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SELECTION OF WIRELESS TECHNOLOGY FOR TRACKING CONSTRUCTION MATERIALS USING A FUZZY DECISION MODEL

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Abstract. As the size and scale of construction projects increase, inefficiencies related to the manual operations about field data in current tracking systems are becoming an important issue. While emerging wireless technologies are providing a feasible vision of ubiquitous computing and sensor networks applicable to the large-scale construction industry, it has become even harder to select a suitable technology for tracking construction materials because of the differing functionalities, capabilities, and scope of application of the specific technology. This research proposes a multi-criteria decision-making model that leverages the decision process in choosing various wireless technologies available on the market. To justify the selection of a specific technology, a fuzzy method was adopted to provide an appropriate way to decide among five alternatives (e.g., RFID, GPS, Wi-Fi, Zigbee, and UWB). Fuzzy ranking was obtained from the aggregated fuzzy appropriate index (FAI) based on a person's point of view (optimist, pessimist, or neutral). The results showed that Wi-Fi might be a suitable solution for optimists and neutral persons, but UWB might be the better alternative for pessimists. The results of this research may assist construction engineers in applying reasonable decision-making procedures in a fuzzy environment such as construction sites, and rank the relative importance of the various criteria and alternatives specified in this research.

Keywords: wireless sensor network, construction material tracking, decision model, fuzzy.

1. Introduction

Due to the information-intensive nature of construction projects, it is crucial that engineers, inspectors, and maintenance personnel have on-demand access to construction project data (Behzadan *et al.* 2008) so they can make real-time decisions (Khoury, Kamat 2009). However, there is a severe lack of up-to-date as-built information about construction projects, and the current practice of manually collecting monitoring data is error-prone, expensive, inaccurate, and inefficient (Grau *et al.* 2009; Navon, Sacks 2007; Sacks *et al.* 2005). Advanced wireless tracking technology for construction assets offers multiple benefits, and can be used for optimizing productivity and cost-saving, as well as the obvious safety and security applications with improved efficiencies and effectiveness, thus providing competitive advantages.

In recent years, a wide range of advanced wireless tracking technology solutions have been developed and applied unprecedented to realize a ubiquitous computing environment in many industries. Numerous research studies have developed approaches for applying wireless tracking technologies to construction projects and facility/infrastructure management, and in particular, construction site assets tracking. Examples of the types of technologies addressed in these studies include radio frequency identification (RFID), global positioning systems (GPS), combination of RFID and GPS, Wi-Fi, Bluetooth, Zigbee, and Ultra Wideband (UWB) (Jaselskis, El-Misalami 2003; Domdouzis *et al.* 2007; Ergen *et al.* 2007; Woo *et al.* 2011; Lu *et al.* 2007; Jang, Skibniewski 2009; Teizer *et al.* 2008; Giretti *et al.* 2009).

The construction environment is characterized as a spatially expansive, object-cluttered, fast-changing, and harsh environment, including both indoor and outdoor environments. Because of the unique nature of construction sites, large amounts of dispersed materials, tools, equipment, and vehicles must be well positioned to provide construction resources in the right place at the right time, which is quite different from other industries. On the other hand, there are a variety of indoor and outdoor location tracking technologies with significantly different characteristics, infrastructure, and device requirements (Behzadan *et al.* 2008). In addition, different kinds of wireless tracking technologies have different functionalities, capabilities, and scopes of application (Fig. 1). Furthermore, it is well documented that a single technology may provide different functionalities and capabilities in different application areas depending on the application's requirements. For example, RFID used in local construction crew monitoring may require exact positioning data and real-time data updates, whereas a nation-wide construction procurement system using RFID may need a higher level of readability and an expandable network infrastructure.

Fig. 1. Various wireless technologies with different functionality, capability and scope of application in construction industry (Song *et al.* 2006; Chin 2006; Pardasani *et al.* 2009)

Because of the heterogeneous and unique characteristics of the construction industry, it is difficult for decision makers to select the right technology for the right application without economic and functional loss. Until now, little research has been conducted on the selection of appropriate wireless tracking technologies for use at construction sites. In addition, the selection of wireless technologies for the construction environment from among the increasing number of technology-alternatives requires challenging multi-criteria decision-making by infrastructure project stakeholders. Consequently, it is essential to encourage construction engineers to select the most suitable wireless tracking technology solution based on their application requirements to make full use of the technologies. This research aims to develop a decision-making model for selecting wireless technologies for construction assets tracking, and to suggest a multi-criteria fuzzy approach for making an appropriate decision from among the various alternatives.

2. An overview of the wireless technologies available for construction assets tracking

In this study, several wireless tracking technology solutions applied to construction assets tracking were considered, including RFID, GPS, a combination of RFID and GPS, Wi-Fi, Bluetooth, Zigbee, and UWB. Below are details about the application of each of these technologies to the construction sector.

2.1. Radio frequency identification (RFID) technology

RFID is a type of automatic identification technology in which radio frequencies are used to capture and transmit data from a tag or transponder and store data in a distributed fashion. A typical RFID system is comprised of two main components: A reader and a tag. A tag, which consists of an electronic chip coupled with an antenna, is attached to an object and stores data about the object. The reader reads/writes data from/to a tag via radio frequencies and transfers data to a host computer. Reading/writing ranges depend on the operation frequency (low, high, ultra high, and microwave), and whether the tag requires a battery to operate (active versus passive). Active tags typically have higher reading ranges; however, they have limited life spans, requiring periodic battery replacement (Kiziltas *et al.* 2008).

RFID technology has specific features that make it suitable for the construction field. RFID can dynamically transmit and receive information to identify objects without "line-of-sight" and does not require close proximity, individual readings, or direct contact. RFID technology enables data entry and access at any time throughout the lifecycle of the tag. Information stored on the tag can be modified, which provides flexibility for managerial medication (Ko 2009). RFID tags can even be read from long distances and are durable in the harsh environment of a construction site (Jaselskis, El-Misalami 2003; Song *et al.* 2005; Ergen *et al.* 2007).

A wide range of applications of RFID in the construction industry have been explored, such as tool inventory and allocation, receiving and keeping track of a variety of pipe spool components used in process-piping construction, precast production management, and so on (Goodrum *et al.* 2006; Yin *et al.* 2009).

2.2. Global positioning system (GPS) technology

GPS is a satellite-based radio-navigation system used for tracking objects in outdoor environments. GPS is based on measuring the time required for radio signals to travel from a specific number of satellites, whose positions are known at each moment, to a receiver. GPS receivers calculate the distance and determine locations in terms of longitude, latitude, and altitude, with great accuracy (Oloufa *et al.* 2003). After 20 years of development, the current stand-alone GPS systems can lock-in positions with an accuracy of around 10 m.

Furthermore, a positioning accuracy of 1–2 m can be achieved with differential GPS (DGPS) technology, which uses a GPS base receiver located at a known fixed point and applies differential corrections to the observations from a rover receiver. Real-time kinematic GPS (RTK GPS) can further enhance positioning accuracy to the centimeter (even millimeter) level by combining the measurements of the signal carrier phases from both the base and rover receivers with special algorithms (Lu *et al.* 2007).

GPS technologies have received particular attention from construction researchers in that they can provide cost-effective solutions to automated data collection. Research has indicated that GPS is a significant step forward in revolutionizing current practices in tracking, managing, and controlling assets, such as equipment, vehicles, and pedestrians (Peyret *et al.* 2000; Oloufa *et al.* 2003; Saeed *et al.* 2010).

2.3. A combination of RFID and GPS technologies

To benefit from the merits of both RFID and GPS, a solution combining RFID and GPS was presented. Using combined active UHF RFID and GPS technologies, Song *et al.* (2005) provided a logical mechanism for locating materials that are scattered at a construction site based on a proximity method. In this approach, construction sites are scanned in detail daily to identify the location of materials at a given site. This approach provides approximate locations for materials at a construction site, and can be used as a front-end solution for identifying components' initial locations in a storage yard. In the storage yard of a manufacturing plant, Ergen *et al.* (2007) proposed an automated system using RFID technology combined with GPS technology that uniquely identified precast components and then tracked and located them using little to no worker input.

2.4. Wi-Fi

Currently, the most prominent specification for IEEE 802.11 WLAN standards is the Wi-Fi alliance. Wi-Fi operates in the license-free 2.4 GHz industrial, scientific, and medical (ISM) band. Received signal strength indicator (RSSI) is widely adopted, and the accuracy of typical Wi-Fi positioning systems is approximately 3–30 m, with an update rate in the range of a few seconds (Vossiek *et al.* 2003). It provides wired LAN extension or replacement in a range of market areas (e.g., enterprises, homes, and hot spots) (Shen *et al.* 2008).

WLAN has distinct advantages. First, it is an economical solution because WLAN systems usually already exist as part of the communications infrastructure. In WLAN mobile devices, the positioning system can be implemented simply in the software. Second, the WLAN-based positioning system covers a large area and may function across many buildings. Third, it is a stable system because of its robust radio frequency signal propagation (Xiang *et al.* 2004). Some research efforts have applied WLAN, including Wi-Fi, in construction assets tracking, such as the identification of construction entities visible in a user's field of view (Khoury, Kamat 2007), as well as labor tracking (Woo *et al.* 2011).

2.5. Bluetooth

Originally designed as a short-range wireless connectivity solution for personal, portable, and hand-held electronic devices, Bluetooth technology radios operate on a license-free, globally available 2.4000–2.4835 GHz industrial, scientific, and medical (ISM) band, which is divided into 79 channels. In addition, Bluetooth employs a fast, frequency-hopping spread spectrum (FHSS) technology (with an incremental frequency of 1600 Hz) to avoid interference in the ISM band and ensure the reliability of data communications (Chatschik 2001; Lu *et al.* 2007).

Bluetooth radio can be classified into three power classes based on RF transmission power. The typical working distance for Bluetooth ranges from 10 to 100 m, depending on the power class of the device. At present, Class 3 Bluetooth with a 10 m radius is embedded in most commercial Bluetooth applications (Hallberg *et al.* 2003). A Bluetooth device assumes the role of either a master or a slave. The master regulates what slave will transmit data and when. In some cases, two types of devices share a common hardware structure and thus can swap their master–slave roles only by altering the core programs. Bluetooth is an industry specification for ensuring compatibility in wireless connectivity of electronic devices, allowing one manufacture's master device to control the slave device made by another. The longer communication range of Bluetooth (an optional 100 m standard is available off-the-shelf compared with less than 20 m for most RFID solutions) may substantially broadened the application domain of Bluetooth (Lu *et al.* 2007).

With respect to the utilization of Bluetooth in construction engineering, Lu *et al.* (2007) embedded Bluetooth technology in roadside beacons for positioning construction vehicles at building sites. In their field trials, they found that the communication range of the Bluetooth module was reduced from a nominal 20 m to 100 m because of the complex conditions at the site.

2.6. Zigbee

As an emerging wireless communication technology, ZigBee has the capability of realizing a ubiquitous environment. ZigBee is a product of the ZigBee Alliance, an organization of manufacturers dedicated to developing a new networking technology, and is aimed at industrial and home wireless applications (Jang, Skibniewski 2009). ZigBee specification takes advantage of the IEEE 802.15.4 wireless protocols as the communications method, and expands on this with a flexible mesh network, wide range of applications, and interoperability. A ZigBee network consists of ZigBee coordinators, ZigBee routers, and ZigBee end devices. The end devices conduct multi-hop communications via connected routers to communicate with other devices connected to the networks. Using the advantages associated with flexible ad hoc networking, the promise of the ZigBee application can be found in the robust, reliable, self-configuring, and self-healing networks that provide a simple, cost-effective, and battery-efficient approach to adding wireless to mobile and fixed communication devices. ZigBee supports many industrial applications, including construction automation, structural health monitoring, and automated control and operations, all of which can benefit from the advantages of the technology.

As for the application of ZigBee in the construction industry, Skibniewski and Jang (2009) proposed a ZigBee-based wireless sensor network for object tracking and monitoring in construction processes. By using ZigBee wireless sensors, Lee *et al.* (2009) presented a Web-based system to monitor the greenhouse gas emissions released by construction equipment. Jang and Skibniewski (2009) introduced system architecture for automated materials tracking in construction processes by deploying these Zigbee networks.

2.7. UWB

Ultra wide band (UWB) is a wireless technology for the low-power transferring of large amounts of digital data through a wide spectrum of frequencies over short distances. Some major distinctive advantages of UWB technology include high immunity to interference from other radio systems, high multipath immunity, high data rate, and fine range resolution capability (Shen *et al.* 2008). The tags in an UWB tracking system decide the localization dimensionality, and reception by three or more receivers permits accurate 2D localizations, whereas reception by four or more receivers allows for precise 3D localization. If only one or two receivers can receive a tag transmission, proximity detection can also be readily accomplished (Khoury, Kamat 2009). Because of its short pulse radio frequency (RF), waveforms and large bandwidth, UWB provides fine time resolution and has good potential for applications in ranging and positioning, and good immunity to multipath effects in indoor applications.

In recent years, UWB technology has been successfully applied in the construction industry. Some examples from both research and industry are as follows. Teizer *et al.* (2008) presented automated real-time three-dimensional location sensing for a construction resource (workforce, equipment, and materials) positioning and tracking system using UWB technology. Giretti *et al.* (2009) reported the design and development of a proactive advanced system that can perform real-time position tracking using UWB and can predict risky events. Chehri *et al.* (2009) proposed that an UWB-based wireless sensor network (WSN) be adopted as a solution for locating equipment and miners in underground mines.

3. Decision criteria for selecting wireless technology

A number of wireless technologies have evolved that support various industrial applications, including building and construction automation, structural health monitoring, and automated control and operation. The main motivation for the deployment of these technologies is to enhance communication efficiency over wired systems, while at the same time reducing the cost and effort associated with its use. With multiple functionalities and services, wireless technologies provide a potential opportunity; however, there are still many concerns that have prevented mass adoption of the technology among the diverse alternatives for the wireless tracking systems at construction sites. From a user's viewpoint, decision makers may ask the following major questions when considering the possible selection of these technologies: 1) What is the sensing or communication ranges required to transmit reliable data, ensure maximum quality of service, and measure accuracy? 2) What density of nodes is needed to configure the networks for optimally efficient cost and power management? 3) What measurement interval is required to collect the most meaningful data? 4) How useful is the wireless technology for general users, requiring minimum effort for programming, installation, control, and management?

As the technology has evolved, selecting an optimal solution from among the various types of wireless technologies has become more difficult because the similar specifications of wireless technologies provides different functionalities, capacities, and costs. For instance, radio frequency identification (RFID) would be superior to UWB in terms of cost savings and ease of use, but RFID may be the wrong solution if an application requires high performance in network flexibility or tracking accuracy. Consequently, understanding the detailed technical functionality that each technology provides for a specific application is critical. At the same time, justification for why a specific decision criterion should be considered in a given application environment and type of technology should be provided.

In this research, we investigated the practical issues in the possible deployment of these technologies and summarized the decision criteria that should be used by a decision maker when he or she chooses a construction tracking system from among the multiple alternatives.

Cost

Because the construction industry has been faced with adopting technology innovations for various projects, cost planners or decision makers must consider the appropriate costs for different phases of a construction process that are required to efficiently complete the project. Typically, the preparation of cost planning for adopting new technologies is vital early in the construction process because successful implementation of the technologies are often manifested in return on investment. When cost is taken into account for adopting a wireless sensor network, there are a number of issues to consider: 1) the number of sensor nodes; 2) monetary value, such as device or installation costs; and 3) maintenance costs once the technology is deployed.

First, the number of nodes required for deployment is the most significant factor in any large-scale application domain such as a construction site. A higher density of sensor nodes reduces the overall uncertainty by increasing the accuracy and quality with which events are sensed. On the other hand, cost trade-offs are possible when a high density of sensor nodes are deployed. Consequently, a preliminary investigation of the optimum density levels corresponding to a reasonable deployment cost should be examined. Second, there is no general rule of thumb to evaluate deployment costs in terms of dollars and cents. Deployment strategies depend on various factors such as actual needs, the purpose of the application, the construction environment, the types of sensors, routing scheme, and so on. Because deployment strategies are heterogeneous, it is not easy for sensor developers to estimate the quantitative benefits of using a sensor network in construction applications. At the same time, this uncertainty makes it difficult for users to adopt new and promising technologies in their applications. Third, because of the limited lifespan of WSNs, as the number of nodes increases, the maintenance costs also have the potential to hamper the adoption of wireless sensor networks. It is not practical to deploy hundreds or thousands of nodes when their batteries must be changed every month or even every year. The cost to investigate and replace failed components in a large network could also be a practical challenge. By integrating the issues described above into the proposed decision-making model, these cost criteria were divided into several sub-criteria, such as device costs, installation costs, and maintenance costs.

Performance

Major progress in the practical deployment of WSN solutions has been made in the past few years; however, it is still a challenge to convince construction engineers to use WSNs in their diverse applications because various types of wireless standards meet the different needs and requirements of various materials tracking systems. Consequently, the most critical criterion for successfully adopting these technologies for materials tracking systems is reviewing the level of performance and functionality of the WSNs. Generally, this would entail both practical and technical issues for many practitioners. In terms of practical measurements, wireless networks should be more reliable than wired systems because they provide a more accurate, real-time, and robust framework in the construction environment (Skibniewski, Jang 2009). However, location accuracy on a nanometer scale or zero-delay in RF transmission may be overcapacity in implementing a material tracking system. For most decision makers, more often than not, optimal levels of performance and functionality for a typical tracking system are the most desirable criteria that they are willing to consider in this situation. Second, these practical measurements are also associated with many technical issues in which the general expectations for WSN performance meets the needs of construction engineers in terms of: 1) packet delivery rate; 2) bit error rate; 3) duty-cycle and latency; 4) fault tolerance; 5) time synchronization; 6) throughput and so on.

Although various performance sub-criteria could affect the outcomes of a decision-making analysis, a preliminary survey of construction engineers indicated that accuracy and data rate were primarily considered sub-criteria to performance criteria. More than 70% of responders answered that accuracy was the major criterion, such that a certain level of accuracy should be provided even though low-level accuracy was generally required in a construction material tracking system. The remaining 30% of responders indicated that data rate was also important when it came to the type of data used. For example, some wireless protocols are not efficient or cannot carry a video stream. Thus, the data rate becomes important to making a decision when the material tracking system is designed to leverage high-tech media with a required amount of data transmission.

Flexibility

Wireless technology should be also scalable and flexible to dynamically expand and adapt to the changes that occur at physical construction sites. Autonomous configuration with guaranteed coverage and scalability would increase the probability of detecting geographically constrained phenomena or events in construction environments. At the same time, a variety of application strategies could be implemented because of the guaranteed reliability and networking capacities of wireless technologies. Because of the nature of the distribution of WSN frameworks, the design for detailed task assignments and corrections made by sensor networks are becoming more complex. Hence, a higher level of abstraction of the low-level hardware layer should be provided so that the applications can be easily implemented.

As new technologies emerge, the different levels of network flexibility and interoperability will make it difficult for decision makers to select wireless technologies. Most personal wireless area networks (PWAN) do not feature a big enough coverage range to cover an entire construction site with only one-hop communication. For instance, Zigbee supported by the IEEE802.15.4 protocol has an indoor coverage range of 10-30 meters and an outdoor coverage range of 50-100 meters (MaxStream 2007); RFID and Bluetooth have reliable communication over even shorter distances (a few meters). Thus, if networking flexibility is not guaranteed, relatively short communication distances may be a technical barrier to fully deploying PWAN. By assuring wireless connectivity in a highly dynamic and complex environment, a framework of WSNs could provide the networking configuration and multihop capability that could efficiently expand the network throughout this large-scale application domain.

Interoperability is another key to successfully integrating various wireless technologies into construction tracking applications. WSNs in most construction applications require heterogeneous collaboration among multiple participants in various sectors, and different hardware and software platforms in a building need to be interoperated with other types of building platforms. WSN compatibility with existing hardware and software will be key to many construction applications. For example, if WSNs are deployed with BACnet-based building automation systems, wireless sensors for resource tracking systems must be well interfaced with the existing architecture of the BACnet protocol (McGowan 2005). In this existing platform, the data-centric design of WSNs should provide sufficient knowledge-sharing with the BACnet application layer, and the networking protocol should be compatible enough to leverage the full capabilities of the installed network. Thus, sensor networks can be easily adapted to the parts of the BACnet modules tailored to the application requirements.

Considering the decision criteria discussed above, in this paper, we categorized networking flexibility and interoperability as sub-criterion under flexibility. For the networking flexibility sub-criterion, the following decision criteria were identified: 1) coverage range, which might affect the number of sensor nodes, network density, and quality of wireless connectivity; 2) communication efficiency, which might affect transmission reliability and networking performance; and 3) topology, which might affect the layout of sensor nodes and the networking configuration.

Interference

Wireless construction tracking applications must function over heterogeneous networks with multi-dimensional types of sensors and networks. At this point, careful planning and consideration of the way that the wireless communication is achieved in the typical construction environment is required. As a wireless signal travels back and forth through the air, signal interference caused by multipath or obstructions becomes one of the key issues in evaluating WSN performance. In open spaces, the received power is inversely proportional to the square of the distance between the receiver and the transmitter; thus, it is obvious that the received power between the receiver and the transmitter must be estimated. However, it is more complicated when walls, floors, equipment, or temporarily stocked materials are present because when the RF signal bounces off these objects, it causes complicated signal attenuation or distortion. Signal attenuation or distortion is often referred to as obstruction, and this interference affects the reliability of wireless communication. For example, very low received power caused by obstruction may increase the frequency of packet loss, resulting in an overall decrease of packet delivery rate in the system. This type of interference is not preventable if wireless nodes will be placed in a layout such as that at a construction site where various objects are already placed or installed. Thus, signal reliability should be quantitatively evaluated carefully, so that network topology can be accordingly configured to provide high signal strength, link quality, and packet delivery rate in a situation with obstructions.

Another factor that can affect interference is the co-existence problem when multiple sensor nodes access a single access point simultaneously or all the channels are in use (Shin *et al.* 2007). This becomes critical if wireless devices are operated in a high-density area or if multiple wireless devices are operated at the same bandwidth are used in a construction site (e.g., co-existence of Zigbee, Wi-Fi, Bluetooth, and microwave ovens operated at 2.4 GHz). In this case, technical problems such as transmission delays or packet collisions can occur, resulting in unreliable wireless communication. There are some technical solutions such as non-overlapping channel selection, radio resource management, or dynamic frequency selection. However, a more important remedy for construction engineers is designing the network topologies so that the co-existence effect can be minimized by placing the different types of devices off their interference coverage.

Maintenance

The major advantage of wireless and battery-powered technology over a wired system is said to be the decreased installation and maintenance costs. The absence of cable reduces the human intervention required to inspect cable connectivity and manage the complicated wiring through the entire lifecycle of the devices. This reduction in labor and maintenance for wireless technology frameworks directly increases labor productivity such that autonomous configuration of the sensor system automatically gathers and transfers field information at a construction site. Consequently, in the long-term, life-cycle maintenance for tracking construction assets would benefit from the minimal use of labor and increased labor productivity.

However, there are some technical challenges in maintaining wireless technologies. First, wireless sensor units used for tracking applications at a construction site must stand up to harsh outdoor environments: high humidity during the rainy season, heat during the day or summer seasons, strong winds or external impact, electromagnetic fields from other test instruments, and attachment conditions when the sensors are placed on construction materials. These environmental factors can make providing a reliable system very difficult, and thus, is an important decision factor when deployed.

Second, energy sources for wireless technologies are very limited and they usually depend on batteries. Normally, the radio component in wireless sensor accounts for the largest energy consumption. Radios are operated through four distinct modes, e.g. transmit, receive, idle; and transmit and receive mode are the largest portions in energy consumption. Typical consumption rate of Zigbee in transmit and receive mode, for example, are 18.8 and 17.4 mA, respectively (Texas Instrument 2007), and the sleep mode may provide the significant energy savings when the wireless devices are inactive. With these radio's modes and low-power strategy, it is possible that battery-powered wireless sensor systems could theoretically last for years according to the duty-cycle. Even though the low power sensor technologies are rapidly being developed by many sensor companies to improve the power management, this energy limitation becomes still critical when hundreds or thousands of nodes are placed in a network for long-term tracking applications. Thus, it may be impractical to frequently change or recharge the batteries in such a large number of nodes. For this reason, power management issues always arise in practical wireless sensor applications, and there are often deals maintenance costs in long-term applications. Issues of power management are often associated with the technical design of the routing scheme, the MAC & PHY layers, throughput, and topology. However, application-specific requirements also play an important role in addressing practical strategies for power management. Such requirements might be associated with the following questions: What time interval is sufficient for monitoring construction materials in a stockyard? How large a coverage area will provide a reliable tracking system? Should event detection or data collection be used? Should passive or active sensing be used? Should data logging or real-time monitoring be used?

Practicability

In general, programming and integrating a commercial platform are relatively difficult in WSNs. Unlike PC-based platform, programming activity for WSN must run on the sensor hardware, which has significantly limited resources in memory and capacity. For example, ATmega128L in Micaz provides 8 MIPS throughput with 4 Kbytes data memory, 128 Kbytes program memory, and 512 EEPROM (Crossbow Technology Inc. 2007). Given limited hardware resources, spatial and temporal complexity should be well defined to utilize the capacity profile of a sensor node fully. An important consideration is that programming architecture must follow an energy efficiency design philosophy. Because of battery operation, special care must be taken to optimally arrange tasks and commands for computations and communications, which are the major factors in power consumption. Another issue is that programming must be supported in the existing OS architecture. Currently available OS platforms that provide reliable dynamic memory allocation, sufficient packet size, and multithread concept are very limited. Consequently, network performance, memory management, and execution model have limited performance in WSNs, resulting in additional challenges involving scalability in a large-scale sensor network. This is crucial in construction applications in which multiple obstructions result in a scaled down communication range; thus, ad hoc mesh networking can only provide unique solutions for large deployments.

There must be new programming paradigms and new operating systems that efficiently satisfy the needs and requirements, supporting user-friendly architecture, and ensuring maximum reliability and modularity. Individual sensor nodes must have high adaptability such that they can be configured in the existing environment and infrastructure, and an easy framework for installation, modification, and removal should be provided to convince users of their practical applications. General construction engineers should easily realize their expected goals and application purposes with given WSN interfaces in which minimal programming expertise and efforts are needed. To provide fully utilized WSN applications, sensor designers and application developers should keep in mind that "ease of use" is a primary factor in design philosophy for the eventual success of a WSN. At the same time, applicability should also be provided to general users: 1) minimal post-processing of the data collected are needed; 2) typical device size should be small enough to be useful and durable in the construction environment without disturbing regular work processes; 3) available commercially so it is easily adoptable to advancements in wireless technologies; and 4) firm and optimum attachment should be guaranteed to increase reliability and applicability of the tracking system.

4. Research method

This chapter introduces a multi-criteria fuzzy approach to facilitate decision making when selecting wireless technology. The Multi-criteria Decision Making (MCDM) model is one of the methods in decision studies in which the factors necessary for a priority decision are many (multi-criteria) (Sasmal, Ramanjaneyulu 2008). This approach is one of the fastest growing areas in decision-making research, and assists decision makers in converting imprecise and vague criteria into numerical values (Sreeda, Sattanathan 2009; Nayagam *et al.* 2011). The selection of WSN technology, which is a typical multi-criteria decision problem in which relevant alternatives are selected, evaluated, or ranked according to a number of criteria, influences a construction project's tracking effect. Subjectivity, uncertainty, and vagueness in selecting WSN technology can be dealt with using linguistic variables. Because linguistic variables can be converted into fuzzy numbers, fuzzy sets theory has proved very convenient for searching for solutions to problems that involve subjective opinion (Plebankiewicz 2009) and can be particularly powerful in handling the inherent uncertainty in MCDM problems (Hajkowicz, Collins 2007; Alipour *et al.* 2010; Chang, Wang 2009).

4.1. Fuzzy set theory

If we denote a universal set of X, then a fuzzy subset A of X is defined by its membership function f_A (Zadeh 1965):

$$A = \{(x, f_A \mid x < X)\},$$
$$\text{where membership space } M = [0,1]. \quad (1)$$

The fuzzy membership function assigns each element x in A to a real number in the interval [0, 1]. The fuzzy set generalizes a classical set and the membership function generalizes the characteristic function.

Bellman and Zadeh (1970) introduced the following concept of fuzzy decision making using O as the fuzzy objective function (alternatives), C as the fuzzy constraints, and D as the fuzzy decision:

$$D = O \cap C. \quad (2)$$

For k fuzzy objectives and m fuzzy constraints, the optimal decision can be written as a membership function as follows:

$$D = O_1 \cap O_2 \cap \cdots \cap O_k \cap C_1 \cap C_2 \cap \cdots \cap C_m ; \quad (3)$$

$$\max_{x \in X} f_D = \max_{x \in X} \min(f_{O_1}(x), \cdots, f_{O_k}(x), \cdots, f_{C_1}(x), \cdots, f_{C_m}(x)). \quad (4)$$

In fuzzy multi-criteria decision-making problems, control and handling of the membership function are performed by the problem domain where the fuzziness lies. If the fuzziness in the problems lies in the objective function coefficients, the membership function can be expressed by:

$$f_k\left(Z^k(x)\right) = \begin{cases} 1 & \text{if } Z^k(x) \le L_k \\ \dfrac{U_k - Z^k(x)}{U_k - L_k} & \text{if } L_k \le Z^k(x) \le U_k \\ 0 & \text{if } Z^k(x) \ge U_k \end{cases} \quad (5)$$

and

$$U_k = \left(Z^k(x)\right)^{\max} = \max_{x \in X} Z^k(x); \quad (6)$$

$$L_k = \left(Z^k(x)\right)^{\min} = \min_{x \in X} Z^k(x),\ k = 1, 2, \cdots, K, \quad (7)$$

where U_k and L_k are the worst upper bound and the best lower bound of the objective function k, respectively. In the membership function, maximal grade represented as $f = 1$ implies the most probable value for membership function in a given alternative.

In the extension principle suggested by Zadeh (1965), the fuzzy arithmetic operations of addition, subtraction, multiplication, and division of two fuzzy numbers, $M = (m_1, m_2, m_3)$ and $N = (n_1, n_2, n_3)$, are as follows:

$$M \oplus N = (m_1 + n_1, m_2 + n_2,\ m_3 + n_3); \quad (8)$$

$$M \Theta N = (m_1 - n_1, m_2 - n_2,\ m_3 - n_3); \quad (9)$$

$$M \otimes N = (m_1 n_1, m_2 n_2,\ m_3 n_3); \quad (10)$$

$$M \oslash N = (m_1/n_1,\ m_2/n_2,\ m_3/n_3). \quad (11)$$

4.2. Linguistic variables

A linguistic variable is defined as a variable whose values are described qualitatively. This concept is very useful for real world problems where many of the decision criteria are either complex or not precisely known. In these situations, the appropriate alternatives for mathematical modeling in a vague and fuzzy environment are very difficult to judge. The concept of linguistic values introduced by Zadeh (1965) aims at the conversion of fuzzy situations to conventional quantitative expressions that provide a suitable way to evaluate alternatives and criteria.

Linguistic fuzzy variables are often denoted on a fuzzy scale that expresses the relative importance of relative weights. For example, a linguistic scale of "very small (VS)", "too small (TS)", "smaller than equal (SE)", "equally important (EI)", "exactly equal (EE)", "larger than equal (LE)", "too large (TL)", and "very large (VL)" indicates the relative importance of various criteria or sub criteria. A graphical representation of a triangular membership function and fuzzy linguistic scale of importance is shown in Fig. 2 and Table 1.

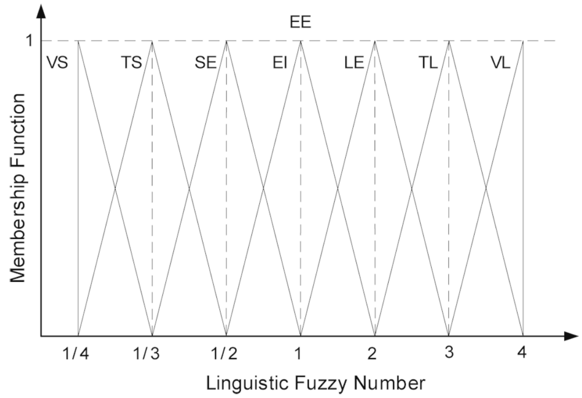

Fig. 2. Graphical representation of triangular membership function for importance

Table 1. Linguistic expression of triangular fuzzy scale and reciprocal scale

Linguistic Expression	Triangular Fuzzy Scale	Triangular fuzzy reciprocal scale
Very Small (VS)	(1/4, 1/4, 1/3)	(3, 4, 4)
Too Small (TS)	(1/4, 1/3, 1/2)	(2, 3, 4)
Smaller than Equal (SE)	(1/3, 1/2, 1)	(1, 2, 3)
Equally Important (EI)	(1/2, 1, 2)	(1/2, 1, 2)
Exactly Equal (EE)	(1, 1, 1)	(1, 1, 1)
Equally Important (EI)	(1/2, 1, 2)	(1/2, 1, 2)
Larger than Equal (LE)	(1, 2, 3)	(1/3, 1/2, 1)
Too Large (TL)	(2, 3, 4)	(1/4, 1/3, 1/2)
Very Large (VL)	(3, 4, 4)	(1/4, 1/4, 1/3)

4.3. Fuzzy weight of criteria

Buckley (1985) offered a method to measure the relative weights scale using geometric row mean. Buckley's approach is often advantageous because its solution is unique and can be applied to both triangular and trapezoidal fuzzy numbers.

If a reciprocal matrix, $A = [a_{ij}]$, for various criteria, as well as sub-criteria, is given, the geometric mean for each row is determined by:

$$r_i = \left(\sum_{j=1}^{m} a_{ij}\right)^{1/m} \quad \text{for all } i, \quad (12)$$

where m is the number of decision criteria.

Then, fuzzy weight, w_i, is given as:

$$w_i = r_i \varnothing (r_1 \oplus \ldots \oplus r_m). \quad (13)$$

This fuzzy appropriate index (FAI) was introduced by Chan *et al.* (2000) to account for the uncertainties in justifying alternatives and criteria by aggregating the hierarchy over all the criteria. If S_{tm} is the weight of an alternative, A_t, under criterion C_m, then the FAI_t for each alternative is given as follows:

$$FAI_t = \left(\frac{1}{k}\right) \otimes \left[(S_{t1} \otimes W_1) \oplus (S_{t2} \otimes W_2) \oplus \cdots \oplus (S_{tm} \otimes W_m)\right]. \quad (14)$$

4.4. Ranking triangular fuzzy numbers

In many practical applications, a ranking method that can give the possible distribution of alternatives is essential for decision makers. As we discussed, the fuzzy appropriate index provides a method to measure the aggregated fuzzy sets over all the alternatives. Thus, the integrated FAI obtained from all the alternatives and their rankings can be used as the best alternative.

However, it is sometimes difficult to interpret a fuzzy situation for a well-accepted choice because comparing fuzzy quantities is subjective. Accordingly, comparison and choice of the best alternatives might reflect the decision maker's point of view and reflect whether her/his personal preference is optimistic or pessimistic.

Kim and Park (1990) proposed a ranking method for comparing fuzzy numbers considering the possible deviation between the left and right sides of the membership functions. This method makes the calculations simple, but it also does not lose information about the decision maker's bias.

To represent a decision maker with an optimistic point of view, let $G_{max} = \{x \setminus f_{G_{max}}(x)\}$ be the maximizing set of x and the grade of membership of point x in G_{max} can be given as follows:

$$f_{G_{max}}(x) = \frac{x - x_{min}}{x_{max} - x_{min}}. \quad (15)$$

For a pessimistic point of view, G_{min} can be similarly defined as the minimizing set and the grade of membership of point x in G_{min} can be given as follows:

$$f_{G_{min}}(x) = \frac{x_{max} - x}{x_{max} - x_{min}}. \quad (16)$$

Also, if $\overline{D} = \{x \setminus f_D(x)\}$ is defined as the fuzzy decision set, then the grade membership of the decision set can be expressed by:

$$f_D(x) = k \cdot f_{D_o}(x) + (1-k) \cdot f_{D_p}(x), \quad (17)$$

where k is an index such that $k = 1$ represents an optimist and $k = 0$ represents a pessimist, f_{D_0} is the membership of the optimist's decision set, f_{D_p} is the membership of the pessimist's decision set, and n is a fuzzy constraint.

5. Scenario-based decision making application: an example

A decision-making problem for selecting wireless technology is designed to implement the multi-criteria fuzzy method described in the previous section. Although wireless technologies have qualitative benefits over conventional methods when deployed in remote construction assets tracking, a comprehensive approach for measuring the expected values has not been fully provided to many construction engineers. This may be critical for decision makers in planning, operating, and controlling the construction process when diverse technologies are available.

This chapter describes a case study of scenario-based decision making process for real world application. This approach deals with variability at a construction site level when a construction field manager tries to select the wireless technologies available in the market. In order to conduct this case study, we first described the hypothetical construction project that wireless technologies would be adopted for assets tracking practices in the construction sites. Then we developed a parameter modeling for decision making scenario taking into consideration the decision criteria and functional properties of the system. Also, the decision making procedure mentioned in the previous chapter was illustrated. Finally, the results obtained from the multi-criteria decision making approach was discussed.

While this case study elaborates a decision making process based on a hypothetical scenario with assumed project parameters, the approach with a multi-criteria fuzzy method could provide an illustration from which decision makers in a construction site can benefit for their practical application.

5.1. Application scenario of WSN selection

Construction sites are generally characterized as a large-scale application domain with complicated site layout and heterogeneous obstructions. Examples are the physical size of construction site that is even larger than several hundreds of thousands square meters, and the construction environment has a variety of irregular obstructions with different shapes, geographical locations, material properties and dielectric characteristics. Such complicated nature of construction environment often challenge the adoption of wireless technologies in various applications because wireless signal experiences signal attenuation, distortion and multipath through/from various types of obstructions, such as construction walls, equipment, temporary structures, and constructed facilities. These obstructions are randomly placed in all around a construction site, affecting the reliability of wireless signal. In a decision making process, therefore, the site manager needs to put careful considerations in designing the fuzzy model based on the realistic decision parameters and technology capabilities. Examples include quantitative analysis and performance investigation on the recent wireless technologies for the efficient and successful adoption.

In order to provide a real-world application scenario, a hypothetical case scenario was adopted to facilitate understanding about the application of the fuzzy decision model presented in this paper for selection of wireless technology for tracking construction materials. The case scenario is a site relative to a 6 story residential building built with a reinforced concrete frame structure and precast slabs in open area close to several other residential buildings. The residential building's total construction area is 4354.56 m^2 and the floor area is 725.76 m^2 (57.6 m by 12.6 m). The size of site is an approximate rectangle of 88 m by 33 m including lay down yard and field office. The major types of construction materials need to be tracked are precast concrete, cement bag, steel member, etc. Traditional construction materials tracking mainly rely on costly manual operation and paper lists, which is labor-intensive, error-prone, and time-consuming. Wireless technology for construction materials tracking provides a key to increase productivity, reduce tedious manual operation, avoid delays, and increase profitability.

5.2. Parameter modeling for decision making

Parameter modeling for the decision making process was developed by considering the major characteristics of wireless technology and a typical facility construction project. We first categorized three essential areas: 1) monetary value; 2) functionality of the technology; and 3) operational effort. Monetary values such as device cost, installation cost, and maintenance cost are prior criteria in most construction project because the successful completion of the project is often evaluated by the return on investment. Functionality of the technology is also an important factor, and careful examination about the technology details can enhance the overall functional benefits and application purposes. Signal propagation, attenuation, and obstruction are the unique properties of wireless technology that could affect the formulation of network, measurement accuracy, interoperability, and communication efficiency. Thus, second category of functional factor is divided into three criteria of performance, flexibility and interference. Third category deals with operational efforts needed to use and manage the adopted technology. Qualitative improvements by adopting the new technology are included in this category, such as maintenance and practicability. Life-cycle maintenance strategy and practical usage of the technology are also important factors that could directly affect the field work level to managers and crews when the technology is adopted and placed in the construction site. Summarizing the decision parameters above, the Fig. 3 illustrates the proposed decision making model for selecting wireless technology.

To provide a way to evaluate technology selections, expert interviews of professional construction engineers were conducted to verify the proposed fuzzy-based decision-making model. Detailed descriptions of each criterion are summarized in Chapter 3. The decision model is comprised of six major criteria (C_1 to C_6) with the objective of selecting a wireless device for a material tracking system. In addition, sub-criteria for each major criterion were considered. The relative importance of each major criterion and sub-criterion is described in a linguistic scale with eight alternatives: "very small (VS)", "too small (TS)", "smaller than equal (SE)", "equally important (EI)", "exactly equal (EE)", "larger than equal (LE)", "too large (TL)", and "very large (VL)".

To justify the objectives for the decision-making problems, professional construction engineers were asked to make a recommendation for each criterion as described in Table 2. At the same time, five different wireless technologies were used in this case study to obtain the relative importance of alternatives versus criteria:

RFID device (A_1): The advantage of RFID is that the information stored in the tag can be scanned and read without physical contact with the RFID reader. Unlike a barcode, the tag can be programmed and reused to contain the useful data, providing mobility and convenience to many applications, such as asset tracking, supply chain management, manufacturing control, and fleet management.

GPS device (A_2): Unlike other local/personal area networks, GPS has the unique feature of global accessibility to GPS receivers on a continuous worldwide basis, thus providing accurate positioning capability to an unlimited number of people at anytime. GPS mapping, car navigation, and industrial asset tracking and positioning are the main areas of application.

Wi-Fi device (A_3): Wi-Fi is designed to allow mobile computers, smart phones, or consumer electronics to have access to other devices on the network. The relatively high data rate, interoperability, and Internet protocol security of Wi-Fi are the major advantages to this certified product that has gained acceptance for use in personal home networks, businesses, and industries over the conventional wired LAN.

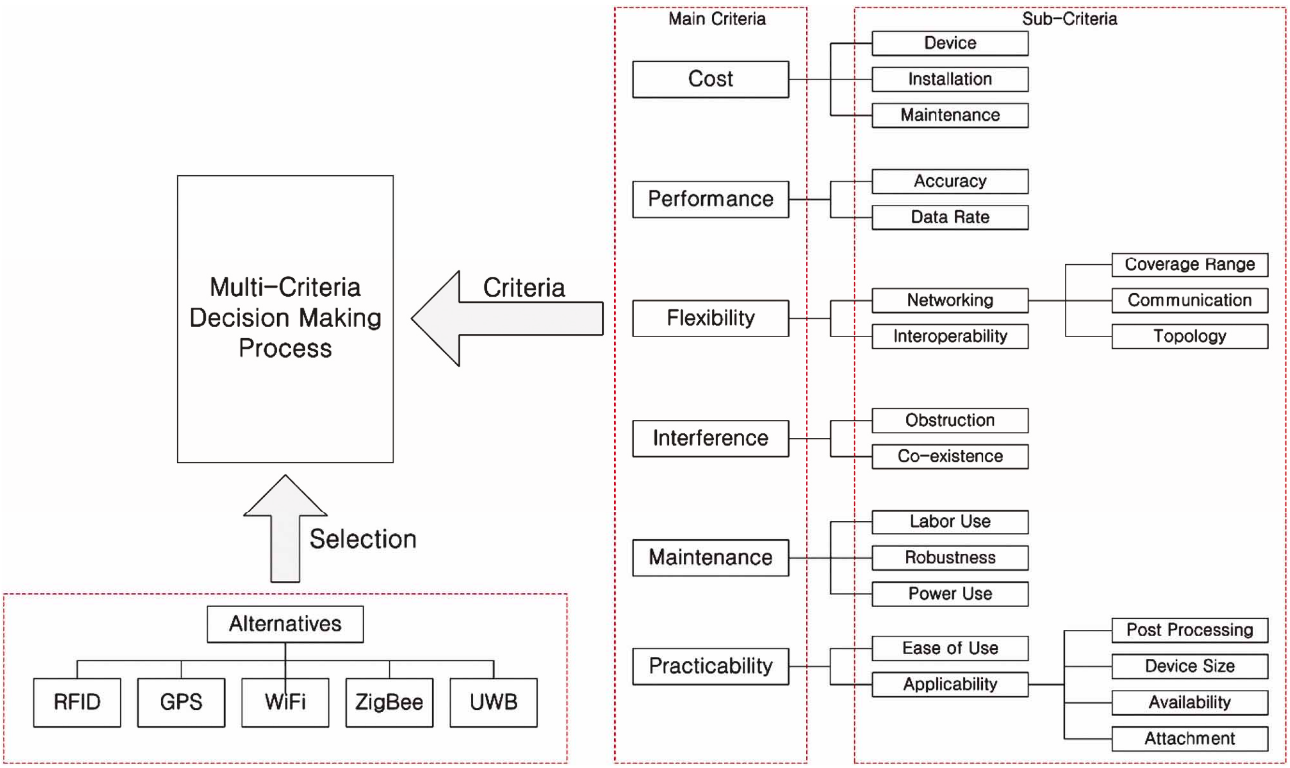

Fig. 3. Proposed decision-making model for selecting wireless technology for a construction assets tracking system

Table 2. Hierarchy of decision criteria and sub-criteria and description

Main Criteria	Sub-Criteria	Bottom-Criteria	Description
Cost (C_1)	Device Cost(C_{11})		A cost for purchase at the beginning stage of construction.
	Installation Cost(C_{12})		A cost needed for the device installation and settings.
	Maintenance Cost(C_{13})		Long-term maintenance cost of the device during construction process.
Performance (C_2)	Accuracy(C_{21})		Positioning accuracy for tracking and monitoring the device attached in materials.
	Data Rate(C_{22})		Amount of data per second transmitted from the device.
Flexibility (C_3)	Networking(C_{31})	Coverage Range(C_{311})	Maximum Transmitter-Receiver separation distance for wireless communication.
		Communication Efficiency(C_{312})	Received signal strength, link quality, data reception rate, communication performance.
		Topology (C_{313})	Expandability and geographic scalability for mesh networking.
	Interoperability(C_{32})		Interoperability with other types of device.
Interference (C_4)	Co-existence(C_{41})		Wireless interference from similar range of bandwidth or frequency.
	Obstruction(C_{42})		Wireless interference from construction materials, built structure, or equipment.
Maintenance (C_5)	Labor Use(C_{51})		Amount of labor hour and efforts required for device maintenance.
	Robustness(C_{52})		Level of survival under harsh environment, such as rain, humidity, or temperature.
	Power Consumption(C_{53})		Power needed for the device to be operated with limited battery condition.
Practicability (C_6)	Ease of Use(C_{61})		Level of easiness to operate the device for general construction engineers.
	Applicability(C_{62})	Post Processing(C_{621})	Time and efforts required to conduct post data processing after data collection.
		Device Size(C_{622})	Unit device size fitted to the construction materials for tracking and monitoring.
		Commercial Availability(C_{623})	Commercial products available in the general market.
		Attachment(C_{624})	Level of attachment to the typical construction materials.

ZigBee device (*A_4*): ZigBee specification is for embedded applications, such as home automation, mobile services, wireless sensing, and ubiquitous solutions. The IEEE802.15.4 protocol is aimed at the inexpensive, self-organizing, expandable mesh networks with the key feature of communication redundancy that could compensate for the risk of a single point failure in wired systems.

UWB device (*A_5*): Unlike a specification using narrow band technology such as 802.11 WLAN or ZigBee, the IEEE802.15.4a UWB in the range 3.1 to 10.6 GHz provides improved WPAN functionalities, such as low energy levels, dynamic channel capacity, a 1 Mbps data rate, and robustness to interference from applications such as home automation, localization, and other wireless solutions.

5.3. Multi-criteria fuzzy analysis and results

Based on the theoretical explanation in Chapter 4, the procedure of the multi-criteria fuzzy analysis is explained below:

Step 1. Identify available alternatives and criteria based on the parameter study for the decision making process. Main criteria are then classified into several sub-criteria to formulate the hierarchical decision model.

Step 2. Define linguistic fuzzy scale to provide quantitative expression for evaluating the alternatives and criteria. Vague and subjective criteria are then converted into relative importance and relative weights.

Step 3. Form a reciprocal matrix A from the judgment of professional experts. The linguistic component of the reciprocal matrix A is then converted into fuzzy numbers.

Step 4. Calculate and normalize the geometric row means and fuzzy weight, and apply them to all the criteria and sub-criteria.

Step 5. Aggregate the relative importance over all the criteria and calculate the fuzzy approximate index for available alternatives.

Step 6. Rank the alternatives by adopting fuzzy approximate index considering the decision maker's attitude in their opinions.

According to the decision criteria and the linguistic scale, the expert's opinions in a linguistic description were firstly converted into a reciprocal matrix that was formulated by fuzzy numbers. Then, the geometric row mean as described in Eq. (12) was applied to measure the fuzzy weights of the major criteria and sub-criteria. The fuzzy weights of all the criteria at each level and the fuzzy weight evaluation of each technology alternative are shown in Tables 3 and 4, respectively.

Table 3. Geometric row mean and fuzzy weights for each criterion

Criteria	Geometric Row Mean	Fuzzy Weight
C_1	(0.74, 1.20, 1.91)	(0.07, 0.17, 0.42)
C_2	(0.89, 1.35, 2.00)	(0.09, 0.19, 0.44)
C_3	(0.33, 0.39, 0.55)	(0.03, 0.06, 0.12)
C_4	(0.44, 0.59, 0.89)	(0.04, 0.08, 0.19)
C_5	(1.44, 2.24, 2.75)	(0.14, 0.32, 0.60)
C_6	(0.74, 1.20, 1.91)	(0.07, 0.17, 0.42)
C_{11}	(1.44, 2.00, 2.29)	(0.33, 0.57, 0.89)
C_{12}	(0.44, 0.50, 0.69)	(0.10, 0.14, 0.27)
C_{13}	(0.69, 1.00, 1.44)	(0.16, 0.29, 0.56)
C_{21}	(1.00, 1.41, 1.73)	(0.37, 0.67, 1.10)
C_{22}	(0.58, 0.71, 1.00)	(0.21, 0.33, 0.63)
C_{31}	(0.71, 1.00, 1.41)	(0.25, 0.50, 1.00)
C_{32}	(0.71, 1.00, 1.41)	(0.25, 0.50, 1.00)
C_{41}	(0.71, 1.00, 1.41)	(0.25, 0.50, 1.00)
C_{42}	(0.71, 1.00, 1.41)	(0.25, 0.50, 1.00)
C_{51}	(1.26, 1.82, 2.29)	(0.28, 0.53, 0.90)
C_{52}	(0.87, 1.14, 1.59)	(0.19, 0.33, 0.63)
C_{53}	(0.40, 0.48, 0.63)	(0.09, 0.14, 0.25)
C_{61}	(1.41, 1.73, 2.00)	(0.52, 0.75, 1.04)
C_{62}	(0.50, 0.58, 0.71)	(0.18, 0.25, 0.37)
C_{311}	(0.40, 0.44, 0.55)	(0.09, 0.12, 0.20)
C_{312}	(0.87, 1.14, 1.59)	(0.20, 0.32, 0.59)
C_{313}	(1.44, 2.00, 2.29)	(0.33, 0.56, 0.84)
C_{621}	(1.19, 1.86, 2.45)	(0.19, 0.43, 0.87)
C_{622}	(0.50, 0.76, 1.19)	(0.08, 0.18, 0.42)
C_{623}	(0.49, 0.71, 1.19)	(0.08, 0.16, 0.42)
C_{624}	(0.64, 1.00, 1.57)	(0.10, 0.23, 0.56)

Using fuzzy weights, the fuzzy approximate index (FAI) was adopted and calculated using Eq. (14) to measure the aggregated fuzzy sets over all the alternatives. The accumulation of fuzzy weights in FAI provides insight into how much the membership function of triangular numbers are biased to the left or right hand sides and where the highest function value is located. Adopting Kim and Park's approach, each alternative can be ranked in order of FAI; the largest FAI with the maximum membership function value is ranked highest (Fig. 4). The ranking index values for technologies A_1 to A_6 are summarized in Table 5.

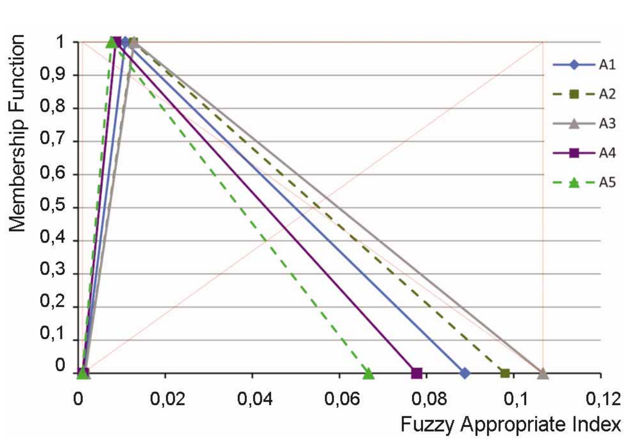

Fig. 4. Aggregated fuzzy appropriate index (FAI) of each alternative

Table 4. Fuzzy weights for each alternative based on each level of criterion

Criteria	A_1	A_2	A_3	A_4	A_5
C_{11}	(0.13, 0.32, 0.66)	(0.05, 0.10, 0.26)	(0.07, 0.15, 0.35)	(0.12, 0.28, 0.64)	(0.07, 0.15, 0.35)
C_{12}	(0.06, 0.12, 0.26)	(0.06, 0.09, 0.17)	(0.09, 0.17, 0.34)	(0.21, 0.38, 0.64)	(0.14, 0.25, 0.42)
C_{13}	(0.23, 0.40, 0.64)	(0.15, 0.27, 0.48)	(0.10, 0.17, 0.32)	(0.06, 0.10, 0.19)	(0.04, 0.06, 0.11)
C_{21}	(0.07, 0.13, 0.30)	(0.19, 0.40, 0.70)	(0.08, 0.17, 0.43)	(0.05, 0.08, 0.18)	(0.10, 0.22, 0.49)
C_{22}	(0.04, 0.06, 0.13)	(0.11, 0.22, 0.46)	(0.17, 0.34, 0.61)	(0.06, 0.10, 0.21)	(0.13, 0.28, 0.56)
C_{311}	(0.08, 0.17, 0.36)	(0.22, 0.43, 0.71)	(0.09, 0.20, 0.44)	(0.06, 0.12, 0.27)	(0.05, 0.09, 0.20)
C_{312}	(0.04, 0.06, 0.12)	(0.12, 0.25, 0.49)	(0.20, 0.39, 0.68)	(0.08, 0.15, 0.31)	(0.08, 0.15, 0.31)
C_{313}	(0.04, 0.06, 0.11)	(0.06, 0.09, 0.17)	(0.12, 0.21, 0.39)	(0.23, 0.40, 0.63)	(0.13, 0.23, 0.44)
C_{32}	(0.04, 0.07, 0.13)	(0.08, 0.14, 0.28)	(0.22, 0.41, 0.67)	(0.13, 0.25, 0.48)	(0.07, 0.13, 0.29)
C_{41}	(0.04, 0.06, 0.11)	(0.07, 0.12, 0.25)	(0.11, 0.22, 0.45)	(0.11, 0.22, 0.45)	(0.19, 0.38, 0.65)
C_{42}	(0.05, 0.09, 0.20)	(0.07, 0.16, 0.36)	(0.23, 0.44, 0.76)	(0.07, 0.16, 0.36)	(0.07, 0.16, 0.36)
C_{51}	(0.10, 0.22, 0.51)	(0.15, 0.33, 0.67)	(0.11, 0.25, 0.58)	(0.05, 0.11, 0.27)	(0.05, 0.09, 0.19)
C_{52}	(0.09, 0.17, 0.35)	(0.20, 0.40, 0.70)	(0.11, 0.24, 0.50)	(0.06, 0.12, 0.26)	(0.04, 0.07, 0.15)
C_{53}	(0.20, 0.40, 0.70)	(0.07, 0.14, 0.31)	(0.05, 0.07, 0.16)	(0.12, 0.26, 0.50)	(0.07, 0.14, 0.31)
C_{61}	(0.11, 0.26, 0.60)	(0.06, 0.13, 0.32)	(0.15, 0.34, 0.69)	(0.07, 0.18, 0.46)	(0.05, 0.10, 0.22)
C_{621}	(0.13, 0.31, 0.66)	(0.07, 0.16, 0.40)	(0.12, 0.29, 0.66)	(0.07, 0.16, 0.40)	(0.04, 0.08, 0.20)
C_{622}	(0.26, 0.45, 0.72)	(0.08, 0.18, 0.37)	(0.05, 0.10, 0.22)	(0.08, 0.18, 0.37)	(0.05, 0.10, 0.22)
C_{623}	(0.05, 0.09, 0.19)	(0.09, 0.19, 0.39)	(0.22, 0.41, 0.67)	(0.12, 0.22, 0.47)	(0.05, 0.08, 0.16)
C_{624}	(0.17, 0.39, 0.75)	(0.07, 0.18, 0.45)	(0.06, 0.12, 0.32)	(0.09, 0.21, 0.49)	(0.05, 0.10, 0.25)

Table 5. Ranking values from the FAI on five alternatives according to the decision maker's attitude ($k = 1$ for optimist, $k = 0$ for pessimist, and $k = 0.5$ for neutral person)

Alternative	Membership function for $k = 1$ (rank)	Membership function for $k = 0$ (rank)	Membership function for $k = 0.5$ (rank)
RFID (A_1)	0.478 (3)	0.915 (3)	0.696 (3)
GPS (A_2)	0.508 (2)	0.900 (4)	0.704 (2)
WI-FI (A_3)	0.530 (1)	0.899 (5)	0.714 (1)
Zigbee (A_4)	0.439 (4)	0.933 (2)	0.686 (4)
UWB (A_5)	0.399 (5)	0.941 (1)	0.670 (5)

The results of the rankings show that alternative A_3 for optimists and neutral persons is the best choice for a long-distance material tracking solution, whereas alternative A_5 is the best selection for pessimists. Although there are a variety of factors that might affect the rankings depending on a person's subjective point of view, the accumulated fuzzy weight and fuzzy appropriate index obtained from the subjective opinion of the experts provided insight into the best selection among the various alternatives. Consequently, the multi-criteria decision-making approach applied in this research might assist decision maker's to select the best alternative from among the many available technologies for which the expected benefits and advantages are vague or undetermined. It should be noted that the five alternatives in this research were the selection of the available technologies that could be perceived as practical devices having general functionality and performance for application to construction material tracking. Thus, the results might be different for other industries or applications.

6. Conclusions

The current practice of manually collecting monitoring data is error-prone, expensive, inaccurate, and inefficient. The recent advent of wireless technologies offers an advanced method of data collection with multiple benefits for optimizing productivity, cost savings, safety, and security applications with improved efficiency and effectiveness. While the multiple functionalities and services that wireless technologies provide have potential application to construction applications, it is difficult to select one unique decision for selecting wireless technologies. With this motivation, this research proposes a multi-criteria fuzzy decision-making model for selecting the wireless technology for tracking construction assets to obtain a suitable decision from among the various alternatives.

In the decision-making model, six major criteria were selected and each criterion was then divided into several sub-criteria to represent detailed decision factors. Using a multi-criteria fuzzy method, qualitative opinions were converted to fuzzy numbers to generate fuzzy weights and a fuzzy approximate index (FAI). Based on the aggregated FAI, five alternative technologies were ranked based on three decision maker's perspectives. The rankings showed that Wi-Fi (alternative A_3) was the best choice for a wireless tracking solution for optimists and neutral persons, whereas UWB (alternative A_5) was the best selection for pessimists. Although these results may differ depending on the responder, application area, and decision criteria, the output obtained from the proposed decision-making model and approach might be helpful to general construction engineers in judging the relative importance of various criteria and alternatives specified in this research.

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Appendix: List of Relative Importance on Each Criterion

1. Relative importance of C_1, C_2, C_3, C_4, C_5, and C_6

	C_1	C_2	C_3	C_4	C_5	C_6
C_1	EE	EI	TL	LE	SE	EI
C_2	EI	EE	VL	TL	SE	EI
C_3	TS	VS	EE	SE	VS	TS
C_4	SE	TS	LE	EE	VS	SE
C_5	LE	LE	VL	VL	EE	LE
C_6	EI	EI	TL	LE	SE	EE

2. In cost factor (C_1), relative importance of C_{11}, C_{12}, and C_{13}

	C_{11}	C_{12}	C_{13}
C_{11}	EE	VL	LE
C_{12}	VS	EE	SE
C_{13}	SE	LE	EE

3. In performance factor (C_2), relative importance of C_{21} and C_{22}

	C_{21}	C_{22}
C_{21}	EE	LE
C_{22}	SE	EE

4. In flexibility factor (C_3), relative importance of C_{31} and C_{32}

	C_{31}	C_{32}
C_{31}	EE	EI
C_{32}	EI	EE

5. In interference factor (C_4), relative importance of C_{41} and C_{42}

	C_{41}	C_{42}
C_{41}	EE	EI
C_{42}	EI	EE

6. In maintenance factor (C_5), relative importance of C_{51}, C_{52}, and C_{53}

	C_{51}	C_{52}	C_{53}
C_{51}	EE	LE	TL
C_{52}	SE	EE	TL
C_{53}	TS	TS	EE

7. In practicability factor (C_6), relative importance of C_{61} and C_{62}

	C_{61}	C_{62}
C_{61}	EE	TL
C_{62}	TS	EE

8. In network flexibility factor (C_{31}), relative importance of C_{311}, C_{312}, and C_{313}

	C_{311}	C_{312}	C_{313}
C_{311}	EE	TS	VS
C_{312}	TL	EE	SE
C_{313}	VL	LE	EE

9. In applicability factor (C_{62}), relative importance of C_{621}, C_{622}, C_{623}, and C_{624}

	C_{621}	C_{622}	C_{623}	C_{624}
C_{621}	EE	TL	LE	LE
C_{622}	TS	EE	EI	EI
C_{623}	SE	EI	EE	SE
C_{624}	SE	EI	LE	EE

10. Relative importance of A_1, A_2, A_3, A_4, and A_5 based on C_{11}

	A_1	A_2	A_3	A_4	A_5
A_1	EE	VL	LE	EI	LE
A_2	VS	EE	SE	EI	SE
A_3	SE	LE	EE	TS	EI
A_4	EI	EI	TL	EE	TL
A_5	SE	LE	EI	TS	EE

11. Relative importance of A_1, A_2, A_3, A_4, and A_5 based on C_{12}

	A_1	A_2	A_3	A_4	A_5
A_1	EE	SE	EI	EI	VS
A_2	LE	EE	TS	VS	VS
A_3	EI	TL	EE	VS	EI
A_4	EI	VL	VL	EE	TL
A_5	VL	VL	EI	TS	EE

12. Relative importance of A_1, A_2, A_3, A_4, and A_5 based on C_{13}

	A_1	A_2	A_3	A_4	A_5
A_1	EE	LE	TL	VL	VL
A_2	SE	EE	LE	TL	VL
A_3	TS	SE	EE	LE	VL
A_4	VS	TS	SE	EE	LE
A_5	VS	VS	VS	SE	EE

13. Relative importance of A_1, A_2, A_3, A_4, and A_5 based on C_{21}

	A_1	A_2	A_3	A_4	A_5
A_1	EE	VS	EI	LE	SE
A_2	VL	EE	LE	VL	LE
A_3	EI	SE	EE	LE	EI
A_4	SE	VS	SE	EE	TS
A_5	LE	SE	EI	TL	EE

14. Relative importance of A_1, A_2, A_3, A_4, and A_5 based on C_{22}

	A_1	A_2	A_3	A_4	A_5
A_1	EE	VS	VS	SE	VS
A_2	VL	EE	SE	LE	EI
A_3	VL	LE	EE	VL	EI
A_4	LE	SE	VS	EE	TS
A_5	VL	EI	EI	TL	EE

15. Relative importance of A_1, A_2, A_3, A_4, and A_5 based on C_{311}

	A_1	A_2	A_3	A_4	A_5
A_1	EE	VS	EI	LE	LE
A_2	VL	EE	LE	TL	VL
A_3	EI	SE	EE	LE	LE
A_4	SE	TS	SE	EE	LE
A_5	SE	VS	SE	SE	EE

16. Relative importance of A_1, A_2, A_3, A_4, and A_5 based on C_{312}

	A_1	A_2	A_3	A_4	A_5
A_1	EE	VS	VS	TS	TS
A_2	VL	EE	SE	LE	LE
A_3	VL	LE	EE	TL	TL
A_4	TL	SE	TS	EE	EI
A_5	TL	SE	TS	EI	EE

17. Relative importance of A_1, A_2, A_3, A_4, and A_5 based on C_{313}

	A_1	A_2	A_3	A_4	A_5
A_1	EE	SE	VS	VS	VS
A_2	LE	EE	TS	VS	TS
A_3	VL	TL	EE	TS	EI
A_4	VL	VL	TL	EE	LE
A_5	VL	TL	EI	SE	EE

18. Relative importance of A_1, A_2, A_3, A_4, and A_5 based on C_{32}

	A_1	A_2	A_3	A_4	A_5
A_1	EE	TS	VS	VS	SE
A_2	TL	EE	VS	SE	EI
A_3	VL	VL	EE	LE	TL
A_4	VL	LE	SE	EE	LE
A_5	LE	EI	TS	SE	EE

19. Relative importance of A_1, A_2, A_3, A_4, and A_5 based on C_{41}

	A_1	A_2	A_3	A_4	A_5
A_1	EE	TS	VS	VS	VS
A_2	TL	EE	SE	SE	VS
A_3	VL	LE	EE	EI	SE
A_4	VL	LE	EI	EE	SE
A_5	VL	VL	LE	LE	EE

20. Relative importance of A_1, A_2, A_3, A_4, and A_5 based on C_{42}

	A_1	A_2	A_3	A_4	A_5
A_1	EE	SE	VS	SE	SE
A_2	LE	EE	TS	EI	EI
A_3	VL	TL	EE	TL	TL
A_4	LE	EI	TS	EE	EI
A_5	LE	EI	TS	EI	EE

21. Relative importance of A_1, A_2, A_3, A_4, and A_5 based on C_{51}

	A_1	A_2	A_3	A_4	A_5
A_1	EE	SE	EI	LE	TL
A_2	LE	EE	EI	TL	VL
A_3	EI	EI	EE	LE	TL
A_4	SE	TS	SE	EE	EI
A_5	TS	VS	TS	EI	EE

22. Relative importance of A_1, A_2, A_3, A_4, and A_5 based on C_{52}

	A_1	A_2	A_3	A_4	A_5
A_1	EE	TS	SE	LE	TL
A_2	TL	EE	LE	TL	VL
A_3	LE	SE	EE	LE	TL
A_4	SE	TS	SE	EE	LE
A_5	TS	VS	TS	SE	EE

23. Relative importance of A_1, A_2, A_3, A_4, and A_5 based on C_{53}

	A_1	A_2	A_3	A_4	A_5
A_1	EE	TL	VL	LE	TL
A_2	TS	EE	LE	SE	EI
A_3	VS	SE	EE	VS	SE
A_4	SE	LE	VL	EE	LE
A_5	TS	EI	LE	SE	EE

24. Relative importance of A_1, A_2, A_3, A_4, and A_5 based on C_{61}

	A_1	A_2	A_3	A_4	A_5
A_1	EE	LE	EI	EI	TL
A_2	SE	EE	TS	EI	EI
A_3	EI	TL	EE	LE	VL
A_4	EI	EI	SE	EE	LE
A_5	TS	EI	VS	SE	EE

25. Relative importance of A_1, A_2, A_3, A_4, and A_5 based on C_{621}

	A_1	A_2	A_3	A_4	A_5
A_1	EE	LE	EI	LE	VL
A_2	SE	EE	SE	EI	LE
A_3	EI	LE	EE	LE	TL
A_4	SE	EI	SE	EE	LE
A_5	VS	SE	TS	SE	EE

26. Relative importance of A_1, A_2, A_3, A_4, and A_5 based on C_{622}

	A_1	A_2	A_3	A_4	A_5
A_1	EE	TL	VL	TL	VL
A_2	TS	EE	LE	EI	LE
A_3	VS	SE	EE	SE	EI
A_4	TS	EI	LE	EE	LE
A_5	VS	SE	EI	SE	EE

27. Relative importance of A_1, A_2, A_3, A_4, and A_5 based on C_{623}

	A_1	A_2	A_3	A_4	A_5
A_1	EE	SE	VS	TS	EI
A_2	LE	EE	TS	EI	TL
A_3	VL	TL	EE	LE	VL
A_4	TL	EI	SE	EE	TL
A_5	EI	TS	VS	TS	EE

28. Relative importance of A_1, A_2, A_3, A_4, and A_5 based on C_{624}

	A_1	A_2	A_3	A_4	A_5
A_1	EE	LE	TL	LE	VL
A_2	SE	EE	EI	EI	LE
A_3	TS	EI	EE	SE	EI
A_4	SE	EI	LE	EE	LE
A_5	VS	SE	EI	SE	EE

BELAIDŽIO RYŠIO TECHNOLOGIJŲ ATRANKA STATYBINĖMS MEDŽIAGOMS STEBĖTI, TAIKANT NEAPIBRĖŽTŲJŲ AIBIŲ SPRENDIMO MODELĮ

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S a n t r a u k a

Augant statybos projektų mastui, rankinis dabartinių stebėjimo sistemų duomenų apdorojimo neefektyvumas tampa svarbia problema. Nors naujos belaidžio ryšio technologijos gali sudaryti galimybę įvesti visur prieinamus kompiuterinius ir jutiklių tinklus, naudojamus plataus masto statybos pramonėje, tampa vis sudėtingiau pasirinkti tinkamas technologijas statybinėms medžiagoms stebėti, nes kiekviena technologija atlieka skirtingas funkcijas, skiriasi jų galimybės ir taikymo apimtis. Šiame tyrime siūlomas daugiakriterinis sprendimų priėmimo modelis, kuris, sprendimų priėmimo procesą pasirenkant rinkoje, siūlomas belaidžio ryšio technologijas išskaido į atskirus lygius. Siekiant pagrįsti tam tikros technologijos pasirinkimą, buvo pritaikytas neapibrėžtųjų aibių metodas, pasirenkant geriausią technologiją iš penkių alternatyvų (t. y. RFID, GPS, Wi-Fi, Zigbee ir UWB technologijų). Neapibrėžtumo rangas buvo gautas taikant agreguotą neapibrėžtumo tinkamumo indeksą (FAI), atsižvelgiant į asmens požiūrį (optimistinis, pesimistinis ar neutralus). Gauti rezultatai parodė, kad Wi-Fi technologija yra tinkama optimistams ir neutraliems asmenims, o UWB technologija būtų geresnė alternatyva pesimistams. Šio tyrimo rezultatai gali padėti statybos inžinieriams priimti pagrįstus sprendimus neapibrėžtoje aplinkoje, tokioje kaip statybos aikštelės, ir suranguoti pagal svarbą įvairius kriterijus bei aptartas šiame tyrime alternatyvas.

Reikšminiai žodžiai: belaidis jutiklių tinklas, statybinių medžiagų stebėjimas, sprendimo modelis, neapibrėžtumas.

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