ORIGINAL ARTICLE

Smart and automation technologies for ensuring the long-term operation of a factory amid the COVID-19 pandemic: an evolving fuzzy assessment approach

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Abstract
The COVID-19 pandemic has severely impacted factories all over the world, which have been closed to avoid the spread of COVID-19. As a result, ensuring the long-term operation of a factory amid the COVID-19 pandemic becomes a critical but challenging task. To fulfill this task, the applications of smart and automation technologies have been regarded as an effective means. However, such applications are time-consuming and budget-intensive with varying effects and are not necessarily acceptable to workers. In order to make full use of limited resources and time, it is necessary to establish a systematic procedure for comparing various applications of smart and automation technologies. For this reason, an evolving fuzzy assessment approach is proposed. A case study has been conducted to demonstrate the effectiveness of the evolving fuzzy assessment approach in ensuring the long-term operation of a factory amid the COVID-19 pandemic.

1 Introduction

An outbreak of COV-19 was discovered in Wuhan, China [4]. Since then, the COVID-19 pandemic has severely affected factories all over the world. Many factories were forced to close or operate on a smaller scale. On the contrary, during the COVID-19 pandemic, some factories have received more orders. For example, the necessity of working from home, distance teaching, and video conferencing has increased the demand for notebooks or tablets [29]. Other factories that have also benefited from the COVID-19 pandemic include factories that manufacture masks and thermometers [56].

A few months after the outbreak, the COVID-19 pandemic eased in some areas. However, it is still difficult for factories to resume normal operations due to the following problems:

- Workers need to be quarantined for several weeks before returning to a factory [3].
- The demand for a product has shrunk and may not recover, that is, the consumption was not delayed but has been canceled [30].
- The demand for a product has been advanced. As a result, the future demand may disappear [29].
- Due to insufficient transportation capacity, products manufactured by a factory cannot be delivered to customers [22].

Since no one can estimate when the COVID-19 pandemic can be successfully resolved, how to ensure the long-term operation of a factory amid the COVID-19 pandemic has become a critical issue. This research aims to address this issue. However, this research is not an investigation into the sustainability of a factory. The (operational) sustainability of a factory is to use its resources as efficiently as possible to minimize the impact on the environment [7, 13, 40, 59, 63], which has three traditional pillars: economic, environmental, and social sustainability [50, 53]. On the contrary, this study attempts to continue the operation of a factory without being affected by the COVID-19 pandemic, i.e., the environment.

In recent years, a number of advanced automation technologies have been proposed in the manufacturing field, such as

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automatic inspection [2, 58], autonomous robots [16, 26, 60], additive manufacturing [8, 9, 11, 62, 67], ubiquitous manufacturing (UM) [11, 39, 61], cloud manufacturing [10, 21, 48], Internet of things (IoT) [54, 55], cyber-physical systems [36, 55], etc. As shown in Table 1, some of these advanced automation technologies are designed to promote the cooperation between factories by sharing manufacturing resources, which is difficult amid the COVID-19 pandemic and may not help mitigate the impact, as illustrated in Table 1. In contrast, applications of smart and automation technologies to assist workers have been considered feasible [6, 45, 47]. For example, using voice commands or gestures to interact with machines can avoid spreading COVID-19 by touching the machines [33, 34]. The same purpose can be achieved by using a smartphone to remotely control a machine [46]. In addition, since body temperature is one of the basic criteria for screening workers who may be infected, workers can wear smart wristbands or watches to detect their body temperature [43]. Wearable sensors can also be used to measure the proximity of workers to ensure physical distance [45].

This study aims to establish a systematic mechanism to assist a factory manager in selecting the most suitable smart and automation technology application to ensure the long-term operation amid the COVID-19 pandemic. So far, no similar mechanisms have been proposed. For this purpose, an evolving fuzzy assessment approach is proposed. The evolving fuzzy assessment approach is composed of three parts: alpha-cut operations (ACO)-based fuzzy analytic hierarchy process (FAHP) [14], genetic algorithm (GA) [12, 35], and fuzzy technique for order preference by similarity to the ideal solution (FTOPSIS) [38]. First, according to the judgment of the factory manager, the ACO-FAHP approach is applied to derive the priorities of criteria for assessing a smart and automation technology application to ensure the long-term operation amid the COVID-19 pandemic. In this step, in order to enhance the computational efficiency of ACO, a GA is designed. Subsequently, based on the derived priorities, FTOPSIS is applied to evaluate the overall performance of each smart and automation technology application. The smart and automation technology application with the best

performance will be selected. The evolving fuzzy assessment approach has been applied to a factory to assess its effectiveness.

The remainder of this paper is organized as follows. Section 2 is dedicated to the literature review. Section 3 is an introduction of the evolving fuzzy assessment approach proposed in this study. Section 4 details the application of the evolving fuzzy assessment approach to a case of choosing the most suitable smart and automation technology application to ensure the long-term operation of a factory amid the COVID-19 pandemic. Several existing methods were also applied to the case for comparison. Section 5 provides the conclusions of this study as well as some possible topics for future investigation.

2 Literature review

2.1 Measures taken by factories in response to the COVID-19 pandemic

Amid the COVID-19 pandemic, affected workers must undergo home quarantine. As a result, a factory runs for reduced work hours temporarily. As an alternative, the workforce in a factory can be reduced by staggering work shifts or introducing weekend working, which also avoids the gathering of workers [42]. In addition, indirect labor, such as administrative, managerial, and accounting staff, is encouraged to work remotely. Then, their offices become extra space for factory workers (Hesse and [24]). Further, Singapore's experience showed that overseas workers (work permit holders) should be distributed among different dormitories to avoid cross-infection [44].

A sanitized working environment needs to be created to prevent any further infection [3]. There are sanitizers at the entrance. Each worker's temperature is checked here. Then, workers wear masks (cloth or surgical masks), protective clothing, sterilizers, and gloves every day [18]. These treatments also apply to visitors and logistics drivers whose names

Table 1 Effects of existing smart and automation technologies on mitigating the impact of the COVID-19 pandemic

| Smart and automation technology	Effect	Mechanism
Automatic inspection	Positive	Reduce workforce
Autonomous robots	Positive	Reduce workforce
Additive manufacturing	Positive	Reduce workforce
Ubiquitous manufacturing	Negative	Increasing the possibility of cross-factory infection
Cloud manufacturing	Negative	Increasing the possibility of cross-factory infection
Internet of things	Positive	Reducing human-machine contact
Cyber-physical systems	Positive	Reducing human-machine contact
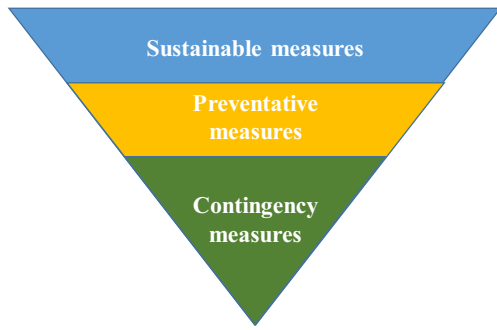
Fig. 1 Measures taken by factories to avoid the spread of COVID-19

and basic data are recorded and activities are restricted. Plastic barriers between machines are raised (Hesse and [24]).

Workers wear masks and keep a minimum distance from each other [31]. When the work rate is low or moderate, wearing a facial mask may not have a significant physiological impact on a worker [49]. For example, dizziness is less likely to occur when wearing a cloth or surgical mask. However, prolonged usage of facial masks may cause fatigue [28]. To solve this problem,

- More rest opportunities need to be arranged into the work schedule [52].
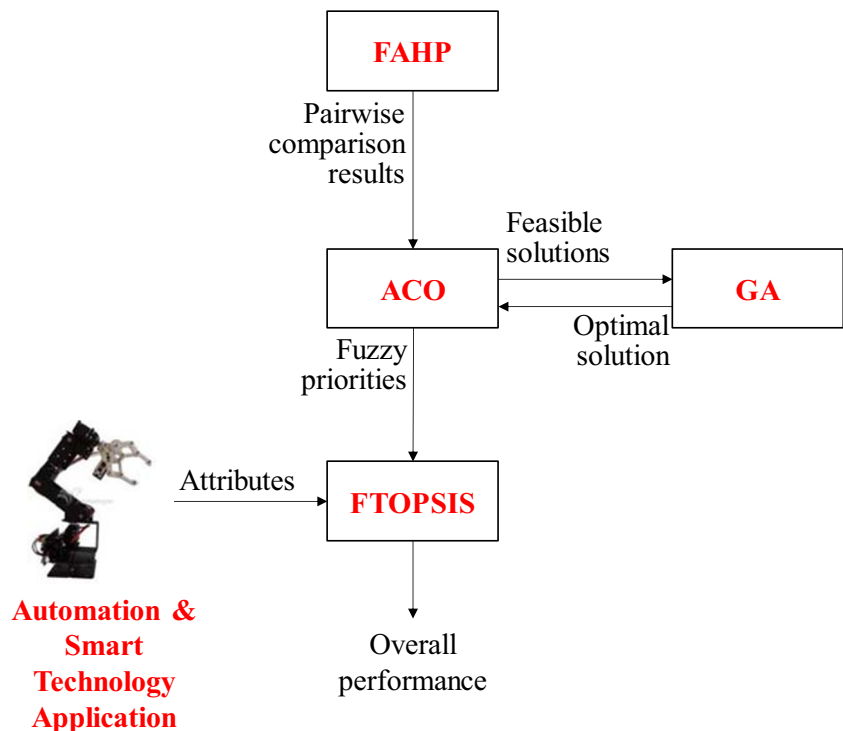- The daily production target can be lowered.
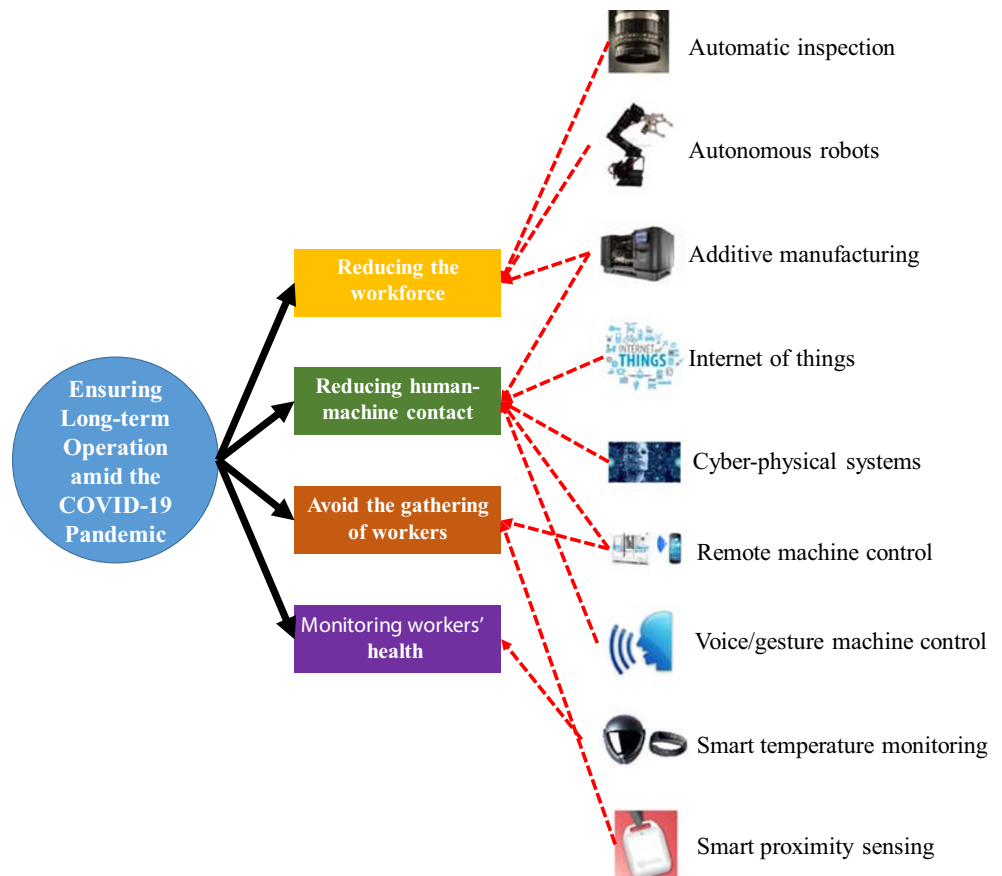
- The work pace can be slowed down by lowering the input rate or implementing pull production [17].
- The standard processing time can be extended.
- A worker is given more time to correct his/her mistakes.

In addition, workers should be provided with incentives to encourage them to wash their hands frequently [65]. After each use, a worker needs to disinfect the machine interface (such as buttons, keyboard, touchscreen, etc.) [64].

In sum, to address to avoid the spread of COVID-19 in the shop floor, factory managers have taken the following measures:

- Contingency measures: Workers are asked to wear facial masks, keep physical distance from each other, wash hands frequently, and take the temperature every day. Some factories were closed during the lockdown of their cities [32].
- Preventative measures: Factory managers actively look for guidelines such as those provided by International Labour Organization (ILO) and Occupational Safety and Health Administration (OSHA), and follow these guidelines by changing work procedures, rescheduling work shifts, adjusting facility layout, and creating a healthier working environment. [24, 31].

Fig. 2 Possible smart and automation technologies for ensuring the long-term operation of a factory amid the COVID-19 pandemic

Fig. 3 The evolving fuzzy
assessment approach

- Sustainable measures: Factory managers develop strategies (such as changing the employment policy, transforming into a laborless factory (i.e., further automation), upgrading the ventilation system, moving the factory to countries with better COVID-19 responses, etc. to reduce the risk and impact of future possible outbreaks [6, 20].

These measures are summarized with an inverted triangle in Fig. 1, which means more measures need to be taken to achieve higher efficacy.

2.2 Smart and automation technology applications

The COVID-19 pandemic provides factories with opportunities to increase automation and remote service delivery [47]. Among existing advanced automation technologies, automatic inspection, autonomous robots, and additive manufacturing can mitigate the impact of the COVID-19 pandemic by reducing the workforce; Internet of things and cyber-physical systems help to prevent the spread of COVID-19 by reducing human-machine contact. Therefore, it is expected that more robots and automation systems will be used earlier than planned [23, 47]. Canadian Plastics [6] described such a trend as "a lasting boom in factory robotics".

Tradition automation is mainly for low-level tasks. In the epidemic, the goal of automation is shifting to tasks that are more labor intensive or difficult to maintain social distance [23]. In addition, whether automation technologies that have

been popular in recent years, such as artificial intelligence (AI) and cloud manufacturing, have brought benefits to factories amid the COVID-19 pandemic is questioned [6]. In addition, automated equipment such as a computer numerical control (CNC) machine tool is controlled by a minicomputer with interfaces such as keyboards and touchscreens that easily spread COVID-19. To solve this problem, such automated equipment can be operated with voice commands or gestures, or can also be remotely controlled through applications on a smartphone [33, 34, 46]. The latter is a joint application of automation and smart technologies.

Smart technologies are technologies that use electronic devices or systems that can be connected to the Internet, used interactively, and are to some extent intelligent (Hollis 2015) [1, 15, 41, 57]. Amid the COVID-19 pandemic, smart technologies can also be applied to enhance the operational efficiency and protect the safety and health of workers. For example, workers can wear smart wristbands or watches to detect their body temperature [43], while supervisors can wear smart helmets to monitor workers' body temperature [5]. In addition, wireless sensors can be worn or carried to measure the proximity of workers to ensure physical distance or record their movements for tracking [45, 68]. If two wearable sensors get too close, they will issue a warning signal. The contact time is also recorded. In-door positioning technologies can also be applied to screen workers who may come into contact with an infected worker [45]. Figure 2 summarizes

possible smart and automation technologies for ensuring the long-term operation of a factory amid the COVID-19 pandemic.

3 The evolving fuzzy assessment approach

The proposed evolving fuzzy assessment approach comprises three major parts: FAHP-ACO, GA, and FTOPSIS, as illustrated in Fig. 3.

In the evolving fuzzy assessment approach, at first the factory manager compares the relative priority of a critical factor over that of another in linguistic terms such as "as equal as," "weakly more important than," "strongly more important than," "very strongly more important than," and "absolutely more important than" [7]. These linguistic terms are usually mapped to triangular fuzzy numbers (TFNs) within [1, 8, 69].

Based on pairwise comparison results, the fuzzy judgment matrix $\widetilde{\mathbf{A}}_{n \times n} = [\widetilde{a}_{ij}]$ is constructed as

$$\widetilde{a}_{ji} = 1/\widetilde{a}_{ij} \tag{1}$$

$$\widetilde{a}_{ii} = 1 \tag{2}$$

The fuzzy eigenvalue and eigenvector of $\widetilde{\mathbf{A}}$, indicated with $\widetilde{\lambda}$ and $\widetilde{\mathbf{x}}$ respectively, satisfy [51]

$$det\left(\widetilde{\mathbf{A}}(-)\widetilde{\lambda}\mathbf{I}\right) = 0 \tag{3}$$

and

$$\left(\widetilde{\mathbf{A}}(-)\widetilde{\lambda}\mathbf{I}\right)(\times)\widetilde{\mathbf{x}} = 0 \tag{4}$$

where (-) and (×) denote fuzzy subtraction and multiplication, respectively. The consistency among pairwise comparison results can be evaluated with fuzzy consistency ratio:

$$\widetilde{CR} = \frac{\dfrac{\widetilde{\lambda}_{\max} - n}{n-1}}{RI} \tag{5}$$

where $\widetilde{\lambda}_{\max}$ is the fuzzy maximal eigenvalue; RI is the random consistency index [51]. $\widetilde{CR}$ should be less than 0.1~0.3, depending on the problem size. Subsequently, ACO is applied to derive the values of $\widetilde{\lambda}$ and $\widetilde{\mathbf{x}}$ as follows.

First, the fuzzy parameters and variables in Equations (3) and (4) are replaced with their α cuts:

$$det\left(\widetilde{\mathbf{A}}(\alpha)-\widetilde{\lambda}(\alpha)\mathbf{I}\right) = 0 \tag{6}$$

$$\left(\widetilde{\mathbf{A}}(\alpha)-\widetilde{\lambda}(\alpha)\mathbf{I}\right)\widetilde{\mathbf{x}}(\alpha) = 0 \tag{7}$$

If α takes 11 possible values (0, 0.1, …, 1), Equations (6) and (7) must be solved $11 \cdot 2^{C_2^n}$ times to derive the α cuts of fuzzy maximal eigenvalue and fuzzy eigenvector as [14]

$$\lambda^L(\alpha) = \min_{det\left(\left[a_{ij}^*(\alpha)\right]-\lambda_t(\alpha)I\right)=0}(\lambda_t(\alpha)) \tag{8}$$

$$\lambda^R(\alpha) = \max_{det\left(\left[a_{ij}^*(\alpha)\right]-\lambda_t(\alpha)I\right)=0}(\lambda_t(\alpha)) \tag{9}$$

$$\mathbf{x}^L(\alpha) = \min_{\left(\left[a_{ij}^*(\alpha)-\lambda_t(\alpha)\mathbf{I}\right]\right)\mathbf{x}_t(\alpha)=0}(\mathbf{x}_t(\alpha)) \tag{10}$$

$$\mathbf{x}^R(\alpha) = \max_{\left(\left[a_{ij}^*(\alpha)-\lambda_t(\alpha)\mathbf{I}\right]\right)\mathbf{x}_t(\alpha)=0}(\mathbf{x}_t(\alpha)) \tag{11}$$

where $* = L$ or R. $\lambda_t^L(\alpha)$, $\lambda_t^R(\alpha)$, $\mathbf{x}_t^L(\alpha)$, and $\mathbf{x}_t^R(\alpha)$ are the results derived from the t-th combination; $t = 1\sim11\cdot2^{C_2^n}$. To enhance the efficiency of ACO, a GA algorithm is designed as follows.

First, the encoding of a chromosome is illustrated in Fig. 4, where 0 represents selecting the left α cut of a fuzzy pairwise comparison result; 1 represents selecting the right α cut. There are two fitness functions. One is to maximize fuzzy maximal eigenvalue (or fuzzy vector), and the other is to minimize fuzzy maximal eigenvalue (or fuzzy vector):

$$\text{Max } fitness = -\lambda^L(\alpha) \quad (\text{or} -\mathbf{x}^L(\alpha)) \tag{12}$$

$$\text{Max } fitness = \lambda^R(\alpha) \quad \left(\text{or } \mathbf{x}^R(\alpha)\right) \tag{13}$$

The optimization results are used to establish the α cut of fuzzy eigenvalue (or fuzzy vector). To this end, two groups of chromosomes are established. Because the two fitness functions are opposite, chromosomes that perform particularly poorly in one group can be moved to the other.

The roulette wheel method is applied to choose parent chromosomes to be paired based on their fitness values. A crossover point is chosen at random. Offspring
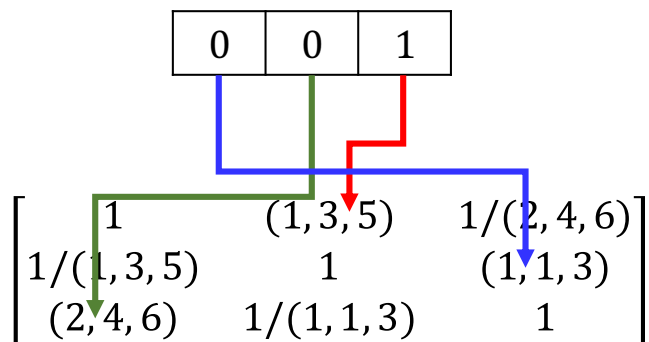

Fig. 4 Encoding of a chromosome

Table 2 Results of pairwise comparisons

Critical factor no. 1	Critical factor no. 2	Relative priority of critical factor no. 1 over critical factor no. 2
High effectiveness for preventing the spread of COVID-19	Low estimated total costs	Weakly or strongly more important than
Low estimated total costs	Low interference with existing operations	Strongly more important than
Low estimated total costs	Easiness of adoption	Weakly or strongly more important than
Low estimated total costs	High acceptability to workers	Weakly more important than
High effectiveness for preventing the spread of COVID-19	Low interference with existing operations	Strongly more important than
High effectiveness for preventing the spread of COVID-19	Easiness of adoption	Strongly more important than
High effectiveness for preventing the spread of COVID-19	High acceptability to workers	Weakly or strongly more important than
Easiness of adoption	Low interference with existing operations	Weakly or strongly more important than
High acceptability to workers	Low interference with existing operations	As equal as or weakly more important than
High acceptability to workers	Easiness of adoption	Weakly more important than

Fig. 6 The value of fuzzy maximal eigenvalue derived using ACO+GA

$$
\widetilde{\rho}_{qi} = \frac{\widetilde{p}_{qi}}{\sqrt{\sum\limits_{\phi=1}^{Q} \widetilde{p}_{\phi i}^{\,2}}}
$$

$$
= \frac{1}{\sqrt{1 + \sum\limits_{\phi \neq q} \left(\dfrac{\widetilde{p}_{\phi i}}{\widetilde{p}_{qi}}\right)^2}} \tag{14}
$$

where $\widetilde{p}_{qi}$ is the performance of the q-th smart and automation technology application in optimizing the i-th critical factor; $\widetilde{\rho}_{qi}$ is the normalized performance. Subsequently, fuzzy prioritized scores are calculated based on the derived fuzzy priorities:

$$
\widetilde{s}_{qi} = \widetilde{w}_i (\times) \widetilde{\rho}_{qi} \tag{15}
$$

Fuzzy ideal (zenith) point and fuzzy anti-ideal (nadir) point are specified respectively as

$$
\widetilde{\Lambda}^+ = \left\{\widetilde{\Lambda}_i^+\right\} = \left\{\max_q \widetilde{s}_{qi}\right\} \tag{16}
$$

$$
\widetilde{\Lambda}^- = \left\{\widetilde{\Lambda}_i^-\right\} = \left\{\min_q \widetilde{s}_{qi}\right\} \tag{17}
$$

The fuzzy distances from the smart and automation technology application to the two reference points are calculated respectively as

chromosomes are generated by exchanging the genes of parents among themselves before or after the crossover point. Finally, FTOPSIS is applied to evaluate the overall performance of a smart and automation technology application as follows.

First, the performance of a smart and automation technology application in optimizing each critical factor is normalized using fuzzy distributive normalization as
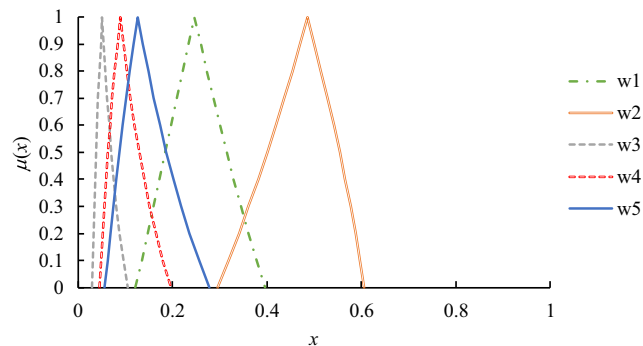

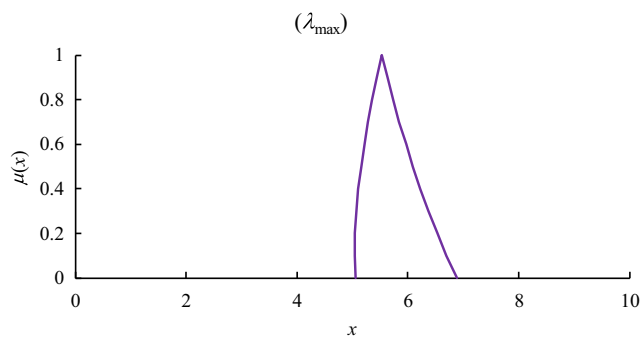**Fig. 5** The values of fuzzy priorities derived using ACO+GA

Fig. 7 Fuzzy consistency ratio

Table 3 Rules for evaluating the performances

Critical Factor	Rule
Low estimated total costs	$\tilde{p}_{k1}(x_k) = \begin{cases} (0,0,1) & \text{if} & 0.1 \cdot \min_r x_r + 0.9 \cdot \max_r x_r \leq x_k \text{ or data not available} \\ (0,1,2) & \text{if} & 0.35 \cdot \min_r x_r + 0.65 \cdot \max_r x_r \leq x_k < 0.1 \cdot \min_r x_r + 0.9 \cdot \max_r x_r \\ (1.5,2.5,3.5) & \text{if} & 0.65 \cdot \min_r x_r + 0.35 \cdot \max_r x_r \leq x_k < 0.35 \cdot \min_r x_r + 0.65 \cdot \max_r x_r \\ (3,4,5) & \text{if} & 0.9 \cdot \min_r x_r + 0.1 \cdot \max_r x_r \leq x_k < 0.65 \cdot \min_r x_r + 0.35 \cdot \max_r x_r \\ (4,5,5) & \text{if} & x_k < 0.9 \cdot \min_r x_r + 0.1 \cdot \max_r x_r \end{cases}$ where x_k is the estimated total costs.
High effectiveness for preventing the spread of COVID-19	$\tilde{p}_{k2}(x_k) = \begin{cases} (0,0,1) & \text{if} & x_k = \text{ineffective} \\ (0,1,2) & \text{if} & x_k = \text{slightly ineffective} \\ (1.5,2.5,3.5) & \text{if} & x_k = \text{quite effective} \\ (3,4,5) & \text{if} & x_k = \text{highly effective} \\ (4,5,5) & \text{if} & x_k = \text{very highly effective} \end{cases}$ where x_k is the effectiveness for preventing the spread of COVID-19.
Low interference with existing operations	$\tilde{p}_{k3}(x_k) = \begin{cases} (4,5,5) & \text{if} & x_k = \text{very low} \\ (3,4,5) & \text{if} & x_k = \text{low} \\ (1.5,2.5,3.5) & \text{if} & x_k = \text{moderate} \\ (0,1,2) & \text{if} & x_k = \text{high} \\ (0,0,1) & \text{if} & x_k = \text{very high} \end{cases}$ where x_k is the interference with existing operations.
Easiness of adoption	$\tilde{p}_{k4}(x_k) = \begin{cases} (0,0,1) & \text{if} & x_k = \text{very difficult} \\ (0,1,2) & \text{if} & x_k = \text{difficult} \\ (1.5,2.5,3.5) & \text{if} & x_k = \text{moderate} \\ (3,4,5) & \text{if} & x_k = \text{easy} \\ (4,5,5) & \text{if} & x_k = \text{very easy} \end{cases}$ where x_k is the easiness of adoption.
High acceptability to workers	$\tilde{p}_{k5}(x_k) = \begin{cases} (0,0,1) & \text{if} & x_k = \text{very low} \\ (0,1,2) & \text{if} & x_k = \text{low} \\ (1.5,2.5,3.5) & \text{if} & x_k = \text{moderate} \\ (3,4,5) & \text{if} & x_k = \text{high} \\ (4,5,5) & \text{if} & x_k = \text{very high} \end{cases}$ where x_k is workers' acceptability.

$$\tilde{d}_q^+ = \sqrt{\sum_{i=1}^{n} \left(\tilde{\Lambda}_i^+ (-) \tilde{s}_{qi} \right)^2} \qquad (18) \qquad \tilde{d}_q^- = \sqrt{\sum_{i=1}^{n} \left(\tilde{\Lambda}_i^- (-) \tilde{s}_{qi} \right)^2} \qquad (19)$$

Table 4 Evaluation results

k	Application	$\widetilde{p}_{k1}$	$\widetilde{p}_{k2}$	$\widetilde{p}_{k3}$	$\widetilde{p}_{k4}$	$\widetilde{p}_{k5}$
1	Machine remote control	(1.5, 2.5, 3.5)	(4.0, 5.0, 5.0)	(0.0, 1.0, 2.0)	(0.0, 1.0, 2.0)	(3.0, 4.0, 5.0)
2	Workers' smart wristbands	(3.0, 4.0, 5.0)	(0.0, 1.0, 2.0)	(4.0, 5.0, 5.0)	(4.0, 5.0, 5.0)	(4.0, 5.0, 5.0)
3	Worker's smart PPEs	(1.5, 2.5, 3.5)	(3.0, 4.0, 5.0)	(3.0, 4.0, 5.0)	(3.0, 4.0, 5.0)	(1.5, 2.5, 3.5)
4	Smart warehouse	(0.0, 1.0, 2.0)	(4.0, 5.0, 5.0)	(0.0, 1.0, 2.0)	(1.5, 2.5, 3.5)	(3.0, 4.0, 5.0)

Finally, the fuzzy closeness of the smart and automation technology application is obtained as

$$\widetilde{C}_q = \frac{\widetilde{d}_q^-}{\widetilde{d}_q^+ (+) \widetilde{d}_q^-} \qquad (20)$$

A smart and automation technology application is more suitable if its fuzzy closeness is higher. To get an absolute ranking, the fuzzy closeness can be defuzzified using the COG method [25]:

$$D\left(\widetilde{C}_q\right) = \frac{\int_0^1 \alpha \left(\frac{C_q^L(\alpha) + C_q^R(\alpha)}{2}\right) d\alpha}{\int_0^1 \alpha d\alpha} \qquad (21)$$

4 Application

The proposed methodology was applied to select a smart and automation technology application to ensure the long-term operation of a machinery works factory in Taichung, Taiwan amid the COVID-19 pandemic. The factory was making metal parts from top-grade raw materials and high-strength alloys using sophisticated manufacturing equipment such as CNC horizontal machining centers, robotic welders, precise scanning probes, and automatic test systems, which laid the foundation for the factory to apply advanced smart and automation technologies.

After reviewing the related literature and practices, the following factors were considered critical to the selection of a

suitable smart and automation technology application to ensure the long-term operation of a factory amid the COVID-19 pandemic:

- Low estimated total costs
- High effectiveness for preventing the spread of COVID-19
- Low interference with existing operations
- Easiness of adoption
- High acceptability to workers

The factory manager first compared the relative priorities of these critical factors with linguistic terms. The results are summarized in Table 2.

Based on Table 2, the following fuzzy judgment matrix was constructed:

$$\widetilde{A} = \begin{bmatrix} 1 & 1/(2,4,6) & (3,5,7) & (2,4,6) & (1,3,5) \\ (2,4,6) & 1 & (3,5,7) & (3,5,7) & (2,4,6) \\ 1/(3,5,7) & 1/(3,5,7) & 1 & 1/(2,4,6) & 1/(1,2,4) \\ 1/(2,4,6) & 1/(3,5,7) & (2,4,6) & 1 & 1/(1,3,5) \\ 1/(1,3,5) & 1/(2,4,6) & (1,2,4) & (1,3,5) & 1 \end{bmatrix} \quad (22)$$

ACO is applied to derive the values of fuzzy priorities and fuzzy maximal eigenvalue with the aid of a GA algorithm from this fuzzy judgment matrix. Both ACO and GA were implemented using MATLAB on a PC with an i7-7700 CPU 3.6-GHz and 8-GB RAM. Without GA, it took 24 s to complete the task. After incorporating GA, the execution time was shortened to less than 5 s. The results are shown in Figs. 5 and 6, respectively. The fuzzy consistency ratio of the fuzzy judgment matrix was around 0.118 with a minimum of 0.013 and a maximum of 0.421, as illustrated in Fig. 7, which was highly consistent.

Table 5 Normalized performances

k	Application	$\widetilde{\rho}_{k1}$	$\widetilde{\rho}_{k2}$	$\widetilde{\rho}_{k3}$	$\widetilde{\rho}_{k4}$	$\widetilde{\rho}_{k5}$
1	Machine remote control	(0.18, 0.46, 0.72)	(0.48, 0.61, 0.71)	(0.00, 0.15, 0.37)	(0.00, 0.14, 0.36)	(0.36, 0.50, 0.69)
2	Workers' smart wristbands	(0.46, 0.74, 1.03)	(0.00, 0.12, 0.28)	(0.54, 0.76, 0.93)	(0.51, 0.72, 0.89)	(0.47, 0.63, 0.69)
3	Worker's smart PPEs	(0.23, 0.46, 0.72)	(0.36, 0.49, 0.71)	(0.41, 0.61, 0.93)	(0.38, 0.58, 0.89)	(0.18, 0.31, 0.48)
4	Smart warehouse	(0.00, 0.18, 0.41)	(0.48, 0.61, 0.71)	(0.00, 0.15, 0.37)	(0.19, 0.36, 0.63)	(0.36, 0.50, 0.69)

Among the five critical factors, "high effectiveness for preventing the spread of COVID-19," "easiness of adoption," and "high acceptability to workers" were the-higher-the-better performances, whereas the others were the-lower-the-better performances. The performances were evaluated according to the rules in Table 3.

Based on the derived fuzzy priorities, four smart and automation technology applications were compared:

- Remote control of machines [33, 34, 46]

- Monitoring workers' health with smart wristbands [43]
- Providing workers with smart personal protection equipment (PPE), such as face masks with tiny sensors in them to detect all symptoms of COVID, fatigue, etc. [19]
- Smart warehousing with automated guided vehicles and robots [37]

Table 4 presents the evaluation results.

Subsequently, the performance of a smart and automation technology application in optimizing each critical factor was

Table 6 Fuzzy weighted scores

q	$\widetilde{s}_{q1}$ (α:α cut)	$\widetilde{s}_{q2}$ (α:α cut)	$\widetilde{s}_{q3}$ (α:α cut)	$\widetilde{s}_{q4}$ (α:α cut)	$\widetilde{s}_{q5}$ (α:α cut)
1	0.0: [0.02, 0.29]	0.0: [0.14, 0.43]	0.0: [0.00, 0.04]	0.0: [0.00, 0.07]	0.0: [0.02, 0.19]
	0.1: [0.03, 0.26]	0.1: [0.16, 0.42]	0.1: [0.00, 0.03]	0.1: [0.00, 0.06]	0.1: [0.02, 0.17]
	0.2: [0.04, 0.24]	0.2: [0.17, 0.40]	0.2: [0.00, 0.03]	0.2: [0.00, 0.05]	0.2: [0.03, 0.15]
	0.3: [0.04, 0.22]	0.3: [0.19, 0.39]	0.3: [0.00, 0.02]	0.3: [0.00, 0.04]	0.3: [0.03, 0.14]
	0.4: [0.05, 0.20]	0.4: [0.20, 0.38]	0.4: [0.00, 0.02]	0.4: [0.00, 0.04]	0.4: [0.03, 0.12]
	0.5: [0.06, 0.19]	0.5: [0.22, 0.37]	0.5: [0.00, 0.02]	0.5: [0.00, 0.03]	0.5: [0.04, 0.11]
	0.6: [0.07, 0.17]	0.6: [0.23, 0.35]	0.6: [0.00, 0.02]	0.6: [0.01, 0.03]	0.6: [0.04, 0.10]
	0.7: [0.08, 0.15]	0.7: [0.25, 0.34]	0.7: [0.00, 0.01]	0.7: [0.01, 0.02]	0.7: [0.05, 0.09]
	0.8: [0.09, 0.14]	0.8: [0.27, 0.32]	0.8: [0.01, 0.01]	0.8: [0.01, 0.02]	0.8: [0.05, 0.08]
	0.9: [0.10, 0.13]	0.9: [0.28, 0.31]	0.9: [0.01, 0.01]	0.9: [0.01, 0.02]	0.9: [0.06, 0.07]
	1.0: [0.11, 0.11]	1.0: [0.30, 0.30]	1.0: [0.01, 0.01]	1.0: [0.01, 0.01]	1.0: [0.06, 0.06]
2	0.0: [0.06, 0.41]	0.0: [0.00, 0.17]	0.0: [0.02, 0.10]	0.0: [0.02, 0.18]	0.0: [0.03, 0.19]
	0.1: [0.07, 0.38]	0.1: [0.00, 0.16]	0.1: [0.02, 0.09]	0.1: [0.03, 0.16]	0.1: [0.03, 0.18]
	0.2: [0.08, 0.35]	0.2: [0.01, 0.15]	0.2: [0.02, 0.08]	0.2: [0.03, 0.14]	0.2: [0.03, 0.16]
	0.3: [0.09, 0.33]	0.3: [0.01, 0.14]	0.3: [0.02, 0.07]	0.3: [0.03, 0.13]	0.3: [0.04, 0.15]
	0.4: [0.10, 0.30]	0.4: [0.02, 0.12]	0.4: [0.02, 0.06]	0.4: [0.03, 0.12]	0.4: [0.04, 0.13]
	0.5: [0.11, 0.28]	0.5: [0.02, 0.11]	0.5: [0.02, 0.06]	0.5: [0.04, 0.10]	0.5: [0.05, 0.12]
	0.6: [0.12, 0.26]	0.6: [0.03, 0.10]	0.6: [0.03, 0.05]	0.6: [0.04, 0.09]	0.6: [0.05, 0.11]
	0.7: [0.14, 0.24]	0.7: [0.04, 0.09]	0.7: [0.03, 0.05]	0.7: [0.05, 0.09]	0.7: [0.06, 0.10]
	0.8: [0.15, 0.22]	0.8: [0.04, 0.08]	0.8: [0.03, 0.05]	0.8: [0.05, 0.08]	0.8: [0.07, 0.10]
	0.9: [0.17, 0.20]	0.9: [0.05, 0.07]	0.9: [0.04, 0.04]	0.9: [0.06, 0.07]	0.9: [0.07, 0.09]
	1.0: [0.18, 0.18]	1.0: [0.06, 0.06]	1.0: [0.04, 0.04]	1.0: [0.06, 0.06]	1.0: [0.08, 0.08]
3	0.0: [0.03, 0.29]	0.0: [0.11, 0.43]	0.0: [0.01, 0.10]	0.0: [0.02, 0.18]	0.0: [0.01, 0.13]
	0.1: [0.03, 0.26]	0.1: [0.12, 0.41]	0.1: [0.01, 0.09]	0.1: [0.02, 0.15]	0.1: [0.01, 0.12]
	0.2: [0.04, 0.24]	0.2: [0.13, 0.39]	0.2: [0.01, 0.08]	0.2: [0.02, 0.14]	0.2: [0.01, 0.11]
	0.3: [0.05, 0.22]	0.3: [0.14, 0.37]	0.3: [0.02, 0.07]	0.3: [0.02, 0.12]	0.3: [0.02, 0.09]
	0.4: [0.06, 0.20]	0.4: [0.16, 0.35]	0.4: [0.02, 0.06]	0.4: [0.03, 0.11]	0.4: [0.02, 0.08]
	0.5: [0.06, 0.19]	0.5: [0.17, 0.33]	0.5: [0.02, 0.05]	0.5: [0.03, 0.10]	0.5: [0.02, 0.07]
	0.6: [0.07, 0.17]	0.6: [0.18, 0.31]	0.6: [0.02, 0.05]	0.6: [0.03, 0.08]	0.6: [0.02, 0.07]
	0.7: [0.08, 0.15]	0.7: [0.20, 0.29]	0.7: [0.02, 0.04]	0.7: [0.04, 0.07]	0.7: [0.03, 0.06]
	0.8: [0.09, 0.14]	0.8: [0.21, 0.27]	0.8: [0.03, 0.04]	0.8: [0.04, 0.07]	0.8: [0.03, 0.05]
	0.9: [0.10, 0.13]	0.9: [0.22, 0.26]	0.9: [0.03, 0.03]	0.9: [0.05, 0.06]	0.9: [0.04, 0.05]
	1.0: [0.11, 0.11]	1.0: [0.24, 0.24]	1.0: [0.03, 0.03]	1.0: [0.05, 0.05]	1.0: [0.04, 0.04]
4	0.0: [0.00, 0.16]	0.0: [0.14, 0.43]	0.0: [0.00, 0.04]	0.0: [0.01, 0.12]	0.0: [0.02, 0.19]
	0.1: [0.00, 0.15]	0.1: [0.16, 0.42]	0.1: [0.00, 0.03]	0.1: [0.01, 0.11]	0.1: [0.02, 0.17]
	0.2: [0.01, 0.13]	0.2: [0.17, 0.40]	0.2: [0.00, 0.03]	0.2: [0.01, 0.09]	0.2: [0.03, 0.15]
	0.3: [0.01, 0.12]	0.3: [0.19, 0.39]	0.3: [0.00, 0.02]	0.3: [0.01, 0.08]	0.3: [0.03, 0.14]
	0.4: [0.01, 0.11]	0.4: [0.20, 0.38]	0.4: [0.00, 0.02]	0.4: [0.02, 0.07]	0.4: [0.03, 0.12]
	0.5: [0.02, 0.09]	0.5: [0.22, 0.37]	0.5: [0.00, 0.02]	0.5: [0.02, 0.06]	0.5: [0.04, 0.11]
	0.6: [0.02, 0.08]	0.6: [0.23, 0.35]	0.6: [0.00, 0.02]	0.6: [0.02, 0.06]	0.6: [0.04, 0.10]
	0.7: [0.03, 0.07]	0.7: [0.25, 0.34]	0.7: [0.00, 0.01]	0.7: [0.02, 0.05]	0.7: [0.05, 0.09]
	0.8: [0.03, 0.06]	0.8: [0.27, 0.32]	0.8: [0.01, 0.01]	0.8: [0.03, 0.04]	0.8: [0.05, 0.08]
	0.9: [0.04, 0.05]	0.9: [0.28, 0.31]	0.9: [0.01, 0.01]	0.9: [0.03, 0.04]	0.9: [0.06, 0.07]
	1.0: [0.05, 0.05]	1.0: [0.30, 0.30]	1.0: [0.01, 0.01]	1.0: [0.03, 0.03]	1.0: [0.06, 0.06]

Table 7 Fuzzy ideal point and fuzzy anti-ideal point

Reference point	$\widetilde{\Lambda}_1^*$ (α:α cut)	$\widetilde{\Lambda}_2^*$ (α:α cut)	$\widetilde{\Lambda}_3^*$ (α:α cut)	$\widetilde{\Lambda}_4^*$ (α:α cut)	$\widetilde{\Lambda}_5^*$ (α:α cut)
Fuzzy ideal point	0.0: [0.06, 0.41]	0.0: [0.14, 0.43]	0.0: [0.02, 0.10]	0.0: [0.02, 0.18]	0.0: [0.03, 0.19]
	0.1: [0.07, 0.38]	0.1: [0.16, 0.42]	0.1: [0.02, 0.09]	0.1: [0.03, 0.16]	0.1: [0.03, 0.18]
	0.2: [0.08, 0.35]	0.2: [0.17, 0.40]	0.2: [0.02, 0.08]	0.2: [0.03, 0.14]	0.2: [0.03, 0.16]
	0.3: [0.09, 0.33]	0.3: [0.19, 0.39]	0.3: [0.02, 0.07]	0.3: [0.03, 0.13]	0.3: [0.04, 0.15]
	0.4: [0.10, 0.30]	0.4: [0.20, 0.38]	0.4: [0.02, 0.06]	0.4: [0.03, 0.12]	0.4: [0.04, 0.13]
	0.5: [0.11, 0.28]	0.5: [0.22, 0.37]	0.5: [0.02, 0.06]	0.5: [0.04, 0.10]	0.5: [0.05, 0.12]
	0.6: [0.12, 0.26]	0.6: [0.23, 0.35]	0.6: [0.03, 0.05]	0.6: [0.04, 0.09]	0.6: [0.05, 0.11]
	0.7: [0.14, 0.24]	0.7: [0.25, 0.34]	0.7: [0.03, 0.05]	0.7: [0.05, 0.09]	0.7: [0.06, 0.10]
	0.8: [0.15, 0.22]	0.8: [0.27, 0.32]	0.8: [0.03, 0.05]	0.8: [0.05, 0.08]	0.8: [0.07, 0.10]
	0.9: [0.17, 0.20]	0.9: [0.28, 0.31]	0.9: [0.04, 0.04]	0.9: [0.06, 0.07]	0.9: [0.07, 0.09]
	1.0: [0.18, 0.18]	1.0: [0.30, 0.30]	1.0: [0.04, 0.04]	1.0: [0.06, 0.06]	1.0: [0.08, 0.08]
Fuzzy anti-ideal point	0.0: [0.00, 0.16]	0.0: [0.00, 0.17]	0.0: [0.00, 0.04]	0.0: [0.00, 0.07]	0.0: [0.01, 0.13]
	0.1: [0.00, 0.15]	0.1: [0.00, 0.16]	0.1: [0.00, 0.03]	0.1: [0.00, 0.06]	0.1: [0.01, 0.12]
	0.2: [0.01, 0.13]	0.2: [0.01, 0.15]	0.2: [0.00, 0.03]	0.2: [0.00, 0.05]	0.2: [0.01, 0.11]
	0.3: [0.01, 0.12]	0.3: [0.01, 0.14]	0.3: [0.00, 0.02]	0.3: [0.00, 0.04]	0.3: [0.02, 0.09]
	0.4: [0.01, 0.11]	0.4: [0.02, 0.12]	0.4: [0.00, 0.02]	0.4: [0.00, 0.04]	0.4: [0.02, 0.08]
	0.5: [0.02, 0.09]	0.5: [0.02, 0.11]	0.5: [0.00, 0.02]	0.5: [0.00, 0.03]	0.5: [0.02, 0.07]
	0.6: [0.02, 0.08]	0.6: [0.03, 0.10]	0.6: [0.00, 0.02]	0.6: [0.01, 0.03]	0.6: [0.02, 0.07]
	0.7: [0.03, 0.07]	0.7: [0.04, 0.09]	0.7: [0.00, 0.01]	0.7: [0.01, 0.02]	0.7: [0.03, 0.06]
	0.8: [0.03, 0.06]	0.8: [0.04, 0.08]	0.8: [0.01, 0.01]	0.8: [0.01, 0.02]	0.8: [0.03, 0.05]
	0.9: [0.04, 0.05]	0.9: [0.05, 0.07]	0.9: [0.01, 0.01]	0.9: [0.01, 0.02]	0.9: [0.04, 0.05]
	1.0: [0.05, 0.05]	1.0: [0.06, 0.06]	1.0: [0.01, 0.01]	1.0: [0.01, 0.01]	1.0: [0.04, 0.04]

normalized using fuzzy distributive normalization. The results are summarized in Table 5.

Subsequently, the fuzzy weighted scores of all smart and automation technology applications, in terms of α cuts, were calculated based on the derived fuzzy priorities. The results are summarized in Table 6.

Based on the fuzzy weighted scores, fuzzy ideal point and fuzzy anti-ideal point were defined, as shown in Table 7. Subsequently, the distances from each smart and automation technology application to the two reference points were measured, respectively. The results are summarized in Table 8.

Finally, the fuzzy closeness of each smart and automation technology application was derived. The results are shown in Table 9.

Subsequently, COG was applied to defuzzify the fuzzy closeness of each smart and automation technology application. The results are summarized in Table 10.

According to the experimental results:

1. There was significant difference between the overall performances of suitable and unsuitable smart and automation technology applications.
2. Among the four smart and automation technology applications, "remote control of machines" achieved the highest overall performance, which was obviously due to its high effectiveness for preventing the spread of COVID-19 and high acceptability to workers.

3. In contrast, "monitoring workers' health with smart wristbands" was considered the least suitable, owing to its low effectiveness for preventing the spread of COVID-19.
4. For comparison, two existing methods, FGM-FWA and fuzzy ordered weighted average (fuzzy OWA), were also applied to compare these smart and automation technology applications. In FGM-FWA, the fuzzy priorities of criteria were approximated using FGM. Then, FWA was applied to assess the overall performance of each smart and automation technology application. In fuzzy OWA, the moderately optimistic strategy was adopted. The ranking results obtained using various methods are compared in Fig. 8. Obviously, the ranking result using the proposed methodology was somewhat different from those using existing methods. Existing methods estimated, rather than derived, the fuzzy priorities of critical factors, which led to incorrect decisions.
5. The proposed methodology can be implemented in the following industrial applications. Factory managers can apply the proposed methodology to select suitable smart and automation technology applications, plan the required budget, and make purchases. In addition, if the budget is limited, the limited budget can also be allocated effectively based on the conclusions of this study.

Table 8 Distances between each smart and automation technology application and the two reference points

q	$\widetilde{d_q^+}$ (α:α cut)	$\widetilde{d_q^-}$ (α:α cut)
1	0.0: [0.00, 0.55]	0.0: [0.00, 0.55]
	0.1: [0.00, 0.50]	0.1: [0.00, 0.52]
	0.2: [0.00, 0.44]	0.2: [0.02, 0.49]
	0.3: [0.00, 0.40]	0.3: [0.05, 0.45]
	0.4: [0.00, 0.35]	0.4: [0.08, 0.42]
	0.5: [0.01, 0.30]	0.5: [0.11, 0.39]
	0.6: [0.02, 0.25]	0.6: [0.13, 0.36]
	0.7: [0.03, 0.21]	0.7: [0.16, 0.33]
	0.8: [0.04, 0.17]	0.8: [0.19, 0.30]
	0.9: [0.06, 0.13]	0.9: [0.22, 0.28]
	1.0: [0.09, 0.09]	1.0: [0.25, 0.25]
2	0.0: [0.00, 0.60]	0.0: [0.00, 0.52]
	0.1: [0.00, 0.56]	0.1: [0.00, 0.47]
	0.2: [0.02, 0.52]	0.2: [0.00, 0.43]
	0.3: [0.05, 0.47]	0.3: [0.00, 0.39]
	0.4: [0.08, 0.43]	0.4: [0.00, 0.35]
	0.5: [0.11, 0.39]	0.5: [0.02, 0.32]
	0.6: [0.13, 0.36]	0.6: [0.04, 0.28]
	0.7: [0.16, 0.32]	0.7: [0.07, 0.25]
	0.8: [0.19, 0.29]	0.8: [0.10, 0.21]
	0.9: [0.21, 0.26]	0.9: [0.13, 0.18]
	1.0: [0.24, 0.24]	1.0: [0.15, 0.15]
3	0.0: [0.00, 0.56]	0.0: [0.00, 0.57]
	0.1: [0.00, 0.51]	0.1: [0.00, 0.52]
	0.2: [0.00, 0.46]	0.2: [0.00, 0.48]
	0.3: [0.00, 0.41]	0.3: [0.01, 0.44]
	0.4: [0.00, 0.37]	0.4: [0.03, 0.41]
	0.5: [0.00, 0.32]	0.5: [0.06, 0.37]
	0.6: [0.00, 0.27]	0.6: [0.08, 0.33]
	0.7: [0.00, 0.23]	0.7: [0.11, 0.30]
	0.8: [0.02, 0.19]	0.8: [0.14, 0.26]
	0.9: [0.05, 0.14]	0.9: [0.17, 0.23]
	1.0: [0.10, 0.10]	1.0: [0.20, 0.20]
4	0.0: [0.00, 0.56]	0.0: [0.00, 0.51]
	0.1: [0.00, 0.51]	0.1: [0.00, 0.48]
	0.2: [0.00, 0.46]	0.2: [0.02, 0.45]
	0.3: [0.00, 0.42]	0.3: [0.05, 0.42]
	0.4: [0.00, 0.37]	0.4: [0.08, 0.39]
	0.5: [0.02, 0.33]	0.5: [0.11, 0.37]
	0.6: [0.04, 0.29]	0.6: [0.13, 0.34]
	0.7: [0.07, 0.25]	0.7: [0.16, 0.31]
	0.8: [0.09, 0.21]	0.8: [0.19, 0.29]
	0.9: [0.12, 0.17]	0.9: [0.21, 0.26]
	1.0: [0.14, 0.14]	1.0: [0.24, 0.24]

Table 9 Fuzzy closeness of each smart and automation technology application

q	$\widetilde{C_q}$ (α:α cut)
1	0.0: [0.00, 1.00]
	0.1: [0.00, 1.00]
	0.2: [0.05, 1.00]
	0.3: [0.12, 1.00]
	0.4: [0.19, 1.00]
	0.5: [0.26, 0.98]
	0.6: [0.34, 0.95]
	0.7: [0.43, 0.92]
	0.8: [0.53, 0.88]
	0.9: [0.63, 0.81]
	1.0: [0.73, 0.73]
2	0.0: [0.00, 1.00]
	0.1: [0.00, 1.00]
	0.2: [0.00, 0.95]
	0.3: [0.00, 0.88]
	0.4: [0.00, 0.82]
	0.5: [0.04, 0.75]
	0.6: [0.11, 0.68]
	0.7: [0.18, 0.61]
	0.8: [0.25, 0.54]
	0.9: [0.32, 0.46]
	1.0: [0.39, 0.39]
3	0.0: [0.00, 1.00]
	0.1: [0.00, 1.00]
	0.2: [0.00, 1.00]
	0.3: [0.02, 1.00]
	0.4: [0.08, 1.00]
	0.5: [0.15, 1.00]
	0.6: [0.23, 1.00]
	0.7: [0.32, 1.00]
	0.8: [0.42, 0.94]
	0.9: [0.54, 0.81]
	1.0: [0.66, 0.66]
4	0.0: [0.00, 1.00]
	0.1: [0.00, 1.00]
	0.2: [0.05, 1.00]
	0.3: [0.11, 1.00]
	0.4: [0.18, 1.00]
	0.5: [0.24, 0.96]
	0.6: [0.32, 0.89]
	0.7: [0.39, 0.83]
	0.8: [0.47, 0.76]
	0.9: [0.55, 0.69]
	1.0: [0.62, 0.62]

5 Conclusions

The COVID-19 pandemic has severely impacted factories all over the world. Ensuring the long-term operation of a factory amid the COVID-19 pandemic becomes an urgent issue. To address this issue, the application of smart and automation technologies has been considered as a viable means. For this reason, a systematic mechanism is needed to assist factories in selecting the most suitable smart and automation technology application amid the COVID-19 pandemic. For this purpose, the evolving fuzzy approach is proposed in this study. In the proposed

Table 10 Defuzzification results

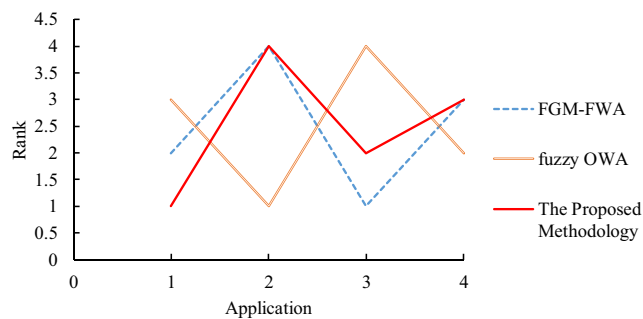| q	Defuzzified closeness
1	0.668
2	0.403
3	0.627
4	0.603

Fig. 8 Comparison of the ranking results using various methods

methodology, ACO-FAHP is first used to derive the priorities of critical factors found after reviewing the related literature and practices. To enhance the computational efficiency of ACO, a GA is also designed. Subsequently, FTOPSIS is applied to evaluate the overall performance of each smart and automation technology application in optimizing all critical factors. Finally, the top-performing smart and automation technology application is the most suitable application and will be recommended to the factory.

The proposed methodology has been applied to compare four possible smart and automation technology applications for a factory to illustrate its applicability. After analyzing the experimental results, the following conclusions were drawn:

1. The most important critical factor for ensuring the long-term operation of the factory was "high effectiveness for preventing the spread of COVID-19".
2. "Remote control of machines" was evaluated as the most suitable smart and automation technology application, followed by "providing workers with smart PPE," to the factory manager.
3. The ranking result using the proposed methodology was different from those using several existing methods, because existing methods did not derive the exact priorities of critical factors.

The contribution of this study includes the following:

(1) Several smart and automation technology applications to ensure the long-term operation of a factory amid the COVID-19 pandemic have been proposed.
(2) A systematic and quantitative procedure was established for comparing these smart and automation technology applications amid the COVID-19 pandemic.

It is difficult to know for how long the COVID-19 pandemic will last. Therefore, the same analysis needs to be performed again to see whether the experimental results obtained in this study are still applicable.

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