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Review Article

Using Intelligent Techniques in Construction Project Cost Estimation: 10-Year Survey

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Cost estimation is the most important preliminary process in any construction project. Therefore, construction cost estimation has the lion's share of the research effort in construction management. In this paper, we have analysed and studied proposals for construction cost estimation for the last 10 years. To implement this survey, we have proposed and applied a methodology that consists of two parts. The first part concerns data collection, for which we have chosen special journals as sources for the surveyed proposals. The second part concerns the analysis of the proposals. To analyse each proposal, the following four questions have been set. Which intelligent technique is used? How have data been collected? How are the results validated? And which construction cost estimation factors have been used? From the results of this survey, two main contributions have been produced. The first contribution is the defining of the research gap in this area, which has not been fully covered by previous proposals of construction cost estimation. The second contribution of this survey is the proposal and highlighting of future directions for forthcoming proposals, aimed ultimately at finding the optimal construction cost estimation. Moreover, we consider the second part of our methodology as one of our contributions in this paper. This methodology has been proposed as a standard benchmark for construction cost estimation proposals.

1. Introduction

Information technology (IT) plays a crucial role in dealing with challenges in construction projects. Thomas et al. [1] have illustrated the importance of using IT to improve the performance of construction projects. The construction industry faces numerous complicated challenges that go beyond IT. These complicated challenges motivate the use of intelligent techniques to handle those challenges. For instance, intelligent techniques may be used to handle challenges such as (1) selecting the best-qualified prime contractor, (2) predicting project performance at different phases, or (3) estimating risk for cost overruns (running beyond a proper plan may lead to greater risks for many contractors). Recently, the civil engineering community has begun to consider Artificial Intelligence (AI) techniques as an optimal art for handling the above 3 fuzzy and ambiguous challenges [2]. The use of AI in the civil engineering sector has been introduced by Parmee [3], who proposes for AI to tackle problem areas characterised by uncertainty and poor definition.

Cost estimation is the most important preliminary process in any construction project. In the construction industry, cost estimation is the process of predicting the costs required to perform the work within the scope of the project [4]. Accurate cost estimation is crucial to ensure the successful completion of a construction project. Estimating construction cost is an example of a knowledge-intensive engineering task [5]; that is, it depends on the expertise of the human professional. In fact, engineers require several years to develop the necessary expertise to conduct the cost estimation process. The main problem here is that the engineers' expertise is often not documented or authenticated. Hence, this expertise is prone to subjectivity (i.e., defined to an extent by one's personal opinion). According to Shane et al. [6], accuracy and comprehensiveness in cost estimation are delicate issues and can be easily affected by many different parameters; in addition, each parameter must be properly addressed in order to maintain an acceptable level of accuracy during the process. Therefore, estimating construction cost to a fair degree of accuracy is mostly impossible to achieve manually.

On the other hand, inaccurate cost estimation leads to many problems, such as change order, construction delay [7], or even business bankruptcy in the worst scenarios. These two factors (i) the impossibility of conducting cost estimation manually and (ii) the effects of incorrect cost estimation thus encourage researchers and construction companies to investigate intelligent solutions to handle the problem of cost estimation.

This paper investigates and summarises the current use of intelligent solutions in the construction industry. In order to leverage the importance of intelligent solutions in project cost estimation, a list of state-of-the-art methods has been analysed, including machine-learning (ML), rule-based systems (RBS), evolutionary systems (ES), agent-based system (ABS), and hybrid systems (HS).

This paper has been organised as follows: we discuss our research methodology in Section 2. In Section 3, we explore and define the construction cost estimation factors that are used in this survey paper. In Section 4, intelligent techniques that are used in construction cost estimation are classified into five groups, and the main strengths and weaknesses of each group are defined. Each proposal is then analysed. Conclusions and future directions are presented in Section 5.

2. Research Methodology

The importance of cost estimation in the construction industry has been discussed in the previous section. However, there is no doubt that intelligent solutions may solve the dilemma of cost overruns, considering all affecting factors. In fact, there are a huge number of intelligent techniques available to deal with problems in construction management [8]. This motivates the researchers to carry out and analyse intelligent techniques with regard to tackling the construction cost estimation problem. This paper surveys the intelligent solutions employed over the last decade and identifies the directions for future development. This will help to provide more precise and in-depth analysis for the most recent proposals. The analytical process will highlight the research gap in this area. Furthermore, it will open a door for defining the available opportunities for future research.

This research has been divided into three parts, as shown in Figure 1. Firstly, we create a literature review database on the intelligent techniques that have been used in cost estimations over the last decade. In this step, specific journals have been selected based on their specialisation both in construction management and in information technology. These journals are Journal of Computing in Civil Engineering (http://ascelibrary.org/journal/jccee5), Journal of Construction Engineering and Management (http://ascelibrary.org/journal/jcemd4), Itcon (http://www.itcon.org/), Journal of Civil Engineering and Management (http://www.tandfonline.com/toc/tcem20/current#.VFlO8Wdh71U), and Automation in Construction (http://www.journals.elsevier.com/automation-in-construction/). Consequently, the collected papers have been classified based on their applied techniques. Secondly, we present an analysis and discussion of each intelligent technique to clarify its strengths and weaknesses. The strengths and weaknesses of specific intelligent techniques will be inherited by the cost estimation method based on that technique. Additionally, cost affecting factors have been established in order to carry out a specific benchmarking process.

Later, an intensive comparison of the surveyed construction projects' cost estimation methods, based on a proposed benchmark, has been conducted. To analyse each proposal, the research has focused on four points:

(i) the intelligent technique in use;
(ii) how the proposal's data is collected;
(iii) validation of the proposed idea;
(iv) the coverage of cost estimation factors.

We will now explain the steps from Figure 1 in detail. The first step is the creation of a literature database from the four journals mentioned earlier. We have used the words "construction cost" as a primary keyword; we have then selected only the proposals that involve the use of intelligent techniques. The second and third steps are parallel. In the second step, the intelligent techniques that have been found in selected proposals are classified based on the scientific concept of each one. The aim of this classification is to define the main features of each class. Step four describes the proposed benchmark, explained in detail in Table 2. This benchmark has been developed on the basis of construction cost factors selected in step five. Step six shows the last step and the main objective of this survey, which is the defining of future directions in the research area of construction cost estimation.

3. Construction Cost Factors

According to Shane et al. [6], Oberlender and Trost [9], and Ahiaga-Dagbui and Smith [10], any construction cost estimation should be developed based on specific parameters such as type of project, material costs, likely design and scope changes, ground conditions, duration, size of project, type of client, and tendering method. Therefore, in this paper we have introduced these factors as a benchmark to compare between the cost estimation proposals.

There are various different factors that affect cost estimation in construction projects. These factors can be clustered into two distinct groups [11]: (i) estimator-specific factors and (ii) design and project-specific factors.

3.1. Estimator Specific Factors. The cost estimator can be one of the three parties: contractor, consultant, or owner. Based on the estimator's background and experience, cognitive

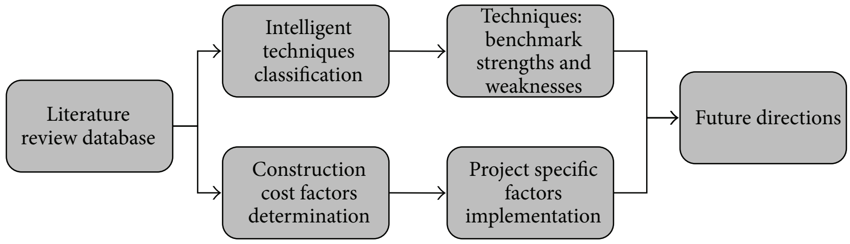

Figure 1: Flow chart illustrating the methodology.

biases or errors in cost estimates may occur accordingly [11]. In many cases, the cost estimator makes decisions based on the likely gains, or losses, of a venture and not necessarily based on the real outcome of the decision [12]. Moreover, the individual estimator may customise pricing based upon best local practices [13], which differ from country to country. For this reason, this paper will focus on design and project-specific factors.

3.2. Design and Project-Specific Factors. These factors include project size, type of project, ground conditions, type of client, material costs, likely design and scope changes, duration, tendering method [6, 9, 10], and contract type. In the following paragraphs, these factors are discussed in detail to explore their meanings and functions regarding cost estimation.

3.2.1. Project Size. There is a strong correlation between project size in square feet or metre and the number of labours. However, as the number of labours increases, the cost estimation of some items may have some biases and become more plausible (e.g., production rate estimation or tasks scheduling). There are many empirical studies on how project size can influence cost estimation (e.g., [14, 15]).

3.2.2. Type of Project. Undertaking particular types of projects requires a suitable choice of technology and equipment used, as well as suitable work methods. However, this can limit the choice of materials and size of crew to be employed; consequently, this will affect the project budget.

Project types can be classified under several different categories. In general, there are six major types of construction projects: (1) building construction, (2) special-purpose construction, (3) heavy construction, (4) highway construction, (5) infrastructure construction, and (6) industrial construction.

3.2.3. Ground Conditions. Before tendering, ground condition should be one of the first concerns in any construction project. Without knowing the ground condition, the contractor should still presume to estimate the cost; however, if the assumption is not proper, this will lead to additional costs for bad ground condition.

3.2.4. Type of Client. As each construction project has its own client ideas, roles, and objectives, the characteristics of the contract and bidding behaviour are mainly affected by client type. There are seven different types of clients as classified by Drew et al. [16].

(1) Government.
(2) Housing Authority.
(3) Other public sector clients.
(4) Large developers.
(5) Large industrial, commercial, and retailing organisations.
(6) Medium and small industrial, commercial, and retailing organisations.
(7) Other private sector clients.

3.2.5. Material Costs. The material selection-time, type of materials, and their availability in the local market all demonstrate a statistically significant impact on the cost estimation of construction projects. Materials can represent up to 70% of the project construction cost [17]; hence, any methods used to estimate the material cost accurately will reduce wastage and improve the major project's cost and time benefits. In addition, the quantity of material required must be accurately measured from the drawing and is not dependent on the crew performance or work method adopted [13]. However, this factor can vary dramatically and is highly dependent on the performance and work method used by the labours.

3.2.6. Likely Design and Scope Changes. Depending on their level of experience, the client retains more influence over the design and once on site during construction. Certain types of projects require the client to appoint a design firm (Figure 2) to design and inspect the project phases, in order to achieve the standards expected by the client.

On the other hand, the right scope definition phase is highly important in the pre-project planning process. Poor scope definition is recognised by industry practitioners as one of the leading causes of project failure, as a high level of pre-project planning effort can result in around a 20% saving on total costs [18].

3.2.7. Duration. Research has indicated that there is a strong relationship between project cost and construction duration for different construction markets (e.g., [19, 20]). A relationship between completed construction cost and the time taken

Table 1: Comparison of proposals based on technique and validation.

Proposal	Technique	Validation
Wilmot and Mei [24]	ML: ANN	Have not been mentioned
An et al. [26]	ML: SVM	Comparison with methods for assessing conceptual cost estimates
Petroutsatou et al. [23]	ML: ANN	By comparison with other models in literature
Jafarzadeh et al. [25]	ML: ANN	Have not been mentioned
Hola and Schabowicz [27]	ML: ANN	Have not been mentioned
Son et al. [28]	ML: SVM	Comparison with other techniques such as ANN and a decision tree (DT)
Cheng and Hoang [29]	ML: SVM	Have not been mentioned
Ji et al. [30]	KBS: case-based reasoning	Using case study
Choi et al. [31]	KBS: case-based reasoning	By comparison with previous conceptual cost estimation studies
K. J. Kim and K. Kim [32]	KBS: case-based reasoning	Have not been mentioned
Yildiz et al. [33]	KBS	By doing interview with experts
Lee et al. [34]	KBS: ontology	Comparison with other techniques
Karakas et al. [41]	ABS: MAS	Interview with expert
Rojas and Mukherjee [42]	ABS: multiagent	Have not been mentioned
Kim [36]	KBS: case-based reasoning and analytical hierarchy process	Case study
de Albuquerque et al. [38]	ES: genetic algorithm	Have not been mentioned
Rogalska et al. [37]	ES: hybrid genetic evolutionary algorithm	By comparing the result with case studies from literature
Ghoddousi et al. [35]	ES: genetic algorithm	By comparing the result with case studies from literature
Afshar et al. [39]	ES: ant colony	By comparing the results with case studies in construction optimisation
Zhang and Ng [40]	ES: ant colony	By comparing the results with an academic benchmark
Kim et al. [43]	HS: statistics, CBR, and database	By comparing the result with case study from literature
Cheng et al. [44]	HS: SVM and DE	By comparing the result with other methods
Kim et al. [45]	HS: ANN and GA	Have not been mentioned
Yu and Skibniewski [46]	HS: ANN and fuzzy system	By using a case study of residential building construction projects in China
Williams and Gong [47]	HS: text mining, numerical data, and ensemble classifiers	Have not been mentioned
Cheng et al. [48]	HS: ANN, GA, and fuzzy system	Have not been mentioned
Zhang and Xing [49]	HS: fuzzy and particle swarm optimisation	Have not been mentioned

to complete a construction project was first mathematically established by Bromilow et al. [20]:

$$T = KC^{B}, \tag{1}$$

where T is the duration of construction period, C is the final project cost, K is a constant value indicating the general level of duration performance, and B is a constant value describing how the duration performance is affected by the size of the construction project measured by its cost.

Figure 3 presents a duration-cost plane frame for small and medium infrastructure projects and identifies three main regions for project scheduling the boundaries of which are defined by general indexed project duration [21].

3.2.8. Tendering Method. There are five tendering methods, including the following.

(i) *Open Tendering*. Contractors are invited to tender for a contract through local advertisements.

(ii) *Selective Tendering*. Contractors are invited to tender on their proven record in relation to the type and size of contract and their own reliability.

Table 2: Comparison of the proposals based on design and project-specific factors.

Work	Project size	Project type	Ground conditions	Type of client	Likely design and scope changes	Contract type	Material costs	Duration	Tendering method
Wilmot and Mei [24]	Y	Y	Y	Y	Y	Y	Y	Y	N
An et al. [26]	Y	Y	Y	Y	N	N	N	Y	N
Petroutsatou et al. [23]	Y	Y	Y	Y	Y	Y	Y	N	N
Jafarzadeh et al. [25]	Y	Y	Y	Y	Y	N	N	N	N
Hola and Schabowicz [27]	Y	Y	Y	N	N	N	Y	Y	Y
Son et al. [28]	Y	Y	N	Y	Y	N	N	Y	N
Cheng and Hoang [29]	Y	Y	Y	N	N	N	N	Y	N
Ji et al. [30]	Y	Y	Y	N	Y	N	Y	N	N
Choi et al. [31]	Y	Y	Y	Y	N	N	N	N	N
K. J. Kim and K. Kim [32]	Y	Y	Y	Y	N	N	N	N	N
Yildiz et al. [33]	Y	Y	N	N	Y	Y	N	Y	N
Lee et al. [34]	Y	Y	Y	N	Y	N	Y	N	N
Karakas et al. [41]	N	N	Y	Y	Y	N	Y	N	N
Rojas and Mukherjee [42]	Y	Y	Y	N	N	N	N	N	N
Kim [36]	Y	Y	Y	N	N	N	N	N	Y
de Albuquerque et al. [38]	Y	Y	Y	N	N	N	Y	N	N
Rogalska et al. [37]	Y	Y	Y	N	N	N	N	N	N
Ghoddousi et al. [35]	Y	Y	Y	Y	N	N	N	N	N
Afshar et al. [39]	Y	Y	Y	N	N	Y	Y	Y	Y
Zhang and Ng [40]	Y	Y	Y	N	N	N	N	N	N
Kim et al. [43]	Y	Y	Y	N	N	N	Y	Y	N
Cheng et al. [44]	Y	Y	Y	N	N	N	Y	Y	N
Kim et al. [45]	Y	Y	Y	N	N	N	Y	Y	N
Yu and Skibniewski [46]	Y	Y	Y	Y	N	N	Y	Y	N
Williams and Gong [47]	Y	Y	Y	N	N	Y	Y	Y	Y
Cheng et al. [48]	Y	Y	Y	Y	N	N	Y	Y	N
Zhang and Xing [49]	Y	Y	Y	Y	N	Y	Y	Y	Y

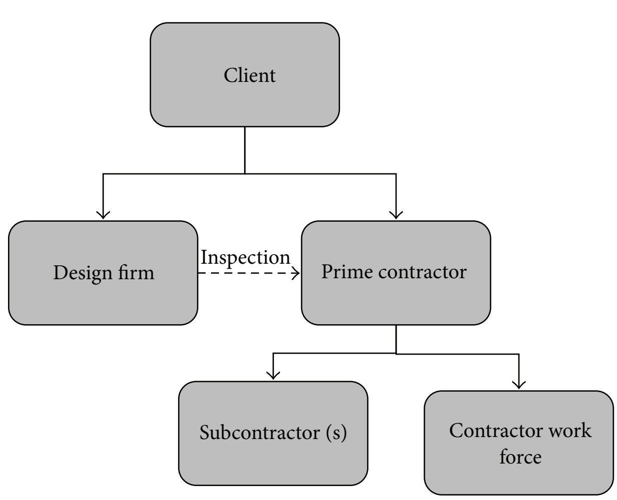

Figure 2: The client appoints a firm to design and inspect the project to meet certain specified (usually, oriented) requirements [50].

(iii) *Negotiated Tendering*. Cost reimbursement contract is a variation of this, which can be used when completion time is more important than cost.

(iv) *Two-Stage Tendering*. It is used to bring in a contractor at the design stage, which is useful to advise the architect of any problems with the design of the building. Unit rates would be negotiated on the basis of the original tender.

(v) *Serial Tendering*. Tenders are invited from a selected list on the basis of a typical (notional) bill of quantities. The chosen contractor normally submits the lowest price and undertakes to enter into a series of contracts to carry out the work using the rates in the notional bill of quantities.

The selection of one of the above methods is basically intended to minimise any additional client risk. To achieve this goal, the client must balance four aspects:

(i) client needs;

(ii) project cost;

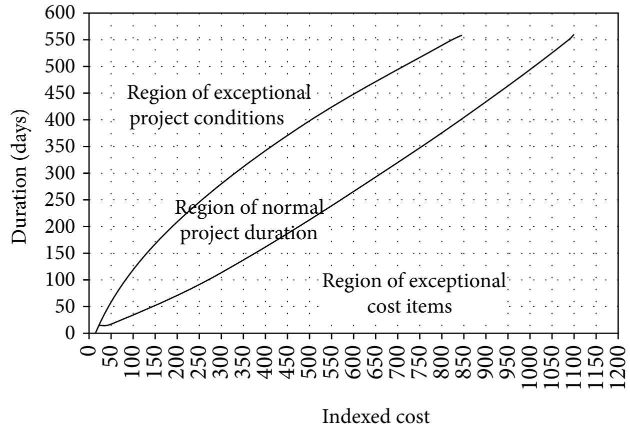

Figure 3: Modelled duration-cost envelope for policy decision support in small and medium projects [21].

(iii) completion time;

(iv) qualification of the tender to perform the job.

4. Intelligent Construction Project Cost Estimation Methods

In this section, analysis of the surveyed intelligent construction cost estimation methods was conducted. These methods have been categorised into five groups, based on the intelligent technique that is used in each group: machine-learning (ML), rule-based systems (RBS), evolutionary systems (ES), agent-based system (ABS), and hybrid systems (HS).

At the first step, each group is explored to highlight their strengths and weaknesses. Subsequently, the methods are analysed in depth in terms of coverage of construction cost estimation techniques. In each proposal, four key questions have been highlighted for analysis. These questions are (1) which intelligent technique is used; (2) how the input datasets are collected; (3) how the proposed method is validated; and (4) which construction cost estimation factors are covered.

In the following subsections, firstly, the intelligent techniques employed are discussed, is the findings of which are considered as an answer to the first question. Secondly, each proposal is analysed individually, which answers question 2. The content of Table 1 illustrates the answer of question 3, while the content of Table 2 illustrates the answer of question 4.

4.1. Machine Learning (ML) Systems. ML systems have been defined as a construction of a system that can learn from data. In general, the main strengths of ML are (i) the ability to deal with uncertainty, (ii) the ability to work with incomplete data, and (iii) the ability to judge new cases based on acquired experiences from similar cases. On the other hand, the main weakness of ML is the lack of technical justification; that is, the causes beyond the decision are not available. This type of decision is called a black box decision. However, in the construction management, the artificial neural network (ANN) and the support vector machine (SVM) are the most common ML techniques. In the next paragraph, we analyse the construction cost estimation proposals that are based on ML.

One of the earliest papers to introduce the benefits and the implementation of ANN in the civil engineering community is published by Flood and Kartam [22]. This research has opened the door for many proposals that suggest ML as the preferred method to tackle various challenges in the construction industry. Petroutsatou et al. [23] introduced the ANN as a technique for early cost estimation of road tunnel construction. The data collection strategy of this research was based on structured questionnaires from different tunnel construction sites. The main drawback of this research was the ignoring of some of the construction cost factors (for more details, see Table 2). Wilmot and Mei [24] introduced an ANN model for highway construction costs. This research used the following factors as a base for cost estimation: price of labour, price of material, price of equipment, pay item quantity, contract duration, contract location, quarter in which the contract was let, annual bid volume, bid volume variance, number of plan changes, and changes in standards or specifications. The main contribution of this work was that it covered all required factors. Nevertheless, the validation of the proposed method and the data collection process used for training and testing the results were not fully presented. Jafarzadeh et al. [25] proposed the ANN method for predicting seismic retrofit construction costs. This study selected data from 158 earthquake-prone schools. The validation of this method is not clear. An et al. [26] proposed SVM for assessing conceptual cost estimates. Although this proposal is introduced as an assessment tool, still it might be considered as a cost estimation method. The method was developed on the basis of data from 62 completed building construction projects in Korea. Furthermore, Hola and Schabowicz [27] developed an ANN model for determining earthworks' execution times and costs. Basically, this model was developed on the basis of a database created from several studies that were carried out during large-scale earthwork operations on the construction site of one of the largest chemical plants in Central Europe. However, the validation of the presented results is not mentioned.

Son et al. [28] developed a hybrid prediction model that combines principal component analysis (PCA) with a support vector regression (SVR) predictive model for cost performance of commercial building projects. They used 64 related variables to define the pre-project planning stage. They developed their dataset based on information from 84 building projects in South Korea that had been completed within three years of the date at which the study was carried out. Questionnaires and interviews were used as a strategy for data collection. Cheng and Hoang [29] developed cost estimation at completion technique using least squares support vector machine. The data sets that are used in Cheng and Hoang [29] were collected from 13 reinforced concrete building projects executed between 2000 and 2007 by one construction company headquartered in Taiwan.

4.2. Knowledge-Based Systems (KBS). This category includes any technique that uses logical rules for deducing the required conclusions. The main strengths of KBS are (i) the ability to justify any result and (ii) uncomplicated methods (i.e., it is relatively easy to develop KBS). On the other hand, the limitations of KBS are (i) the difficulty of self-learning and (ii) time consumption during the rule acquisition process. Expert system and case-based reasoning are the common techniques used in KBS. The accuracy of case-based reasoning is highly dependent on the number of selected cases. Recently, KBS has been combined with other techniques to handle the limitation of the self-learning process. However, this mixture will be discussed in more detail in the section of this paper that deals with hybrid systems.

Ji et al. [30] proposed case-based reasoning to prepare strategic and conceptual estimations for construction budgeting. The data for this project were collected from 129 military barrack projects. Choi et al. [31] proposed a cost prediction model for public road planning. The research data had been collected from a total of 207 real public road projects. Choi et al. [31] used rough-set theory to control the data collection and a genetic algorithm to optimise the rough-set model. Their work was classified as KBS since the authors implemented the case-based reasoning component in their cost estimation. K. J. Kim and K. Kim [32] developed a cost estimation model using CBR. This research overcomes the uncertainty in choosing the correct case by using a genetic algorithm. For this research, data were collected from 65 projects that constructed 585 bridges over a 5-year period. K. J. Kim and K. Kim [32] focused on construction of national bridges. However, it was not mentioned how the results were validated.

Yildiz et al. [33] developed a knowledge-based risk mapping tool to estimate costs for international construction projects. The required data and cost estimation parameters were collected from related literature. The validation process was performed in the form of expert interviews to get feedback on the developed tool. Lee et al. [34] proposed an ontological inference process for building cost estimation, by automating the process of searching for the most appropriate work items. Ghoddousi et al. [35] proposed a solution for determining total cost, time, and resources for construction projects; this was developed on the basis of a nondominated sorting genetic algorithm.

Kim [36] developed a cost estimation model based on case-based reasoning and analytical hierarchy process (AHP). In this project, data have been selected from literature and only 13 studies have been analyzed. Kim [36] developed his model based on data from high-way construction projects. The validation has been conducted based on case study that contains data from 48 construction projects.

4.3. Evolutionary Systems (ES). ES is a group of intelligent systems concerned with continuous optimisation with heuristics. As the results of ES are generated based on specific heuristics, they are very difficult to generalise, which is considered to be the main limitation of ES. The ability to solve complicated and uncertain problems is the main motivation for researchers to use ES. Evolutionary systems are used mainly as optimisation tools where there are many solutions; however, the ES algorithm assists in obtaining the correct solution.

Rogalska et al. [37] proposed a method based on genetic algorithm to deal with the problem of construction project scheduling. de Albuquerque et al. [38] developed a tool for estimating the cost of concrete structures. This tool is developed based on genetic algorithm. The cost has been estimated in all construction phases, such as manufacture, transport, and erection. Afshar et al. [39] developed a multicolony ant algorithm to solve the time/cost multiobjective optimisation problem. This method estimated both direct and indirect costs. Zhang and Ng [40] developed a Decision Support System (DSS) for cost estimation based on ant colony system. Zhang and Ng [40] used synthetic data to develop their DSS and they do validate their system by comparing it with a standard academic project. However, validation is done. Still Validation with real projects provide more accurate results.

4.4. Agent-Based System (ABS). ABS has been considered as one of the main tracks in Artificial Intelligence, simulating the actions and interactions of autonomous agents with a view of assessing their effects on the system as a whole. In ABS, the generalisation of extracted results is the main challenge.

Karakas et al. [41] developed a multiagent system (MAS) that simulates the negotiation process between contractor and client regarding risk allocation and sharing of cost overruns in construction projects. This MAS was tested by interviewing eight professionals from the construction industry. In addition, Rojas and Mukherjee [42] developed a general multiagent simulation framework that can be used as an effective training environment. This framework could be used to estimate direct and indirect costs for construction projects.

4.5. Hybrid Systems (HS). HS is defined as a collection of techniques used together to solve a specific problem. Usually, researchers use HS to overcome the techniques' individual limitations. Implementation of HS could represent a challenge, due to the unavailability of computational tools that could support its implementation. Furthermore, Kim et al. [43] proposed a hybrid conceptual cost estimating model for large mixed-use building projects. In this proposal, statistical analysis, CBR, and database methodologies were used together as a hybrid methodology. More recently, Cheng et al. [44] proposed a hybrid intelligence system for estimating construction cost. This hybrid system was developed based on support vector machine (SVM) and differential evolution (DE). In this proposal, data were collected across a number of public projects in Taiwan. Kim et al. [45] proposed hybrid models of ANN and GA for cost estimation of residential buildings, in order to predict preliminary cost estimates. In Kim et al.'s proposal, data were collected from residential buildings constructed in the years between 1997 and 2000 in Seoul, Korea. Yu and Skibniewski [46] proposed integrating a neurofuzzy system with conceptual cost estimation to discover cost-related knowledge from residential construction projects. The data used in this proposal was based on historical data from previous construction projects collected by the

Ministry of Construction of PRC in the years between 1996 and 2002. Most recently, Williams and Gong [47] proposed text mining, numerical data and ensemble classifiers for estimating construction costs. Data used in this proposal were collected from 121 competitively bid highway projects. These data were collected from California Department of Transportation websites. Cheng et al. [48] proposed web-based conceptual cost estimates for construction projects, using an Evolutionary Fuzzy Neural Inference Model. Data were collected from 28 construction projects spanning the years from 1997 to 2001 in Taiwan. In this regard, Zhang and Xing [49] proposed a hybrid model for estimating construction costs, based on fuzzy and swarm optimisation. The data were collected from national bridge construction projects.

Table 1 shows the comparison of surveyed proposals, based on two issues. The first issue is the intelligent technique used in a proposal. The second issue is the type of validation that is used to prove the applicability of the proposal. Table 2 shows the comparison of surveyed proposals, based on design and project-specific factors used to estimate construction cost in each proposal. The letter "Y" means that this factor has been considered in this proposal, while the letter "N" means that this factor has not been considered. It is very obvious that there is no proposal that satisfies all the design and project-specific factors. On the other hand, in Table 1, there are some proposals that are provided without clear and scientific validation.

5. Conclusion and Future Directions

In this paper, a survey and analysis were performed on different proposals in order to tackle the problem of developing construction cost estimation based on intelligent techniques. A scientific methodology has been designed to implement this survey. The method of the presented paper was based on two parts. The first part was concerned with a literature survey to examine the current state of intelligent solutions in the construction industry. Regarding this matter, we have chosen exclusively the journals that specialise in both information technology and construction management, within a time frame of ten years. In the research context, a ten-year period is sufficient to surround the directions of research in a specific area.

The second part was concerned with analysis of the proposals collected in the first part. Four key questions were selected to analyse each proposal. These questions are as follows.

(i) What is the intelligent technique used?

(ii) How is the proposal's data collected?

(iii) How is the proposed idea validated?

(iv) What are the construction cost estimation factors used?

A justification of the four questions has been provided as follows.

(1) *Defining the Intelligent Technique Used*. This question is used to highlight the general strength and limitations of each proposal, which are reflected by the technique employed.

(2) *Defining Data Collection Method*. This question is used to ensure the degree of accuracy. The degree of accuracy mainly depends on the collected data.

(3) *Defining the Validation of the Proposed Idea*. This question is used to ensure the applicability of the proposed idea.

(4) *Defining the Commonly Used Cost Estimation Factors*. This question is used to ensure the completeness of the proposal.

As mentioned in Section 3, there are two types of construction estimation factors: estimator-specific factors and design and project-specific factors. The first type, estimator-specific factors, depends on estimator expertise and skills and on lack of standardisation. The second type, design and project-specific features, is well defined and established in the civil engineering community. Due to the standardisation and stability of design and project-specific factors, this research paper considered only those factors mentioned in the designed methodology when applying the benchmark.

In conclusion, this paper provides two contributions to this area of knowledge: (1) an analysis of construction cost estimation proposals and (2) a standard survey methodology that can be used in any future surveys that deal with construction cost estimation.

According to the results of this research paper, the research gaps that have been deduced from this survey are as follows.

(1) There is a crucial necessity for a cost estimation method that covers all estimation factors from both types; that is, there is a need for one method that involves all "estimator specific" and "design and project-specific" factors. In Table 1, it is obvious that no proposal has a full row of "Y."

(2) There is a real need for a standard validation method which can be used to determine the accuracy level of a cost estimation proposal.

(3) There are many proposals that suffer from a lack of scientific justification for the results, that is, lack of describing how technically the results have been achieved.

Finally, future research directions are suggested for cost estimation in order to overcome the gaps that have been discussed. These directions are as follows.

(1) Providing cost estimation proposals that encourage the acquisition of human expertise: however, this releases the construction cost estimation from human dependability. Computerized expert systems are the better mechanism that might be used to replace human expertise. On another hand, knowledge management models and systems will assist in establishing computerized management systems that are

free from the constraints of humanitarian. The main goal of knowledge management systems should be to capture and deal with estimator-specific factors. The first future direction is to encourage researchers and industry experts to adopt the direction of knowledge management systems in construction projects.

(2) Providing cost estimation proposals that are developed based on all "design and project-specific" factors: in Section 3, eight "design and project-specific" factors have been mentioned. The second future direction is to encourage researchers and industry experts to develop one integrated construction cost estimation system that works to achieve the all eight "design and project-specific" factors which have been mentioned.

(3) Providing a scientific justification for the cost estimation proposals based on real-world data: this will provide an explanation of how the estimates work and gives a justification on estimator's biases. Add the scientific justification for any proposal to increase the level of confidence in it. In addition, providing scientific justification assists in tracing the details of the cost estimation process which increase the level of transparency. Finally, providing scientific justification helps increase the maintainability.

(4) Providing a standard benchmark for determining the accuracy level of the construction cost estimation proposals: standard benchmarking leads to establishing a rule of thumb when other means of cost estimation are unavailable.
This might be achieved by establishing a database containing information from previous projects. In addition, any future cost estimation models should consider this database "known value" to provide a useful benchmark for how accurately those models can estimate the cost. Using standard benchmark could help in classification, clustering, and ranking of cost estimation proposals.

The limitations of this research paper can be summarised in two points: (a) data was collected from specific journals only; (b) the survey was limited to a ten-year period.

While this paper acknowledges these limitations, it is nevertheless able to provide valid answers on the current state of this area of research and to propose future directions.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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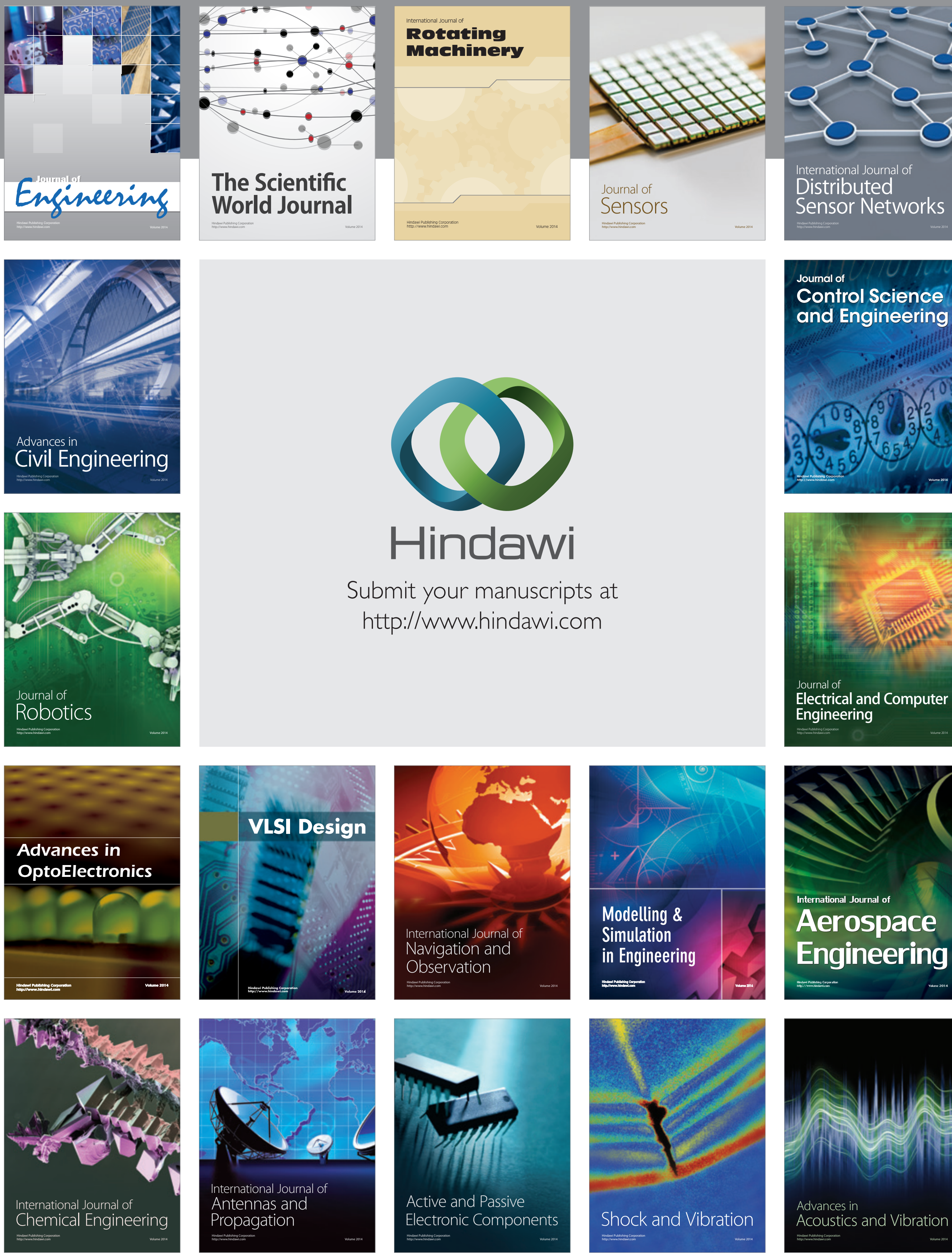
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