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Multi-criteria decision making in evaluating digital retrofitting solutions: utilising AHP and TOPSIS

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Abstract

In an era of digital transformation, evaluating effective strategies for upgrading manufacturing systems is crucial to maintaining competitiveness. Digital retrofitting has become a strategic approach integrating new digital technologies into legacy systems to share data and align with Industry 4.0 principles. However, various techniques and criteria exist for implementing digital retrofitting. Despite its importance, there is a notable lack of studies assessing these retrofitting approaches using multi-criteria decision making (MCDM) methodologies. This study addresses this gap by employing two MCDM techniques: the analytic hierarchy process (AHP) and the technique for order of preference by similarity to ideal solution (TOPSIS). It assesses three digital retrofitting alternatives, starter kit solutions, embedded gateway solutions, and IoT hardware-based solutions, against ten critical criteria. These criteria were weighted through pairwise comparison analysis based on a survey of twelve industry practitioners to reflect industry preferences. The aim is to determine the most effective digital retrofitting approach to aid manufacturers in transitioning to Industry 4.0. This study addresses the complexities of managing conflicting criteria in digital transformation. Moreover, the results contribute to decision-making methodologies by demonstrating their practical applications, thus guiding manufacturers through the intricate landscape of digital retrofitting.

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1. Introduction

Multi-criteria decision making (MCDM) has emerged as a pivotal methodology for decision-making. MCDM encompasses many techniques to evaluate decision-making alternatives against defined criteria [1]. The importance of MCDM lies in its ability to facilitate informed and rational decisions, particularly in situations that consider conflicting criteria [2, 3]. One must balance trade-offs between conflicting criteria [4]. This balance becomes crucial in the manufacturing sector, where decision-making involves complex considerations, including balancing conflicting goals such as cost re-

duction and quality enhancement, which can significantly affect efficiency, productivity, and technological advancement [5]. The significance of MCDM extends far beyond its theoretical basis in the industry sector, finding practical applications across diverse domains. Many areas use this method, including sustainable energy planning, sustainable energy decision-making, forest management and planning, supplier evaluation and selection, and green supplier evaluation and selection. For instance, Pohekar and Ramachandran [6] employed MCDM techniques to select optimal strategies for sustainable energy planning, considering various criteria, such as environmental impact, cost, and social acceptance.

Wang et al. [7] utilised MCDM to facilitate sustainable energy decision-making by evaluating energy sources and technologies based on criteria like efficiency, cost, and sustainability. Ananda and Herath [8] applied MCDM methods in forest management to prioritise strategies that balance ecological sustainability with economic benefits and social preferences. In supplier evaluation and selection, Ho et al. [9] demonstrated using MCDM to assess and rank suppliers based on multiple criteria, including quality, cost, delivery, and environmental performance. Similarly, Govindan et al. [10] utilised MCDM to evaluate and select green suppliers by considering environmental practices, cost, and supplier performance. A review by Hamzeh and Xu [11] highlighted the use of MCDM in technology selection within advanced manufacturing technology and supply chain management, emphasizing its versatility and effectiveness. Additionally, Hagag et al. [12] illustrated the application of MCDM methods in selecting machinery for manufacturing and construction projects, while Jamwal et al. [13] underscored its utility in sustainable manufacturing practices.

Popular MCDM methods include the analytic hierarchy process (AHP) and the technique for order of preference by similarity to ideal solution (TOPSIS). Additionally, sensitivity analysis plays a crucial role in MCDM by evaluating how changes in criteria weights and other parameters influence decision outcomes, thus ensuring the robustness and reliability of the alternatives [14]. According to Shirali and Rashnoudi [15], the AHP and TOPSIS methods are used most in engineering contexts for decision-making and problem-solving processes. AHP assists decision-makers in prioritising alternatives based on multiple criteria [16]. It determines the importance of factors by establishing a hierarchy of criteria and alternatives, constructing pairwise comparison matrices, and calculating weight ratios [17, 18]. In contrast, TOPSIS is a method for ranking alternatives based on their similarity to an ideal solution. It is commonly used with AHP to evaluate and select the best alternative based on the criteria [19]. AHP and TOPSIS are MCDM techniques that provide systematic approaches to complex decision-making [20]. Yurdakul and Tansel [21] use these two methods to introduce a performance measurement model in operational activities for manufacturing companies. Similarly, Singh and Kumar [22] propose using AHP and TOPSIS to measure the effectiveness of advanced manufacturing technologies. Rahul et al. [23] use the same approach to prioritise the essential attributes for successfully implementing agile manufacturing. Despite these extensive applications, research has not explored using MCDM to evaluate approaches for upgrading legacy manufacturing systems. In this sector, MCDM is crucial for selecting the most suitable methods for digital retrofitting. Digital retrofitting entails adding new digital technologies, such as Internet of Things (IoT) components like sensors, gateways, and actuators to existing systems. This integration facilitates connectivity and real-time data analytics, enabling modernisation, which results in increased efficiency and reduced costs, thus maintaining competitiveness [24, 25]. As no one solution fits all situations, evaluating various digital retrofitting approaches is crucial for successful upgrading.

According to a McKinsey report [26], 70% of digitalisation efforts fail to achieve their goals. Despite the critical importance of upgrading legacy manufacturing systems within Industry 4.0, studies have not thoroughly explored applying MCDM to evaluate approaches in this area. This study addresses two pivotal questions central to enhancing the decision-making process in digital retrofitting within the manufacturing sector:

Q1: *How do industry practitioners prioritise the key criteria when assessing digital retrofitting solutions?*

Q2: *What are the rankings of the digital retrofitting alternatives according to MCDM methods, and how stable are these rankings to changes in criteria weights?*

Understanding how industry practitioners prioritise these key criteria provides insights into the practical considerations and challenges faced during digital retrofitting. This prioritisation ensures that proposed solutions align with industry needs. The criteria employed in this study were selected based on a comprehensive literature review and industry surveys [25, 27]. The most significant factors influencing successful digital retrofitting were identified and are presented in Table 1. Although a wide range of factors could influence decision-making, this study focuses on ten critical criteria that consistently emerged as the most relevant from both the literature and industry feedback. To assess the robustness of the rankings, sensitivity analysis is applied to evaluate how changes in the criteria weights impact the outcomes. This ensures that the rankings are not overly sensitive to slight variations in the weighting of the criteria, providing a comprehensive understanding of potential variability in decision-making. This study delivers actionable insights to address these questions and guide manufacturers in making informed decisions about digital upgrades, ensuring a smooth and strategically sound transition.

2. Background

MCDM, a comprehensive branch of decision science, facilitates evaluating, comparing, and selecting alternatives [2]. This approach proves indispensable when reliance on a single criterion is insufficient. Instead, it considers various factors to achieve an optimal decision [28]. There are two primary classifications within MCDM: multi-objective decision-making (MODM) and multi-attribute decision-making (MADM) [29]. MODM focuses on designing alternatives to optimise multiple objectives, typically involving many choices where the ideal selection meets management's priorities and constraints [30]. Conversely, MADM entails selecting the best alternative from a predetermined set based on specific attributes, typically applied to scenarios with a finite number of options [31]. Accordingly, this study determines the most effective digital retrofitting solutions under MADM. Three digital retrofitting alternatives, identified by Alqoud et al. [25, 27, 32], serve as the focus of this analysis. These alternatives include:

- **Starter kit solutions (A1):** Integrated packages provided by vendors, which encompass sensors, connectivity software, hardware, and a data analytics platform designed to monitor machine status and performance.
- **Embedded gateway solutions (A2):** Updates to machine software that provide connection to IoT networks.
- **IoT hardware-based solutions (A3):** Enhancements to legacy systems with specialised IoT hardware to improve connectivity and data extraction and integration capabilities.

This study evaluates these alternatives against ten criteria, as detailed in Table 1, to ascertain their effectiveness and suitability for upgrading manufacturing systems.

Table 1. Criteria in digital retrofitting with explanation.

Criteria	Explanation	Symbol
IoT hardware requirement	The specific Internet of Things hardware needed for successful retrofitting.	C1
Interconnectivity	The ability of the system to connect and communicate with various devices and protocols.	C2
Risk	Considers potential challenges related to coding/programming or impacts on the main function of machines.	C3
Time to Install	The duration required to set up and integrate the retrofitting solutions into the existing system.	C4
Power of Data	Evaluates the capacity to utilise internal data from the machine and external data from sensors.	C5
Cost	This includes the total expenditure on hardware and software for the first year of implementation.	C6
Complexity	The degree of difficulty in integrating data and aligning with various protocols.	C7
Show Machine Status	The capability to display the operational status of the machine.	C8
Predictive Maintenance	The ability to predict potential failures or maintenance needs before they occur.	C9
Remote Control	The capacity to control or monitor the system remotely.	C10

These alternatives and criteria from previous studies [25, 27] comprehensively assess the effectiveness and suitability of each solution for upgrading manufacturing systems.

3. Methodology

The methodology of this study commences by reviewing criteria and alternatives from previous research on digital retrofitting [25, 27], which outlined these elements but did not quantify preference trade-offs among the criteria. The study addresses this gap by conducting an AHP pairwise comparison survey to determine the relative weight of each criterion. This approach reveals the criteria priorities from the participants' perspective, answering the first research question. Following the AHP survey, it performs a consistency analysis to validate the pairwise comparison matrix for the criteria proposed by [33, 34]. The next step involves a multi-criteria

analysis using two analytical methods, AHP and TOPSIS, to ensure a comprehensive approach. The final step conducts a sensitivity analysis to test the stability of the ranking under a variety of assumptions.

3.1. Survey

The study conducts an online survey using pairwise comparison methods to establish the preferences and priorities of participants concerning a predefined set of criteria. The survey gathers insights from industry professionals with practical experience in digital retrofitting to align the proposed solutions to their needs. Respondents include engineers, managers, and decision-makers from various manufacturing sectors, ensuring a representative sample. The inclusion and exclusion criteria appear in Table 2.

Table 2. Inclusion and exclusion criteria for participants.

Inclusion
People who work in the manufacturing sector
People who serve as digitalisation solution providers for manufacturers
People who have experience in digital transformation to Industry 4.0
Aged 18 and above, all genders
Exclusion
People who do not work in the manufacturing sector
People who have no experience in the digitalisation of factories
People under 18 years old

Participants rate their choices between criterion pairs on a scale of 1 to 9, where 1 represents equal importance, and 9 indicates a strong preference for one criterion over the other (refer to Figure 1). The process evaluated all possible pairs of criteria to ensure a comprehensive assessment. As a result, participants had to answer 45 pairwise comparisons. The survey is distributed electronically to professionals in the manufacturing sector. Engagement strategies include email invitations and social media campaigns, primarily through LinkedIn, with detailed instructions to enhance data reliability and validity. Responses from twelve qualified participants were analysed.

Please evaluate the relative importance of the criteria presented below :
Indicate your choice by selecting a number and specifying if the left or right criterion is more important.

		9	7	5	3	Equal Important 1	3	5	7	9	
Predictive maintenance		☐	☐	☐	☐	☐	☐	☐	☐	☐	Remote Control

Fig.1. Example of a pairwise comparison questions.

The data analysis processes the pairwise comparison matrices to generate a value score for each criterion, reflecting the collective preferences of the participants.

These scores are crucial for prioritising the criteria and subsequently ranking the digital retrofitting solutions in later stages of the study.

3.2. Analytic hierarchy process (AHP) method

AHP is a structured technique for organising and analysing complex decisions based on mathematics and psychology. The method progresses through several steps:

- I. **Assessing significance:** The method evaluates criteria and alternatives based on the survey findings to compute an aggregate score. This step ensures that it quantifies each criterion's importance according to participants' preferences.
- II. **Pairwise comparison matrix:** It creates a matrix to compare the relative importance of each criterion. This step compares criteria in pairs to judge which is more important and by how much.
- III. **Normalisation and weight calculation:** It normalises the matrix and determines weights for each criterion by averaging the normalised values. Normalisation adjusts the scales of the data, ensuring comparability.
- IV. **Weighted matrix formation and aggregate weight calculation:** Then, the method integrates these weights into a matrix, forming the foundation for a detailed analysis. This step calculates aggregate weights to establish the relative importance of each criterion, providing a clear hierarchy.
- V. **Consistency assessment:** It ensures the decision-making process's reliability by evaluating judgment consistency through the Consistency Index (CI) and Consistency Ratio (CR). This assessment checks if the comparisons are consistent to validate the reliability of the results.
- VI. **Ranking of alternatives:** It ranks the alternatives by applying normalised values and calculating average weights for each option. This final step identifies the best alternatives according to the established criteria weights.

3.3. Technique for order of preference by similarity to ideal solution (TOPSIS)

TOPSIS is a multi-criteria decision analysis method. It progresses through structured steps to evaluate and rank alternatives:

- I. **Development of the decision matrix:** The method systematically organises data into a matrix comparing all alternatives against set criteria.
- II. **Normalisation and derivation of weighted matrix:** It normalises the decision matrix and forms a weighted matrix to emphasise the significance of each criterion.
- III. **Distance calculations:** The method calculates the Euclidean distances from each alternative to the ideal best and worst solutions, assessing how closely each

option aligns with optimal conditions. This step evaluates the performance of each alternative against the best possible scenario.

- IV. **Relative closeness and ranking:** It ranks the alternatives according to their closeness to the ideal solution, effectively identifying the most suitable options based on their proximity to the optimal conditions. This ranking helps select the best alternative from a set of feasible options.

3.4. Sensitivity analysis

Sensitivity analysis assesses the robustness and reliability of the rankings under different scenarios [36]. The rankings are reassessed by assigning equal weights to each criterion, enabling an evaluation of how weight distribution affects the final rankings. This approach checks the sensitivity of the results to changes in criterion weights [37].

4. Result and discussion

This section presents the results and discusses the survey result, the analytic hierarchy process (AHP) result, the technique for order of preference by similarity to ideal solution (TOPSIS) result, and finally, the sensitivity analysis result.

4.1. Survey result

It is crucial to consider the preliminary survey findings to thoroughly discuss the results of the MCDM analysis on digital retrofitting solutions. This survey gauged the importance attributed to various criteria relevant to digital retrofitting, involving participants who rated ten criteria (C1 to C10) by their relevance for assessing digital retrofitting solutions (see Figure 2).

The findings from this survey are revealing. Predictive Maintenance (C9) emerged as the most valued criterion, with a commanding score of 21%. This result underscores its critical importance in digital retrofitting, reflecting the industry's shift towards proactive maintenance strategies. These strategies are pivotal for enhancing operational efficiency and reducing unplanned downtimes and are crucial for maintaining continuous industrial operations. Risk (C3), with a significant score of 17.5%, highlights the concern regarding the potential challenges and threats associated with digital retrofitting. It underscores the need for comprehensive risk management strategies in such projects. Following is Power of Data (C5), scoring 16.3%. This criterion emphasises the critical influence of data in driving improvements and strategic decisions within digital retrofitting frameworks. Show Machine Status (C8) also scores highly at 15.2%, pointing to the importance of real-time monitoring capabilities in digital retrofit solutions for optimal machine performance management.

The rest of the criteria received relatively lower scores, with Cost (C6) and Complexity (C7) receiving about 9% each, followed by Remote Control (C10), Interconnectivity

and Interoperability (C2), Time to Install (C4), and IoT Hardware Requirement (C1), the last of which received the lowest score at 1.34%. These scores collectively provide a nuanced understanding of the priority areas and concerns in digital retrofitting. This stage addresses the first research question.

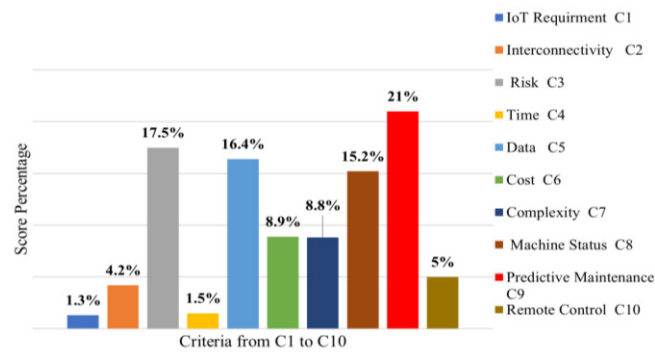


Fig. 2. Survey result shows participants preferences.

4.2. Analytic hierarchy process (AHP) result

The derived results of AHP illuminate the influence of each criterion within the decision-making process. The computed aggregate scores for the criteria delineate the variations in their contributions, allowing for an in-depth assessment of the impact of each criterion on the overall decision-making process. The integrity of the judgments within the AHP was confirmed through a sequence of calculated metrics, as detailed below. First, the Ratio Index (RI) for $n = 10$ (where n is the number of criteria) is determined to be 1.49. This value is a standard used in AHP calculations [34, 35]. To calculate the Ratio for each criterion, the following formula (1) is used:

$$\text{Ratio} = \text{Weights sum} / \text{Weights} \quad (1)$$

This formula is applied to each criterion individually. For each criterion, the Weights sum (the total weighted score for that criterion from the Weighted Matrix) and the Weights (the relative importance of that criterion) are used to calculate the Ratio, as outlined in steps III and IV.

Table 3. Aggregate weights and corresponding ratios.

Criteria	Weights sum	Weights	Ratio (Weights sum / Weights)
C1	0.142566	0.013415	10.63
C2	0.439532	0.041999	10.47
C3	1.807435	0.175312	10.31
C4	0.157075	0.014859	10.57
C5	1.653594	0.163774	10.10
C6	0.916304	0.089106	10.28
C7	0.913359	0.088183	10.36
C8	1.584514	0.152516	10.39
C9	2.147870	0.210439	10.21
C10	0.512558	0.050397	10.17

These individual Ratios are then averaged to derive λ_{max} . For example, the λ_{max} value for the Ratios in Table 3 is 10.348, which represents the average of all the individual ratios calculated across the 10 criteria. The Consistency Index (CI) derives from the following formula (2):

$$\text{Consistency Index (CI)} = \lambda_{max} - n / n - 1 \quad (2)$$

Where $n=10$, the CI was calculated to be 0.039. Finally, the Consistency Ratio (CR) is derived from the formula (3):

$$CR = CI / RI \quad (3)$$

Given that the CI is 0.039 and the RI is 1.49, the CR is calculated to be 0.0256. Since this CR value is well below the acceptable threshold of 0.1, it indicates a high level of consistency in the pairwise comparisons, underscoring the reliability of the AHP results.

Following the establishment of the pairwise comparison matrix and subsequent normalisation, weights were assigned to each criterion to reflect their relative importance. These weights helped form the weighted matrix, further quantifying the criteria's influence. Normalising values across each criterion for the alternatives facilitated a more accurate visualisation of their respective positions, allowing for a more refined comparison. The Final ranking of these alternatives using the AHP method appears in Table 4.

Table 4. AHP ranking of alternatives.

Alternatives	Score	Rank
A1 (Starter Kit)	0.65	2 nd
A2 (Embedded Gateway)	0.54	3 rd
A3 (IoT Hardware)	0.88	1 st

The AHP analysis reveals that IoT Hardware solutions (A3) lead with a score of 0.88, highlighting their superiority in fulfilling the criteria established for digital retrofitting. This impressive score indicates that A3 offers exceptional performance in key areas such as functionality and compatibility. Next, Starter Kit solutions (A1) achieve a score of 0.65, suggesting that while A1 presents a feasible option, it does not meet the criteria as effectively as A3. Embedded Gateway solutions (A2), with the lowest score of 0.54, demonstrate a comparative deficiency in satisfying these criteria as competently as the other solutions.

4.3 Technique for order of preference by similarity to ideal solution (TOPSIS) result

This section discusses the TOPSIS results. A decision matrix featured criteria C1 through C10 and alternatives A1, A2, and A3, like the approach in AHP methods and following the steps in section 3.3. This method then normalised the matrix to enable an objective comparison among the alternatives. Weighted values were applied to the normalised scores, re-

flecting the relative importance of each criterion. The Euclidean distances to the ideal best and worst solutions were calculated as follows:

$$S_i^+ = \sqrt{\sum_{j=1}^m (V_{ij} - V_j^+)^2} \quad (4)$$

$$S_i^- = \sqrt{\sum_{j=1}^m (V_{ij} - V_j^-)^2} \quad (5)$$

Where V_{ij} represents the weighted value for each criterion of an alternative, V_j^+ is the ideal best value, and V_j^- is the ideal worst value. The relative closeness to the ideal solution was assessed using the performance score, calculated by:

$$P_i = \frac{S_i^-}{S_i^+ + S_i^-} \quad (6)$$

This performance score quantitatively reflects each alternative's proximity to the ideal solution. Higher scores indicate a closer alignment to the ideal solution. Table 5 displays the final rankings based on these scores.

Table 5. TOPSIS ranking of alternatives.

Alternatives	Score	Rank
A1 (Starter Kit)	0.44	2 nd
A2 (Embedded Gateway)	0.23	3 rd
A3 (IoT Hardware)	0.75	1 st

In the TOPSIS analysis, the IoT Hardware solution (A3) secured the highest rank with a score of 0.75, affirming it as the preferable solution. The Starter Kit solution (A1), with a score of 0.44, occupies an intermediate position, indicating moderate conformity with the ideal solution. Finally, the Embedded Gateway solution (A2) scored the lowest at 0.23, revealing a substantial deviation from the ideal criteria.

From the results section, IoT Hardware (A3) ranked highest in the AHP analysis with a score of 0.88 and similarly led in the TOPSIS analysis with a score of 0.75. Starter Kit (A1) followed with scores of 0.65 and 0.44 in AHP and TOPSIS, respectively, while Embedded Gateway (A2) scored 0.54 and 0.23.

4.4. Sensitivity analysis results

The sensitivity analysis used the AHP and TOPSIS decision-making methodologies, focusing on equal criterion weighting. This phase uniformly adjusted each criterion's weight to reflect equal importance. The reassessment with equal weights displayed a significant shift in ranking Alternatives A1 and A2, with A2 showing an improved ranking in both the AHP and TOPSIS methods (see Table 6).

Table 6. Sensitivity analysis ranking equal weights.

Alternatives	Ranks before sensitivity analysis	Ranks after sensitivity analysis
A1	2 nd	3 rd
A2	3 rd	2 nd
A3	1 st	1 st

	AHP	TOPSIS	AHP	TOPSIS
A 1	2 nd	2 nd	3 rd	3 rd
	0.65	0.44	0.26	0.30
A 2	3 rd	3 rd	2 nd	2 nd
	0.54	0.23	0.34	0.49
A 3	1 st	1 st	1 st	1 st
	0.88	0.75	0.40	0.58

This change indicates that Alternative A2 improves its ranking when all criteria receive equal importance. Meanwhile, Alternative A3 consistently maintains its top position, reinforcing its status as a robust and reliable choice. The results of this sensitivity analysis demonstrate the impact of weight distribution on the final rankings. The application of AHP and TOPSIS methods, coupled with sensitivity analysis, effectively addresses the second research question by providing insights into the stability and robustness of the rankings.

5. Conclusion

This study provides concrete insights into how industry practitioners prioritise critical criteria when assessing digital retrofitting solutions. The implementation of pairwise comparison surveys reveals that Predictive Maintenance, Risk Management, Power of Data, and Show Machine Status are among the most critical factors. These preferences significantly influence the prioritisation process, with Predictive Maintenance and Risk Management emerging as the top priorities, indicating their critical importance in digital retrofitting decisions. The rankings of the digital retrofitting solutions, as determined by the MCDM methods AHP and TOPSIS, highlight the IoT Hardware solution (A3) as the optimal choice in this study. This conclusion is based on evaluations using weighted criteria reflecting industry preferences. A3 consistently ranks highest, demonstrating robust performance in terms of functionality, compatibility, and proactive maintenance. Sensitivity analysis, which includes scenarios with equal weight distribution for the criteria, further confirms the robustness of A3, maintaining its top ranking across various weighting scenarios. Conversely, the Embedded Gateway solution (A2) ranks lower overall but shows improved performance under equal weight distribution, underscoring the importance of considering weight distribution in decision-making processes. These findings provide significant insights for decision-makers in the manufacturing sector, offering valuable guidance for selecting digital retrofitting solutions. This study emphasises the necessity of a comprehensive approach when selecting digital retrofitting solutions, considering diverse criteria and methodological perspectives. While A3 emerges as the preferred option in this analysis, decision-makers should customise their decisions to each industry's unique requirements and objectives. Through applying AHP and TOPSIS methodologies, practitioners can systematically evaluate various digital retrofitting solutions, ensuring alignment with their needs. This approach offers a structured framework for decision-makers, promoting a balanced consideration of all relevant factors and ultimately leading to more effective and strategic digital retrofitting initiatives.

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