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IoT-based application for construction site safety monitoring

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ABSTRACT

Hong Kong construction safety has witnessed substantial improvement in the last three decades, however, accidents still occur frequently as more than 4,000 accidents are reported in the year 2017. Against this background, this research, firstly, aims to investigate the effectiveness of safety training for construction personnel in Hong Kong. A questionnaire is designed to explore the efficacy and weaknesses of mandatory basic safety training. The results indicate the inadequate knowledge of the concept of personal protective equipment as the main weakness of the workers. Secondly, to overcome the training weakness, an Internet-of-Things (IoT) based innovative safety model is designed to provide real-time monitoring of construction site personnel and environment. The proposed model not only identifies real-time personnel safety problems, i.e., near misses, to reduce the accident rates but also stores the digital data to improve future training and system itself. The proposed model in this research provides a cost-effective solution for optimal construction safety to the stakeholders. A cost comparison analysis suggests that the IoT system can provide 1) 78% cost-savings with respect to the traditional manual system and 2) 65% cost-savings with respect to the traditional sensor system.

KEYWORDS

Construction safety; safety training; internet of things; site accidents; Hong Kong; safety management system; IoT

Introduction

The linkage between the construction industry and economic competitiveness has been well-established through empirical evidence (Giang and Pheng 2011; Dlamini 2012). Governments worldwide have used construction investment as a tool to stabilize the country's economy, further reinforcing the position of the construction industry in the national development policy (Giang and Pheng 2011). In fact, global construction-related spending represents 13% of the global GDP (McKinsey Global Institute 2017). Despite the pivotal role in the economy, it is also a bitter reality that the construction industry is widely considered as one of the hazardous industries due to the high rate of accidents causing injuries, occupational diseases, and even deaths (Zhang et al. 2017). For example, in China, the death toll due to construction accidents averaged above 2500 annually from 1997 to 2014 (Guo et al. 2017). Besides developing countries, 20% of the overall industrial accidents in Japan, South Korea, and Hong Kong, from 1996 to 2005, were related to the construction industry (Poon et al. 2008). In this sense, one of the most vulnerable related construction trades, if not the only endangered, are construction workers (Zhang et al. 2020). Considering the essence of this group for propelling the construction projects, more and more researchers are becoming motivated to promote the safety and health of construction workers (Ayhan and Tokdemir 2019). Despite this, the figure for construction mutilated workers has not experienced a tangible downward trend in many countries, that even include some developed countries from where the idea of zero-accident construction site originates (Mohandes et al. 2020). In accordance with a recent report, the construction industry makes up approximately 20 percent of the total proportions of accidents reported in Europe and the US, illustrating the perilousness of this industry for the workers involved in the associated activities (Ayhan et al. 2020).

In Hong Kong, construction projects value over 9.4% of the GDP (Census and Statistics Department 2017) with more than 0.7 million workers are involved (CIC 2017). Given the hazardous nature of the construction workplace environment and the risks exposed to such a large workforce, construction safety has become a matter of serious concern in Hong Kong. As a mitigation measure since the 1990s, firstly, the Labour Department and registered public sector institutions, and other large construction companies have started providing mandatory basic safety training to the workers and site staff. Secondly, regular seminars, exhibitions, and promotional campaigns are being conducted to raise awareness about Environment, Health, and Safety (EHS) among stakeholders. Thirdly, substantial resources are being put into day-to-day on-site construction operations, especially by well-known building services companies, to ensure the effective application of EHS safety factors among frontline workers, engineers, and the site management staff (Choudhry et al. 2008a).

In the late 1980s and early 1990s, construction site safety in Hong Kong was far from being satisfactory i.e., twice than the figure obtained for the USA in the same years and 25 times higher than Japan and Singapore (Chan and Tam 1999). 374 accidents per 1000 workers were reported annually in 1989 (Robson 1999). Drastic improvements have been observed after three decades of stakeholders' efforts, with the rate falling to 32.9 accidents per 1000 workers in 2017 (Hong Kong Housing Authority 2019). Despite the positive change, safety hazards and fatal incidents, nevertheless, are recorded each year. For example, the Labour Department of Hong Kong reported 4,114 construction accidents in 2017. Out of overall industrial fatalities, around 22% were construction-related (Labour Department 2017).

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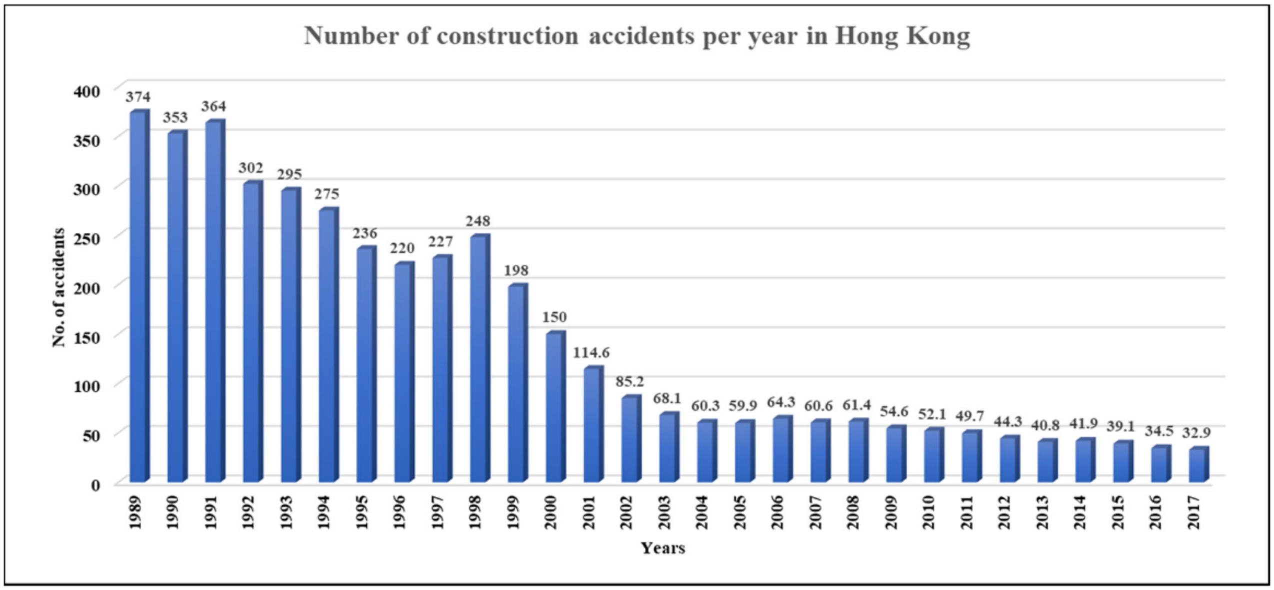

Figure 1. Accidental rate of Hong Kong construction industry (Source: Hong Kong Housing Authority, 2019).

Figure 1 depicts a continuous decrease in accident rates over time, however, the safety risk levels in the Hong Kong construction industry are still worth considerations and a massive improvement is required to reduce site accidents through effective and innovative means.

Past research has indicated that the causes of construction accidents vary considerably but falling from height is the most common cause. Tam et al. (2001) classified the reasons behind 'falls from height' into four categories, namely planning error, routine violations, hidden hazards created by other parties, and poor crew resource management. According to the Labour Department of Hong Kong, around 25% of the fatal industrial accidents were caused by falls from height (Labour Department 2017). Moreover, construction accidents also occur due to lifting materials, tripping on the same level, and mishaps by contact with moving machinery. Traditionally, safety training is regarded as the most significant and low-cost technique to minimize construction accident rates. Such pieces of training not only serve as a means to enhance the safety knowledge of site personals but also as a purposeful reminder of the importance of safety. Previous studies have explicitly discussed the importance of safety training as an effective way to reduce the risks of construction accidents such as Tam et al. (2001); Wong et al. (2016); Choudhry et al. (2008b); Enshassi et al. (2016) and so on. Cunningham et al. (2018) and Başağa et al. (2018) reported less absenteeism among the workers with the declination in occurrences of fatal- or non-fatal accidents on construction sites. Thus, the related construction activities can be performed in a more focused way (which results from reduced injuries), leading to delivering high-quality products and finishes for end-users Başağa et al. (2018).

In Hong Kong, four types of training are provided to the construction workers and site staff. The first type is Mandatory Basic Safety Training (Green Card Safety Training) which has come into operation in 2001 (Labour Department 2019). It is a one-day training course that focuses on the local ordinance and personal protective equipment (PPE) for all types of site personnel. Under section 6BA(2) of the Factories and Industrial Undertakings Ordinance, Chapter 59, the participants are awarded a green card with a 1 to 3 years validity period (Labour Department 2019). The cardholder has to renew the green card before its expiration. Coverage of the ordinance include factories, construction sites, cargo and container handling, repair workshops, and other industrial workshops. The second type is designed for special workers such as gantry crane operators (duration = 10days), skilled metalworkers (duration = 18–42hrs), forklift truck operators (duration = 7 days), and confined space operators (duration = 8hrs). The third type is composed of a half-day site safety induction and toolbox training, tailor-made for individual construction sites. The content covers the location of the first aid room, vehicle logistics, storage room for dangerous goods, etc. This type of training is a part of the Pay-for-Safety Scheme and a prerequisite for some construction projects. The fourth type is special training (duration = 12hrs approx.) designed by the main contractors to illustrate in-house rules and other particulars not covered by the other types of training e.g., handling 110 V portable tools, wearing a helmet belt, prohibiting the use of a ladder, and bamboo scaffolding.

All these four safety trainings expect different outcomes and therefore, the time duration for each is different. However, several researchers in the past argued that the training hours and work experience are not directly correlated to construction safety such as Perlman et al. (2014) and Chan et al. (2020). The former did not find any correlation between hours of safety training and work experience and between hazard identification and perception skills. Whereas, the latter, only found an indirect impact of working experience on the accidents among building maintenance workers. In addition, the contents of the four types of training are sometimes overlapping. Part of the training modules can be easily understood through common sense. Those types of modules were useful for site personals of the past due to their low educational backgrounds. Nowadays, more educated individuals enter the construction industry owing to attractive salary packages (Census and Statistics Department 2016, 2020b). These individuals usually have common know-how of safety-related issues covered by the training. This makes traditional training less useful and the development of effective safety promotion has gained importance. In addition to this, the current work culture in the industry is also a big hurdle in safety promotion. On the one hand, contractors are usually focused more on the time, cost, and quality, and sometimes put safety in a low priority list. For example, metal scaffolding is considered a safer option but due to the amount of time and money spent on installation and removal, many contractors prefer bamboo scaffolding (Fang et al. 2003). On the other hand, construction laborers are typically reluctant to wear life-rope as it lessens the efficiency of installation works. In Hong Kong, the most efficient monitoring method to check PPE on each worker is to install guard booth scanners at the entrance of construction sites; workers without PPE are rejected to enter the site. Another monitoring method is the safety supervisor's routine site walk and penalty to the worker not using PPE properly. Since the area of most construction sites in Hong Kong is large typically a hundred thousand square feet with more than 30+ floors, main contractors and sub-contractors do not hire sufficient safety supervisors to conduct real-time monitoring to all areas in each site. Moreover, some workers abandon the use of PPE during the absence of safety supervisors due to various reasons such as peer pressure, hot weather, carelessness, etc.

To overcome the loopholes in safety monitoring, the objective of IoT model design is to ensure that every worker in the specified area must carry PPE and also to trigger alarms in the site office in case of improper use for real-time monitoring. Additionally, the data collected from the system can be stored in a database automatically instead of a paper record from the site safety supervisors. The data can be utilized for future betterments in safety training course designs as well as the IoT system itself. In regards to the real-life IoT implementation, the Hong Kong Convention and Exhibition Centre (HKCEC) upgraded its Building Management System (BMS) in 2017 to include an IoT network for the collection of data on temperature, humidity, water leakage, and internal air quality. Over 500 IoT sensors were installed and connected to a wireless IoT gateway. It was a major IoT project in Hong Kong that addressed a number of installations constraints, cost, and IoT-sensors effectiveness issues. Conceptualizing from the HKCEC IoT system, the current research examined its application in the improvement of construction site safety and proposed an innovative design model of the real-time safety monitoring system using IoT technology with sensor recommendation. With LoRa protocol and existing Class A type of wireless sensors, the system performs real-time data collection from the construction site, generates instant alerts to safety officers, and compiles data for further safety training modifications.

Several systems have been proposed in the past using heavy equipment that improves safety performance. These systems have incorporated sensors, robotics, laser scanning, and data management (Skibniewski 2014; Kanan et al. 2018). IoT is rapidly becoming a new trend offering major benefits to the construction industry. For example, Zhong et al. (2017) introduced a multidimensional IoT enabled platform for real-time achievability and traceability for the whole processes in prefabricated construction. Lee et al. (2009) developed a safety management system for detecting falling objects using different types of sensors. Wu et al. (2010) established a real-time solution for near-miss accidents. Lower cost, higher safety, and smarter designs are some of the benefits that favor IoT in comparison to the other advanced safety systems (Kanan et al. 2018). Woodhead et al. (2018) reported that the construction industry needs to transform itself from a low-tech labor extensive industry into a high-tech capital intensive industry to increase the productivity and profit margin. IoT provides the decision-making ability and emergent needs through the availability of information from sensors that will pave the way for such transformation (Woodhead et al. 2018). In this regard, our study has made a step forward by purposing a cost-effective IoT design model for construction safety in Hong Kong. All the required network equipment, internet services, sensors, servers, and workstations can be easily purchased in local markets. Besides, skilled solution providers can also be found with ease to supply, install, and commission services in accordance with the IoT model design. The major objectives of this research are: 1) to verify the effectiveness of current safety training, 2) to develop an innovative construction site monitoring model using IoT technology, and 3) to verify the cost effectiveness of the system.

Literature review on safety issues

The literature on safety issues is vast due to the continuous interest of researchers. 'Improvement of safety performance', 'safety effectiveness measurements', and 'innovative approaches for safety training' and 'innovative approaches for safety monitoring' are the most active areas in the safety arena, which are discussed in detail in the following lines.

Improvement of safety performance

Sunindijo et al. (2017) identified 4 areas conducive to the improvement of safety performance in the construction industry: 1) quantitative study for experienced construction practitioners, 2) learning-in-practice and interaction with people and machinery at work, 3) skill development methods to enrich the workers' safety knowledge, and 4) universities involvement to improve the safety learning process. While the basic safety training fulfills the minimum regulatory requirements, they argued that additional processes such as information exchange are also important to the enhancement of safety knowledge and awareness.

Cultural and language issues are also important factors to be considered in designing training modules. To gauge such issues, Harvey et al. (2001) conducted two surveys, one immediately after a safety training and another 16 months later. The results showed that training effectiveness varies with the participants' cultural backgrounds. They further discussed the feasibility of changing training design to suit different cultures and established that the modules matching with the cultural background of employees yield optimal results. Demirkesen and Arditi (2015) also pointed towards the challenges in safety training arising from language differences among workers.

Tam et al. (2004) examined the manual safety approaches in China and identified that the improper behavior of contractors such as lack of provision of PPEs and inadequate training programs make such approaches ineffective. 'Poor safety awareness of top management', 'lack of training', 'poor safety awareness of project managers', 'reluctance to input resources to safety', and 'reckless operations' were found to be the main factors affecting safety performance. Other popular studies on manual safety systems include Hale et al. (1997), Jaselskis et al. (1996), and Tam et al. (2001). Besides, behavioral-based safety approaches that focus on the carelessness and conscious/unconscious unsafe behavior of the workers were also given due attention in the literature such as Frederick and Lessin (2000), Lipscomb et al. (2015), and Wirth and Sigurdsson (2008).

Safety effectiveness measurements

The safety performance of construction projects can be said to have fully been blossomed if proper Safety Management System (SMS) is taken into account within different layers of the respective organization. SMS was introduced in the Singaporean construction industry around three decades ago, but no significant improvements in safety standards were visible. To fill this gap, Teo and Ling (2006) conducted research with 15 steps consisting of surveys, safety expert's consultation, interviews, and workshops. They attempted to work out a multi-attribute value model subjected to the validation via site-audits for boosting safety standards and to calculate Construction Safety Index (CSI) to gauge safety effectiveness for management purposes at various sites.

Ricci et al. (2016) proposed a method of effectiveness measurement by employing training using a questionnaire, practical tests, on-job reservation, physiological data, and documentary databases. In total, 28 studies were included in the meta-analysis to calculate the effect-size of training efficiency based on 44 measures. It was found that the training effects were reduced significantly 3 months after the training.

Innovative approaches for safety training

One viable solution to come up with appropriate and prudent safety measures for the sake of improving construction site safety is through the exploitation of up-to-date technologies and equipment. In this regard, the utilization of BIM has made a giant leap towards improving the occupational health and safety of construction crew members. Considering this, a BIM-enabled safety training method was proposed by Clevenger et al. (2015) which included the 3 D-visualisations environment and interactive features for trainees. Feedback from participants was hugely positive, with the computer models were being commended as an attractive feature making the training more interesting. This research paved the way for the replacement of traditional paper, slide, and video teaching methods in safety training by advanced computing technology. Zolfagharian et al. (2014) proposed an automated safety plug-in to mitigate site accidents for scheduling software.

Sacks et al. (2013) identified the importance of Virtual Reality (VR) training as a tool to engage the attention and concentration of trainees. The method was incorporated into the compulsory site entry training program of one of Hong Kong's large-scale construction companies but with a larger group size of 20–30 as opposed to the proposal of a small group of 10–20 in the research. In Hong Kong, only a few developers/contractors provide the VR training to engineers and site supervisors due to the high fixed cost (such as equipment and the corresponding software) and the running cost (maintenance and the wages for the trainers) relative to the traditional training.

For Internet-of-Things (IoT) application, Jiang et al. (2013) explored the idea of a wireless network for site safety surveillance systems based on IoT. WIFI LAN was proposed to connect various field equipment such as digital cameras, smoke detector, and other kinds of the sensor. Although the issue of field device (power supply, mobility, battery life, and size) was not tackled, applying IoT to construction site safety was an innovative idea.

Innovative approaches for safety monitoring

Yang et al. (2012) proposed an early-stage design of a safety identification system to improve the performance of proactive safety monitoring. Radio-frequency identification (RFID) and Wireless Sensor Network (WSN) was introduced in the access control over heavy equipment (such as tower cranes and fork-lift truck), material usage and restricted area. This method applied the RFID reader and Zigbee protocols to the daily operation of the construction sites for monitoring site safety and for gathering and analyzing data for future safety plan designs. However, the technological limitations of the processor's power, bandwidth, and hardware especially the size and battery life imposed constraints on the type, complexity, and quantity of data collection.

Augustin et al. (2016) provided a detailed evaluation of the LoRa protocol consisted of modulation, effective data rate, spreading factor, sensor application, and sensitivity, frame format, etc. A field test was conducted to verify the performance of LoRa coverage in the suburban area. The characteristics of the LoRa network made IoT application suitable for safety monitoring provided the constraints related to the battery be tackled properly.

Kanan et al. (2018) established a safety monitoring system to operate, in the 868 MHz radiofrequency, with GRPS and wearable devices to secure the hazardous areas such as at the back of the vehicle's rear end and to provide smart alerts for real-time avoidance of potential danger. IoT platform was introduced as the middleware to connect with the cloud server for data collection and analytics. Thanks to the advanced hardware production technology, battery life, and RF wake-up sensor application, wearable devices could be deployed and integrated seamlessly into the construction site with relatively low fixing and running costs. Nonetheless, the IoT platform was semi-mature and the performance was subjected to the limited bandwidth, sensor type, and support. Park and Brilakis (2012) used computer vision wireless sensing technology for monitoring whether the construction workers have worn the specified personal protective equipment or not. Ray and Teizer (2012) and Seo et al. (2013) came up with three-dimensional motion information for detecting the postures of workers, leading to improving the musculoskeletal-related safety hazards menacing the workers involved in particular construction activity. Yang et al. (2010) developed a tracking scheme using cameras to track multiple workers being embroiled in particular construction activity. The developed scheme was based on an online color model learning in conjunction with Kernel covariance tracking.

Using the concept of IoT, Yang et al. (2020) developed a personal protective equipment-detection-based tool to ensure the relative workers are provided with appropriate PPE before the commencement of particular construction activities. In another study, a protective-IoT-based system for automatically monitoring, localizing, and warning construction workers working in perilous areas was developed by Kanan et al. (2018).

Knowledge gap and point of departure

The former researches are focused on the feasibility test of the IoT equipment with no mass production and locally available sensors are involved. This paper has made use of sensors that are easily available in the Hong Kong market. The cost of such sensors is typically low because of the rapid market competition in the building management system (BMS). This study provides a comprehensive cost-effective safety monitoring system, in comparison with the traditional wiring monitoring system, with easy-to-install and easy-to-learn features as most of the interfaces are web-based. More importantly, this research aims to grapple with the stagnant and inactive training practices that are rampant in

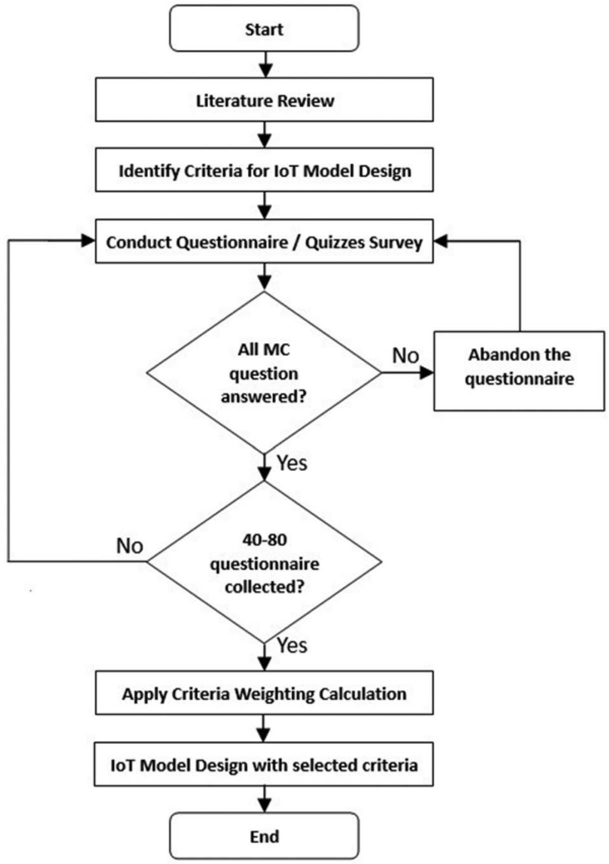

Figure 2. Research methodology.

the construction industry by incorporating the idea of IoT into such procedures. As far as traditional training practices are concerned, a number of serious shortcomings exist, including the inability to perceive the trainee's safety performance in a real environment, and lack of existence of a feedback system for both the trainer and trainee to rectify their performances immediately, to name but a few (Teizer et al. 2013). Unraveling ways to alleviate these shortcomings have given impetus to the authors of this paper for coming up with a conceptualized IoT-based framework for enhancing the status quo training practices. This research has also performed a cost analysis of the system in comparison with traditional systems to provide a more practical safety solution. Such a cost comparison is rarely reported in the previous literature.

Research methodology

In order to achieve the research objectives, firstly, a brief literature review was conducted to illustrate different research approaches to safety performance, measurements, and the application of IoT technology in the construction industry. Secondly, a questionnaire survey was conducted to verify the relationship between the effectiveness of safety training and safety consciousness. The results of the questionnaire offered the basis for the further IoT system design to enhance the safety monitoring performance and safety training content modification. Ten selected questions were extracted from the examination questions of mandatory basic safety training course in Hong Kong. Each question referred to a particular category of construction site work such as electrical installation work, high-level work, toxic material, and transportation, etc. The aim was to find out the knowledge of workers after a certain period of training (0 to 3 years, same as the validation period of Green Card). The target respondents were construction workers such as engineers, supervisors, and frontline workers exposed to the risk of accidents at the site. Survey samples among workers were picked up randomly on different construction sites of company A, however, prior approval was taken from the company to administer the survey. A sample validity check was made through the background information collected from the respondents. 75 questionnaires were distributed among different teams of company A and 15 minutes were given to fill the survey. Thirdly, relative weight calculation similar to that of AHP (analytical hierarchy process) was then conducted for the first part questionnaire results of the completed surveys to define the majority of the respondents. This was later mapped with the multiple-choice correction rates to find out the question with the lowest average score, which was the criterion selected to apply IoT design. Fourthly, in comparison with the available IoT products and network topology, a new IoT safety monitoring system design was proposed to provide real-time on-site monitoring to enhance the capacity of safety officer and project management staff with complete logging. Figure 2 shows an overview of the research methodology.

Questionnaire survey and data collection

A questionnaire survey was conducted to gauge the degree of safety knowledge of the respondents. The questionnaire consisted 2 parts: the first part collected the background information of respondents, such as age group, working experience, and their self-perception of personal attitude towards safety in the construction industry (see Table 1); the 2nd part included 10 multiple-choice questions (with four possible answers) on safety from the mandatory basic safety training or green card training examination (see Table 2). The questions were taken from the mandatory basic safety training course distributed by the Hong Kong safety training association published in 2018. The course material has 8 sections that focus on general safety concepts, relevant legislation, safety hazards, and preventive measures. As a requirement, the workers should be familiar with the course content and description. Therefore, questions were prepared from the material considering comments from experts from the industry. Care has been taken to cover all parts of the course, thus, each section was given representation.

The questionnaire was distributed by email to various departments of company A beforehand which then distribute it to the workers by hand on the day of the test. Care has been taken 1) to avoid cheating and handover the questionnaire back within the allocated 15 minutes' time limit and 2) in confirming that all the survey respondents had passed the mandatory basic safety training and learned all the corresponding knowledge covered in the multiple-choice questions. There was no requirement concerning the work experience of respondents except that they had to be holders of a valid green card. Since all the workers held the green card holders, they were expected to have sufficient knowledge of safety issues at the site. In total, 75 questionnaires were distributed and 74 completed questionnaires were received (98.6% response rate). The respondents' occupations varied, spanning project managers, project engineers, site engineers, technicians, and safety department staff.

Table 1. Background information questions.

Questions	Selectable answers
1) Are you a careful person?	Strongly Disagree ☐ Disagree ☐ No Comments ☐ Agree ☐ Strongly Agree ☐
2) Do you agree that peer pressure is the strongest reason behind people refuse taking safety precautions?	Strongly Disagree ☐ Disagree ☐ No Comments ☐ Agree ☐ Strongly Agree ☐
3) How many times did you receive safety training in the past year?	0 ☐ 1 ☐ 2 ☐ 3 ☐ 4+ ☐
4) Do you think that the training was conducted frequently?	Strongly Disagree ☐ Disagree ☐ No Comments ☐ Agree ☐ Strongly Agree ☐
5) Do you think that the content of safety training allowed you to identify the potential hazard at your workplace?	Strongly Disagree ☐ Disagree ☐ No Comments ☐ Agree ☐ Strongly Agree ☐
6) Your age group?	16-25 ☐ 26-35 ☐ 36-45 ☐ 46-55 ☐ 56+ ☐
7) Your work experience in years?	0-4 ☐ 5-9 ☐ 10-14 ☐ 15-19 ☐ 20+ ☐
8) Your educational level?	Primary ☐ Secondary ☐ Dip/A.D. ☐ Tertiary ☐ Masters ☐

Table 2. Multiple choice quiz from mandatory basic training.

Questions
1) The concept of Personal Protection Equipment (PPE)
2) The concept of work at height (working platform requirement)
3) The knowledge of safety belt selection
4) The concept of firefighting
5) The concept of safety electrical equipment operation
6) The concept of safety of crane operation
7) The safety knowledge of working platform setup
8) The safety awareness of heavy material transportation
9) The responsibility of the government to the construction industry safety
10). The safety knowledge of working in a confined area

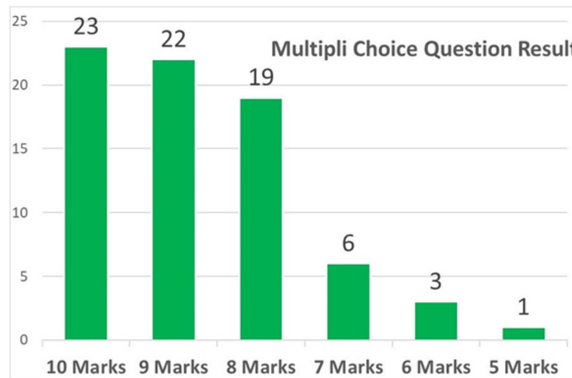

Figure 3. Multiple choice questions results.

Data analysis and weightage calculation

Multiple choice quiz results

Pass threshold for the MCQs part is taken from the green card training examination i.e., 60%. Each correct answer carried 1 mark. 64 out of 74 respondents i.e., 86.5% passed the MCQs test. Since no respondent was allowed to review the training materials before the quiz, the results confirmed that the performance of Green Card training is satisfactory. With reference to the criteria listed in Table 1, the average scores under different criteria are shown in figures (Figure 4–11). The distributions of answers of all respondents are shown in the pie charts and the corresponding average scores of the quiz are shown in the bar charts.

According to the figures below, light, medium, and heavyweight criteria were defined based on the average scores of the test. If results showed a clear and strong positive correlation (e.g., higher education level got higher average score), the category was identified as 'heavyweight group'. If the results did not depict any obvious (or ambiguous) correlation (e.g., self-proclaimed careful respondents did not correspond to any particular trends in score distribution), then the category in question was identified as 'lightweight group'. In the middle, groups from which partial correlation with scores was observed (e.g., those who 'Agreed' with the statement that training content is helpful earned higher scores, while those who 'Strongly Agreed' with the statement stood at a lower score level on a par with respondents who chose 'No Comment' or 'Disagree' as answer) were identified as 'medium weight group'. 2 criteria (Careful Person and Peer Pressure) were found to be lightweights, 3 (Training too much, training content help to identify the hazard and working experience) to be medium weights, and 3 (Training times, age group and education) were found to be heavyweights (Figure 3).

Lightweight categories

According to Figures 4 and 5 (left side), the majority of the respondents 'agreed' to the statements: 'are you a careful person?' and 'do you agree that peer pressure is the strongest reason behind people refuse taking safety precautions?'. However, according to their multiple-choice quiz results, no obvious correlation could be identified. Therefore, these 2 categories were defined as lightweight categories.

Medium weight categories

According to Figure 6, the majority of respondents 'agreed' with the statement that training is conducted too frequently, and their scores in the multiple-choice quiz were higher than those whose responses to the statement were 'no Comments', 'disagree' and 'Strongly Disagree'. Although those who stated 'Strongly Agree' also had lower scores, however, they were the minority respondents and therefore, had no significant impact on the final average score. Similar observations can be made for Figure 7. From Figure 8, although it seems that the working experience was not proportionate to the multiple-choice score, the results show that all groups have passed the examination (> =60%). Therefore, these three categories were identified as medium weight categories.

Heavyweight categories

According to Figures 9 and 10, respondents who possessed the highest level of education and the most frequent training gained the highest scores on the multiple-choice quiz; thus the scoring trends went in proportion to the level of education and frequency of training. A similar correlation existed between age groups and quiz results (Figure 11). In total three categories were thus identified as a heavyweight.

Analytic hierarchy process

Besides the grouping of respondents and their total scores, the correction rate of each multiple-choice question is also a major factor in weighting to identify the weakest spot in construction

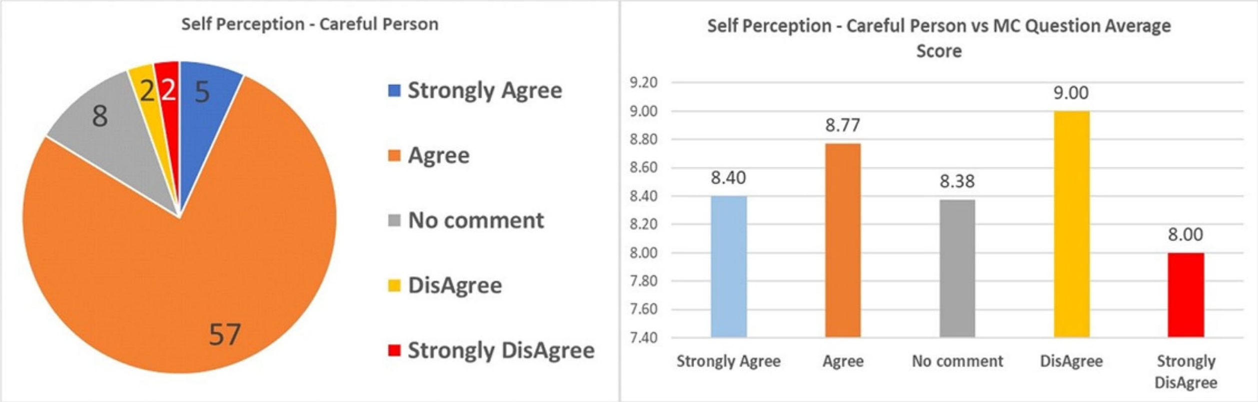

Figure 4. Respondent's self perception – careful person and quiz result of each group (light weight).

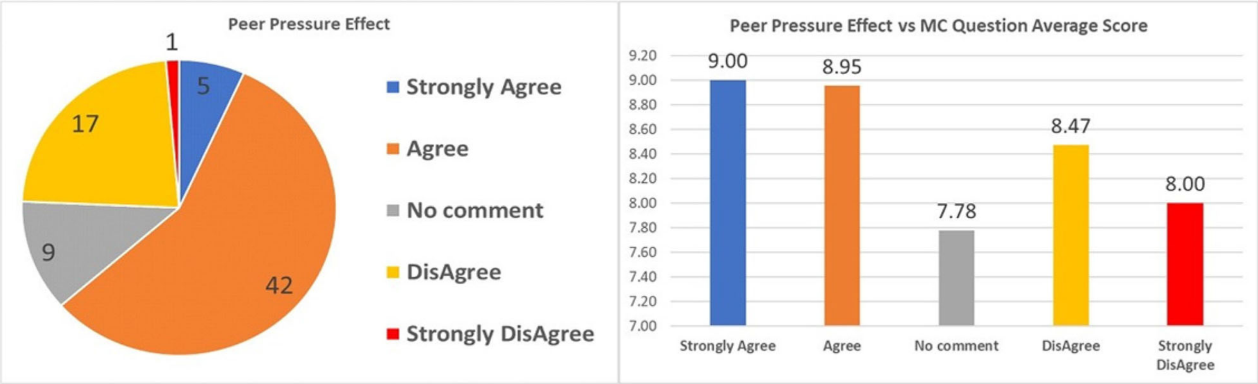

Figure 5. Respondent's perception of peer pressure and quiz result of each group (light weight).

Figure 6. Respondent's training frequency perception and quiz result of each group (medium weight).

site safety across 8 categories. Figure 12 shows the priorities and decision matrix of category selection using the Analytic Hierarchy Process (AHP). All categories underwent pairwise comparison with respect to the objective: Heavy categories were taken as '5', medium categories as '3', and light categories as '1'. After the calculation for determining the Eigenvectors of the matrix, priorities of individual categories are shown in the left part of Figure 13.

Calculations in Figure 12 were done following the AHP theory. Based on the correction rate of each question in the 2nd part of the questionnaire, an alternative method was applied to find out the behavior of respondents regarding their answers to each question in the 1st part. The alternative calculations were done by multiplying the following items:

- the correction rate of each 2nd part question,
- the ratio of each answer to each question in the 1st part questionnaire, and
- the weight ratio of each category.

As shown in Figure 13. This calculation was subjected to all questions in the questionnaire and found that the focus of the majority of respondents affected the final average score of each 2nd part question. Since each question in the 2nd part quiz corresponded to a category of safety in the construction industry, the final result (lowest average score) pinpointed the category with the weakest awareness. Therefore, the IoT safety system model design of this paper focused on that category.

Figure 7. Respondent's perception of training content and quiz result of each group (medium weight).

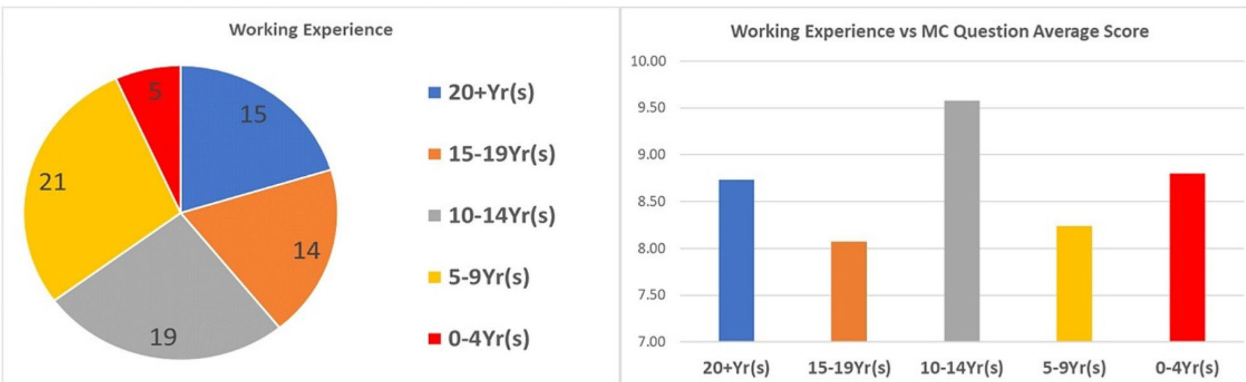

Figure 8. Respondent's working experience and quiz result of each group (medium weight).

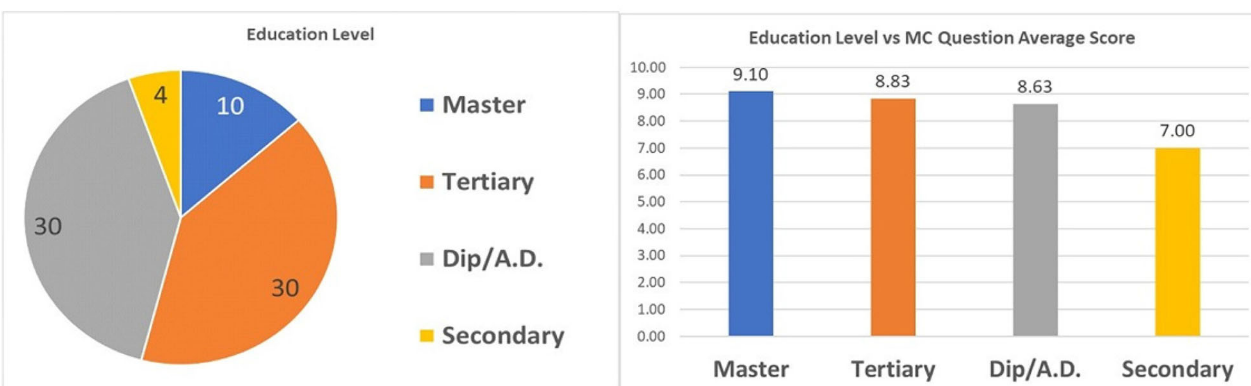

Figure 9. Respondent's education level and quiz result of each group (heavy weight).

Category selection calculation

Data pertaining to self-perception ('Are you a careful person?') as shown in Figure 4 is used here to demonstrate the calculation. The following figure shows the respondents' answers (from strongly disagree to strongly agree) and the correction rates of multiple-choice questions:

Step 1

The correction rate of MC Q1 = 60.00%

The weighting of category = 3.75% (from Figure 12)

The respondents who chose 'Strongly Agree' as answer = 5/74 = 6.76% (see Figure 14).

Step 2

The actual weight of MC 01 in regards to respondents who 'Strongly Agreed' with the self-perceived assumption and with the correct answer to MC 01:

$$60.00\% \text{ x } 3.75\% \text{ x } 5.76\% \;=\; 0.15\% \;(0.0015)$$

Calculated along the same lines, the actual weightings of MC 01 to MC 10 in Category 1 are listed in Figure 15.

Step 3

Repeat this calculation to all categories and 10 MC questions and sum up the value, the actual weight of each Multiple-choice question is given in Figure 16.

Figure 10. Respondent's training frequency within 1 year and quiz result of each group (heavy weight).

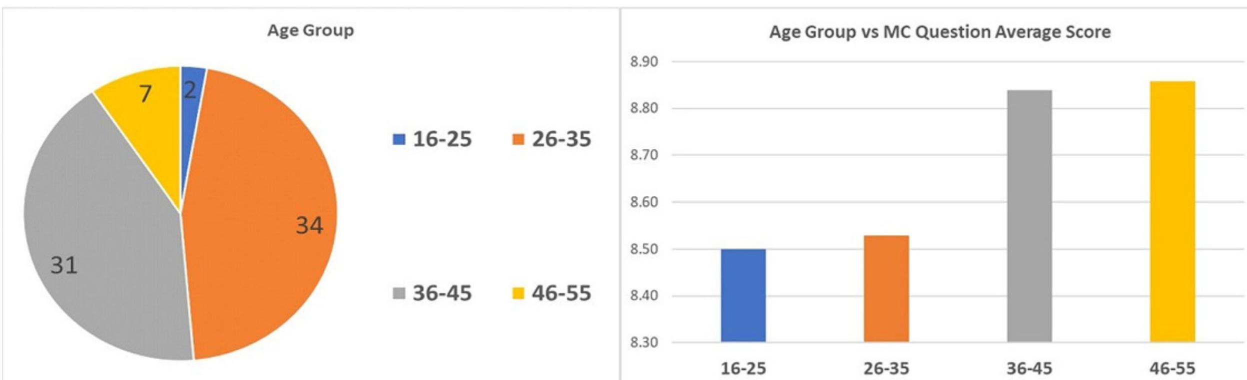

Figure 11. Respondent's age group and quiz result of each group (heavy weight).

Cat		Priority	Rank
1	Careful	3.7%	7
2	Peer Pressure	3.7%	7
3	Training Times	22.4%	1
4	Training Too Much?	10.5%	4
5	Content help identify hazard	10.5%	4
6	Age Group	20.0%	2
7	Working Experience	10.5%	4
8	Education	18.7%	3

	1	2	3	4	5	6	7	8
1	1	1.00	0.20	0.33	0.33	0.20	0.33	0.20
2	1.00	1	0.20	0.33	0.33	0.20	0.33	0.20
3	5.00	5.00	1	2.00	2.00	1.00	2.00	2.00
4	3.00	3.00	0.50	1	1.00	0.50	1.00	0.50
5	3.00	3.00	0.50	1.00	1	0.50	1.00	0.50
6	5.00	5.00	1.00	2.00	2.00	1	2.00	1.00
7	3.00	3.00	0.50	1.00	1.00	0.50	1	0.50
8	5.00	5.00	0.50	2.00	2.00	1.00	2.00	1

Figure 12. Priorities and decision matrix of category selection (Source: calculated using an online system managed by BPMSG, 2019).

Major observation on the lowest score to apply IoT design model

According to Figure 16, the multiple-choice question 1 (the concept of Personal Protection Equipment (PPE)) got the lowest score and the question 7 (the safety knowledge of working platform set up) got the 2nd lowest. According to the actual construction industry operation in Hong Kong, the working platform installation is regulated as per the Construction Site (Safety) Regulations to ensure the proper installation of high-level platform or scaffolding (Cap. 59, section 7, Labour Department). Only the trained workers are permitted to install the working platform, and the authorized person (AP) then issue the written permit to the installed working platform. It is not a major issue for all construction site workers but every worker who enters the construction site must wear the PPE and understand the usage of equipment. Therefore, the concept and knowledge of how to use the PPE is a major issue for all workers. The IoT model design thus focused on the category of question 1 i.e., the concept of Personal Protection Equipment (PPE).

Internet-of-things (IoT) model design

'IoT is a system of interrelated computing devices, mechanical and digital machines, objects, animals or people that are

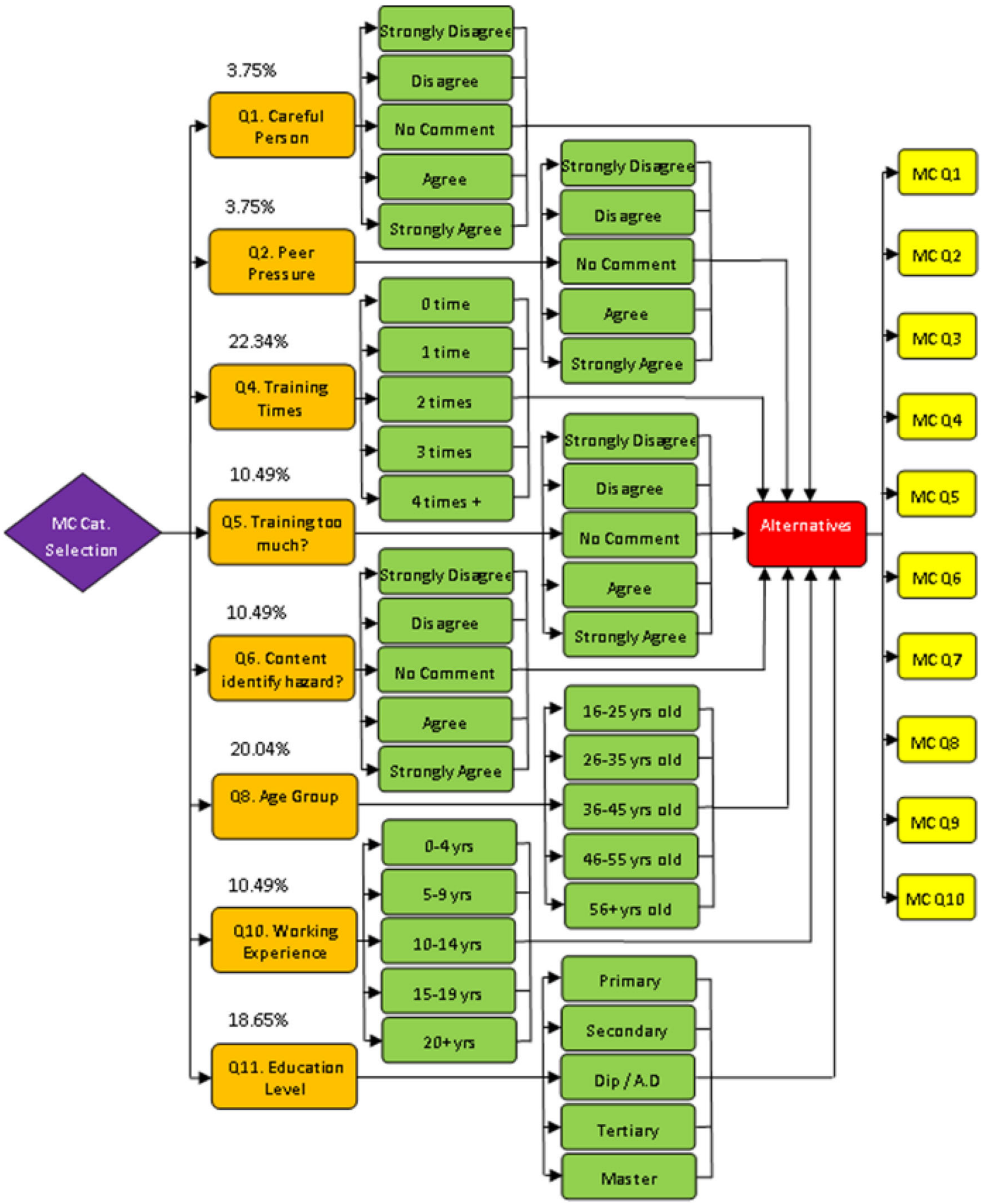

Figure 13. AHP components with weighting for category selection.

Weighting: 3.75%	Respondents'	Respondents'	Multiple-Choice Correction Rate									
Careful Person?	Reply	Reply (%)	MC Q1	MC Q2	MC Q3	MC Q4	MC Q5	MC Q6	MC Q7	MC Q8	MC Q9	MC Q10
Strongly Agree	5	6.76%	60.00%	100.00%	60.00%	80.00%	80.00%	80.00%	80.00%	100.00%	100.00%	100.00%
Agree	57	77.03%	63.16%	100.00%	89.47%	89.47%	98.25%	82.46%	71.93%	100.00%	98.25%	84.21%
No comment	8	10.81%	37.50%	100.00%	100.00%	87.50%	87.50%	87.50%	50.00%	100.00%	100.00%	87.50%
Disagree	2	2.70%	100.00%	100.00%	50.00%	50.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%
Strongly Disagree	2	2.70%	0.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	0.00%

Figure 14. Respondents' reply and correction rate of MC question.

provided with unique identifiers (UIDs) and the ability to transfer data over a network without requiring human-to-human or human-to-computer interaction' (Margaret 2019). Figure 17 describes the basic concept of IoT: 1) sensors collect and transmit data to the data collection and storage platform automatically; 2) collected data is stored in a specified format and digested for model building; 3) useful information from the model is used to appropriate action-taking to improve the system and enhance the sensor deployment; and 4) accurate data is collected to further enhance the system performance itself and to

Part 1 Q1 (3.75%) You are a careful person	Respondents' Reply	Respondents' Reply (%)	Part 2 - Multiple-Choice Question Correction Rate MC Q1	MC Q2	MC Q3	MC Q4	MC Q5	MC Q6	MC Q7	MC Q8	MC Q9	MC Q10
Strongly Agree	5	6.76%	0.0015	0.0025	0.0015	0.0020	0.0020	0.0020	0.0020	0.0025	0.0025	0.0025
Agree	57	77.03%	0.0182	0.0289	0.0258	0.0258	0.0284	0.0238	0.0208	0.0289	0.0284	0.0243
No comment	8	10.81%	0.0015	0.0041	0.0041	0.0035	0.0035	0.0035	0.0020	0.0041	0.0041	0.0035
Disagree	2	2.70%	0.0010	0.0010	0.0005	0.0005	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010
Strongly Disagree	2	2.70%	0.0000	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010	0.0000
Total Average Score (Q1)			0.0223	0.0375	0.0329	0.0329	0.0360	0.0314	0.0269	0.0375	0.0370	0.0314

Figure 15. Actual rate of MC questions for category 1.

Part 1 Q1 (3.75%) You are a careful person	Respondents' Reply	Respondents' Reply (%)	Part 2 - Multiple-Choice Question Correction Rate MC Q1	MC Q2	MC Q3	MC Q4	MC Q5	MC Q6	MC Q7	MC Q8	MC Q9	MC Q10
Total Average Score (Q1)			0.0223	0.0375	0.0329	0.0329	0.0360	0.0314	0.0269	0.0375	0.0370	0.0314
Part 1 Q2 (3.75%) Peer pressure affects safety	Respondents' Reply	Respondents' Reply (%)	MC Q1	MC Q2	MC Q3	MC Q4	MC Q5	MC Q6	MC Q7	MC Q8	MC Q9	MC Q10
Total Average Score (Q2)			0.0223	0.0375	0.0329	0.0329	0.0360	0.0314	0.0269	0.0375	0.0370	0.0314
Part 1 Q4 (22.34%) Training taken	Respondents' Reply	Respondents' Reply (%)	MC Q1	MC Q2	MC Q3	MC Q4	MC Q5	MC Q6	MC Q7	MC Q8	MC Q9	MC Q10
Total Average Score (Q4)			0.1328	0.2234	0.1962	0.1962	0.2143	0.1872	0.1600	0.2234	0.2204	0.1872
Part 1 Q5 (10.49%) Training too much?	Respondents' Reply	Respondents' Reply (%)	MC Q1	MC Q2	MC Q3	MC Q4	MC Q5	MC Q6	MC Q7	MC Q8	MC Q9	MC Q10
Total Average Score (Q5)			0.0624	0.1049	0.0921	0.0921	0.1006	0.0879	0.0751	0.1049	0.1035	0.0879
Part 1 Q6 (10.49%) Training allows identification	Respondents' Reply	Respondents' Reply (%)	MC Q1	MC Q2	MC Q3	MC Q4	MC Q5	MC Q6	MC Q7	MC Q8	MC Q9	MC Q10
Total Average Score (Q6)			0.0624	0.1049	0.0921	0.0921	0.1006	0.0879	0.0751	0.1049	0.1035	0.0879
Part 1 Q8 (20.04%) Age	Respondents' Reply	Respondents' Reply (%)	MC Q1	MC Q2	MC Q3	MC Q4	MC Q5	MC Q6	MC Q7	MC Q8	MC Q9	MC Q10
Total Average Score (Q8)			0.1192	0.2004	0.1760	0.1760	0.1923	0.1679	0.1435	0.2004	0.1977	0.1679
Part 1 Q10 (10.49%) Working Experience	Respondents' Reply	Respondents' Reply (%)	MC Q1	MC Q2	MC Q3	MC Q4	MC Q5	MC Q6	MC Q7	MC Q8	MC Q9	MC Q10
Total Average Score (Q10)			0.0624	0.1049	0.0921	0.0921	0.1006	0.0879	0.0751	0.1049	0.1035	0.0879
Part 1 Q11 (18.65%) Education Level	Respondents' Reply	Respondents' Reply (%)	MC Q1	MC Q2	MC Q3	MC Q4	MC Q5	MC Q6	MC Q7	MC Q8	MC Q9	MC Q10
Total Average Score (Q11)			0.1109	0.1865	0.1638	0.1638	0.1789	0.1563	0.1336	0.1865	0.1840	0.1563
Grand Total			**0.5946**	**1.0000**	**0.8784**	**0.8784**	**0.9595**	**0.8378**	**0.7162**	**1.0000**	**0.9865**	**0.8378**

Figure 16. Actual rate of MC questions (after weighting calculation).

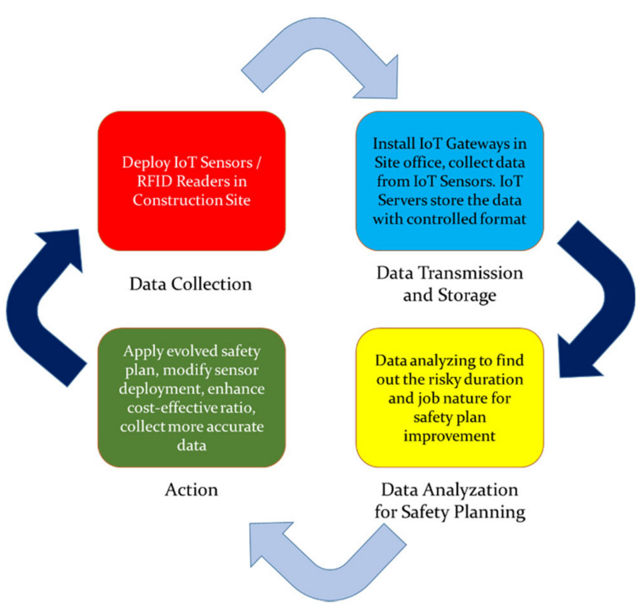

Figure 17. Construction site safety monitoring with internet-of-things (IoT).

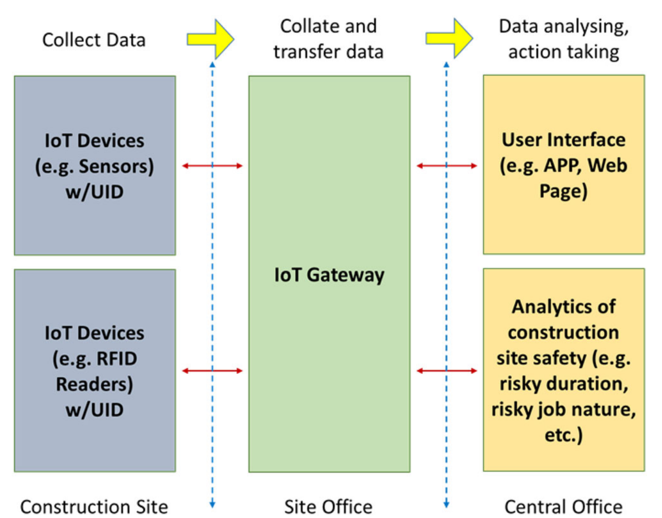

Figure 18. IoT system for construction site safety monitoring – from data collection to action taking.

avoid 'near-miss' instants on the construction site. Figure 18 shows how the IoT system works as a construction site safety monitoring system. People-count-sensors and RFID readers are deployed at the floor entrance for data collection. The data is transmitted to the IoT controller in the site office. IoT server analyzes the data for the safety department's further investigation. Real-time alerts are provided for safety supervisors to approach the workers without inappropriate personal protection equipment.

Design concepts from case studies

Lee et al. (2018) conducted an experiment for mesh and star networking system design over 800 m x 600 m area on a university campus. 1 gateway and 19 LoRa devices were installed. Packet

Table 3. Available IoT sensor names and their functions.

Sensor Names	Functions/remarks
1) Water Leakage Detector-I	Line type
2) Water Leakage Detector-I	Point type
3) Temperature/Humidity Sensor – I	For normal temperature
4) Temperature/Humidity Sensor – II	For low temperature
5) PM 2.5 Sensor	For air quality
6) CO Sensor	For carbon mono-oxide
7) CO^2 Sensor	For carbon-di-oxide
8) People-counting Sensor Detection	For movements, distances, and relative velocities
9) Power Meter	For electrical input current detection
10) Water Flow Meter	To measure liquids in industrial applications
11) GPS Tracker	For location tracking
12) Light Sensor	To detect external ambient light intensity
13) Occupancy Sensor	For motion detection in indoor areas
14) Door/Window Sensor	To detect whether door/window is closed or open
15) Dry Contact Interface (button/switch)	For connection of external dry contact devices
16) Emergency Push Button	For sending alerts to the gateway
17) Push Button Interface	For third party push-button connection
18) Smoke Detector	To detect smoke
19) Combustible Gas Detector	To detect combustible gas leakage
20) Air Quality Sensor	To detect indoor air quality
21) Geomagnetic Parking Sensor	To detect vehicle presence
22) Liquid Level Sensor	To monitor and check liquid levels in tank/container
23) Soil Moisture Sensor	To detect the amount of soil water

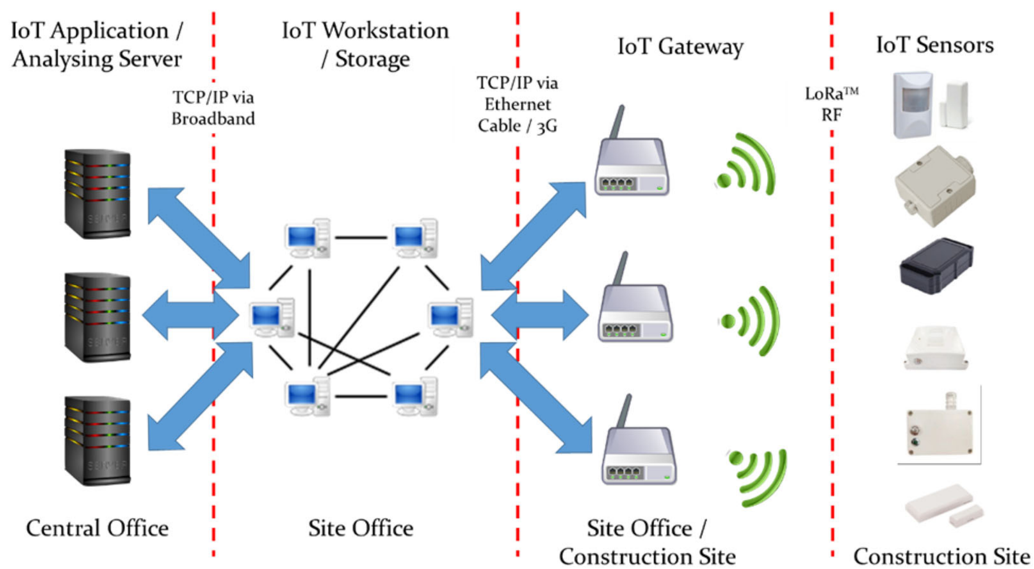

Figure 19. Traditional block diagram of LoRa applications.

Delivery Ratio (PDR) was tested with a 1-min data collection interval. It was found that the Mesh network can significantly increase PDR without installing additional gateway. However, the high-power consumption was unavoidable to maintain the node transmission, therefore, the battery life of the sensor was affected. Furthermore, security issues were not discussed in their research, which also affects the effective data-rate of LoRaWAN. Besides, Hwang et al. (2019) developed an APP that estimated the effective distance between the gateway and sensors under LoRaWAN in smart grids. 3 factors were found affecting the performance of LoRa: distance, obstacles, and noise production randomness. These factors affected the propagation attenuation, shadowing effect, and multipath fading. Based on the various theoretical calculations, experiments in 81 different locations were conducted to verify the accuracy and feasibility of the APP. Their research provided an initial step that assisted engineers to design the LoRaWAN network effectively. All this research tested the applicable distance between LoRa Gateway and LoRa sensors which was over 100 m. Following their research, we can assume all sensors are under the applicable coverage of the gateway. Table 3 show some of the available IoT sensors in the market which provide opportunities for the innovative safety monitoring system design.

Hong Kong Convention and Exhibition Centre (HKCEC) owns a total of 92,061m2 rental space and, the maximum capacity is 140,000 visitors per day. According to the Hong Kong Convention and Exhibition Centre, for the BMS upgrade project in 2017, 500 additional sensors were required for the water leakage detection, room temperature and humidity monitoring, and internal air quality (IAQ) monitoring. Most of the sensors were needed to be installed at a high level and the installation was difficult as it required additional cable containment and wirings. LoRaWAN (920–925 MHz) with IoT sensors was one of the best solutions for that project. The project was completed in late 2018. Figure 19 shows the traditional block diagram for LoRa applications. Part of the as-built schematic diagram for the IoT

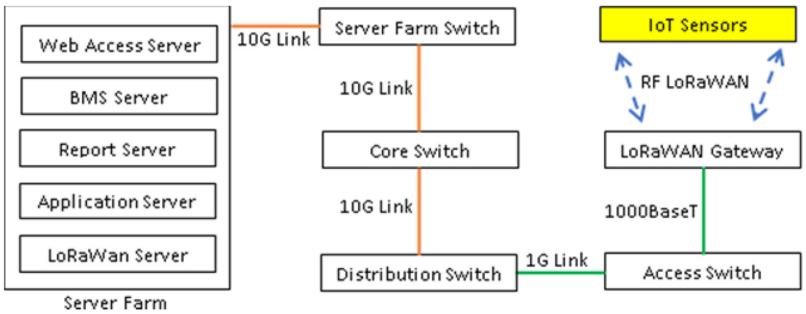

Figure 20. Part of system schematic of LoRaWan network.

Figure 21. Selected construction site (hotel) with site office for the IoT model design (Google Map).

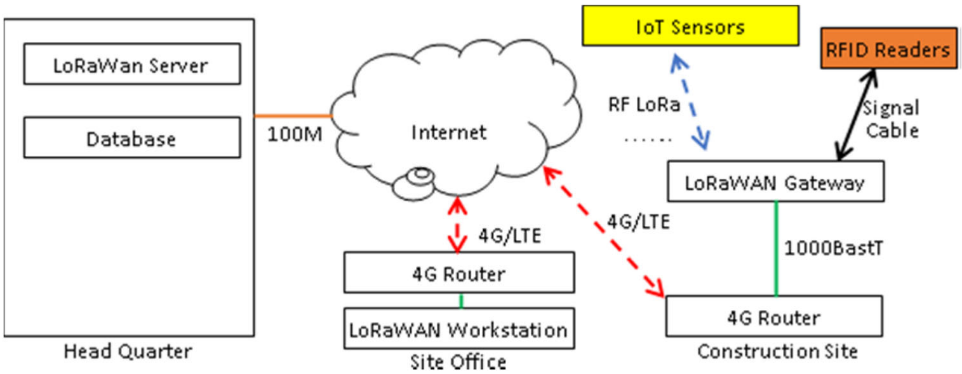

Figure 22. Proposed system schematic of LoRaWAN network for selected construction site.

network built for Building Management System (BMS) is shown in Figure 19. LoRa was the physical layer or the wireless modulation utilized to create a long-range communication link. LoRa is a chirp spread spectrum modulation, which maintains the same low power characteristics as the Frequency Shift Keying (FSK) modulation but provides a significantly longer communication range. LoRa was chosen because there are several solution providers in Hong Kong which provide the IoT solution with LoRa sensors (Figure 20).

Advantages of IoT wireless solution

The advantages of IoT wireless solution are 1) Time and cost-saving: less hard-wiring work and power supply for sensors, 2) Cost-effective sensor installation: sensors are small, easy to install and relocate, and 3) Cost-effective infrastructure installation in comparison with the traditional wireless technology: 1 gateway can communicate with around 50–70 sensors, thus corresponding quantity of network switches can be reduced.

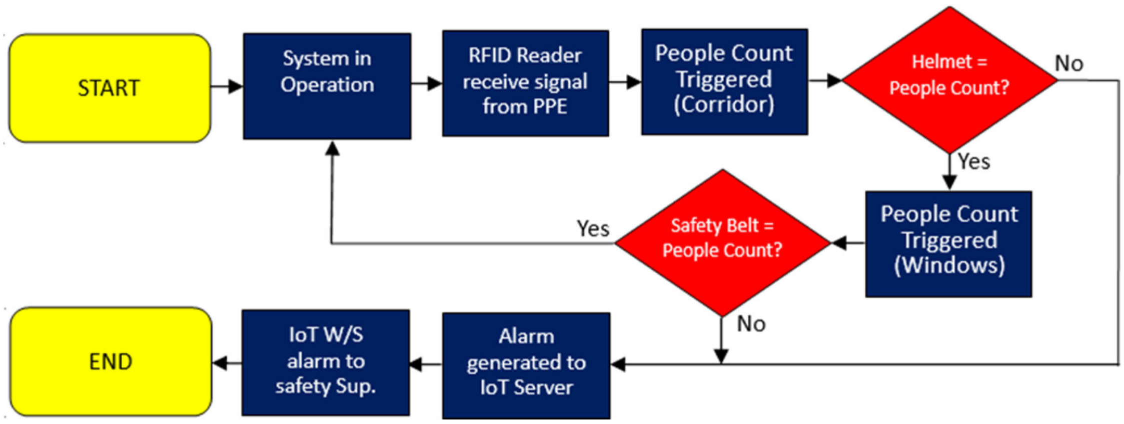

Figure 23. Workflow diagram of IoT safety monitoring system.

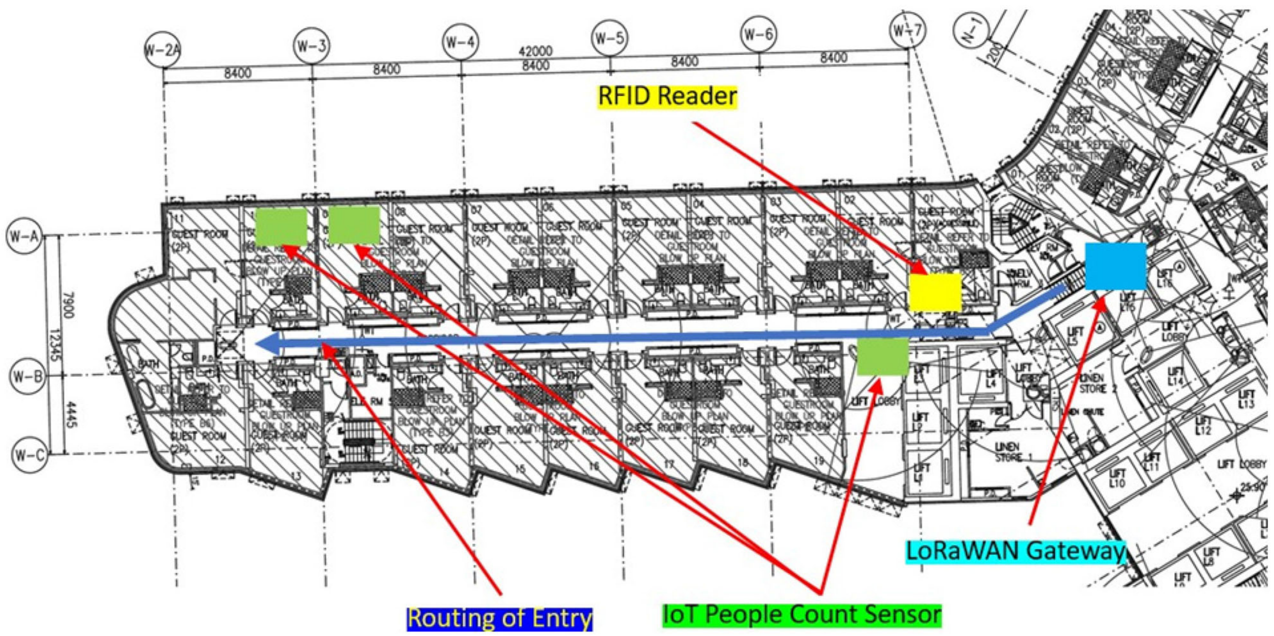

Figure 24. Proposed equipment installation location in construction site.

Iot model design - site layout

The following map (Figure 21) shows the selected construction site in Tung Chung for the IoT model design. It is a Y-shape hotel building and the site-office, built by the containers, is situated beside the construction site. Both construction sites and site-offices were provisioned with wireless 4 G/LTE Internet service. The distance between the construction site and the site office was under 200 m. As per the network size requirements, internet support limitations, and budget constraints, the system schematic of the IoT network is modified in Figure 22. Please see Figure 23 for the workflow diagram of the IoT safety monitoring system and Figure 24 for the proposed IoT equipment installation location in the construction site.

Equipment installation at construction site

- 1 x 4G router and the LoRaWAN gateway are proposed to install near the lift lobby (central of the building) for the signal exchange with the IoT sensors.
- 3 x RFID tag reader connected with the LoRaWAN is proposed to install in each corridor, to record the workers and their personal protection equipment (PPE) entry and exit record.
- IoT people-counting sensors are proposed to install near the RFID readers, to monitor the number of workers entering the specified area.

Equipment installation at site office

- 1 x 4G router and 1 x workstation are proposed to install in the site office for real-time safety monitoring. A real-time alarm from the construction site will be triggered and will alert the safety supervisor for follow-up action.

Equipment installation at head quarter

- A server farm that contains the LoRaWAN server and database server are proposed to install for the data collection from RFID readers and IoT sensors to be installed in the construction site. The servers will also repeat the alarm signal to the workstation in the site office.

RFID tag installation for all personal protection equipment (PPE)

- A registered RFID tag is proposed to be installed on each PPE (including the safety helmet, light reflection coat, and safety belt for work at height) for the real-time monitoring of workers' locations to check whether they are carrying the PPE or not.

System operation

Upon entering the monitoring floor, the RFID tags attached to the workers' PPE will trigger the RFID readers. The system will then record the number of PPEs entering the specified floor. If the quantity of safety helmet RFID tag detection by RFID reader is different from the IoT people-counting sensor detection, the system will generate an alarm and record the events in the server. At the same time, the workstation will display the alarm to the operators for further action. If the workers open the window to go outside for a high-level work, the people-count sensor near the window will be triggered. The system will compare the safety belt RFID tag detection and the people-count quantity. The alarm will be triggered if the quantity does not match. The real-time data collected in the database is fundamental for the detailed design or regular safety reviews allowing the safety officer to conduct training focusing on the high-risk near-misses.

Item	Cost	Unit
Cost of Network Switch	5,000.00	No(s)
Cost of Controller	6,000.00	No(s)
Cost of RFID Reader	1,500.00	No(s)
Cost of People Count Sensor	4,000.00	No(s)
Cost of Power Provision	2,000.00	Point(s)
Cost of Conduit	1,800.00	Point(s)
Cost of Cabling	500.00	Point(s)
Cost of IoT RFID Reader	2,500.00	No(s)
Cost of IoT People Count Sensors	2,500.00	No(s)
Cost of IoT Gateway	18,000.00	No(s)
Cost of Installation	400.00	Point(s)

Figure 25. Brief cost breakdown of traditional sensor system installation and iot based sensor installation.

	Traditional Sensor System	IoT Sensor System
Network Switch	2	N/A
IoT Gateway	N/A	2
Controller	1	N/A
RFID Reader	2	2
People Count Sensor	2	2

Figure 26. Equipment quantity of each system.

Cost-effectiveness of the system

Besides the IoT based solution, the most popular methodologies of Hong Kong construction site safety monitoring are as follows:

1. Employ sufficient safety site supervisor as the 'gatekeeper' of the construction site and conduct routine site inspection; and
2. Traditional wired RFID reader/People Count Sensor deployment.

The Tung Chung construction project, Hong Kong is taken as an example. The project started on Aug-2017 and completed on Aug-2020 (total 3 years). There was a total of 22 floors and 2 main entrances. According to the SalaryCheck by CTgoodjobs (CTgoods 2020), the typical salary of a safety supervisor is HK$19,000 per month. A total of 2 additional safety supervisors must be employed for personal protection equipment (PPE) checking at the entrance and the routine site inspection.

The brief cost of equipment, corresponding installation, test and commissioning, and maintenance cost of the whole project period are given in Figure 25. Items that are highlighted in yellow are typically required for a traditional sensor system including the cost of equipment, corresponding accessories such as power provisions to all equipment, cabling, and conduit. Green highlighted items represent the cost of sensors used for IoT-based system. Since all equipment can communicate with the IoT gateway wirelessly, no power provision, conduit, and wiring are required. The blue highlighted item is the common item required for both systems. Figure 26 shows the equipment quantity of each system on each floor according to the situation of the construction site. Red highlighted cells represent the quantity for the whole site whereas green highlighted cells represent the quantity for each floor.

The brief comparison of the IoT system with the other two traditional systems in Table 4. Table 4 shows the cost of the IoT Sensor System is only 35% of the traditional Sensor System and

Table 4. Cost comparison between manual monitoring, traditional sensor system and IoT based sensor system.

Items	Manual monitoring	Traditional sensor system	IoT sensor system	Remarks
Cost of Overhead (3 years)	$1,368,000.00	N/A	N/A	Average Salary of Site Safety Supervisor * 36 months
Cost of Equipment	N/A	$263,000.00	$201,000.00	Cost of Equipment * Total Equipment Quantity
Cost of Conduit	N/A	$158,400.00	$3,600.00	Cost of Conduit * Total Conduit Point
Cost of Cabling	N/A	$44,000.00	$1,000.00	Cost of Cabling * Total cabling
Cost of Power Provision	N/A	$176,000.00	$4,000.00	Cost of Power Provision * Total Power Point Requirement
Cost of Equipment Installation	N/A	$35,200.00	$27,200.00	Cost of Installation * Total Installation
Cost of Test and Commissioning	N/A	$54,128.00	$18,944.00	8% of total cost
Cost of 1st Year Maintenance	N/A	Included	Included	1st Year Warranty included
Cost of 2nd Year Maintenance	N/A	$54,128.00	$18,944.00	8% of total cost
Cost of 3rd Year Maintenance	N/A	$81,192.00	$28,416.00	12% of total cost
Cost of Overhead (3 years)	$1,368,000.00	N/A	N/A	Average Salary of Site Safety Supervisor * 36 months
Total Cost	HK$1,368,000.00*	HK$866,048.00**	HK$303,104.00	1 HK$= 0.13 US$

*IoT system provides 78% cost savings with respect to the traditional manual system.
**IoT system provides 65% cost savings with respect to the traditional sensors system.

22% of manual monitoring i.e., cost savings of 65% and 78%, respectively. It is because of the high overhead of safety supervisors in Hong Kong and the high accessories installation cost for the traditional sensor system.

In the Hong Kong construction site, main contractors take charge of monitoring, maintaining, and improving site safety matters. According to the Report on the Quarterly Survey of Construction Output (Census and Statistics Department 2020a), there are total HK$135,982 million construction works at construction sites by the main contractor in 2019. In general practice, safety investment in building projects is around 1% of the project amount. Thus the market for construction site safety is $1,359.82 million annually. Most of the Hong Kong companies use traditional safety systems that involve manpower consumption such as registration, checking, and documentation. If IoT systems are deployed, at least part of monitoring works and documentation works can be shared and the cost-saving would be huge which provides an attractive business opportunity. A market analysis showed that there are building services engineering companies in Hong Kong that supply a series of IoT sensors, controllers and provide a total solution to suit companies' needs.

Conclusions

This paper evaluates the effectiveness and weakness of mandatory basic safety training in Hong Kong. Firstly, a questionnaire survey was conducted and over 80% of questionnaire respondents were able to pass the quiz. Then, using criteria weighting calculation calculated through AHP analysis, the weakness of respondents were located. After that, the paper creates an IoT network model design for a real-time construction site safety monitoring system and suggested the basic infrastructure of the system, operation flowchart, and the optimal sensors' locations.

IoT network technology has been applied in various types of workspaces such as warehouses, exhibition centers, and commercial buildings, however, there is a lack of discussions on the application of this technology to the construction site for large-scale safety monitoring and storing the data systematically. This research provides a guideline for further investigation of innovative IoT networks' application networks and the data collection methods from the IoT sensors. IoT network can be of worth considerations for construction companies due to 1) the affordable costs of IoT sensors and 2) easy installation/relocation characteristics of the system. Because of the limited budget and time, only one category (personal protection equipment) was proposed to conduct the IoT model design. As literature pointed out towards the cost-effectiveness of the IoT solutions, a cost comparison was made with the traditional manual safety system and the traditional sensor-based safety system. It was found that our system can provide cost savings of 78% relative to the traditional manual safety system and 65% cost savings relative to the traditional sensor-based system.

The proposed system can also provide functions such as access control for plant rooms, heat or water detection in specified areas, preliminary air quality monitoring for the confined areas, and smoke detections. The combination of various types of sensors with appropriate control logic can create several innovative functions for the system. This system is currently at the design stage. More benefits will emerge after the real implementation of the system in an actual project. However, the cost comparisons have already established the usefulness of this system. The principle investigator is already in a process of obtaining funding for the project. Future research will be carried out, firstly, on the challenges of implementing this system in real-life projects, and secondly, on the improvements in the overall construction site monitoring using this system relative to the traditional systems.

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