sustainability

MDPI

Article

Economic Analysis of USN-Based Data Acquisition Systems in Tall Building Construction

Hyunsu Lim [1], Jin Woong Lee [2], Taehoon Kim [3,*], Kyuman Cho [3] and Hunhee Cho [4]

1. BK21 Innovative Leaders for Creating Future Value in Civil Engineering, Korea University, Anam-Dong, Seongbuk-Gu, Seoul 02841, Korea; iroze00@korea.ac.kr
2. Department of Architectural Engineering, Chosun University, 309, Pilmun-Daero, Dong-Gu, Gwangju 61452, Korea; elwoong91@naver.com
3. School of Architecture, Chosun University, 309, Pilmun-Daero, Dong-Gu, Gwangju 61452, Korea; cho129@chosun.ac.kr
4. School of Civil, Environmental and Architectural Engineering, Korea University, Anam-Dong, Seongbuk-Gu, Seoul 02841, Korea; hhcho@korea.ac.kr

* Correspondence: thoonkim@chosun.ac.kr; Tel.: +82-62-230-7145

Received: 11 July 2017; Accepted: 31 July 2017; Published: 2 August 2017

Abstract: The successful construction of tall buildings requires effective construction management based on various quantitative data. The recent development of ubiquitous sensor networks (USNs) enables massive amounts of data to be collected in real-time. However, the application of USN-based data acquisition systems to repetitive tasks on typical floors of tall buildings can be inefficient, because this may involve the repetitive reinstallation of sensors and the repositioning of data loggers and routers to enable continuous data transfer. To minimize this cumbersome work, a modified data acquisition method using reusable sensor nodes and mobile devices can be a useful solution. This study analyzes the economic aspects of the USN-based systems for concrete temperature monitoring by using the activity-based costing technique. The case study shows that the modified system can reduce the process cost by about 19%. It can also reduce the resource input time of management by about 55%, freeing up time for other management activities. Moreover, the cost benefits should scale up as projects increasingly require more measurement and monitoring. This study should facilitate the application of USN-based information management systems, particularly for tall building construction.

Keywords: ubiquitous sensor network; data acquisition; quality control; activity-based costing; tall building construction

1. Introduction

Following recent developments in the information and communications technology (ICT) industry, construction management technology utilizing wireless sensor networks is being applied in various fields. For example, ubiquitous sensor network (USN) technology at construction sites is being used for concrete quality management, curing management, and structure monitoring technology [1]. This involves transmitting information collected from various sensors to the site PC in real-time. In particular, real-time control of the concrete temperature is very important, not only to prevent cracking but also to obtain the required strength [2]. Therefore, accurate and continuous temperature control is required. Moreover, as the size and complexity of buildings increase, the importance of using USN technology for concrete temperature control in tall building construction will also increase.

However, the application of USN technology to tall building construction can be inefficient because of the repetitive floor-by-floor repositioning of sensor nodes, repeaters, and routers. This cumbersome work can result in additional workforce requirements and cost. In addition, the numerous sensors and wires embedded in the concrete of every floor cannot be reused, which may negatively impact construction waste management through source reduction and material reuse [3]. Therefore, temperature measurement using existing USN technologies should be modified and supplemented to match the repetitive construction involved in tall buildings.

This study analyzes the economic aspects of the USN-based data acquisition systems for concrete temperature measurement by using an activity-based costing (ABC) technique. In this study, process cost and resource input time are compared targeted at an existing and modified system proposed by Jo et al. [4]. The result of this study will contribute to establishing an efficient and systematic quality control system for tall building construction sites, and facilitate the application of USN-based construction management systems.

2. Preliminary Considerations

2.1. Ubiquitous Sensor Network

A USN is a system that can acquire and manage desired information at any time through sensors. In particular, it detects and recognizes objects and supplies environmental information such as temperature, humidity, pollution, or cracking by using wireless sensors and communicates the information via a network in real time. The USN's most critical technology is its wireless sensor network. When USN is applied to a construction site, it is possible to measure, manage, and monitor data at a location remote from the construction site by installing wireless sensor nodes at a required site and configuring a wireless network.

A typical USN comprises sensor nodes, sink nodes, and gateways (Figure 1). Each sensor node includes sensors, communication modules, and batteries. It measures and stores information from the sensors and transmits information to sink nodes and gateways. Each sink node is a repeater, which transmits data collected from a number of sensor nodes to a gateway. The gateway transmits information collected from sensor nodes and/or sink nodes to a remote server or Internet Protocol-based network through some type of communication network [5].

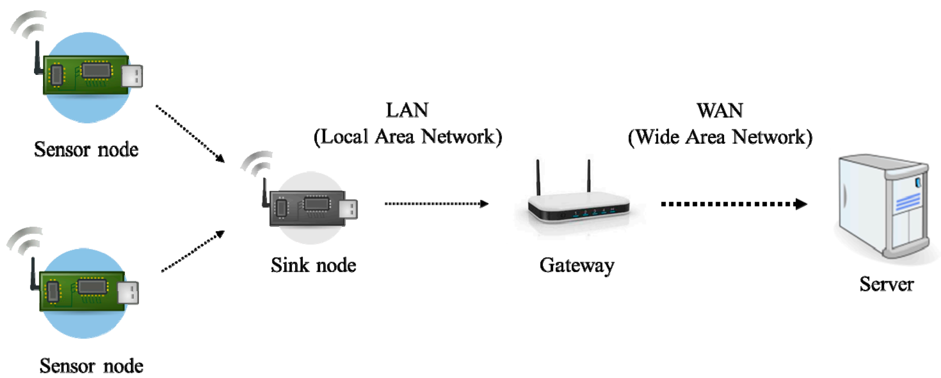

Figure 1. Typical data acquisition process in a ubiquitous sensor network (USN).

2.2. Activity-Based Costing

ABC is a technique developed to solve the problem of overhead allocation [6]. Overhead costs are difficult to track or allocate for cost control because the classification of the input costs is unclear. To address this problem, ABC is a method that identifies activities in an organization and assigns the cost of each activity resource to all products and services according to the actual consumption by the resource and activity [7,8]. Figure 2 shows the cost calculation of the ABC method. First, the cost driver rate is calculated by multiplying the time and the unit cost of the resources required for the activity. Next, the total cost is calculated by multiplying the cost driver rate and the volume of activity required for the cost object. In this way, the ABC method enables the cost management of a detailed cost unit by activity, making it easy to track and manage improvements in overheads because it is based on the relationship between cost and activity [9].

Figure 2. Cost calculation of the activity-based costing (ABC) method.

For tall building frames, the temperature management of the structure is included in the quality management cost and is therefore calculated as an overhead cost. Because the quality management cost is set as a fixed ratio according to the size of the construction, it is difficult to estimate any improvement in the process through the introduction of USN technology. Therefore, in this study, the process of temperature measurement using existing USN technology and temperature measurement with the improved USN technology is compared, with the cost analysis and system application effects being analyzed in terms of ABC. In particular, this study utilizes the time-driven ABC proposed by Kaplan and Anderson [10]. Time-driven ABC is composed of parameters for activity time and cost of resources, making it easy to analyze and change even after time changes or additional resource inputs [10]. In the case of temperature measurement, all activities are undertaken only by managers. It is therefore appropriate to apply time-driven ABC because the resource inputs (i.e., managers) may change with time.

3. USN-Based Systems for Concrete Temperature Measurement

A concrete temperature measurement system using existing USN technology is shown in Figure 3. First, the temperature is measured by the temperature sensors, and data are collected in the data logger. The collected data are transmitted to the router via a local area network (LAN) such as Zigbee. The router transmits data to a server computer in the site office using a wide area network (WAN) such as wideband code-division multiple access. By storing or sharing the transmitted data on the server computer, the site manager can monitor the current construction situation and enable efficient temperature management.

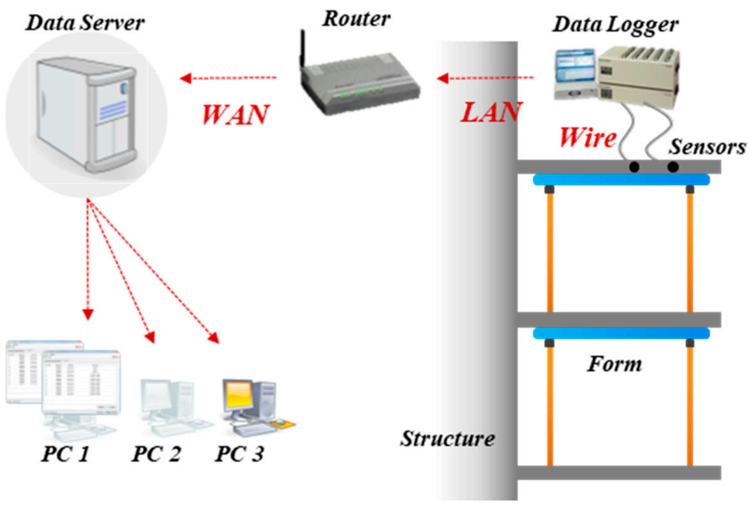

Figure 3. Existing temperature measurement system.

However, there are two limitations to applying existing USN-based concrete temperature management systems to tall building construction. First, because the construction of a tall building requires a great deal of repeated floor-by-floor work, it is inconvenient to repeatedly install sensors and data loggers, whether using wires or wirelessly. Second, as the construction progresses, the height of the building increases, with the data transmission performance possibly deteriorating. Therefore, Jo et al. [4] proposed a modified system that addresses these limitations.

In the modified system (Figure 4), the temperature sensor, the data logger, and the communication module are integrated into the sensor node to minimize reinstallation work for the sensors and the data logger. By attaching the sensor node to the form and installing the sensor node at the same time as the formwork construction, the repetitive installation and reinstallation work are minimized. In addition, the smartphones of workers and managers can collect measured data from the sensor nodes instead of from existing routers, thereby reducing manpower and cost inputs.

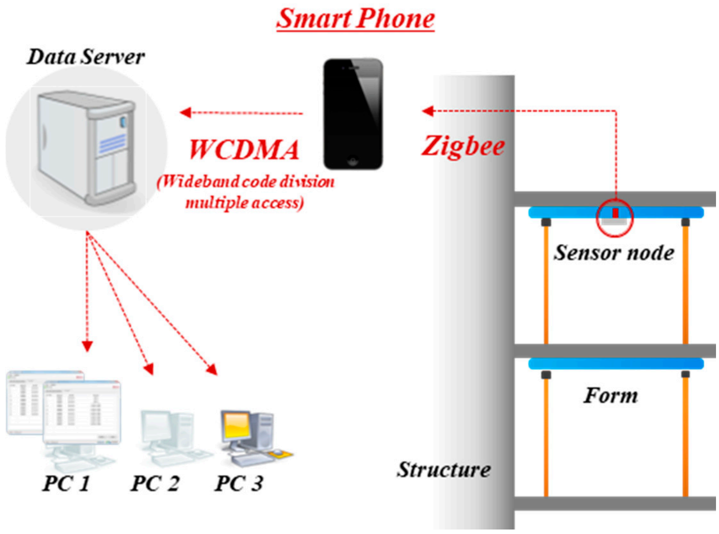

Figure 4. Modified temperature measurement system (modified from [4]).

This system is optimized for the repetitive construction required for tall buildings, thereby enabling shortening of work time and cost reductions. In addition, managers can obtain real-time information on-site through smartphone applications, making it easy to manage the site. In this way, the modified system is expected to enable more effective management than the existing system.

4. Economic Analysis of USN-Based Data Acquisition Systems

4.1. Process Modeling

The process for the temperature management systems utilizing existing and modified USN technology is shown in Table 1. In the existing system, (1) the "preparation" step checks whether each sensor node and temperature sensor is operational. (2) In the "sensor node installation" step, each temperature sensor is embedded in the concrete and connected to its sensor node by wires. (3) The "temperature measurement" step measures each temperature via a temperature sensor and transmits it to the server through a sensor node and a gateway. (4) The "sensor node separation" step separates the temperature sensors from the sensor nodes, and sensor node installation is repeated for each floor by separating the sensor nodes in the lower floor. (5) The "gateway installation" step uses the next upper floor for effective data transmission, and the gateway is generally installed for two floors while considering the transmission range for data. (6) The "temperature review" step enables managers to check and examine the temperature.

Table 1. This comparison of process in existing and modified system.

Activity	Order of Activity	
	Existing	Modified
Preparation	1	1
Sensor node installation	2	2
Temperature measurement	3	3
Sensor node separation	4	-
Gateway installation	5	-
Maintenance	-	4
Temperature review	6	5
Sensor node disassembly	-	6

In the modified system, (1) "Preparation" is implemented in the same way as for the existing system. (2) "Sensor node installation" involves installing the sensor node in the form and operating the sensor node. (3) "Temperature measurement" is the step for which each sensor node continuously measures and transmits temperatures during a construction period. (4) "Maintenance" checks that each sensor node is undamaged and that its battery is charged. Maintenance is performed every three floors in consideration of the discharge rate of the sensor node. (5) In "temperature review", the managers review the temperature record. (6) "Sensor node disassembly" separates the sensor nodes from the form after the construction period.

4.2. ABC Modeling

4.2.1. ABC Calculation Method

ABC is a method of assigning input resources to each activity and then assigning each activity to the cost object to calculate the cost. The activity cost driver rate is calculated by multiplying the unit cost of the resources required by the time required for the activity, and the cost object is calculated by multiplying the cost driver rate of each activity by the volume of activity required for the cost object [6].

As given in Equation (1), the cost driver rate C_j is calculated as the sum of the values for the product of R_{ij} and c_i.

$$C_j = \sum (R_{ij} \times c_i) \tag{1}$$

Here, C_j represents the cost driver rate for activity j, R_{ij} represents the amount of resource i required for activity j, and c_i represents the unit cost of resource i.

The total cost of the cost object T_{Ck} is calculated as the sum of the values for the product of the cost driver rate of activity C_j and the volume of the cost driver.

$$T_{Ck} = \sum (C_j \times d_{jk}) = \sum (\sum (R_{ij} \times c_i \times d_{jk}) \tag{2}$$

Here, T_{Ck} is the overhead allocated to the total cost object, d_{jk} is the amount of cost driver required for activity j, and C_j is the cost driver rate of activity j.

4.2.2. Calculation of Activity Cost Driver Rate

For our ABC modeling case study, the resources and unit costs required for the temperature measurements were calculated from interviews with the quality manager and the site manager for an actual project (Table 2).

Table 2. Resources and the unit cost of resources.

Resource	Unit Cost (US$/hour)
Quality manager (QM)	28
Site manager (SM)	33
Construction manager (CM)	44
Site supervisor (SS)	44

Next, we calculated the cost drivers and the time spent on the resources in the existing system and the modified system through interviews with the site manager and the quality manager (Tables 3 and 4). The temperature measurement activity is excluded because these processes are automatic.

Table 3. Cost drivers and required times in the existing system.

Activity	Resource				
	Cost Driver	Required Time (hours)			
		QM	SM	CM	SS
Preparation	Number of construction starts	0.2	-	-	-
Sensor node installation	Number of concrete pouring	-	0.3	-	-
Sensor node separation	Number of form removals	-	0.2	-	-
Gateway installation	Once every two floors	-	0.3	-	-
Temperature review	Number of form removals	0.05	-	0.05	0.05

Table 4. Cost drivers and required times in the modified system.

Activity	Resource				
	Cost Driver	Required Time (hours)			
		QM	SM	CM	SS
Preparation	Number of construction starts	0.2	-	-	-
Sensor node installation	Number of construction starts	-	1.5	-	-
Maintenance	Once every three floors	1.0	-	-	-
Temperature review	Once every two floors	0.05	-	0.05	0.05
Sensor node disassembly	Number of construction ends	-	1.5	-	-

Table 3 refers to the temperature management system utilizing existing USN technology, where the preparation for measurement is performed once in the initial installation. The cost driver is therefore set as the number of construction starts. Because sensor nodes are installed every time concrete is poured, this cost driver is set as the number of installations. The separation of sensor nodes and the temperature review are performed at every form removal. The cost drivers are therefore set as the number of form removals. The gateway installation is performed once every two floors.

Table 4 refers to the modified temperature management system. Because the preparation for measurement, the system installation, and the system disassembly are all performed once during the concrete structural work, the cost drivers are set as the number of start and end times for the construction. Maintenance is performed once every three floors, by considering the discharge rates for sensor-node batteries. The temperature review was set to the number of form removals as in the existing system. Based on Tables 3 and 4, the cost driver rate (C_j) for each process is calculated according to Equation 1.

4.3. ABC-Based Cost Analysis

For an economic evaluation of each process, a cost analysis should be carried out based on the calculated cost driver rates. The number of cost drivers for the cost analysis is calculated using the temperature measurement records from the construction site of an actual tall building. The project comprised three buildings, with the slabs for each building being divided into three sections. During the construction period, concrete was poured for 58 floors, and there were 174 concrete pouring (Table 5). The number of gateway installations was set as 29 (i.e., one installation every two floors), and maintenance was set as 19 (i.e., a maintenance operation every three floors).

Table 5. Cost driver quantities.

Cost driver	Quantity	Estimated Standard
Concrete pouring	174	58 floors
Start/end of construction	3	Building unit
Gateway installation	29	Every 2 floors
Maintenance	19	Every 3 floors

In the calculation of the cost of the measuring equipment, the selling price is applied to the existing system, and the product cost is applied to the modified system. In the existing system, 486 temperature sensors were installed, with three sensor nodes and one gateway being installed per pouring area. In the modified system, the number of temperature sensors is ignored because sensor node and temperature sensors are integrated. As for the existing system, the number of sensor nodes was set to three per pouring area. The Zigbee USIM was distributed to 10 workers per building. The server cost for receiving and processing information was also included (Table 6).

Table 6. Equipment cost calculations per system.

System	Equipment	Unit Cost (US$)	Quantity	Total Cost (US$)
Existing system	Temperature sensor	6	486	2916
	Sensor node	110	27	2970
	Gateway	330	9	2970
	Server	1650	1	1650
		Total		10,506
Modified system	Sensor node	275	27	7425
	Zigbee USIM	33	30	990
	Server	1650	1	1650
		Total		10,065

Table 7 shows the comparative results of the cost analysis in the existing and modified system with reference to the cost driver rate. For the existing system, the cost required for the activity was calculated as $4184, whereas for the modified system the cost was $1855—that is, a reduction of 55.67% compared with the existing system. In addition, the cost of the initial investment (equipment cost) was $10,506 for the existing system and $10,065 for the modified system, meaning a saving of 4.2%. The total costs for the existing system and the modified system were $14,960 and $11,920, respectively, meaning a savings of 18.86%. The difference in costs arises from the repeated installation of the sensor nodes in the existing system.

Table 7. Results of cost analysis per system.

System	Activity	Cost Driver	Quantity	Cost Driver Rate ($)	Costs ($)
Existing system	Preparation	Start of construction	3	5.6	16.8
	Sensor node installation	Concrete pouring	174	9.9	1722.6
	Sensor node separation	Form removal	174	6.6	1148.4
	Gateway installation	Once every two floors	29	9.9	287.1
	Temperature review	Form removal	174	5.8	1009.2
		Equipment cost			10,506.0
		Total			14,690.1
Modified system	Preparation	Start of construction	3	5.6	16.8
	Sensor node installation	Start of construction	3	49.5	148.5
	Maintenance	Once every three floors	19	28	532.0
	Temperature review	Form removal	174	5.8	1009.2
	Sensor node disassembly	End of construction	3	49.5	148.5
		Equipment cost			10,065.0
		Total			11,920.0

4.4. Time Analysis

A time analysis was performed to analyze the improvements in the modified system. Table 8 shows the time required for the temperature measurement by the managers. The quality manager spent more time for the modified system than for the existing system because it took a long time to maintain the sensor nodes. This means that the battery-discharge time for the sensor nodes needs to be improved in the future. On the other hand, the site manager spent much more time for the existing system than for the modified system. This was because repeated installation of the sensor nodes and installation of the gateway were very time-consuming. Because repetitive installation work for the sensor nodes takes more time for the higher floors of the building, this improvement by the modified system would be even more marked for taller buildings. Based on these results, the modified system can save 55.31% of the time required by the existing system, and can improve management efficiency by enabling the reallocation of time spent on temperature measurements to other tasks.

Table 8. Results of time analysis per system.

System	Activity	Quantity	QM	SM	CM	SS	Time (h)
Existing system	Preparation	3	0.2	-	-	-	0.6
	Sensor node installation	174	-	0.3	-	-	52.2
	Sensor node separation	174	-	0.2	-	-	34.8
	Gateway installation	29	-	0.3	-	-	8.7
	Temperature review	174	0.05	-	0.05	0.05	26.1
	Total		9.3	95.7	8.7	8.7	122.4
Modified system	Preparation	3	0.2	-	-	-	0.6
	Sensor node installation	3	-	1.5	-	-	4.5
	Maintenance	19	1	-	-	-	19
	Temperature review	174	0.05	-	0.05	0.05	26.1
	Sensor node disassembly	3	-	1.5	-	-	4.5
	Total		28.3	9	8.7	8.7	57.7

5. Discussion

The cost and time analysis results show that the modified system can reduce the cost by reducing the process time. In particular, the difference in the amount of cost driver to install and dismantle the sensor is the major cause of cost reduction. The amount of cost driver in the existing system increases as the number of floors increases by repeating floor-by-floor work. In contrast, the cost savings in the modified system can scale up as the number of floors increases because the amount of cost driver for the installing and dismantling activity is fixed regardless of the number of floors. For this reason, the cost increase rate per number of pouring operations is $40.43 in the existing system and $8.83 in the modified system. The modified system is therefore more economical than the existing system if the number of pouring operations exceeds 88. Since tall buildings have more than 50 floors, the number of pouring operations is generally over 100 considering the construction zoning. Therefore, the modified system is suitable for tall building construction, and the higher the building, the more cost-efficient is the modified system.

The modified system is also expected to reduce the environmental load by waste minimization. Sensors and wires in the existing system are embedded in concrete and cannot be reused regardless of sensor life. In contrast, the modified system can reuse sensors until they are exhausted, thus preventing unnecessary waste of resources. Thus, the modified system is expected to contribute to reducing the environmental load by source reduction and material reuse.

6. Conclusions

The quality of concrete used to secure structural performance has become crucial as buildings have become higher and more irregular. Although temperature management using USNs is already being utilized in current construction activity, the application of a USN-based temperature management system in a tall building has some limitations. Because tall building construction requires the repeated construction of a typical floor design, the application of USN technology leads to unnecessary work such as repeatedly installing temperature sensors and data loggers. To address such issues, a modified system proposed in a previous research uses a type of sensor node that incorporates a temperature sensor, a data logger, and a communication module, and can be embedded in a form. In addition, smart phones are used to enable the managers to monitor temperatures in real time.

In this study, an economic evaluation of each system was conducted through an ABC method to analyze the effectiveness of the modified system. For an actual case study, the modified system saved 18.86% of the cost and 55.31% of the time required by the existing system. These savings mainly arise from the minimization of the management cost for quality control by the installation of sensor nodes in every floor. These savings in resource also reduce environmental load in construction sites. The modified USN-based temperature measurement system should help managers to perform management activities more efficiently in terms of cost, time, and safety and improved sustainability of structure throughout quality management. In addition, managers' decision-making during tall building construction will be better informed by obtaining data in real-time.

Acknowledgments: This research was supported by Individual Basic Science & Engineering Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education (NRF-2015R1D1A1A01058681) and by research fund from Chosun University, 2016. This work was also supported by the Ministry of Trade, Industry & Energy of the Republic of Korea (No. 20164010201020).

Author Contributions: In this paper, Hyunsu Lim and Taehoon Kim developed the research ideas and completed the writing; Jin Woong Lee and Kyuman Cho collected and analyzed data; and Hunhee Cho designed and organized the overall research flow.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Barroca, N.; Borges, L.M.; Velez, F.J.; Monteiro, F.; Gorski, M.; Castro-Gomes, J. Wireless sensor networks for temperature and humidity monitoring within concrete structures. *Constr. Build. Mater.* **2013**, *40*, 1156–1166. [CrossRef]
2. Jo, H.K.; Kim, H.R.; You, K.J. A Curing concrete for carbon-reduction and quality management system based on USN. In Proceedings of the Korea Institute of Construction Engineering and Management, Incheon, Korea, 5–6 November 2010; KICEM: Seoul, Korea, 2010.
3. Kibert, C.J. *Sustainable Construction: Green Building Design and Delivery*, 1st ed.; John Wiley & Sons, Inc.: Hoboken, NJ, USA, 2005; p. 357. ISBN 0471661139.

4. Jo, A.; Kim, T.; Cho, H.; Kang, K.I. Data acquisition method using a smartphone on construction site. In Proceedings of the 5th International Conference on Construction Engineering and Project Management, Anaheim, CA, USA, 9–11 January 2013; KICEM: Seoul, Korea, 2013.
5. Kim, K.T. A study on the implementation of USN technologies for safety management monitoring of architectural construction sites. *J. Korea Inst. Build. Constr.* **2009**, *9*, 103–109. [CrossRef]
6. Kim, Y.W.; Kim, S.C. Cost analysis of information technology assisted quality inspection using activity-based costing. *Constr. Manag. Econ.* **2011**, *29*, 163–172. [CrossRef]
7. Kim, Y.W.; Han, S.; Shin, S.; Choi, K. A case study of activity-based costing in allocating rebar fabrication costs to projects. *Constr. Manag. Econ.* **2011**, *29*, 449–461. [CrossRef]
8. Cokins, G. *Activity-Based Cost Management Making It Work: A Manager's Guide to Implementing and Sustaining an Effective ABC System*; Irwin Professional Pub: Chicago, IL, USA, 1996; ISBN 0786307404.
9. Lim, J.Y.; Kim, M.J.; Park, C.G. Analysis of cost and efficiency of a medical nursing unit using time-driven activity-based costing. *J. Korean Acad. Nurs.* **2011**, *41*, 500–509. [CrossRef] [PubMed]
10. Kaplan, R.S.; Anderson, S.R. *Time-Driven Activity-Based Costing*; Harvard Business Review: Boston, MA, USA, 2004; pp. 131–138, ISBN 1422101711.