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METHODS

Assessing the digital transformation maturity of motherboard industry: a fuzzy AHP approach

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The coronavirus disease-19 pandemic and the impact of Sino-US trade have accelerated and intensified changes in consumer behavior and promoted the motherboard industry's digital transformation. However, before entering the implementation stage of digital transformation, enterprises need to examine their readiness. Therefore, we hope to provide a reference for the motherboard industry in the implementation stage of digital transformation in the face of fast-changing market demands by constructing a digital transformation maturity assessment scale. Previously, maturity assessments were performed for manufacturing and smart manufacturing. The digital transformation maturity assessment of the motherboard industry lacks rigorous research in relevant literature. Therefore, this study uses the current state of the motherboard industry to assess its digital transformation maturity and uses the fuzzy analytic hierarchy process and expert interviews to summarize and analyze the assessment mode of the digital transformation maturity of the motherboard industry. By analyzing digital transformation maturity and using an objective assessment scale, we can understand the current state of operations and set the right direction. This enables enterprises to obtain maximum benefits with limited resources when facing rapid changes in consumer behavior. We further show the implications of the industry's operations, and finally, provide practical recommendations and conclusions.

Keywords: motherboard industry, digital transformation, maturity assessment, fuzzy AHP

Introduction

With advancement of information technology, technologies, such as cloud technology, the Internet of Things, and big data have swept across the world. Technology-led digital transformation is considered the key to promoting the growth of enterprises (1). Digital transformation can restart economic growth and drive enterprises to transform. To further understand digital transformation, however, it is necessary to first understand the hardware involved. The motherboard is the main component of the computer. Its main function is to connect various key components on the computer. The motherboard industry functions as a user of electronic components from upstream manufacturers and plays a pivotal role for downstream suppliers. Therefore, the motherboard industry is regarded as the aircraft carrier of the computer industry (2). Computers and peripheral equipment require motherboards. The upstream of this industry is component suppliers, and the downstream is suppliers of computer terminal products and computer peripheral equipment. The motherboard industry has two main sales models. One is through the sale of desktop computers, and the other is through the sale of the motherboard to the assembly market for retail sale. However, the motherboard industry is a saturated and mature industry, and it has entered a recession period. Although the boom in cryptocurrency mining in recent years has indirectly increased its overall output and demand, this indirect effect is still smaller than that of the global recession. Therefore, enterprises need to remodel themselves as soon as possible to keep up with the era of digital transformation (3).

In terms of research on digital transformation, Westerman et al. (4) were the first to discuss the importance of enterprise digitalization. Subsequently, Verhoef and

Bijmolt (5) also pointed out that digitalization is the premise of digital transformation. Enterprises can optimize existing business processes more effectively through digital technology applications, enhance customer experience, and gain value through the establishment of other customers. Coupled with the impact of coronavirus disease-19 (COVID-19), the impact of digital transformation on the development and competitiveness of enterprises in various countries has prompted governments worldwide to pay attention to digital transformation. The Organization for Economic Cooperation and Development (OECD) has pointed out that the foundation of digital transformation is digitization (6). To clarify, information (such as sound, images, and text) can be stored, transmitted, and reprocessed at low cost and high speed after digitization. Through the combined use of digitization and emerging technologies [such as robots, cloud computing, and artificial intelligence (AI)], we can generate new application modes and values that greatly improve the efficiency of industries and society. Schwertner (7) indicated that the gradual maturity of digital technologies (such as cloud technology, mobile computing, the Internet of Things, and big data) will enable enterprises to change their business models and current situation using multiple emerging technologies. They will be able to develop new digital products, services, operational processes, and even business models and thus find new business opportunities and industry competitors.

Taiwan's motherboard industry has developed over many years and has an extensive business scope, covering commercial products, household products, e-sports, cloud services, and multiple technology fields (8). In addition, it uses AI, IoT, and cloud computing over a 5G network to create high-efficiency, high-quality, and ultra-durable technologies. Therefore, it has long been considered indispensable in the global supply chain. Nevertheless, it is necessary to promote digital transformation under the general trend of digital transformation and the Sino-US trade war. However, there is a significant gap between the supply and demand for digital transformation. Taiwan's motherboard industry has long fallen behind that of advanced countries, although it remains ahead of the less advanced ones (9). The accelerating transformation speeds of advanced countries will increase the gap between advanced countries and Taiwan. The accelerating transformation speed of some less developed countries will threaten the status of Taiwan's motherboard industry in the international industrial supply chain. Taiwan's manufacturing industries may face severe challenges. Therefore, how to guide the digital transformation of Taiwan's motherboard industry and propose appropriate policy governance has become an issue and task to which enterprises must pay attention (10).

Therefore, to overcome the abovementioned problems, this study proposes a systematic evaluation using the MCDM model. First, we establish a complete evaluation framework based on the current situation of the case company, the evaluation criteria of experts, and related literature.

Therefore, this study has three main contributions:

(1) This paper discusses and constructs an evaluation framework for the motherboard industry from the perspective of digital transformation.
(2) This paper establishes dimensions, including procurement management, research and development design, manufacturing, logistics warehousing, after-sales service, customer demand, relationship maintenance, and evaluation criteria.
(3) This paper discusses the maturity assessment scale of the motherboard industry based on the evaluation framework. It helps the motherboard industry evaluate its performance and examine its overall digital transformation maturity. The assessment scale is initially constructed based on a literature review and expert interviews. Following this, we use the fuzzy analytic hierarchy process (AHP) to analyze the weight of dimensions and criteria and understand the causal relationship between dimensions and criteria. Finally, we use a case study to verify the assessment scale proposed in this study.

Literature review

Digital transformation

Several stages of digitization precede the digital transformation stage. Bican and Brem (11) pointed out that the digital transformation process has three different stages, namely, digitization, digital optimization, and digital transformation. The first stage is "digitization." In the digital transformation process, industries that use a high proportion of paper-based management methods start using information tools and technologies to build software and hardware systems and environments for information management. In the operation process, they record all processes using digital tools and generate information that can be stored and managed. In the second stage, "digital optimization," enterprises can use the information accumulated by digital tools to improve the operation process, improve production quality and the management process, enhance operation efficiency, and improve the internal system. In the third stage, "digital transformation," digital technologies are integrated and applied to various operational functions of the enterprise, and the overall process of the enterprise is changed owing to the introduction of information technology. According to a survey on digitization for small- and medium-sized enterprises, most small- and medium-sized enterprises in Taiwan are still in the digitization or digital optimization stage. There is still a long way to go to enter the digital transformation stage. The enterprise must clearly understand its current situation to make the best investment on the road to digital transformation (12).

Komninos et al. (13) pointed out that digital transformation can be described as the process of sustainable digital development. Overall, we can summarize two developmental characteristics of digital transformation. The first developmental characteristic is from the perspective of applications and strategic insights. In terms of enterprises' strategic insights, digital transformation emphasizes client-driven strategies. In addition to the application of digital technology, more emphasis is placed on organizational change across departments. The second developmental characteristic is from the perspective of its wider impacts. The proliferation and use of digital technologies drives systematic restructuring at the economic, institutional, and social levels. Comparisons are made among corporate strategy, the digitization process, the three stages of digital transformation, and the impact of digital technology.

Mihardjo et al. (14) discussed the digital transformation of the manufacturing industry in the past, in the Industry 4.0 era. The digital transformation includes customer journey analysis, personalized experience, etc. Based on the one-stop supply chain from raw materials, production, to finished products and the use of emerging digital technologies, enterprises can make more real-time dynamic adjustments. In the overall supply chain, big data analysis is used to establish a forecast plan and technologies are used to connect the data from the upstream and downstream of the supply chain to achieve precise control of production and inventory. Therefore, warehousing and logistics costs can be reduced, as can the risk of out-of-stock, supply–demand imbalance, and uncertainty and overall operational efficiency can be improved.

This study takes the dimensions proposed by Mihardjo et al. (14) as the basis of the value chain of the motherboard industry and focuses on the value activities in the manufacturing process, which are used as the dimensions and factors of the subsequent maturity assessment. The following are the descriptions and assessment factors of digitization, digital optimization, and digital transformation.

Digitization

For the motherboard industry, two information systems, namely, enterprise resource planning (ERP) and the e-procurement system, are the keys to effectively solving issues with supply chain processes or "improving supply chain processes." The inspection of these systems and the sharing of information can solve the problem of information asymmetry and poor decision-making (15).

The minimum requirement for digitization is the deployment of information systems or assistance tools. There are different value activities in processing, the procurement process, research and development design, manufacturing, and logistics warehousing. In the research and development design stage, the digitization stage can be achieved through digital design aids. In the manufacturing stage, digital devices equipped with a manufacturing execution system (MES) are used to understand the data of each site and machine and the operation status of the production equipment (16).

Digital optimization

Hartley and Sawaya (17) pointed out that during digital optimization, with the development of digital technology, three technologies can change supply chain business processes. These are robotic process automation (RPA), AI, machine learning (ML), and block chain. RPA is usually the first step for a company to move toward digital transformation, and the automation process includes data entry, simple calculations, and reading and collecting data from ERP systems (18). RPA can automate the processes of procurement, operations, and logistics. For example, in the payment process, RPA can send requests for quotations, create purchase orders, match purchase orders, invoices, and receipts, and streamline the payment process (19). RPA can be used in other automated operations, such as setting up suppliers in ordering systems and maintaining purchasing catalogues. RPA is also used in logistics. After inputting information into transportation management systems (TMS), we can use RPA for logistic planning and tracking, thereby improving efficiency and customer satisfaction (20).

AI aims to use intelligent machines in design and manufacturing processes (21). The supply chain applications of ML include demand planning and forecasting, warehouse order picking operation scheduling, determining equipment maintenance plans, analyzing weather data to improve transportation management, rerouting vehicles to avoid traffic congestion, and risk assessment (22).

The turbulent global economy and the impact of the pandemic have lead to the transformation of the global supply chain. The traditional mass-and-standardized manufacturing mode has gradually shifted to a customized consumption mode of small quantity and large variety, so it can respond quickly to market changes and qualitatively change the traditional business model (23). In terms of procurement, enterprises can take the first step toward intelligent procurement by optimizing internal procurement processes. By integrating digital information platforms, we can simplify some complicated steps, such as inquiry, negotiation, procurement, payment, and invoice processing. Optimization of external supplier management is also important for enterprises to realize intelligent procurement. Centralized procurement based on a single digital information platform helps enterprises connect supply chain networks, collaborate, and reduce time and cost (24).

Duberg et al. (25) pointed out that owing to rapid progress in recent years, the manufacturing industry is no longer limited to large-scale original equipment manufacturer production. In the entire supply chain, the after-sales market also becomes an important part of customer relationship maintenance. Manufacturers can further increase service revenue by providing good after-sales services and customer experience. In terms of customer relationship maintenance, they can use three levels of contract management, namely, analysis, monitoring, and integration. In terms of monitoring, they can use a convenient interface to monitor contracts and understand the content of all transactions, including the details of contracts. Finally, by integrating tools and solutions, they can simplify the workflow and connect it to existing databases to achieve a smooth after-sales process.

Agrawal and Narain (26) pointed out that under the continuous optimization of the digital environment, six trends will affect the overall supply chain, namely, globalization, sales growth, supply chain visibility, process standardization and automation, supply chain collaboration, and flexibility in responding to the volatile market. It is important to understand the trends and impacts on supply chain management to respond to changes and optimize operations. Applying new technologies, such as big data, cloud computing, and the Internet of Things, can help with overcoming these challenges. Digitalization will help improve supply chain visibility. The use of innovative digital technologies will make it possible to modularize, simplify, and standardize products and services.

Digital transformation

(1) As pointed out by Tavoletti et al. (27), digital transformation means that enterprises use innovative information technologies and use data as the core to provide innovative products and services or to adjust existing profit models and promote innovative business models.

From the perspective of intelligent manufacturing, Singh et al. (28) stated that in the digital transformation process, the manufacturing industry could use digital technologies to achieve visualization, big data prediction, automated response, and instant response and continuously improve and optimize the overall industrial chain to meet the small and diverse needs of customers. It can also provide perfect after-sales services through dynamic allocation and adjustment of inventory. Ibarra et al. (29) pointed out that in the operation of the business ecosystem, digital transformation can be divided into four levels: from factories to platform ecosystems, including the digitization of production processes; the digitization of vertical supply chains; the digitization of platform ecosystems; and the creation of new product ecosystems.

Massaro (30) pointed out that the deployment of digital supply chains is the key to realize digital transformation. The key is to use simple and intelligent services (self-service) to help enterprises use AI analysis tools more easily. On the contrary, if the operation method is too complicated, introducing new technologies becomes meaningless. In the supply chain planning process, the main applications of AI and ML focus on three sections, namely, demand forecasting, material requirements planning, and production scheduling. By focusing on the three sections, AI analysis can help customers better understand market changes, product life cycles, and customer demand patterns, reduce the risk of inventory shortages or high costs, and improve overall productivity and efficiency in factories.

In conclusion, this study summarizes the value activities of the motherboard industry in the three stages of digital transformation and five value chain dimensions, as shown in **Table 1**.

Digital transformation maturity model

Becker et al. (31) pointed out that a maturity model is composed of dimensions and criteria that describe future fields for action and the path of maturity indicators toward maturity. Maturity models are primarily used to assess the current situation and set potential, expected, or desirable goals. The maturity model is widely used in the field of digital transformation. It has three purposes, namely, descriptive, prescriptive, and comparative purposes, which are described hereunder.

(1) Descriptive purpose: A descriptive maturity model is suitable for assessing the current situation of an organization.
(2) Prescriptive purpose: Prescriptive models focus on performance and indicate how to improve maturity to affect business value.
(3) Comparative purpose: Comparative models can be used for cross-company benchmarking. These models are suitable for comparing similar organizations across industries to measure the maturity of different industries.

To identify the various stages of digital transformation, Vial (32) reviewed the maturity model, referred to the dimensions of the digital maturity model (DMM) proposed in a previous study, and used a quantitative method to calculate maturity stage. The nine dimensions of the DMM provide more relevant measures for digital transformation. The descriptive maturity model is used to show that digital transformation affects overall organization and development (for example, "product innovation") and summarize the maturity stage from the data to derive typical transformation paths. The DMM is composed of (1) customer experience, (2) product innovation, (3) strategy, (4) organization, (5) process digitalization, (6) collaboration, (7) digital technology, (8) culture and expertise, and (9) transformation management. By summarizing and screening, they constructed five items

TABLE 1 | Three stages of digital transformation.

Stages	Procurement management dimensions	Research and development design dimensions	Manufacturing dimensions	Logistics warehousing dimensions	After-sales service dimensions
Digitization	Information system deployment Supplier database system maintenance Procurement workflow maintenance	Digital product design Digital design aids	Information system deployment Digitization equipment deployment	Transportation management system (TMS) establishment Logistics tracking Global positioning system shipment tracking	Equipment maintenance plan Digitization of maintenance records
Digital optimization	Procurement system integration Electronic procurement platform	Automated design aids Fully automatic virtual measurement system Product design management system	Production scale simulation Planning and scheduling system Production management, planning, and optimization Automated optical inspection (AOI)	Collaborative transportation management Delivery efficiency optimization Warehousing and handling automation	After-sales contract monitoring Customer service system and platform deployment
Digital transformation	Intelligent cloud management platform Just-in-time inventory management Supplier ecosystem	3D printing or sensor-driven design improvements Virtual design simulation Product cycle management and design verification management deployment	Intelligent production scheduling Provide in-depth customized services Small quantity and large variety production	AR/VR technology for logistics optimization Intelligent logistics Dynamic prediction of optimal transportation routes Dynamic adjustment of shipping routes	Intelligent customer service robot After-sales predictive maintenance Immediate notification of abnormality Service demand feedback

of similar difficulty that represent the five maturity stages of the DMM, which are explained hereunder.

Stage 1: promote and support

The cluster at this stage is mainly related to strategic prioritization, flexible work, and management support of digital transformation. Basic digital services for existing products and customer experiences across multiple channels are initiated. Employees are familiar with existing digital products. The internal information technology staff ensures the availability of relevant digital technologies and maintains an up-to-date infrastructure. Digitization has become a priority on the strategic agenda. Digital transformation projects are supported and prioritized by senior and middle management.

Stage 2: create and build

At this stage, digital innovation has a significant effect on product innovation, both at the strategic and internal levels. The importance of innovation strategies is emphasized by explicitly promoting digitalization and systematically evaluating potential of new technologies. Suitable conditions for innovation are created by strengthening digital competencies, collaborating more strongly with the internal information technology department, and liaising with external partners.

Stage 3: commit to transform

The items in this stage mainly belong to the field of culture and expertise, but they also fall under organization and transformation management. In stage 3, the focus appears to be on validating organizational innovations in the digitization stage and their profound influence on the changes within the organization. Important capabilities in the company culture are proactive error management, the communication of learning from failed projects, and a willingness to take risks. As a company undergoes more radical change, it needs to define roles and responsibilities for all processes related to digital transformation, as well as devise a strategic plan for the transformation process that the company is willing to follow.

Stage 4: user-centered and elaborated processes

This is demonstrated by user participation in innovation processes, personalization of customer experiences, and the collection and consideration of customer data when designing interactions. This stage emphasizes open innovation by engaging users, personalizing customer experiences and processes based on usage data, and improving the process by establishing measurable goals. This stage is considered a "user-centric detailed process."

Stage 5: data-driven enterprise

The items with the highest difficulty metric are clustered in Stage 5. These items are related to the use of advanced data analysis technologies for expenditure planning. Only advanced companies use them appropriately for decision support or product development. Prerequisites for the implementation of a data-driven business are internal expertise for data utilization, appropriate technological infrastructure, and data governance across different business units. This is the most advanced stage in the maturity model.

Sjödin et al. (33) categorized digital maturity levels from the perspective of smart factories and categorized the key activities that support the development of smart factories by maturity level to create a smart factory maturity model.

Level 1: connected technologies

This maturity level is highly correlated with understanding the technological requirements for a smart factory concept and developing a vision for connecting various systems. This vision creates the foundation for groundwork and smart factory implementation.

Level 2: structured data gathering and sharing

At this stage, organizations must create models for structured data collecting and sharing to facilitate the development of improved data management practices and processes that enable efficient storage and utilization of the increasing amount of production data being collected.

Level 3: real-time process analytics and optimization

This maturity level yields the beneficial effects of collecting and communicating data. In this stage, organizations build competencies for real-time process analytics and optimization. The focus shifts toward benefiting from the data and system.

Level 4: smart and predictable manufacturing

As the factory reaches the apex of the maturity model, continuing the focus on smart and predictable production requires continuous innovation and improvement. Efforts to build predictability in manufacturing make it increasingly possible to know what to expect, leading to greater production reliability and profits. This stage includes the potential of developing processes for utilizing data analytics and visualization for real-time decision-making and clarifies how visual representations of activities in the factory help key decision-makers adapt to the need for adjustment and improvement. Another process development in this stage involves creating proactive processes for predicting, forecasting, and planning future production. Production activities should be planned in a proactive environment with a focus on predicting future requirements.

Methodology

Digital transformation maturity assessment criteria of motherboard industry

This study explores the maturity stages of the digital transformation of Taiwan's motherboard industry. We integrated them into a digital transformation maturity assessment model based on relevant literature. Digital transformation is divided into three stages, namely, digitization, digital optimization, and digital transformation. Following the creation of the assessment model, this study summarizes the value chain of the motherboard industry. According to the definition provided in the literature, relevant characteristics and dimensions are used as the basis for the evaluation criteria of fuzzy AHP. This study summarizes 7 dimensions and 21 evaluation criteria, as shown in **Table 2**. Then, this study clarifies the evaluation criteria by comparing them with industry data, and it selects and revises the criteria that align more with the current situation.

In this study, the scoring criteria used in the maturity assessments of digitization in the first stage and digital optimization in the second stage are shown in **Table 3**.

In this study, the minimum thresholds of assessment scores change with the core of the industry. For example, the motherboard industry must achieve a minimum threshold of four points in the manufacturing dimension and a minimum threshold of three points in the remaining dimensions. The assessment thresholds are shown in **Table 4**.

Fuzzy analytic hierarchy process footnotes

Saaty (42) proposed an AHP to analyze decision-making problems with complex and multiple evaluation criteria under uncertainty and find consistency in the chaotic decision-making process. **Saaty (43)** stated that AHP obtains the weight and execution priority of each criterion by constructing pairwise comparison matrices, comparing the criteria in the upper level with each criterion in the lower level individually, and identifying the degree of influence of one level on the other. Traditional AHP has the problem of ambiguity. **Buckley (44)** combined AHP with fuzzy theory and proposed the fuzzy analytic hierarchy process (FAHP).

Subsequently, many scholars used FAHP to conduct various studies. **Cheng et al. (45)** combined FAHP and

TABLE 2 | Evaluation criteria of digital transformation maturity of motherboard industry.

Dimensions	Criteria	Definitions	References
1. Procurement management	1. Inventory control	Measure inventory status through inbound and outbound inventory management.	(34)
	2. Information system	Use information systems, such as ERP system for procurement management.	(35)
	3. Demand forecast	Measure purchase quantity based on customer demand.	(34)
2. Research and development design	4. Innovation management and collaborative development	Use new management methods, such as agile management, to collaborate and jointly develop products.	(34)
	5. Virtual measurement	It has the effect of promoting communication and simulation in each stage of research and development design. For example, sensors are used to shorten the time of research and development design and improve the accuracy of prediction.	(36)
	6. Technical innovation	Use innovative methods to effectively transform design concepts into design drawings and thus better meet customer demand.	(37)
3. Manufacturing	7. Manufacturing schedule	Estimate the demand that can be handled and calculate the delivery time for each demand based on the entire production capacity and the full consideration of various constraints.	(35)
	8. Small quantity and large variety production	A flexible production method that responds to the small and diverse needs of customers.	(37)
	9. Material requirements planning	Use enterprise management software to effectively manage enterprises' inventory and production.	(38)
4. Logistics warehousing	10. Cargo tracking	Logistic tracking based on the connection of logistics platforms.	(34)
	11. Automated warehousing	Reduce labor costs by using cargo-handling robots.	(36)
	12. Collaborative transportation management	Achieve collaborative transportation management based on collaborative forecasting and replenishment, information sharing, and supply chain collaboration.	(34)
5. After-sales service	13. Return and exchange system	A system in which a customer can return or exchange a product when the customer finds the product is of poor quality.	(36)
	14. Equipment health status prediction	Master the health status and production efficiency of equipment and machines, analyze and refine insights, and grasp the status and performance of equipment.	(39)
	15. Intelligent customer service robot	Build customer service robots on official websites or e-commerce platforms to optimize users' website experience.	(40)
6. Customer demand	16. Customized service	According to customer demand, the products are changed and adjusted based on limited components and their preferences.	(41)
	17. Customer experience value	A consumer's overall, subjective, or even comparative (with competitors' products or services) perception of a product or service.	(40)
7. Relationship maintenance	18. Information gathering and understanding	Understand the overall operating trend based on market trends and customer demand.	(41)
	19. Customer repurchase rate	Increase customer repurchase rate through customer relationship maintenance.	(41)
	20. Customer perception	Customers' subjective evaluation of products or services and the quantified benefit obtained from the entire product.	(36)
	21. Customer loyalty	The influence of factors such as price, quality, and service results in an emotional connection between customers and products.	(41)

Fuzzy Delphi to study enterprises' choice of Fourth-Party Logistics (4PLs) in uncertain and complex business environments. **Borjalilu and Ghambari (46)** combined AHP and fuzzy theory to help factory maintenance staff determine the optimal maintenance strategy for each component of different equipment.

Step 1: form an expert group, and clarify and revise the criteria

Establish the criteria for the study based on the literature review. Form an expert group and utilize the industry experience and suggestions of experts to adjust the

TABLE 3 | Scoring criteria.

Scores	Definitions
1	Not at all important
2	Slightly Important
3	Important
4	Fairly Important
5	Very Important

dimensions and criteria, thereby revising the formal questionnaire of this study.

Step 2: establish the fuzzy semantic scale of FAHP factors

Establish a pairwise comparison matrix A and use each level as a benchmark to calculate the weight values of the evaluation criteria A_1, A_2, · · · , A_n in the next level after the pairwise comparison. Each level's relative importance of criteria can be expressed as a_{ij} (i, j = 1,2,· · · ,n). Subsequently, place the comparison results of the evaluation criteria on the upper right of the main diagonal of matrix A and place the reciprocals of the upper right values on the lower left of matrix A. Because the main diagonal is the self-comparison (i = j), the criterion value is one. The comparison matrix is shown in Equation (1).

$$A \quad \left[a_{ij}\right] \quad \begin{bmatrix} 1 & a_{12} & \cdots & a_{1n} \\ a_{21} & 1 & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & 1 \end{bmatrix}, i, j \quad 1, 2, \text{n}, \tag{1}$$

$$\text{where } a_{ij} \quad {}^{1}\!/_{a_{ji}} \quad \begin{bmatrix} 1 & a_{12} & \cdots & a_{1n} \\ {}^{1}\!/_{a_{12}} & 1 & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ {}^{1}\!/_{a_{1n}} & {}^{1}\!/_{a_{2n}} & \cdots & 1 \end{bmatrix}$$

Owing to the ambiguity of human decision-making, we define fuzzy semantic variables so experts can compare and assign scores to criteria in pairs. In addition to accurately reflecting the implied meaning of semantic variables, the degree of influence between criteria can also be evaluated. The triangular fuzzy numbers corresponding to the FAHP semantic variables are shown in **Table 5**.

Step 3: calculate the eigenvector and maximum eigenvalue of the matrix

After constructing the pairwise comparison matrix, we can use the eigenvalue method to obtain the eigenvector $\mathbf{w_i}$ or priority vector. Most matrices are inconsistent matrices. Referring to the four approximation methods of eigenvectors proposed by **Saaty and Vargas** (**47**), we use the row normalization method based on the row-wise mean, as shown in Equation (2), to increase the accuracy of the eigenvector calculation results. We then use the obtained eigenvectors to calculate the maximum eigenvalue $\boldsymbol{\lambda_{max}}$, as shown in equation (3).

$$w_i \quad \frac{1}{n}\sum_{j\ 1}^{n}\frac{a_{ij}}{\sum_{i\ 1}^{n} a_{ij}} \tag{2}$$

$$\lambda_{max} \quad \sum_{1}^{n}\frac{(AW)_i}{nW_i} \tag{3}$$

Step 4: consistency check

Because the values in the pairwise matrix are subjective scores assigned by experts, large amounts of evaluation criteria and varying levels may cause inconsistency between experts' judgments on different criteria. Therefore, it is necessary to conduct a consistency check to judge whether the scores assigned by experts are within a reasonable margin of error. We can use a consistency index (CI) and a consistency ratio (CR) to check the consistency of the weights.

CI: Referring to **Saaty** (**42**), when CI = 0, the expert's judgments are completely consistent. When CI > 0.1, the judgments are completely inconsistent. When CI < 0.1, the judgments are within the permissible error range. It is calculated using Equation (4).

$$C.I \quad \frac{\lambda_{max} - n}{n - 1} \tag{4}$$

CR: **Saaty** (**42**) mentioned that the CI values (that is, the value of n) generated by different levels also differ. We adopt the CR to judge whether the matrix is consistent (as shown in Equation 5) for the matrices with the same value of n. When CR < 0.1, it means that there is an acceptable level of consistency. If not, we should re-examine the correlation between levels and criteria.

$$C.R \quad \frac{C.I}{R.I} \tag{5}$$

Step 5: calculate the triangular fuzzy number at each level

To obtain the relative fuzzy weights of the overall evaluation criteria, **Dubois and Prade** (**48**) used the minimum ($\mathbf{L_i}$), median ($\mathbf{M_i}$), and maximum ($\mathbf{R_i}$) values of each criterion in the questionnaire to construct and calculate triangular fuzzy numbers h represents number of experts, i represents number

TABLE 4 | Motherboard industry maturity assessment threshold.

	Digital transformation maturity assessment of motherboard industry						
Threshold scores	**Procurement management**	**Research and development design**	**Manufacturing**	**Logistics warehousing**	**After sales service**	**Customer demand**	**Relationship maintenance**
5 points	V	V	V	V	V	V	V
4 points	V	V	V	V	V	V	V
3 points	V	V		V	V	V	V
2 points							
1 point							

of evaluation criteria, and n represents the total number of experts, as shown in Equations (6)–(8).

$$L_i \;\; min_h\{L_i^h,\; h \;\; 1, 2, \cdots, n\} \tag{6}$$

$$M_i \;\; [\prod_{h \;\; 1}^{m} \left\{M_i^h,\; h \;\; 1, 2, \cdots, n\right\}]^{\frac{1}{n}} \tag{7}$$

$$R_i \;\; max_h \;\left\{R_i^h,\; h \;\; 1, 2, \cdots, n\right\} \tag{8}$$

Step 6: Normalize the triangular fuzzy number at each level

We should normalize the triangular fuzzy number obtained in Step 5 for a more rigorous and accurate calculation result. $\mathbf{nL_i}$, $\mathbf{nM_i}$, and $\mathbf{nR_i}$ represent the normalized triangular fuzzy numbers, as shown in Equations (911).

$$nL_i \;\; \frac{L_j}{\left\{\left[\sum_i^k R_i\right]^* \left[\sum_i^k L_i\right]\right\}^{0.5}} \tag{9}$$

$$nM_i \;\; \frac{M_i}{\sum_i^k M_i} \tag{10}$$

$$nR_i \;\; \frac{R_i}{\left\{\left[\sum_i^k R_i\right]^* \left[\sum_i^k L_i\right]\right\}^{0.5}} \tag{11}$$

TABLE 5 | FAHP fuzzy semantic transformation scale.

Fuzzy number evaluation scale	Semantic variables	Triangular fuzzy numbers (l, m, u)
9	Extremely important	(8,9,10)
8	Between extremely important and very important	(7,8,9)
7	Very important	(6,7,8)
6	Between very important and moderately important	(5,6,7)
5	Moderately important	(4,5,6)
4	Between moderately important and somewhat important	(3,4,5)
3	Somewhat important	(2,3,4)
2	Between somewhat important and similarly important	(1,2,3)
1	Similarly, important	(1,1,1)

Step 7: defuzzification and normalization

Because the triangular fuzzy number is not a clear numerical value, the normalized triangular fuzzy number needs to be defuzzified to facilitate the subsequent ordering of weights. **Tzeng and Teng (49)** indicated that the center of area (COA) method does not consider the preference of expert scores for defuzzification, finds the best non-fuzzy performance value **(BNP)**, and converts each element into a weight, as shown in Equation (12). However, to ensure the defuzzified weight $(\mathbf{BNP_i})$ of each level adds up to one, we should repeat the normalization process to obtain the final weight $(\mathbf{NW_i})$ of each dimension and criterion, as shown in Equation (13).

$$BNP_i \;\; \frac{\{(nR_i - nL_i)\,(nM_i - nL_i)\}}{3} nL_i,\; \forall i \tag{12}$$

$$NW_i \;\; \frac{BNP_i}{\sum_{i \;\; 1}^k BNP_i} \tag{13}$$

Step 8: connect and sort the weight of each level

After calculating the final weight of each criterion at each level in step 7, we should connect the weight of each dimension and criterion in the different levels to calculate the relative weight of the experts' selection criterion, as shown in Equation (14). NW_j represents the weight of the jth criterion in the third level under the first level (target level), NW_i represents the weight of the ith dimension in the second level under the first level, and NW_{ij} represents the weight of the

TABLE 6 | Expert scoring results of digitization stage and digital optimization stages.

Dimensions	Evaluation criteria	Threshold	Digitization stages		Digital optimization stages	
			Average score	Degree of consensus	Average score	Degree of consensus
Procurement management	1. Inventory control	3	4.67	High	5.00	Extremely high
	2. Information system	3	5.00	Extremely high	5.00	Extremely high
	3. Demand forecast	3	4.00	High	4.33	High
Research and development design	4. Innovation management and collaborative development	3	4.33	High	4.00	High
	5. Virtual measurement	3	4.00	High	4.67	High
	6. Technical innovation	3	5.00	Extremely high	5.00	Extremely high
Manufacturing	7. Manufacturing schedule	4	4.67	High	5.00	Extremely high
	8. Manufacturing schedule	4	5.00	Extremely high	5.00	Extremely high
	9. Small quantity and large-variety production	4	4.67	High	4.67	High
Logistics warehousing	10. Cargo tracking	3	4.33	High	4.33	High
	11. Automated warehousing	3	4.33	High	4.67	High
	12. Collaborative transportation management	3	4.67	High	4.67	High
After-sales service	13. Return and exchange system	3	4.67	High	5.00	Extremely high
	14. Equipment health status prediction	3	4.33	High	4.67	High
	15. Intelligent customer service robot	3	4.33	High	4.33	High
Customer demand	16. Customized service	3	4.33	High	4.67	High
	17. Customer experience	3	4.00	High	5.00	Extremely high
	18. Information gathering and understanding	3	5.00	Extremely high	5.00	Extremely high
Relationship maintenance	19. Customer repurchase rate	3	4.33	High	4.33	High
	20. Customer perception	3	4.67	High	4.67	High
	21. Customer loyalty	3	4.33	High	4.33	High

jth subcriteria in the third level under the ith criterion in the second level.

$$NW_j \quad NW_i^{*}NW_{ij} \tag{14}$$

Through the above calculation of hierarchical connection, we can obtain the weight of each subcriterion of the overall hierarchy evaluation structure and prioritize important evaluation criteria.

Results and analysis

Case description

This study uses G company as a case study for digital transformation maturity assessment. The company was established in 1986 and it mainly provides products such as home and business computers, computer peripheral components, host servers, and expansion devices. It is a leader in the motherboard industry. In the past years, it focused more on the research and development of key technologies and continued to increase its brand awareness and sales of products such as servers, AIoT (AI + IoT), notebook computers, monitors, and gaming peripherals. Under the impact of COVID-19 and given the fact that consumer experience has become the mainstream of the market, G company is following technology trends such as AI, edge computing, and virtual services, creating more efficient products, providing industry-leading products and services, providing cloud and 5G services for customers, and actively moving toward digital transformation and innovation.

TABLE 7 | Defuzzified weight ranking of main dimensions of FAHP.

Dimensions	Normalized weight	Ranks	Evaluation criteria	Normalized weights	Intragroup weight rankings	Hierarchical connection weights	Overall rankings
Procurement management (A)	0.0782	7	A1	0.3507	1.0000	0.0274	15
			A2	0.3228	3.0000	0.0252	18
			A3	0.3265	2.0000	0.0255	17
Research and development design (B)	0.2135	2	B1	0.4413	2.0000	0.0942	3
			B2	0.1074	3.0000	0.0229	20
			B3	0.4513	1.0000	0.0963	2
Manufacturing (C)	0.2345	1	C1	0.5637	1.0000	0.1322	1
			C2	0.2538	2.0000	0.0595	5
			C3	0.1826	3.0000	0.0428	10
Logistics warehousing (D)	0.1137	4	D1	0.2343	3.0000	0.0266	16
			D2	0.3466	2.0000	0.0394	11
			D3	0.4191	1.0000	0.0476	8
After-sales service (E)	0.0935	6	E1	0.5685	1.0000	0.0531	6
			E2	0.3275	2.0000	0.0306	13
			E3	0.1040	3.0000	0.0097	21
Customer demand (F)	0.1619	3	F1	0.1785	3.0000	0.0289	14
			F2	0.2786	2.0000	0.0451	9
			F3	0.5429	1.0000	0.0879	4
Relationship maintenance (G)	0.1048	5	G1	0.2214	3.0000	0.0232	19
			G2	0.4798	1.0000	0.0503	7
			G3	0.2988	2.0000	0.0313	12

Analysis of fuzzy AHP

In this study, according to the results of the three experts' questionnaires in the pilot test, we calculated the average score of the digitization and digital optimization stages. An average score of one indicates that the degree of consensus is deficient. An average score of two indicates a low degree of consensus. An average score of three indicates a medium degree of consensus. An average score of four indicates a high degree of consensus. Finally, an average score of five indicates that the degree of consensus is exceptionally high. The pilot test results of the experts are shown in **Table 6**.

TABLE 8 | Conversion table of maturity level and score.

Stages	Maturity levels	Scores
Digitization stages	Needs significant improvement	Greater than or equal to 1 and less than 3
	Needs improvement	Greater than or equal to 3 and less than 5
Digital optimization stage	Good	Greater than or equal to 5 and less than 7
	Very good	Greater than or equal to 7 and less than 9
Digital transformation stage	Excellent	Greater than or equal to 9 and less than or equal to 10

Regarding the digitization assessment, the average scores of all the 21 evaluation criteria in the 7 dimensions are equal to or above 3 in the evaluation of digital factors. This means that the experts reached a consensus on the evaluation criteria. Then, we calculated the average scores of the evaluation criteria of digital optimization, and all the average scores were equal to or above three. This means that the experts reached a consensus on the evaluation criteria of the digital optimization stage. In addition, 11 experts from the motherboard industry selected relatively objective factors of the digital transformation of the motherboard industry. This study compared the relative importance of two factors through the pairwise comparison of factors, integrated expert opinions to construct a fuzzy positive reciprocal matrix, calculated the fuzzy weights and normalized weights of factors at each level, and ranked them in the order of importance.

The analysis results in **Table 7** show that manufacturing (0.2345) is the most critical evaluation dimension among the digital transformation maturity dimensions

TABLE 9 | Weighted scores of experts.

Items	Dimensions	Evaluation Criteria	Weights	Scores	Weighted scores	Weighted scores of dimensions
1	Procurement management (A)	A1	0.027	8	0.219	0.651
		A2	0.025	9	0.227	
		A3	0.026	8	0.204	
2	Research and development design (B)	B1	0.094	8	0.754	1.662
		B2	0.023	6	0.138	
		B3	0.096	8	0.771	
3	Manufacturing (C)	C1	0.132	9	1.190	2.008
		C2	0.060	8	0.476	
		C3	0.043	8	0.343	
4	Logistics warehousing (D)	D1	0.027	8	0.213	0.957
		D2	0.039	8	0.315	
		D3	0.048	9	0.429	
5	After-sales service (E)	E1	0.053	9	0.478	0.761
		E2	0.031	7	0.214	
		E3	0.010	7	0.068	
6	Customer demand (F)	F1	0.029	7	0.202	1.399
		F2	0.045	9	0.406	
		F3	0.088	9	0.791	
7	Relationship maintenance (G)	G1	0.023	7	0.162	0.765
		G2	0.050	7	0.352	
		G3	0.031	8	0.251	
Total weighted score						8.203

of the motherboard industry, followed by research and development design, customer demand, logistics warehousing, and relationship maintenance, after-sales service, and procurement management. In terms of overall ranking, material requirements planning (0.1322) is the most critical factor among the 21 evaluation criteria, followed by technical innovation (0.0963) and innovation management and collaborative development (0.0942). Hence, in the overall value chain, planning of material requirements is essential for digitization and digital optimization.

We use the normalized weights to analyze the main dimensions. Of the seven dimensions, C and B are necessary for the motherboard industry. Based on the analysis, in the overall value chain of the motherboard industry, the front-end value chain is relatively crucial for the motherboard industry in the digitalization and digital optimization stages. However, the analysis results of 21 evaluation criteria show that C1, B3, and B1 are the most important criteria for the motherboard industry. In addition, because of the current small and diverse needs of customers, flexible material requirements' planning is the most crucial factor.

Application of digital transformation maturity assessment scale

This study used the digital transformation assessment of the motherboard industry constructed using FAHP to understand the causal relationship between evaluation criteria. It used the hierarchical connection weight values obtained through the FAHP method presented in the section titled, "Analysis of Fuzzy AHP" to assess the digital maturity of the motherboard industry (**Table 8**). It provides a review of the digital transformation maturity of the motherboard industry by experts of the industry. It also reviews the performance related to the implementation of digital transformation. The maturity assessment is based on the actual situation of the enterprise and the 21 assessment criteria defined in this study. Therefore, we need to examine whether the evaluation criteria are suitable for evaluating the enterprise.

In addition, because of different business types, the achievement rates of evaluation criteria differ by enterprise. Enterprises can also use this assessment to improve weak items. Therefore, it can effectively solve the pain points of business operations. In this study, the maturity assessment shown in **Table 8** was distributed to the managers of company G, and the weighted scores were calculated and ranked. Managers assigned a score from 1 to 10 for each evaluation criterion. The discussion and analysis results are as follows.

Table 9 shows that the maturity assessment score of the motherboard industry assigned by Company G is 8.203. According to the classification of maturity level in this study, it can be classified as "very good maturity." This means that although the industry has achieved good operational results in all aspects, there is room for improvement in certain aspects. Overall, the results show that Company G is in the "digital optimization" stage.

Conclusion

With the rapid development of the industry, digital transformation has accelerated the economic growth and impact of the motherboard industry and increased its added value. The maturity of enterprises in digital transformation varies by industry and company size. Therefore, it is necessary to examine the enterprise's digital transformation maturity through maturity assessment. Based on the digital transformation maturity assessment of the motherboard industry, this study summarizes the 7 dimensions and 21 evaluation criteria of the motherboard industry for enterprises to evaluate their digital transformation maturity. Following this, in this study we have used fuzzy AHP to understand the importance and weights of the dimensions and criteria.

The analysis results of FAHP show that "manufacturing" has the highest weight among the seven evaluation dimensions. This is reasonable as the motherboard industry focuses on manufacturing. Enterprises can prioritize the optimizations of the manufacturing process, which will move them toward the digital transformation stage and effectively enhance their overall operating value. "Procurement management" has the lowest rank, so it can be listed as the last dimension to improve.

From the perspective of the 21 evaluation criteria, the criterion "material requirements planning" has the highest weight, and the second and third highest weights are "technical innovation" and "innovation management and collaborative development," respectively. These three criteria are important to enterprises. The changes and impacts resulting from emerging technologies and disruptive innovations have enabled enterprises to change the original value chain more efficiently through requirements planning and the introduction of new techniques and technologies. Conversely, "smart customer service robot" has the lowest weight among all the evaluation criteria, but in the long run, the application of smart customer service robots can not only improve service efficiency and maintain customer service quality but also create a new customer experience. Therefore, this evaluation criterion can still be included among the criteria for enterprise improvement.

We have summarized seven major transformation directions, namely, new products, new techniques, new technologies, new services, new channels, new applications, and new markets, which are described as follows:

In terms of new products, we take the motherboard, personal computer (PC), AI card, and graphics card in the motherboard industry as examples. With the advent of new technologies, the motherboard will not involve just the traditional PC. It will have multiple applications, such as with AIoT and servers. The future trend of cloud platforms will move toward cloud platforms and highly modular and diversified intelligent devices. With the increasing demand for block chain mining, there will be the opportunity to implement AI cards in reality. Finally, graphics cards will continue to be developed together with augmented reality (AR) technology in the future.

In terms of new techniques, the motherboard industry will continue to develop two-dimensional (2D) techniques into 3D techniques and have breakthrough technical innovations and applications in AI chips and AI visual recognition. In terms of new technologies, new technologies such as AIoT, IoT, block chain, and 5G have been adopted. In terms of new services, OTO, maintenance services, and server data centers built by the motherboard industry have been added to implement rental and pay-per-use models.

In terms of new channels, we can use multiple channels, such as physical channels, e-commerce platforms, preorders, and cross-industry alliances, to achieve the development of new channels. In terms of applications, diverse applications are being developed, such as system platforms, cloud applications, and smart applications, to meet the needs of different applications and groups.

In terms of new technologies, technologies such as AIoT, IoT, block chain, and 5G have been adopted to accelerate the accumulation of digital assets and serve as the basis for new service models. In terms of applications, diverse applications are being developed using data accumulated through digitization and digital optimization. These include system platforms, cloud applications, and intelligent applications to meet different application-related needs. It is suggested to use the evaluation criteria of different industries as the research content and standard. In the future, we should also explore the correlation between digital transformation and the accumulation of digital assets and whether a developed data service industry (including open data) can accelerate enterprises' digital transformation.

Finally, the proposed maturity assessment produces different assessment results and dimensions to be improved according to the different business types and business models of enterprises. Enterprises can understand their strengths and weaknesses from the quantitative results. It enables enterprises to follow the pace of digital transformation and develop new markets. The digital transformation stage involves many aspects, but this study only discussed the criteria related to the digital transformation maturity of the motherboard industry. It is suggested that the evaluation criteria of different industries be studied and defined in the future.

Author contributions

YC and MC built the evaluation system and performed the research together. YC and HW analyzed the data and wrote the manuscript. MC and C-MW revised the manuscript. All authors have read and approved the final manuscript.

Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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