accessibility Matrix (CFDRM) (Table 7). For that, the principles of fuzzy matrix multiplication suggested by Kandasamy et al. [59] were adopted to obtain the stabilization of FDRM. Fuzzy matrix multiplication is essentially a generalization of Boolean matrix multiplication, equation (2). According to the fuzzy set theory, the result is still a fuzzy matrix when two fuzzy matrices are multiplied. To obtain the CFDRM, FDRM is multiplied repeatedly until the DEPs and DVPs are constant. DEPs and DVPs are calculated by summing the entries of CFDRM in the rows and columns separately.

$$IZ = X.Y = [X_{ik}].[Y_{kj}] = Max_k[Min(X_{ik}, Y_{kj})] \quad (2)$$

Table 7. Converged Fuzzy Direct Reachability Matrix.

B(*i*/*j*)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**DVP**
1	1.0	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	1.5
2	0	1.0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.0
3	0	0	1.0	0	0	0	0	0	0	0	0	0	0	0	0	1.0

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4	0	0	0.5	1.0	0	0	0.7	0	0	0	0	0	0	0	0	2.2
5	0	0	0.5	0.5	1.0	0	0.5	0	0	0	0	0	0	0	0	2.5
6	0.3	0.5	1.0	0.7	0.3	1.0	0.7	0.3	0	0.3	0	0	0	0	0	5.1
7	0	0	0.5	0.7	0	0	1.0	0	0	0	0	0	0	0	0	2.2
8	0	0.7	0.5	0.7	1.0	0	0.7	1.0	0	0	0	0	0	0	0	4.6
9	0	0.7	0.7	0.7	0.7	0	0.7	0.7	1.0	0	0	0	0	0	0	5.2
10	0	0.5	0.5	0.7	0.5	0	0.7	0.5	0	1.0	0	0	0	0	0	4.4
11	0	0.7	0.7	0.7	0.9	0	0.7	0.9	0.7	0	1.0	0	0	0	0	6.3
12	0.3	0.7	0.7	0.7	0.3	0.7	0.7	0.3	0	0.3	0	1.0	0	0	0	5.7
13	0.3	0.7	0.7	0.7	0.7	0.7	0.7	0.3	0	0.3	0	0.7	1.0	0	0	6.8
14	0	0.1	0.5	0.5	0.5	0	0.5	0.1	0	0	0	0	0	1.0	0	3.2
15	0	0	0.5	0.5	0.9	0	0.5	0	0	0	0	0	0	0	1.0	3.4
DEP	1.9	6.1	8.3	8.1	6.8	2.4	8.1	4.1	1.7	1.9	1.0	1.7	1.0	1.0	1.0	

Notes: B(i/j) – Barrier in line i, or column j; DVP – driving power; DEP – dependence power.

4.3.4. Classification of the Barriers to BIMI into Four Clusters

Finally, in step 4, the barriers to BIMI are placed, according to their DEP and DVP in the CFDRM, in one of the four clusters of the fuzzy MICMAC diagram (Figure 3).

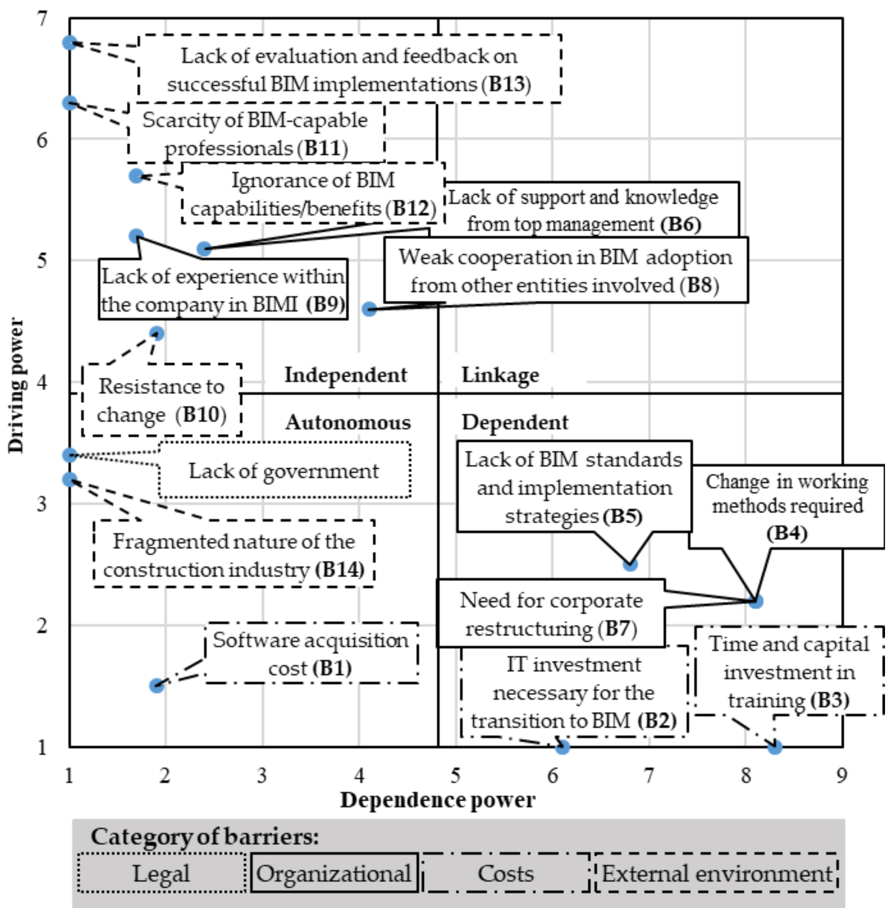

Figure 3. Fuzzy MICMAC diagram of the barriers to BIMI in Portugal.

5. Discussion and Mitigation Measures

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With the help of the experts in the FG-2, this section discusses the results of the ISM model and fuzzy MICMAC analysis and recommends mitigation measures (MMs) for the barriers to BIMI.

5.1. Discussion

Concerning the ISM model, some findings can be signalled (Figure 2). The necessary investment in training in time and capital (B3) and IT investments needed for the transition to BIM (B2) are at the top of the ISM model, level I, the lowest hierarchical level. Although these barriers may significantly affect BIMI [9,26], they are greatly influenced by other barriers and will likely have little or no influence on others.

Level II comprises the need to change the structure of the business (B7), the need to change the working method (B4), and the software acquisition cost (B1). B7 and B4 influence each other and directly B3, which is expected once corporate restructuring and changes in the work methods aggravate the need for time and capital to invest in training [26]. B1 is isolated at this level and directly influences B2; the higher the software acquisition cost, the higher the impact of B2.

The lack of BIM standards and implementation strategies (B5) at level III directly influences B7 and B4. Changing the corporate structure and working methods is more difficult without BIM standards and implementation strategies [47].

Weak cooperation in adopting BIM between the entities involved (B8) and the lack of government regulation (B15) are at level IV. These barriers are not interconnected, and both directly influence B5 since the difficulties in BIMI associated with the lack of standards and implementation strategies are aggravated by B8 and B15 [8]. Note that no barriers influence B15.

Lack of experience within the company in BIMI (B9), resistance to change (B10), and the fragmented nature of the construction industry (B14) are at level V. They are not interconnected and directly influence B8. The fragmented nature associated with the traditional resistance to change in the industry [60] and the lack of experience worsens the impact of B8 [9].

At level VI are the barriers of lack of BIM professionals (B11) and support and knowledge from senior management (B6), which are not interrelated. B11 understandably worsens the impact of B9, and, according to the experts, if senior managers do not support and have knowledge of BIM, the impacts of B10 and B1 (at level II) on BIMI increase.

Ignorance of BIM capabilities/benefits (B12) is at level VII and directly influences B6. BIM allows productivity gains and improvements in service levels, to which top managers are susceptible. Therefore, reducing B12 drives managers to support BIMI (B6) [20].

The lack of evaluation and feedback on BIMI (B13) is at the bottom of the ISM model, the highest hierarchy level, level VIII. It directly influences B12 [61], indirectly influences the other barriers at lower hierarchical levels, except B11, B14 and B15, and is not influenced by any barrier. In conclusion, B13, concerning the ISM model, is considered the root barrier to BIMI in Portugal. However, to some extent, B11, B14, and B15, which are little or not influenced by other barriers, must also be considered when developing MMs.

Looking now at the fuzzy MICMAC diagram, the linkage cluster is empty (Figure 3), which is not novel in the literature [39]. Barriers in this category would have strong DVP and DEP.

The Autonomous cluster comprises three barriers: B1, B14, and B15. They have weak DVP and DEP, meaning they are, to some extent, detached from the remaining system of barriers to BIMI. Thus, specific MMs may be required for these barriers.

The Dependent cluster comprises five barriers: B2, B3, B4, B5 and B7. Weak DVP and strong DEP characterize these barriers. Thus, they are strongly influenced, but their influence on others is negligible. Therefore, if appropriate MMs are developed for the barriers in the Independent cluster, specific measures for these barriers will not be necessary in principle.

Lastly, the Independent cluster includes seven barriers: B6, B8, B8, B10, B11, B12 and B13. These barriers have a strong DVP and a weak DEP, influencing most others but being barely affected by them. These barriers should be the main target of MMs due to their ability to influence the others in the Dependent cluster.

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Considering the categories, environment-related barriers are at the highest hierarchical levels of the ISM model (B13 and B12 at levels VIII and VII) and the intermediate/high position (B11, B10, and B14 at levels VI and V). Concerning the fuzzy MICMAC analysis, these barriers are all in the Independent cluster except for B14. This reveals the significant role of this type of barrier on BIMI, confirming the findings of Saka et al. [26].

The cost-related barriers (B1, B2 and B3) are at the lowest levels of the ISM model (levels I and II), showing that the others strongly influence them, which is confirmed by the fuzzy MICMAC analysis, except for B1. Nevertheless, the experts confirmed the importance of the costs related to BIMI [25,51].

B15, a legal-related barrier, is at an intermediate level of the ISM model and the Autonomous cluster of the fuzzy MICMAC analysis. Thus, as other barriers do not influence it, B15 must be tackled with specific MMs. Experts agreed that the lack of government regulations has a prominent role in BIMI, confirming the results of Manzoor et al. [19].

Finally, organization-related barriers (B6, B8, B9, B5, B4, and B7) are positioned in intermediate levels (IV to II). Thus, these barriers, which influence others at lower levels and are also influenced by others at higher levels, play an intermediary role in the system of barriers to BIMI [57]. Nevertheless, some care must be taken with these findings because, in the MICMAC fuzzy analysis, B6, B8 and B9 are in the Independent cluster, with high DVP, and B4, B5 and B7 are in the Dependent cluster, with high DEP.

5.2. Mitigation Measures

After identifying the main barriers to BIMI in Portugal (the root barriers and those in the Independent cluster), the experts were asked to develop MMs to target these main barriers while simultaneously being able to reach and mitigate the remaining barriers (Table 8). They were also reminded of the need to establish additional MMs to address barriers in the Autonomous cluster that previous measures had not yet impacted.

Table 8. Mitigation measures for the barriers to BIMI.

Code	Mitigation measure description	Main barriers	Autonomous cluster	Dependent cluster
MM1	Government funding of research studies to evaluate and collect feedback on BIMI	B:6,8, 9,10,12,13	B1	B:3,4,5,7
MM2	Promoting collaboration with industry leaders to build the necessary support and knowledge base on BIMI	B:6,8,10,12,13	B:1,14,15	B:2,3,4,5,7
MM3	Implementation of Integrated Project Delivery (IPD)	B:6,8,10,12,13	B1	B:2,3,4,5,7
MM4	Creation of BIMI pilot projects through consortium participation of multiple organizations	B:6,8,10,12,13	B:1,14	B:2,3,4,5,7
MM5	Promoting joint work between industry and experts to assess current processes and structures to have a phased implementation of BIM	B:6,8,9,10,12,13	B:1,15	B:3,4,5,7
MM6	Introduction of BIM in university curricula and promoting research on this topic	B:6,8,9,10,11,12	B1	B:2,3,4,5,7
MM7	Organization of BIM training seminars and workshops to raise awareness and encourage professional development	B:6,8,9,10,11,12	B1	B:2,3,4,5,7
MM8	Organization of BIM awareness seminars and conferences aimed at top management	B:6,8,10,12	B:1,14,15	B:2,3,4,5,7

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MM9	Development of government-led legislation and guides to BIMI, as well as subsidizing BIM-related costs	B:6,8,10,12	B:1,14,15	B:2,3,4,5,7
MM10	Development awareness campaigns aimed at all entities of the construction industry	B:6,8,9,10,11, 12	B1	B:2,3,4,5,7
MM11	Creation of incentives, in the form of prizes, for organizations that effectively implement BIM	B:6,8,9,10	B:1,14	B:2,3,4,5,7
MM12	Prioritization of BIM-capable professionals when hiring	B:8,9,10,11		B:3,4,5,7
MM13	Involvement of employees in the BIM implementation process from the beginning	B:8,9,10,11		B:4,5,7
MM14	Sharing BIM-related expenses among entities involved in construction projects	B8		B:2,3,4

The lack of evaluation and feedback for BIM implementations (B13) means that the success of BIMI in the Portuguese construction industry is left to speculation and comparison to other studies, which may not necessarily be replicable in the Portuguese context [16]. The experts end up suggesting five measures. MM1 enable the collection of valuable data and feedback on BIMI cases in Portugal, as well as the effectiveness of the implementation process. In the literature, several authors suggest that government incentives for research studies addressing BIM should increase the available literature on the topic [8,9].

MM2 would increase collaboration and knowledge of BIMI, which could help future implementations avoid common mistakes and highlight key challenges encountered by prior implementation attempts [8,50,62].

MM3 would bring entities into the project early and build trust among them [43]. IPD implies all entities working together as a single team, sharing information and risks, and making collective decisions to achieve project goals [18]. Olanrewaju et al. [51] conclude that IPD could help the construction industry in the UK use BIM more effectively and widely.

MM4 would enable the pooling of resources to build practical experience and explore the BIM process. This measure would help companies gain practical experience with BIM and could serve as a stepping stone for employees' training [19]. It could also identify areas where improvements to the BIMI process are needed [8].

Lastly, MM5 would promote a continuous feedback loop between companies and experts, allowing progress to be monitored and the essential information to be gathered to assist future BIMI efforts [16].

The experts suggested five more measures concerning the ignorance of BIM capabilities/benefits (B12). MM6 would result in graduates with BIM education and training better equipped to handle BIM-related decisions and increase BIM awareness within companies [63].

MM7 would provide participants with hands-on experience with BIM tools while explaining the fundamentals of it. This measure would help demystify BIM, increase awareness of its benefits, and create a continuous growth and learning culture, enabling companies to keep up with BIM practices [19].

MM8 should be designed to address the concerns of the top management, who may not have a technical background but have key decision-making power [48], and should focus on the benefits of BIM for their organization and provide a roadmap for BIMI [8,27].

MM9 would guarantee companies a stable and transversal BIM environment and guide them through the necessary steps for a successful BIM [27,61]. Moreover, by subsidizing BIM-related costs, companies could reduce the financial burden of implementing BIM [9].

Lastly, MM10 would help address the general lack of BIM knowledge (in all the entities), thus increasing support for the implementation process (Olanrewaju et al., 2020). Moreover, experts

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reinforced that these awareness campaigns, involving all entities simultaneously, will help them understand the benefits of cooperation in implementing BIM.

To overcome the lack of support and knowledge of BIM from top management (B6), the experts suggested one additional measure, MM11. This measure would reduce the financial costs of BIMI, like MM9, but in particular, the prize competition would contribute to the promotion and visibility of BIM.

The scarcity of BIM-capable professionals (B11) can lead to competition for available professionals, driving up wages and thus making it difficult for companies to hire and retain them. To address this barrier, the experts added two more measures. MM12, which may not be effective in the short term as BIM-trained professionals are scarce, would emphasize their need and thus signal to the market that BIM skills are in high demand, encouraging training and certification in this way.

MM13 would encourage employees to give feedback and voice their concerns. This measure would allow companies to gain valuable insights into specific skills gaps and workforce training needs, thus adapting their training and development programs accordingly [9].

Regarding the last three main barriers (B10, B9, B8), the experts considered that they were already targeted by some of the MMs designed for the previous barriers (see Table 8) and that no further measures are necessary.

Regarding the three barriers of the Autonomous cluster, the experts considered that for B14 and B15, the previously proposed measures were adequate and enough (see Table 8). They suggested an additional measure for the software acquisition cost (B1). MM14 would minimize risk and lead to more coordinated and integrated BIMI processes [31]. This measure should improve communication and collaboration by providing a common platform for all entities involved. Additionally, sharing BIM-related expenses should contribute to creating a level playing field, as smaller entities may not be able to afford the high upfront costs of BIM and its associated risks [30].

Finally, the experts check that the measures previously proposed reach and impact all the barriers in the Dependent cluster (see Table 8). Furthermore, on average, each MM addresses almost 11 barriers, with each barrier being impacted (directly or indirectly) by nearly 10 MMs, revealing the predictable effectiveness of the MMs proposed to BIMI.

6. Conclusions

BIM offers a collaborative digital environment for facility design, planning, construction, and operation, integrating all pertinent information in a cloud-based model accessible to all involved entities. It may provide solutions to traditional and new challenges of the Architecture, Engineering, and Construction (AEC) industry. However, widespread adoption across the European Union (EU) remains uneven despite the desire for BIM to be standardized and unified.

This study focuses on understanding the barriers to BIM implementation (BIMI) in Portugal, a late-adopting EU country, and proposes mitigation measures (MMs)) to overcome them. Initially, a Delphi survey was undertaken to reduce the list of 28 barriers identified in the literature to 15 considered critical. A notable finding surfaced during the analysis: technology-related barriers did not emerge as critical in the study. Subsequently, an approach combining ISM with fuzzy MICMAC analysis was employed to elucidate the hierarchical interrelations among barriers and their corresponding driving and dependence powers, resulting in the identification of seven main barriers. Finally, a focused group discussion involving domain experts led to the formulation of 14 mitigation measures (MMs).

The main barriers to successful BIMI encompass the absence of comprehensive evaluation and feedback mechanisms, inadequate support and understanding of BIM among top management, insufficient in-house expertise for BIMI, limited awareness of BIM capabilities and benefits, shortage of BIM-capable professionals, organizational resistance to change, and week collaboration among entities in adopting BIM practices. These identified barriers serve as foundational barriers within the barrier system dynamics and thus necessitate prioritized MMs.

The proposed MMs encompass government funding for research studies on BIMI, fostering collaboration among industry leaders to establish a comprehensive knowledge base on BIMI and

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facilitate BIM pilot projects through consortiums, promoting the industry's adoption of Integrated Project Delivery (IPD), integrating BIM into university curricula, and facilitating collaborative efforts between industry stakeholders and experts to delineate a phased approach to BIMI. These mitigation measures are designed to address barriers associated with the external environment of organizations. Some measures involve active participation from the government, universities, and research centres, while others necessitate collaboration among entities spanning across the ACE industry.

The primary contributions of this study are twofold. Firstly, it presents a novel perspective on the barriers to BIMI within a late-adopting EU country, Portugal, thus expanding the literature. Secondly, by developing MMs deliberately designed to address main barriers while also having the potential to impact other hierarchically dependent barriers, this study broadens the scope of applicability for methodologies combining ISM and fuzzy MICMAC analysis. Considering the hierarchical relationships and the driving and dependence powers among barriers, this methodology offers a broad understanding of the intricate dynamics inherent in BIMI challenges.

There are also practical implications to consider. Managers should embrace a holistic approach when designing MMs to address barriers to BIMI. This entails leveraging both the individual expertise of professionals and group interactions, such as focus groups, to determine the criticality of the barriers. Additionally, employing methodologies like ISM and fuzzy MICMAC analysis helps the identification of the main barriers and the development of MMs accordingly. By integrating these approaches, managers can ensure a comprehensive strategy for effectively overcoming barriers to BIMI.

Notwithstanding its contributions, this study is not without limitations. The methodology utilized for developing MMs relies on experts' subjective input, potentially introducing biases into the analysis. Furthermore, the findings derived from the specific context of Portugal may not be directly applicable to other late-adopting countries within the EU. Nonetheless, it is important to recognize that the methodology presented holds potential for adaptation and application in diverse contexts. These limitations offer paths for future research endeavours to apply the proposed methodology across different contexts.

Supplementary Materials: The following supporting information can be downloaded at the website of this paper posted on Preprints.org, Supplementary Material S1: Initial Reachability Matrix; Supplementary Material S2: Level partitioning.

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