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# Analysis of the benefits, challenges and risks for the integrated use of BIM, RFID and WSN: a mixed method research

Senem Seyis
*Department of Civil Engineering, Faculty of Engineering, Özyeğin University, Istanbul, Turkey, and*

Alperen Mert Sönmez
*Department of Civil Engineering, Faculty of Engineering, Işık University, Istanbul, Turkey*

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## Abstract

**Purpose** – The purpose of this study is to identify, classify and prioritize the benefits, challenges and risks for the integrated use of building information modeling (BIM), radio frequency identification (RFID) and wireless sensor network (WSN) in the architecture, engineering, construction and operation (AECO) industry.

**Design/methodology/approach** – This study relies on the mixed method approach which consists of systematic literature review, semistructured interviews and Delphi technique. A systematic literature review was performed and face-to-face semistructured interviews with seven subject matter experts (SMEs) were conducted for identification and classification purposes. Delphi method was applied in two structured rounds with eleven SMEs for prioritization purpose. These three research techniques were chosen to reach the most accurate data by combining different perspectives on the subject matter. Data gathered by these three methods was triangulated to increase the validity and reliability of this research.

**Findings** – Thirteen benefits, ten challenges and four risks for the integrated use of BIM, RFID and WSN were identified. The results could aid the practitioners and researchers comprehend the pros and cons of this integration by representing SMEs' valuable insights and perspectives about the current and future status, trends, limitations and requirements of the AECO industry. The identified risks and challenges show the requirements for future studies while the benefits demonstrate the capabilities and the potential contributions of this hybrid integration to the AECO industry.

**Originality/value** – The integration of BIM, RFID and WSN is still not commonly implemented in the AECO industry. Some studies focused on this topic; however, none of them reveals the benefits, risks and challenges for integrating BIM, RFID and WSN in a holistic manner. This research makes a significant contribution to the AECO literature and industry by uncovering the benefits, challenges and risks for the integrated use of BIM, RFID and WSN that could increase industry applications.

**Keywords** Building information modeling, Radio frequency identification, Wireless sensor network, IoT, Delphi method, AECO

**Paper type** Research paper

## Introduction

The architecture, engineering, construction and operation (AECO) industry consists of several stakeholders who work together to achieve a unique project. Successful completion

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of construction projects requires collaboration of numerous multidisciplinary team members. For this reason, the information and communication technology (ICT) has become important for the AECO industry in the last decade. ICT allows to ensure communication among stakeholders and accordingly to create a collaborative working environment (Teizer *et al.*, 2020). Using ICT in the construction projects provides continuous, accurate and real-time data sharing among project participants (Costin and Eastman, 2019). This plays a vital role for preventing any disputes arising in the projects, solving conflicts among stakeholders (Gao *et al.*, 2021; Chen *et al.*, 2020) and achieving projects on time and budget (Becerik-Gerber and Rice, 2010; Li *et al.*, 2017).

Studies show that real-time data flow ensures to obtain the most up-to-date project data, promote quality and efficiency of construction process, coordinate all disciplines and achieve the project within the expected duration and budget throughout monitoring construction process in a continuous manner (Mejjaouli and Babiceanu, 2015). Accordingly, real-time data transmission prevents data loss, increases the quality of inter-stakeholder communication and facilitates interdisciplinary information exchange (John *et al.*, 2020; Costin and Eastman, 2019; Rashid *et al.*, 2019; Zhou *et al.*, 2019; Nizetic *et al.*, 2020; Zhou *et al.*, 2021; Chen *et al.*, 2021). Hence, collecting tangible and real-time data from construction sites enables the project delivery process to progress more effectively and efficiently (Zhong *et al.*, 2017; Tang *et al.*, 2019). However, only one technology could not be able to accomplish all these features (Sobral *et al.*, 2018). Therefore, researchers highly suggested to employ the integrated use of building information modeling (BIM), radio frequency identification (RFID) and wireless sensor network (WSN) in the AECO industry (Chang *et al.*, 2018; Sobral *et al.*, 2018; Li *et al.*, 2018; Teizer *et al.*, 2020; Zhou *et al.*, 2021).

BIM is a digital platform that provides a collaborative and integrated working environment for team members from different disciplines throughout the project life cycle (BuildingSMARTalliance, 2010; Seyis, 2020). BIM is becoming widespread in the AECO industry as it boosts the productivity, streamlines processes by removing non-value-added activities such as reworks and defects and accordingly promotes successful project completion (Seyis, 2019). On the other hand, RFID enables objects to be automatically identified through radio waves and information stored on objects that allows their identification and traceability (Fang *et al.*, 2016). Hence, researchers utilize BIM and RFID together to streamline material, equipment and information flows on construction projects (Chen *et al.*, 2020; Zhou *et al.*, 2021; Chen *et al.*, 2021). Similarly, the sensor technology (i.e. WSN) is the other effective and efficient technology to collect real-time data from construction site (Othman and Shazali, 2012; Zhou *et al.*, 2021; Chen *et al.*, 2021; Pan and Zhang, 2021; Wang *et al.*, 2021). WSNs are small, low-cost device networks that are capable of sensing, data processing and communicating (Bashir *et al.*, 2011). Another fact making the use of WSNs attractive in the AECO industry is that WSNs do not need a wired connection to provide communication (Wang *et al.*, 2014). Within the scope of this integration, WSN technology plays an important role in collecting and transmitting continuous, tangible and real-time data, RFID technology supports automatic identification and traceability and BIM provides a digital environment for collaboratively working throughout the project life cycle. Using the integration of these three technologies may decrease the deficiency of each while increase efficiency of each. Accordingly, such an integration ensures optimized project processes that in turn aid to increase project quality and value as well as decrease time and money.

Previous studies mainly examined the integration of BIM and RFID (Li *et al.*, 2017; Costin *et al.*, 2014; Lu *et al.*, 2011; Fang *et al.*, 2016; Chen *et al.*, 2020), or BIM and WSN (Riaz *et al.*, 2014; Cheung *et al.*, 2018; John *et al.*, 2020; Gao *et al.*, 2021), or RFID and WSN (Shin *et al.*, 2011;

Mejjaouli and Babiceanu, 2015; Moon *et al.*, 2018). Major goal of these studies is to ensure continuous information flow throughout the life cycle of the facility. More specifically, BIM and RFID are integrated for the purpose of visualizing, monitoring and tracking real-time data (Zhong *et al.*, 2017; Kanan *et al.*, 2018). Previous studies also implemented the integration of WSN and BIM for construction safety management (Jin *et al.*, 2020; Teizer *et al.*, 2020; Boje *et al.*, 2020; Chen *et al.*, 2021; Yao *et al.*, 2021), facility management (Nizetic *et al.*, 2020; Zhou *et al.*, 2021; Pan and Zhang, 2021; Gao *et al.*, 2021), localization (Rashid, 2019; Zhou *et al.*, 2021), tracking building structural condition (Valinejadshoubi *et al.*, 2019), risk-informed decision-making for infrastructure management (Ham and Kim, 2020) and monitoring building energy consumption (Chang *et al.*, 2020). In addition, some of the prior studies applied the integrated use of WSNs and RFID for various purposes such as promoting traceability of the products or materials (Mejjaouli and Babiceanu, 2015), facilitating supply chain management (Shin *et al.*, 2011), preventing accidents on site (Yeo *et al.*, 2020) and enhancing the performance of internet of things (IoT) which is the network of physical objects (e.g. sensors, tags and software) (Sobral *et al.*, 2018).

The integration of BIM, RFID and WSN is not entirely new subject in the construction management literature and several researchers shed some light into the potential usefulness of such an integration. However, it is still not commonly implemented in the AECO industry. A limited number of studies only applied the integrated use of BIM, RFID and WSN for the purpose of monitoring greenhouse gas emissions (Tao *et al.*, 2018), real-time data acquisition and exchange for construction applications (Teizer *et al.*, 2020) and promoting on-site assembly services through continuous and real-time data sharing among stakeholders (Zhou *et al.*, 2021). Furthermore, one study determined the current and future status of integrating BIM and IoT devices in the AEC industry (Tang *et al.*, 2019). However, the study conducted by Tang *et al.* (2019) only performed a literature review for establishing common emerging areas of application and future directions. Although some studies focused on integrating these advanced technologies (i.e. BIM and RFID, BIM and WSN or WSN and RFID), none of them reveals the benefits, risks and challenges for the integrated use of BIM, RFID and WSN in the AECO industry in a holistic manner. Such a study may provide insightful information about the current and future status, trends, limitations and requirements of the AECO industry and accordingly, could aid the practitioners and researchers comprehend pros and cons of this integration that may expand its applications in the AECO industry.

The research objective of this study is to identify, classify and prioritize the benefits, challenges and risks for the integrated use of BIM, RFID and WSN in the AECO industry. A systematic literature review was performed and face-to-face semistructured interviews with seven international subject matter experts (SMEs) were conducted for the identification and classification purposes while the Delphi method was applied for the prioritization purpose. Prioritization results allow professionals to comprehend the benefits, challenges and risks of this robust integration in a holistic manner. Results of this study may help increase the utilization of the BIM, RFID and WSN integration in the AECO industry which would promote a more efficient and realistic project delivery process by streamlining material, equipment and information flows.

## Research methodology

Research methodology of this study relies on a mixed method approach which consists of systematic literature review, semistructured interviews and Delphi method. These three research techniques were chosen to reach the most accurate data by combining different perspectives on the subject matter, provide a multidimensional insight on the topic and analyze the findings in a qualitative and quantitative manner (Jick, 1979; Fellows and Liu, 2015; Creswell, 2014; Cooper, 2010). Data gathered with these methods was triangulated to increase the validity and reliability of this research (Jick, 1979; Yin, 1994; Denzin, 2009).

*Systematic literature review*

In the first stage of this study, a systematic literature review was performed. The reason of selecting the systematic literature review as a research technique is that this method enables researchers to examine and integrate previous studies on the subject domain and identify and analyze the main issues (Creswell, 2014; Cooper, 2010). In the systematic literature review, certain procedures based on keywords were followed with the aim of mitigating the subjectivity. The identification and selection of the publications are performed in accordance with the following keywords: "IoT," "internet of things," "digital twin," "BIM, RFID and WSN integrat*," "BIM and Sensor," "BIM and RFID," "RFID and WSN," "BIM and WSN," "BIM and RFID integrat*," "BIM and RFID implement*," "linking sensor with other technologies," "challenges of BIM and RFID," "challenges of BIM and WSN," "challenges of WSN and RFID," "risks of BIM and RFID," "risks of WSN and RFID," "risks of BIM and WSN," "benefits of BIM and RFID," "benefits of BIM and WSN," "benefits of RFID and WSN," "advantages of BIM and RFID," "disadvantages of BIM and RFID," "advantages of BIM and WSN," "disadvantages of BIM and WSN," "advantages of WSN and RFID" and "disadvantages of WSN and RFID." Web of Science Core Collection and Scopus databases were used for detecting the publications on this research domain. In the review, publications in English were included, whereas publications in other languages were excluded. After searching the studies, all results were exported to an Excel file. The relevant publications were detected by title and abstract screening as well as full-text screening. Thus, the irrelevant publications were eliminated. Each publication was manually reviewed to extract data, assess its quality and select the ones addressing this subject domain. All publication types were included to perform a comprehensive review. Accordingly, the following sources were included within the scope of the literature review:

- articles published in Q1 and Q2 journals (e.g. journals under American Society of Civil Engineers (ASCE) and Elsevier);
- conference proceedings published by ASCE and the International Council for Research and Innovation in Building and Construction (Conseil International du Bâtiment) (CIB);
- book chapters; and
- scientific reports.

In this manner, publications addressing the relevant topics were analyzed to identify the benefits, challenges and risks for the integrated use of BIM, RFID and WSN in the AECO industry, while publications on the irrelevant topics were excluded from this research. Correspondingly, 62 studies published between 2011 and 2021 were analyzed in this research.

*Face-to-face semistructured interviews*

In the second stage, face-to-face semistructured interviews were conducted with seven international SMEs to determine the benefits, challenges and risks of using the BIM, RFID and WSN integration in the AECO industry. Interviews were chosen as the second research technique because interviews are the essential source of evidence (Yin, 1994) and important mechanisms to build structure into the data collection process (Pettigrew, 1997). Interviewees were selected based on their education level and experience level in the ICT in the AECO industry. Criterion for education level is to have at least bachelor's degree (BSc) (e.g. architecture, civil engineering or mechanical engineering) and/or master's degree (MSc) (e.g. construction management or ICT or smart technologies) and/or Doctor of Philosophy (PhD) (e.g. studies or publications related to the research subject). Criterion for experience level is to have at least five years of professional experience in the ICT in the AECO industry. Further, interviewees have experiences in different countries such as Qatar, Egypt, Bulgaria, Canada, Germany, Russia and United Arab Emirates (UAE). SMEs from various countries provides to collate different perspectives that in turn may allow identifying particular benefits, risks and challenges for the BIM, RFID and WSN integration in the AECO industry. Interviewees' profile is given in Table 1.

Explanatory open-ended interview questions were asked to understand experts' opinion about the benefits, risks and challenges of the BIM, RFID and WSN integration. The interview durations were approximately 1 h. Three of the interviews were conducted face-to-face while four interviews were performed online due to being in different countries. A total of six benefits, nine challenges and four risks for the BIM, RFID and WSN integration was identified from the interviews with SMEs (Sonmez and Seyis, 2019).

*Triangulation*

The results of literature review and interviews were triangulated to identify the benefits, challenges and risks of using the BIM, RFID and WSN integration in the AECO industry. Triangulation was defined by Denzin (2009) as "the application and combination of several research methodologies in the study of the same phenomenon." The reason for triangulating the findings gathered from literature review and interviews is to validate and/or extend the results (Jick, 1979; Denzin, 2009; Yin, 1994). In this step, data triangulation and methodological triangulation were performed (Denzin, 2009; Yin, 1994). Data triangulation was used in this research because information was collected from various sources (e.g. journal articles and conference proceedings) and professionals in different locations (i.e. Canada, Germany, Turkey and UAE) (Denzin, 2009; Yin, 1994). Methodological triangulation was used in this study as different research techniques (i.e. systematic literature review and interviews) were conducted to approach the same topic (i.e. identifying the benefits, challenges and risks for the integrated use of BIM, RFID and WSN in the AECO industry) (Denzin, 2009; Yin, 1994). Data and methodological triangulation show that the findings of literature review are corroborated with the outcomes gathered from the interviews. Accordingly, the results (i.e. the benefits, challenges and risks for the integrated use of BIM, RFID and WSN in the AECO industry) are validated using data and methodological triangulation (Jick, 1979; Denzin, 2009; Yin, 1994).

| Profession | Education level | Title | Experience in ICT (years) | Experience in industry (years) | Location |
|---|---|---|---|---|---|
| Civil engineer | PhD | Assistant Professor | 14 | None | Canada |
| Mechanical engineer | BSc | BIM Consultant | 15 | 23 | Canada |
| Civil engineer | PhD | BIM Coordinator | 9 | 9 | Turkey |
| Mechanical engineer | BSc | BIM Consultant | 15 | 24 | Turkey |
| Architect | MArch | BIM Consultant | 8 | 11 | Turkey |
| Civil engineer | MSc | BIM Manager | 11 | 13 | Germany |
| Civil engineer | MSc | BIM Manager | 14 | 15 | UAE |

**Table 1.**
Interviewees' profile

*Delphi method*

After triangulating the results from systematic literature review and semistructured interviews, Delphi method was applied with the aim of prioritizing the benefits, challenges and risks for the integrated use of BIM, RFID and WSN in the AECO industry. Delphi method was selected as the third research technique because it is a well-organized survey procedure for collecting and estimating qualitative and quantitative information from the SMEs (Hasson and Keeney, 2011; Seyis, 2020). This systematic and interactive research technique allows to collect controlled and anonymous feedback from a preselected group of independent SMEs through structured questionnaires in several rounds (Brown, 1968; Hasson and Keeney, 2011) that ensures to achieve higher reliability, consistency and quality in outputs (Mitchell, 1991; Rowe *et al.*, 1991; Seyis and Ergen, 2017). Specifically, Delphi method is useful where experimental research is unrealistic or unethical or objective data is inaccessible to obtain or where the heterogeneity of participants should be conserved to ensure the validity of the results (Hallowell and Gambatese, 2010).

In this study, Delphi method consists of six steps which are as follows:

(1) to determine the criteria for the qualifications of the panel participants;

(2) to prepare the questionnaire;

(3) to distribute the questionnaire to the panel participants for scoring the benefits, challenges and risks (i.e. first round);

(4) to calculate mean, median and standard deviation values using the scores given in the first round;

(5) to redistribute the questionnaire to the panel participants with the mean values for rescoring (i.e. second round); and

(6) to calculate mean, median, standard deviation, the interrater agreement (IRA) level and significance level statistics using the scores given in the second round.

In the Delphi method, the aim is to reduce the variability of the answers received from the experts and achieve a group consensus. The reliability, validity and trustworthiness of Delphi method are based on the right panel participants who are experts on the subject matter (Brown, 1968; Dalkey, 1969; Hasson and Keeney, 2011; Seyis, 2019). Hence, the first step is to determine the criteria for the profile of the panel participants to decide whether the participants have sufficient knowledge and experience on the subject domain. The criteria for selecting Delphi panel participants were same with the selecting criteria for the interviewees (i.e. education level and experience level). Experts were selected among practitioners and researchers to combine different perspectives and make a heterogeneous group (Seyis, 2020). Based on the Delphi method procedure, 8–12 qualified panel participants are suggested to obtain reliable information (Hallowell and Gambatese, 2010). Accordingly, 11 highly qualified panel participants from five countries were selected according to the predefined criteria. Delphi panel experts' profile can be found in Table 2. Four of the SMEs (i.e. three civil engineers and one mechanical engineer) who participated in the Delphi method were also interviewees. However, this situation does not affect the reliability of the outputs because only the lists of benefits, challenges and risks were identified using the triangulation results of the literature review and interviews and the identities of participants are kept confidential.

In the second step of the Delphi method, the questionnaires including the list of benefits, challenges and risks of BIM, RFID and WSN integration were prepared using the triangulation results of systematic literature review and semistructured interviews. Conducting two rounds is highly recommended to obtain more accurate outputs in the Delphi method (Dalkey *et al.*, 1972;

| Profession | Education level | Title | Experience in ICT (years) | Experience in industry (years) | Location |
|---|---|---|---|---|---|
| Civil engineer | PhD | Assistant Professor | 14 | None | Canada |
| Mechanical engineer | BSc | BIM Consultant | 15 | 23 | Canada |
| Civil engineer | PhD | BIM Manager | 8 | 10 | Russia |
| Architect | BSc | BIM Manager | 11 | 18 | Italy |
| Civil engineer | PhD | Project Coordinator | 7 | 15 | Turkey |
| Mechanical engineer | MSc | BIM Consultant | 15 | 23 | Turkey |
| Architect | BSc | BIM Manager | 18 | 20 | Italy |
| Civil engineer | PhD | Engineering and Design | 23 | 25 | Turkey |
| Civil engineer | MSc | BIM Engineer | 6 | 7 | Turkey |
| Civil engineer | MSc | BIM Manager | 11 | 13 | Germany |
| Civil engineer | PhD | Professor | 18 | 1 | Turkey |

**Table 2.** Delphi panel participants' profile

Seyis and Ergen, 2017) and reach a consensus among SMEs (Hallowell and Gambatese, 2010). In this study, two structured rounds were performed to minimize possible nonconformity and biases among experts in the Delphi method (Dalkey *et al.*, 1972; Seyis *et al.*, 2016; Seyis, 2019, 2020). In the first round, a list of benefits, challenges and risks for the integrated use of BIM, RFID and WSN was presented to the participants who were asked to score by using the five-point Likert scale. In the scoring system for the benefits of BIM, RFID and WSN integration, a score of 1 indicates "no benefit" while a score of 5 indicates to "extremely high level of benefit." In the scoring system for the risks and challenges of the BIM, RFID and WSN integration, a score of 1 corresponds to "no risk/challenge" while a score of 5 corresponds to "extremely high level of risk/challenge." The standard deviation, mean and median values were calculated considering the scores given by the Delphi panel participants. The mean and median values were calculated to analyze the central tendency of the respondents (Dalkey, 1969). The standard deviation ($\sigma$) value was calculated to evaluate the group consensus reached among the Delphi panel participants (Hallowell and Gambatese, 2010). When standard deviation ($\sigma$) drops in consecutive rounds, it shows that consensus has been reached (Hallowell and Gambatese, 2010). A value $\sigma$ less than 1 indicates a high level of consensus is achieved (Vidal *et al.*, 2011; Seyis *et al.*, 2016; Seyis, 2019, 2020). If a consensus is not achieved, it is necessary to make another round for the factors that have not achieved consensus (Hallowell and Gambatese, 2010).

The list of the benefits, challenges and risks of BIM, RFID and WSN integration was redistributed with their mean values based on the scores in the first round to the Delphi panel participants for rescoring. The benefits, risks and challenges of BIM, RFID and WSN integration were ranked according to their mean values calculated from the scores gathered in the second round of Delphi method. Median values were used for ranking if the mean values of the risk or challenges or benefits are equal (Seyis *et al.*, 2016; Seyis, 2019, 2020). Standard deviation values for the benefits, challenges and risks dropped in the second round of Delphi questionnaire that proves a consensus has been achieved among SMEs.

In addition, the IRA level and significance level statistics were calculated for each benefit, challenge and risk of the BIM, RFID and WSN integration to analyze and validate the consensus reached by the Delphi panel participants. Significance level statistics allows the priority rankings to be more meaningful and coherent (Seyis, 2019, 2020). Mean values (M) were used for calculating significance level statistics. The significance level was denoted by the scale interval interpretation which was adopted as follows: "$M \leq 1.5$" stands for "not important," "$1.51 \leq M \leq 2.5$" stands for "somewhat important," "$2.51 \leq M \leq 3.5$" stands for "important," "$3.51 \leq M \leq 4.5$" stands for "very important" and "$M \geq 4.51$" stands for "extremely important" (Li *et al.*, 2013; Seyis, 2019, 2020).

The IRA level and significance level for factors rely on the consensus reached by the expert panel after the second round of Delphi method and validate the results. The IRA analysis range was adopted as follows: "$0.00 \leq r_{wg} \leq 0.30$" stands for "lack of agreement," "$0.31 \leq r_{wg} \leq 0.50$" stands for "weak agreement," "$0.51 \leq r_{wg} \leq 0.70$" stands for "moderate agreement," "$0.71 \leq r_{wg} \leq 0.90$" stands for "strong agreement" and "$0.91 \leq r_{wg} \leq 1.00$" stands for "very strong agreement" (Lebreton and Senter, 2008; Seyis, 2019, 2020). The IRA formula [equation (1)] was used for analyzing and validating the agreement for each factor:

$$r_{wg} = 1 - \frac{2 * \sigma^2}{\{(A+B)M - (M^2) - (A-B)\} * \frac{n}{n-1}} \quad (1)$$

In this formula, "$\sigma$" refers to standard deviation, "A" refers to maximum scale value (i.e. 5), `"B" refers to minimum scale value (i.e. 1), "M" refers to mean value of that benefit or risk or challenge of BIM, RFID and WSN integration and "$n$" (i.e. 11) is the sample size of respondents (Seyis, 2019, 2020).

## Results

### *Identification and classification of the benefits, challenges and risks*

According to the triangulation results of systematic literature review and semistructured interviews, thirteen benefits, ten challenges and four risks for the integrated use of BIM, RFID and WSN in the AECO industry were identified. Tables 3–5 indicate these identified benefits, challenges and risks of this hybrid integration with source of data.

### *Prioritization of the benefits, challenges and risks*

The results obtained from the second round of Delphi method are given in the Tables 6–8. These tables demonstrate the mean value, median value, standard deviation, IRA level and significance level for each benefit, challenge and risk of BIM, RFID and WSN integration in the AECO industry.

## Discussion

SMEs stated that the integrated use of BIM, RFID and WSN would ensure the main contractor to view the physical building information of the project and monitor construction progress in a real time. Hence, the efficiency of interdisciplinary communication would increase dramatically and waste of time and cost could be significantly reduced. Furthermore, this integration allows conducting more effective safety management; and thus, construction risks could be minimized throughout traceability and visualization of data. Therefore, data gathered from the construction site could be stored more reliably and used with more added value.

According to the Delphi method results, B8 (provide effective and continuous data acquisition and transmission by preventing data loss) and B13 (streamline facility management in operation and maintenance phase) have the highest mean values (4.30) among thirteen benefits of BIM, RFID and WSN integration. According to the SMEs, the reason why these two benefits have the highest scores is that this hybrid integration would effectively promote the real-time data flow, and thus, data losses could be reduced at a minimum level. SMEs highlighted that this integration would be an efficient and effective

| Identifier | Benefits | Related source of data |
|---|---|---|
| B1 | Real-time traceability and visibility (e.g. physical building information, building energy consumption and greenhouse gas emissions) | Zhong *et al.* (2017), Tao *et al.* (2018), Louis and Dunston (2018), Xue *et al.* (2018), Xu *et al.* (2018), Han and Ye (2018), Kochovski and Stankovski (2018), Mao *et al.* (2018), Gao *et al.* (2021), Costin and Eastman (2019), Valinejadshoubi *et al.* (2019), Rashid *et al.* (2019), Tang *et al.* (2019), Zhou *et al.* (2019), Chen *et al.* (2020), Francisco *et al.* (2019), John *et al.* (2020), Chang *et al.* (2020), Boje *et al.* (2020), Ham and Kim (2020), Lin and Cheung (2020), Lu *et al.* (2020), Nizetic *et al.* (2020), Zhou *et al.* (2021), Chen *et al.* (2021), Pan and Zhang (2021) |
| B2 | Real-time stock management/quantity monitoring | Fang *et al.* (2016), Zhong *et al.* (2017), Han and Ye (2018), Mao *et al.* (2018), Tang *et al.* (2019), Lin and Cheung (2020), Nizetic *et al.* (2020), Zhou *et al.* (2021) |
| B3 | Localization (i.e. worker, equipment and material) | Ding *et al.* (2013), Fang *et al.* (2016), Zhong *et al.* (2017), Louis and Dunston (2018), Kanan *et al.* (2018), Rashid *et al.* (2019), Zhou *et al.* (2019), Tang *et al.* (2019), Chen *et al.* (2020), Cheng *et al.* (2020), Quinn *et al.* (2020), Teizer *et al.* (2020), Ham and Kim (2020), Lin and Cheung (2020), Ma and Cha (2020), Nizetic *et al.* (2020), Zhou *et al.* (2021), Chen *et al.* (2021) |
| B4 | Real-time visualization/monitoring | Ding *et al.* (2013), Zhong *et al.* (2017), Iacovidou *et al.* (2018), Tao *et al.* (2018), Xu *et al.* (2018), Louis and Dunston (2018), Mao *et al.* (2018), Han and Ye (2018), Kanan *et al.* (2018), Kochovski and Stankovski (2018), Costin and Eastman (2019), Valinejadshoubi *et al.* (2019), Zhou *et al.* (2019), Tang *et al.* (2019), Rashid *et al.* (2019), Francisco *et al.* (2019), John *et al.* (2020), Chen *et al.* (2020), Cheng *et al.* (2020), Gao *et al.* (2021), Chang *et al.* (2020), Jin *et al.* (2020), Ham and Kim (2020), Lin and Cheung (2020), Yeo *et al.* (2020), Lu *et al.* (2020), Nizetic *et al.* (2020), Quinn *et al.* (2020), Teizer *et al.* (2020), Boje *et al.* (2020), Zhou *et al.* (2021), Chen *et al.* (2021), Pan and Zhang (2021), Yao *et al.* (2021) |
| B5 | Real-time data sharing and transmission among various stakeholders | Shin *et al.* (2011), Iacovidou *et al.* (2018), Zhong *et al.* (2017), Han and Ye (2018), Woodhead *et al.* (2018), Xu *et al.* (2018), Kochovski and Stankovski (2018), Tang *et al.* (2019), Zhou *et al.* (2019), Cheng *et al.* (2020), Nizetic *et al.* (2020), Ma and Cha (2020), Jin *et al.* (2020), Zhou *et al.* (2021), Chen *et al.* (2021), Pan and Zhang (2021) |
| B6 | Increase safety | Ding *et al.* (2013), Costin *et al.* (2014), Riaz *et al.* (2014), Riaz *et al.* (2017), Kochovski and |

(*continued*)

**Table 3.**
Benefits of the BIM, RFID and WSN integration

| Identifier | Benefits | Related source of data |
|---|---|---|
| | | Stankovski (2018), Xu *et al.* (2018), Costin and Eastman (2019), Zhou *et al.* (2019), Tang *et al.* (2019), Lin and Cheung (2020), Yeo *et al.* (2020), Okpala *et al.* (2020), Nizetic *et al.* (2020), Jin *et al.* (2020), Teizer *et al.* (2020), Boje *et al.* (2020), Chen *et al.* (2021), Yao *et al.* (2021) |
| B7 | Improve the construction management performance | Woodhead *et al.* (2018), Louis and Dunston (2018), Kochovski and Stankovski (2018), Xu *et al.* (2018), Qi *et al.* (2018), Zhou *et al.* (2019), Tang *et al.* (2019), Lin and Cheung (2020), Boje *et al.* (2020), Jin *et al.* (2020), Chen *et al.* (2020), Teizer *et al.* (2020), Pan and Zhang (2021) |
| B8 | Provide effective and continuous data acquisition and transmission by preventing data loss | Zhong *et al.* (2017), Kochovski and Stankovski (2018), John *et al.* (2020), Costin and Eastman (2019), Rashid *et al.* (2019), Zhou *et al.* (2019), Nizetic *et al.* (2020), Zhou *et al.* (2021), Chen *et al.* (2021), SMEs (semistructured interviews) |
| B9 | Support the logistics management in construction | Zhong *et al.* (2017), Woodhead *et al.* (2018), Han and Ye (2018), Tang *et al.* (2019), Nizetic *et al.* (2020), Cheng *et al.* (2020), Teizer *et al.* (2020), SMEs (semistructured interviews) |
| B10 | Increase productivity | Woodhead *et al.* (2018), Xu *et al.* (2018), Louis and Dunston (2018), Tang *et al.* (2019), Zhou *et al.* (2019), Costin and Eastman (2019), Valinejadshoubi *et al.* (2019), Teizer *et al.* (2020), Ma and Cha (2020), Boje *et al.* (2020), SMEs (semistructured interviews) |
| B11 | Provide easy access to maintenance records, warranties, installation and operation manuals | Zhong *et al.* (2017), Woodhead *et al.* (2018), Han and Ye (2018), Mao *et al.* (2018), Zhou *et al.* (2019), Tang *et al.* (2019), Lin and Cheung (2020), Lu *et al.* (2020), Chen *et al.* (2020), Nizetic *et al.* (2020), Teizer *et al.* (2020), Zhou *et al.* (2021), SMEs (semistructured interviews) |
| B12 | Reduce non-value-added activities (e.g. rework and defect) | Woodhead *et al.* (2018), Xu *et al.* (2018), Louis and Dunston (2018), Tang *et al.* (2019), Boje *et al.* (2020), Nizetic *et al.* (2020), Teizer *et al.* (2020), Zhou *et al.* (2021), SMEs (semistructured interviews) |
| B13 | Streamline facility management in operation and maintenance phase | Woodhead *et al.* (2018), Han and Ye (2018), Tang *et al.* (2019), Costin and Eastman (2019), Tang *et al.* (2019), Francisco *et al.* (2019), Boje *et al.* (2020), Teizer *et al.* (2020), Gao *et al.* (2021), Lu *et al.* (2020), Cheng *et al.* (2020), Quinn *et al.* (2020), Nizetic *et al.* (2020), Zhou *et al.* (2021), Pan and Zhang (2021), SMEs (semistructured interviews) |

**Table 3.**

management tool for the facility managers. Hence, B11 (provide easy access to maintenance records, warranties, installation and operation manuals) is ranked as the third benefit and its mean value is 4.10. B12 (reduce non-value-added activities [e.g. rework and defect]), ranked as the fourth benefit, has a high mean value (4.00) because the BIM, RFID and WSN integration allows data visualization, traceability and tangible data acquisition. In this

**Table 4.** Challenges of the BIM, RFID and WSN integration

| Identifier | Challenges | Related source of data |
|---|---|---|
| C1 | Heavy infrastructure on site for data processing and visualization | Fang *et al.* (2016), Zhou *et al.* (2019) |
| C2 | Lack of effective strategy for visualizing location information | Zhou *et al.* (2019), SMEs (semistructured interviews) |
| C3 | Long-range data transmission | Zhong *et al.* (2017), Zhou *et al.* (2019), Boje *et al.* (2020), John *et al.* (2020), SMEs (semistructured interviews) |
| C4 | High initial cost of installing such an integrated system | Woodhead *et al.* (2018), Costin and Eastman (2019), Valinejadshoubi *et al.* (2019), John *et al.* (2020), SMEs (semistructured interviews) |
| C5 | Lack of trained personnel | Woodhead *et al.* (2018), Teizer *et al.* (2020) Wang *et al.*, 2021; SMEs (semistructured interviews) |
| C6 | Steel structures (i.e. RFID frequency reflection) | Zhou *et al.* (2019), SMEs (semistructured interviews) |
| C7 | Constant Wi-Fi connection on-site | Woodhead *et al.* (2018), Zhou *et al.* (2019), Tang *et al.* (2019), John *et al.* (2020), SMEs (semistructured interviews) |
| C8 | Periodically system update requirement | Woodhead *et al.* (2018), Tang *et al.* (2019) SMEs (semistructured interviews) |
| C9 | Different user interfaces | Zhong *et al.* (2017), Boje *et al.* (2020), Gao *et al.* (2021), SMEs (semistructured interviews) |
| C10 | High cost of the data solutions, especially, for the large-scale construction projects | Gao *et al.* (2021), SMEs (semistructured interviews) |

**Table 5.** Risks of the BIM, RFID and WSN integration

| Identifier | Risks | Related source of data |
|---|---|---|
| R1 | Cybersecurity (i.e. cyberattack on the software platform) | Woodhead *et al.* (2018), Kochovski and Stankovski (2018), John *et al.* (2020), Boje *et al.* (2020), Nizetic *et al.* (2020), Gao *et al.* (2021), SMEs(semistructured interviews) |
| R2 | A software breakdown | Kochovski and Stankovski (2018), Gao *et al.* (2021), SMEs (semistructured interviews) |
| R3 | Frequent sensor breakdowns | John *et al.* (2020), SMEs (semistructured interviews) |
| R4 | System interoperability | Xu *et al.* (2018), Tang *et al.* (2019), Costin and Eastman (2019), Boje *et al.* (2020), Gao *et al.* (2021), SMEs (semistructured interviews) |

manner, strong insights into the possible scenarios encountered throughout the project process could be achieved. Accordingly, activity planning and value engineering could be applied more efficiently.

Results of the Delphi method show that C5 (lack of trained personnel) is one of the most important challenges and its mean value is 4.0. SMEs highlighted that all project employees need to have a good training and knowledge about the subject to use these advanced technologies effectively. Otherwise, an efficient use of such an integration could be very

| Rank | Identifier | Benefit | Mean | Median | Σ | $r_{wg}$ | Agreement level | Significance level |
|---|---|---|---|---|---|---|---|---|
| 1 | B8 | Provide effective and continuous data acquisition and transmission by preventing data loss | 4.30 | 4.00 | 0.75 | 0.56 | Moderate agreement | Very important |
| 2 | B13 | Streamline facility management in operation and maintenance phase | 4.30 | 4.00 | 0.45 | 0.84 | Strong agreement | Very important |
| 3 | B11 | Provide easy access to maintenance records, warranties, installation and operation manuals | 4.10 | 4.00 | 0.51 | 0.83 | Strong agreement | Very important |
| 4 | B12 | Reduce non-value-adding activities (e.g. rework and defect) | 4.00 | 4.00 | 0.85 | 0.57 | Moderate agreement | Very important |
| 5 | B2 | Real-time stock management/quantity monitoring | 3.91 | 4.00 | 0.51 | 0.85 | Strong agreement | Very important |
| 6 | B4 | Real-time visualization/ monitoring | 3.91 | 4.00 | 0.51 | 0.85 | Strong agreement | Very important |
| 7 | B1 | Real-time traceability and visibility (e.g. physical building information, building energy consumption, greenhouse gas emissions) | 3.82 | 4.00 | 0.39 | 0.92 | Very Strong agreement | Very important |
| 8 | B5 | Real-time data sharing and transmission among various stakeholders | 3.82 | 4.00 | 0.39 | 0.92 | Very strong agreement | Very important |
| 9 | B7 | Improve construction management performance | 3.82 | 4.00 | 0.83 | 0.63 | Moderate agreement | Very important |
| 10 | B3 | Localization (i.e. worker, equipment, material) | 3.73 | 4.00 | 0.75 | 0.74 | Strong agreement | Very important |
| 11 | B6 | Increase safety | 3.55 | 4.00 | 0.78 | 0.70 | Moderate agreement | Very important |
| 12 | B9 | Support the logistics management in construction | 3.45 | 3.00 | 0.66 | 0.79 | Strong agreement | Important |
| 13 | B10 | Increase productivity | 3.09 | 3.00 | 0.51 | 0.88 | Strong agreement | Important |

**Table 6.**
Priority rankings for the benefits of BIM, RFID and WSN integration

difficult and time-consuming. The second-highest ranked challenge is C4 (high initial cost of installing such an integrated system). The mean value of C4 is 3.82. SMEs specified that the cost of these technologies could increase the initial cost of projects and may cause stakeholders to hesitate to use this integration. Accordingly, “high initial cost of such an

| Rank | Identifier | Challenge | Mean | Median | Σ | $r_{wg}$ | Agreement level | Significance level |
|---|---|---|---|---|---|---|---|---|
| 1 | C5 | Lack of trained personnel | 4.00 | 4.00 | 0.60 | 0.78 | Strong agreement | Very important |
| 2 | C4 | High initial cost of such an integrated system installation | 3.82 | 4.00 | 0.72 | 0.72 | Strong agreement | Very important |
| 3 | C7 | Constant Wi-Fi connection on site | 3.82 | 4.00 | 1.03 | 0.43 | Weak agreement | Very important |
| 4 | C8 | Periodically system update requirement | 3.27 | 3.00 | 0.75 | 0.74 | Strong agreement | Important |
| 5 | C1 | Heavy infrastructure on site for data processing and visualization | 3.18 | 3.00 | 0.39 | 0.93 | Very strong agreement | Important |
| 6 | C6 | Steel structure (i.e. RFID frequency reflection) | 3.09 | 3.00 | 0.29 | 0.96 | Very strong agreement | Important |
| 7 | C10 | High cost of the data solutions, especially, for the large-scale construction projects | 3.09 | 3.00 | 0.67 | 0.80 | Strong agreement | Important |
| 8 | C3 | Long-range data transmission | 2.73 | 3.00 | 0.62 | 0.82 | Strong agreement | Important |
| 9 | C2 | Lack of effective strategy for visualizing location information | 2.70 | 2.50 | 0.78 | 0.72 | Strong agreement | Important |
| 10 | C9 | Different user interfaces | 2.64 | 3.00 | 0.64 | 0.81 | Strong agreement | Important |

**Table 7.** Priority rankings for the challenges of BIM, RFID and WSN integration

| Rank | Identifier | Risk | Mean | Median | Σ | $r_{wg}$ | Agreement level | Significance level |
|---|---|---|---|---|---|---|---|---|
| 1 | R2 | A software breakdown | 3.18 | 3.00 | 0.83 | 0.69 | Moderate agreement | Important |
| 2 | R3 | Frequent sensor breakdown | 3.18 | 3.00 | 0.83 | 0.69 | Moderate agreement | Important |
| 3 | R1 | Cybersecurity (i.e. cyberattack on the software platform) | 3.09 | 3.00 | 1.08 | 0.47 | Weak agreement | Important |
| 4 | R4 | System interoperability | 3.00 | 3.00 | 0.85 | 0.67 | Moderate agreement | Important |

**Table 8.** Priority rankings for the risk of BIM, RFID and WSN integration

integrated system installation" (C4) could be a serious challenge to a widespread use of the BIM, RFID and WSN integration in the AECO industry. C7 (constant Wi-Fi connection on site) is the third-highest ranked challenge and its mean value is 3.82. However, the agreement level of C7 is weak. Some SMEs have stated that constant Wi-Fi connection on site is an important problem. In addition, any interruptions in the wireless connection on site will adversely affect the construction process as it may result in discontinuous data flow and accordingly cause data loss. In contrast, other SMEs have stated the need for a constant Wi-Fi connection on site will not be a problem that can be overcome by developing infrastructure technologies. SMEs also underlined that wireless connection is an indispensable part of today and should be used in every way.

Similarly, R2 (software breakdowns) and R3 (sensor breakdowns) have received the highest mean values (3.18) among the four risks for the integrated use of BIM, RFID and WSN in the AECO industry. Experts indicated that any software breakdowns or sensor breakdowns may prevent continuous and real-time data acquisition, transmission and exchange. Another significant risk of BIM, RFID and WSN integration is R1 (cybersecurity [i.e. cyberattack on the software platform]). Although most experts stated that cyberattack on the software platform is not a significant risk, some SMEs highlighted that this risk should not be ignored and further research is needed on this critical subject. Furthermore, they indicated that data could be stolen, changed or deleted as a result of a possible cyberattack in the process of collecting, transferring and storing all kinds of information related to the project. SMEs also underlined that encountering such a situation would jeopardize the project data security. Moreover, another critical issue for the integrated use of BIM, RFID and WSN is the system interoperability (R4) which is ranked as the fourth risk. System interoperability (R4) is highly important as it may prevent to be realized such a very complex heterogeneous network to its full potential (Yim *et al.*, 2017; Costin and Eastman, 2019).

## Conclusion

This study comprehensively identifies, classifies and prioritizes the benefits, challenges and risks for the integrated use of BIM, RFID and WSN in the AECO industry through a mixed methodological approach. For identification and classification purposes, a systematic literature review and semistructured interviews with seven SMEs were performed. For prioritization purposes, a two-round Delphi method with eleven SMEs was conducted which increase the validity and reliability of data.

Six benefits, nine challenges and four risks for the BIM, RFID and WSN integration were determined from the interviews with the international SMEs. When the findings from literature review and interviews were triangulated, thirteen benefits, ten challenges and four risks for the integrated use of BIM, RFID and WSN were identified. All benefits, risks and challenges for the BIM, RFID and WSN integration were mentioned in some previous studies separately. However, none of these studies collates and reveals the benefits, risks and challenges for integrating BIM, RFID and WSN in a holistic manner.

This research makes a significant contribution to the AECO literature and industry by uncovering the benefits, challenges and risks for the integrated use of BIM, RFID and WSN. This study could aid the practitioners and researchers comprehend the pros and cons of this integration by representing SMEs' valuable insights and perspectives about the current and future status, trends, limitations and requirements of the industry. Therefore, this research could expand the applications of the integrated use of BIM, RFID and WSN in the AECO industry.

The identified risks and challenges show the requirements for future works. Prioritizing the challenges and risks of BIM, RFID and WSN integration could help conduct effective risk analysis for the construction projects. The decision-makers who will carry out risk analysis can have the foresight by considering the highest-ranked challenges and the possibility of the risks to be realized that allow them to take the necessary precautions and allocate resources and consequently minimize the possible risks.

The identified benefits demonstrate the capabilities and the potential contributions of this hybrid integration to the AECO industry. Accordingly, this study allows the investor and/or contractor to comprehend the benefits of using this integration in the construction projects. However, each technology needs to be studied in a concrete way on its technical designs. In the line with the experts' comments, appropriate technology types (e.g. RFID type or antenna type or design of WSN nodes) should be specifically determined to apply this integration on the construction site.

The limitation of this research is that four of the interviewees also participated in the Delphi survey. However, this situation does not affect the reliability of the findings because only the lists of benefits, challenges and risks were identified using the triangulation results of the literature review and semistructured interviews and the identities of participants are kept confidential.

One of the future directions could focus on developing a prototype model for the BIM, RFID and WSN integration and testing its efficiency on the construction site that help practitioners determine mainly what benefits it would provide and what challenges would be faced with. In accordance, the benefits and challenges identified in this study could be observed in a more realistic way. The other future research could address how to solve the system interoperability problem for such a complex integration. Another future work of this study would be incorporating the cost of this integration. This could provide more precise data on the applicability of such an integration in construction projects. Moreover, cybersecurity could be another crucial future research direction.

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**Corresponding author**
Senem Seyis can be contacted at: senem.seyis@ozyegin.edu.tr