FUZZY-BASED CONFIGURATION OF AUTOMATED DATA ACQUISITION SYSTEMS FOR EARTHMOVING OPERATIONS

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SUMMARY: *This paper presents a fuzzy-set-based method for the configuration of efficient and cost-effective on-site automated data acquisition systems for earthmoving operations. Due to the dynamic nature of construction projects, each project has unique characteristics that require distinctive customization of the utilized data acquisition system. The literature lacks a well-defined methodology for customization of the configuration of data acquisition systems. Several research efforts have focused on efficient utilization of different wireless sensing technologies, but the majority integrates black-box and off-the-shelf technologies, where there was no mean for customized configuration. Most widespread on-site data acquisition systems configuration depends on subjective views and market available technologies. The proposed method overcomes subjective configuration of data acquisition systems and provides a systematic selection procedure of the needed sensors. The proposed method first identifies, evaluates and analyzes the factors affecting the performance of earthmoving operations in construction projects. The results of that analysis are then used to customize the configuration of the required data acquisition system. This procedure includes selection of necessary sensors and technologies for efficient tracking of earthmoving operations. Finally, results are discussed, and conclusions are drawn highlighting the key features of the proposed method and how it can assist project managers in customizing the configuration of automated on-site data acquisition systems considering the unique nature of their projects.*

KEYWORDS: *Earthmoving, Data Acquisition, Automation, Fuzzy Set Theory*

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1. INTRODUCTION

The construction industry plays a key role in national economies in various countries around the world by influencing both GDP (Gross Domestic Production) and workforce (Arditi and Mochtar, 2000, Haupt, 2001). Upon the importance of construction industry, it is crucial to improve the construction productivity by identifying, evaluating and analyzing the factors that influence it and to determine the extent of each affecting factor. Productivity measurement and evaluation are utilized as a pointer for the status of the construction operations progress. Obtaining relevant information is crucial for productivity improvement. However, there are many ways to acquire information that can be helpful for productivity improvement. Two of the superior ones are: (1) asking those who are involved in the processes, and (2) observation of the processes to obtain factual records of how it is being done. Each of these two approaches has its advantages while no fixed rules on which is better (Oglesby et al., 1989). Throughout the last century, both of the two mentioned methods were human dependent, and consequently, the collected information and observations are subjective and time-consuming. Also, these conventional methods for obtaining related productivity information are not only time-consuming and subject to human error but also are delivered with a time lag that diminishes a significant part of its value and effectiveness. Estimating productivity of construction operations is regularly experience-based due to the complexity involved. However, primarily empirical practices do not guarantee a reliable estimate because of the absence of a fastening system that relates the current case to former patterns (Chao and Skibniewski, 1994, Rueda and Javier, 2011).

Several research efforts have been made for efficient utilization of different wireless sensing technologies, but most of these utilized technologies were black boxes and off-the-shelf technologies, where there was no mean for configuration or customization. The research is continuous in that field to augment the efficiency and to reduce the cost of implementation of such on-site data acquisition systems, while there is no code for the configuring of these systems. In the last two decades, several research endeavors have been done to study and develop automated on-site data acquisition systems. Most widespread on-site data acquisition systems configuration depends on subjective human views and market available technologies. The proposed method utilized a fuzzy-set-based model to analyze questionnaire responses that investigate the effect of different factors influencing construction productivity. The results of the questionnaire identify the most influencing factors that need to be monitored and subsequently, the data acquisition system is configured, and remote sensing technologies were selected. The productivity of earthmoving operations has been used as an applied example to illustrate the key features of the proposed method in configuring the data acquisition system for earthmoving operations in construction projects. The main objective of this study is to develop a method for customizing the configuration of the automated on-site data acquisition system that supports current practice in tracking and control of earthmoving operations. The developed method considers the configuration of adaptable open-source hardware and software, hence cost-effective automated on-site data acquisition prototypes that integrate different sensor technologies to address limitations of off-the-shelf technologies.

2. LITERATURE REVIEW

The construction industry has an emergent need for automated means to measure the progress, in particular for approaches that employ remote-sensing technology, because the methods that are typically used to measure progress are labor intensive and therefore time-consuming (Abeid et al., 2003, Wu et al., 2009). In this regard, several efforts have been made to replace subjective data collection paper-based with a project monitoring and control systems providing project-wide automated solutions. These studies have utilized several technologies, and they have targeted a wide range of applications in construction. Throughout these studies, the recent advancement in sensing, computing technologies, and wireless communication have played a vital role to automate the process of on-site data acquisition not only on construction job sites but also on the constructed facilities (Li et al., 2016). These research studies have incorporated different technologies such as barcode, radio frequency identification system (RFID), GPS, image processing and Photogrammetry, laser scanners, remote and embedded sensors, wireless sensor networks (WSN), and mobile computing. Potential remote sensing advancement provides innovative models for productivity measurement and evaluation, for example, but not limited to (Alshibani and Moselhi, 2016, Ibrahim, 2015).

Experience-based configuration is the most common practice in both research and professional projects in the domain of data acquisition, productivity measurement, and analysis. This configuration was limited not only to the subjective selection of sensors but also to available off-the-shelf technologies (Montaser and Moselhi, 2012, Caldas et al., 2006, Hildreth et al., 2005, Navon and Shpatnitsky, 2005). Earthmoving operations have vital importance where it forms about 20% of overall cost of civil and infrastructure projects (Kang et al., 2009). Earthmoving operations have received substantial interest from researchers and industry professionals. In earthmoving operations, GPS has played a crucial role in both research studies and practical applications. GPS technology has been identified as a truthful and robust technology for automated data acquisition for highway construction control and earthmoving operations. However, there are inaccuracies associated with GPS data collected which are caused by objects hindering communication between GPS receiver and satellites (Navon and Shpatnisky, 2005). GPS technology has been utilized in tracking, e.g., to track earthmoving operations and highway construction (Alshibani and Moselhi, 2007, Hildreth et al., 2005, Montaser and Moselhi, 2012, Navon and Shpatnitsky, 2005). Also in tracking pipe spools position in a construction project (Caldas et al., 2006).

Many research studies used GPS as an individual tool (Hildreth et al., 2005, Navon and Shpatnitsky, 2005, Montaser and Moselhi, 2012), while most of these studies concluded that standalone GPS could not usually satisfy the needed requirements to solve the research problems. In the case of standalone GPS utilization, the obtained data are limited to time and location, which is sometimes hard to differentiate between productive and idle times. Furthermore, the acquired records do not present enough information that could be used to estimate the quantities of the excavated soil or confirm that the trucks are fully loaded (Ibrahim, 2015). (Montaser and Moselhi, 2012) Used RFID to acquire data concerning earthmoving operations to calculate the loading-dumping cycle. This study demonstrated how economical the use of RFID over GIS technologies in case of single loading and dumping areas using a predetermined number of hauling trucks. The review above brings out identification of the limitations and gaps in interrelated research work and indicates the need for a typical methodology that assists in enhancing on-site data acquisition system in a way that satisfies requirements of the performance monitoring process, which meets its specific desires. In other words, the need for a systematic method to study, configure, design and develop a cost-effective automated data acquisition system was the main motivation behind this research.

3. PROPOSED METHOD

The developed method introduces a new fuzzy set-based model to; (1) Identify the factors that affect the performance of earthmoving operations using a questionnaire method, (2) Evaluate the effects of each factor, and (3) Analyze the consequences of each factor and select the most influencing factors on the performance of earthmoving operations. Then, results of the analysis are used to customize the configuration of the required data acquisition system and to select the necessary sensors and technologies for efficient tracking and monitoring of these operations. Figure 1, shows the flowchart of the proposed method.

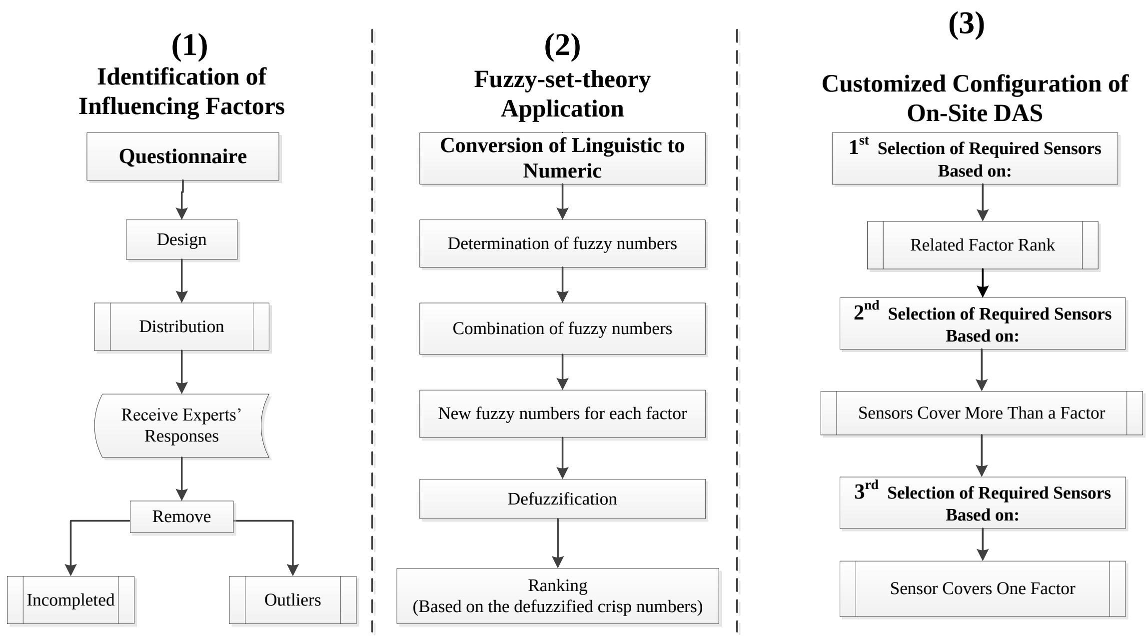

Figure 1: Proposed Method Flowchart

However, the factors that might influence the productivity of earthmoving operations are extensive; the literature is worthy of the identification of these factors. Although a wide range of factors were cited to have an impact on productivity of earthmoving operations, the reasons behind their impact are not well documented and require further studies. There is a need for prioritizing those factors with respect to their impact on productivity of these operations. Then, the customized on-site data acquisition system is appropriately configured and required sensing technologies are selected to measure and monitor the status of these factors. In other words, the sensor related to influencing factors are those to be integrated into the proposed data acquisition system.

In other words, different factors could affect the productivity of earthmoving operations in various influencing scenarios either individually or collectively; distinctive signs ease the identification of each of factor using a particular sensor or set of sensors. Hence, the efficient selection process of sensors, which need to be incorporated in the data acquisition system has a crucial role in recognition of the factors affecting the productivity of earthmoving operations.

3.1 Questionnaire-based Evaluation of Influencing Factors

Literature has been investigated to identify the different factors that are mostly influencing productivity in earthmoving and highway construction projects. Consequently, a questionnaire has been designed to comprise the majority of those factors to acquire the evaluation of their impact on productivity using a fuzzy-set-based model. Then the questionnaire distributed online to eighty (80) construction firms and professionals who are involved in such kind of construction projects. The targeted sample of experts was considered to include professionals from different countries. Twenty-seven (27) out of eighty (80) responses have been received from experts of different countries and in different job positions as shown in Figure 2 and Figure 3 respectively.

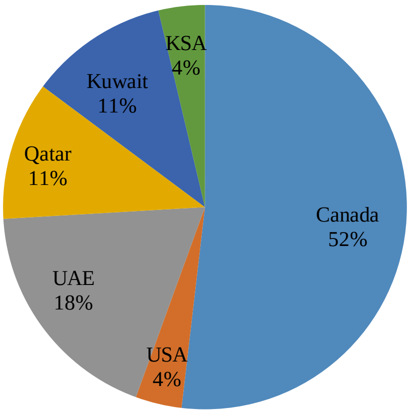

Figure 2: Location-Based Distribution of Respondents

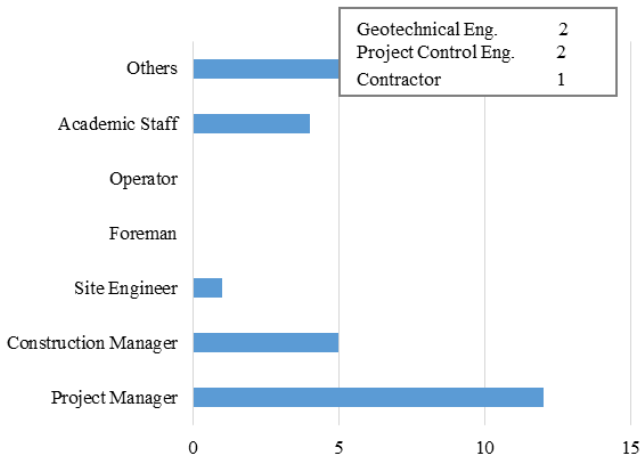

Figure 3: Position-Based Distribution of Respondents

The aim of this questionnaire was to get experts' evaluation of various factors that affect productivity of earthmoving operations. The different influencing factors have been categorized into four main groups; 1) excavated soil conditions, 2) hauling and access roads conditions, 3) equipment and operational conditions, and 4) weather conditions. Figure 4, shows the different influencing categories and their respective factors.

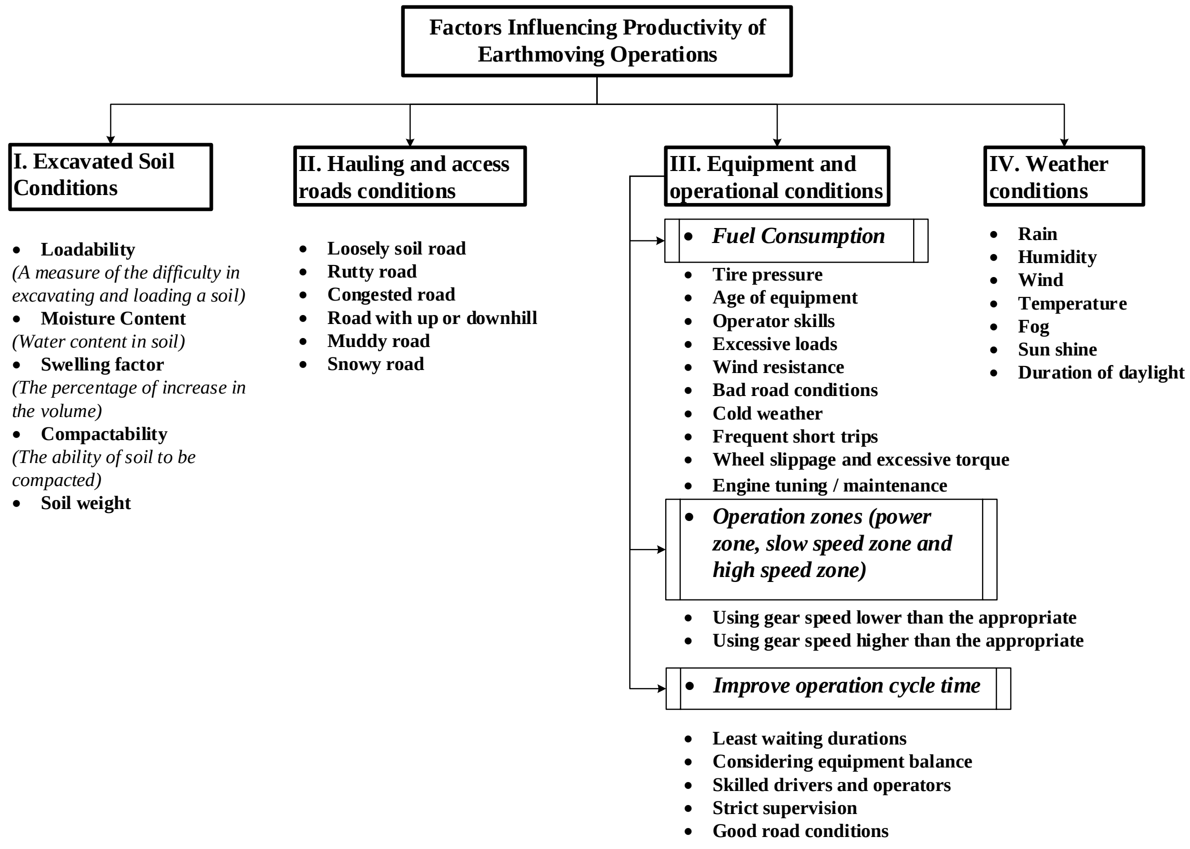

Figure 4: Factors influencing productivity of earthmoving operations

Evaluation is usually a subjective and qualitative process that often associated with uncertainty. Fuzzy-Set-Theory (Zadeh, 1965) has been recommended to model and account for the uncertainty and imprecision associated with expert judgment. Fuzzy set theory can be used regardless of the availability of historical data (Salah and Moselhi, 2016). Also, fuzzy theory eases the utilization of linguistic evaluation, or natural language terms, which is complicated to express with probability theory (Salem et al., 2017, Salah et al., 2017, Pinto et al., 2011). Therefore, fuzzy set theory was selected to model the uncertainty associated with the input of the developed model. The developed method applies fuzzy set theory for the identification, assessment, and prioritization of the factors influencing the efficiency and productivity of earthmoving operations and highway construction. The respondents have been advised to express their experience and knowledge to evaluate the impact of each factor in a linguistic term for more convenience.

3.2 Linguistic - Numeric Conversion

Quantitative assessment methodology is used for conversion of expert linguistic evaluation into numeric fuzzy numbers (Salem et al., 2017, Salah and Moselhi, 2016). **Error! Reference source not found.**(a) Shows the linguistic-numeric conversion scheme for the different expert evaluations from no effect up to extreme effect on productivity. Figure 5 (b) shows the numeric consequence for the various influencing factors on 1-10 scale. Membership functions can be of different shapes, but practically, trapezoidal and triangular membership functions are most frequently used. In the majority of practical applications, trapezoidal membership functions work well (Barua et al., 2013). Also, the application of trapezoidal membership function eases and simplifies getting target results without any distortion. Based on that, the fuzzy membership functions have been established.

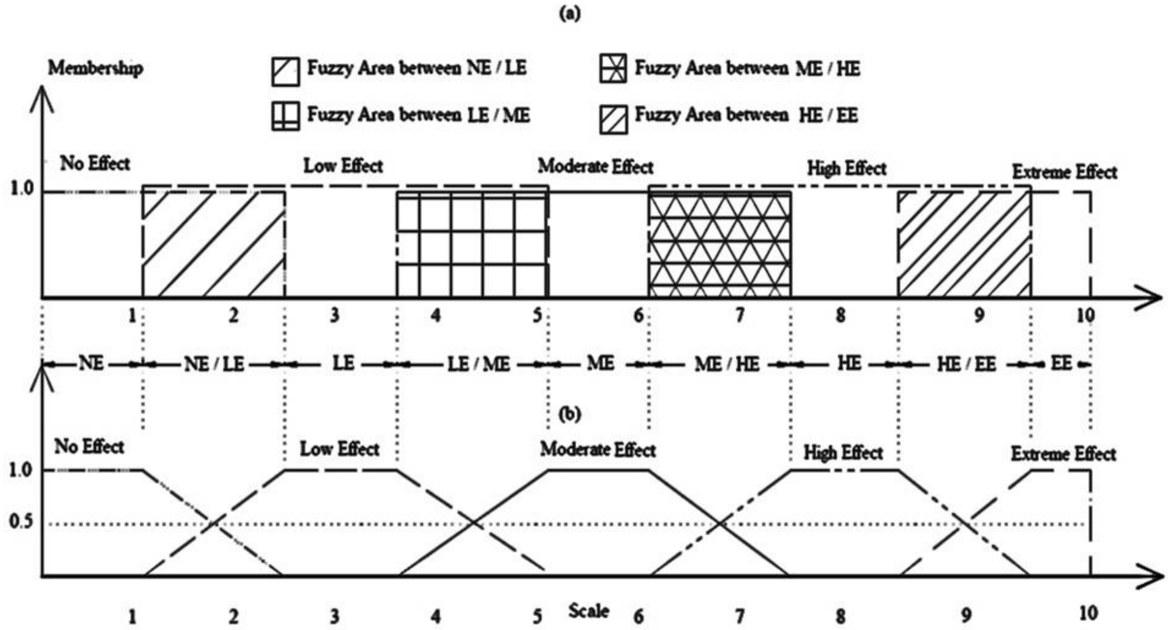

Figure 5: Fuzzy linguistic - numeric conversion scheme: preliminary (a) and final (b)

This Linguistic-Numeric scheme provides flexibility in reflecting the predefined organization scale for each linguistic term that represents an impact. The incorporated effects on productivity for each factor vary from; no effect (NE) to extreme effect (EE) as shown in Figure 5. Explicitly, the different included effects were; no effect, low effect, moderate effect, high effect and finally extreme effect. The projected linguistic terms were labeled to cover a scale of 1:10. Each linguistic term covers a particular organization's predefined range; for example, a factor has a moderate effect means it has an expert evaluation 5 to 6 on the 1:10 organization's predefined scale. The distribution of experts' assessments for the effect of each factor is shown in **Error! Reference source not found.**.

Table 1: Experts' votes on the effect of influencing factors

Influencing Factors		N	L	M	H	E
I. Excavated Soil Conditions						
A. Soil Properties						
1.	Loadability	0	2	7	14	4
2.	Moisture content	1	1	9	15	1
3.	Swelling factor	0	2	14	7	4
4.	Compactability	0	3	10	10	4
5.	Soil Weight	0	3	14	7	3
B. Bucket Fill Factor						
1.	Soil hardness	0	3	8	11	5
2.	Change of cut depth	0	1	8	16	2
3.	Operator skills	0	2	3	12	10
4.	Excavated soil particle size	0	1	9	12	5
5.	Power of machine	0	3	7	13	4
II. Hauling and Access Roads Conditions						
1.	Loosely soil road	0	2	5	17	3
2.	Rutty road	0	1	10	12	4
3.	Congested road	0	4	4	4	15
4.	Road with up or downhill	1	3	5	14	4
5.	Muddy road	0	2	6	13	6
6.	Snowy road	0	3	1	10	13
III. Equipment and Operational Conditions						
A. Fuel Consumption						
1.	Tire pressure	1	2	9	14	1
2.	Age of equipment	0	2	3	18	4
3.	Operator skills	1	3	4	15	4
A. Fuel Consumption ...Continue.						
4.	Excessive loads	0	0	7	16	4
5.	Wind resistance	0	4	14	8	1
6.	Bad road conditions	0	2	5	17	3
7.	Cold weather	0	4	13	8	2
8.	Frequent short trips	0	4	13	9	1
9.	Wheel slippage / excessive torque	0	2	19	6	0
10	Engine tuning / maintenance	0	0	13	9	5
B. Operation zones						
1.	Using improper lower gear speed	1	3	13	8	2
2.	Using improper higher gear speed	1	3	6	15	2
C. Improve Operation Cycle						
1.	Least waiting durations	0	3	4	6	14
2.	Considering equipment balance	0	2	6	15	4
3.	Skilled drivers and operators	1	0	4	17	5
4.	Strict supervision	0	4	5	15	3
5.	Good road conditions	1	1	3	16	6
IV. Weather Conditions						
1.	Rain	0	1	4	18	4
2.	Humidity	1	9	15	0	2
3.	Wind	0	2	9	14	2
4.	Temperature	0	4	17	4	2
5.	Fog	0	0	6	8	13
6.	Sun shine	13	2	6	3	3
7.	Duration of daylight	0	2	3	7	15

(N, L, M, H, E: Experts' Evaluation)

The linguistic-numeric conversion scheme shown in Figure 5 supposes to be created once for each influencing factor to convert the respective linguistic evaluations of experts into numeric fuzzy numbers as shown in Table 2.

Table 2: Numerical fuzzy numbers for each influencing state

Linguistic Evaluation	Numerical Fuzzy Numbers
No Effect	[0.0 0.0 1.0 2.5]
Low Effect	[1.0 2.5 3.5 5.0]
Moderate Effect	[3.5 5.0 6.0 7.5]
High Effect	[6.0 7.5 8.5 9.5]
Extreme Effect	[8.5 9.5 10.0 10.0]

3.3 Data Reliability Examination

Reliability of the data collected through the questionnaire is a fundamental aspect of the evaluation of measurements, and it is a vital mean to enhance the accuracy of the collected data evaluation. A statistical reliability analysis has been done to examine the consistency of the received data through the questionnaire. Cronbach's alpha (α) measure has been used to check the internal consistency of the acquired data. Cronbach's alpha (α) test has been applied using IBM® software package SPSS. There are different reports about the satisfactory values of alpha, ranging from 0.70 to 0.95 (Bland and Altman, 1997). A low value of alpha could be due to a low number of questions, poor correlation between items or heterogeneous constructs. The test result shows a robust data consistency with 0.962 as shown in

Table 3.

Table 3: Reliability Statistics

Cronbach's Alpha	Cronbach's Alpha Based on Standardized Items	N of Items
0.962	0.961	27

3.4 Combination of Fuzzy Numbers

The combination process takes into account the significance of the fuzzy numbers produced from the evaluation of different impacts provided by respondents. Equation (1) is used to calculate the combination of fuzzy numbers uses to calculate the fuzzy number that represents each factor influencing productivity of earthmoving operations. Prior realization of the combined fuzzy numbers, large figure of fuzzy numbers were obtained, where, these numbers depict the fuzzy number for each attribute versus each of the influence five criterion. Hence, these five numbers have been combined as shown in Table 4.

. Due to the sizable number of mathematical operations, the combination formula has been programmed using a Microsoft Excel®.

$$\tilde{F}_i = \frac{N_r}{N_T} \times \widetilde{NoEffect} + \frac{N_r}{N_T} \times \widetilde{Minor} + \frac{N_r}{N_T} \times \widetilde{Moderate} + \frac{N_r}{N_T} \times \widetilde{High} + \frac{N_r}{N_T} \times \widetilde{Extreme} \qquad \text{Equation (1)}$$

Where,

$\tilde{F}_i$, represents the fuzzy number of factor i=1...to 27

N_r, represents the number of responses for each attribute A (e.g., No Effect)

N_T, represents the total number of responses each factor

Table 4: Combined Fuzzy Number for Each Influencing Factor

Influencing Factors		Combined Fuzzy Number	Influencing Factors		Combined Fuzzy Number
I. Excavated Soil Conditions			***A. Fuel Consumption ……..Continue***		
A. Soil Properties			4.	Excessive loads	[5.722 7.148 8.074 9.056]
1.	Loadability	[5.352 6.778 7.704 8.722]	5.	Wind resistance	[4.056 5.537 6.519 7.815]
2.	Moisture content	[4.852 6.315 7.259 8.426]	6.	Bad road conditions	[5.444 6.889 7.833 8.852]
3.	Swelling factor	[4.704 6.130 7.056 8.204]	7.	Cold weather	[4.241 5.704 6.667 7.907]
4.	Compactability	[4.889 6.315 7.241 8.333]	8.	Frequent short trips	[4.148 5.630 6.611 7.889]
5.	Soil Weight	[4.426 5.870 6.815 8.019]	9.	Wheel slippage / excessive torque	[3.870 5.370 6.370 7.759]
B. Bucket Fill Factor			10	Engine tuning / maintenance	[5.259 6.667 7.574 8.630]
1.	Soil hardness	[5.167 6.574 7.481 8.500]	***B. Operation zones***		
2.	Change of cut depth	[5.259 6.722 7.685 8.778]	1.	Using improper lower gear speed	[4.204 5.648 6.574 7.815]
3.	Operator skills	[6.278 7.593 8.407 9.130]	2.	Using improper higher gear speed	[4.852 6.296 7.222 8.333]
4.	Excavated soil particle size	[5.444 6.852 7.759 8.759]	***C. Improve Operation Cycle***		
5.	Power of machine	[5.167 6.593 7.519 8.556]	1.	Least waiting durations	[6.370 7.611 8.352 8.963]
II. Hauling and Access Roads Conditions			2.	Considering equipment balance	[5.444 6.870 7.796 8.796]
1.	Loosely soil road	[5.444 6.889 7.833 8.852]	3.	Skilled drivers and operators	[5.870 7.259 8.130 9.037]
2.	Rutty road	[5.259 6.685 7.611 8.667]	4.	Strict supervision	[5.074 6.519 7.463 8.519]
3.	Congested road	[6.278 7.500 8.222 8.815]	5.	Good road conditions	[5.870 7.241 8.093 8.963]
4.	Road with up or downhill	[5.130 6.537 7.426 8.444]	**IV. Weather Conditions**		
5.	Muddy road	[5.630 7.019 7.907 8.833]	1.	Rain	[5.800 7.220 8.140 9.080]
6.	Snowy road	[6.556 7.815 8.574 9.167]	2.	Humidity	[2.860 4.300 5.220 6.600]
III. Equipment and Operational Conditions			3.	Wind	[4.900 6.360 7.320 8.460]
A. Fuel Consumption			4.	Temperature	[3.900 5.360 6.320 7.620]
1.	Tire pressure	[4.667 6.130 7.074 8.259]	5.	Fog	[6.500 7.780 8.560 9.240]
2.	Age of equipment	[5.722 7.148 8.074 9.019]	6.	Sun shine	[2.660 3.880 4.380 5.640]
3.	Operator skills	[5.222 6.630 7.519 8.519]	7.	Duration of daylight	[6.521 7.771 8.521 9.125]

3.5 Defuzzification of Combined Fuzzy Numbers

The acquired combined fuzzy numbers are not suited for demonstrating the importance of each influencing factor and which of these factors transcends the others. Therefore, it is preferable to have these fuzzy numbers in a crisp format. Accordingly, each fuzzy number is defuzzified using Equation (2). The defuzzified value of each factor represents its score as shown in Table 5.

$$F_i = \frac{\int x\mu_A dx}{\int \mu_A dx}$$ Equation (2)

Where,
F_i, represents the defuzzified value of fuzzy number $\tilde{F}_i$
μ_A, represents the membership function for each attribute A (e.g., No Effect)

Table 5: Defuzzification Output for the Studied Influencing Factors

Influencing Factors		Defuzzification Output	Influencing Factors		Defuzzification Output
I. Excavated Soil Conditions			***A. Fuel Consumption ...Continue.***		
A. Soil Properties			4.	Excessive loads	7.500
1.	Loadability	7.139	5.	Wind resistance	5.981
2.	Moisture content	6.713	6.	Bad road conditions	7.255
3.	Swelling factor	6.523	7.	Cold weather	6.130
4.	Compactability	6.694	8.	Frequent short trips	6.069
5.	Soil Weight	6.282	9.	Wheel slippage / excessive torque	5.843
B. Bucket Fill Factor			10.	Engine tuning/maintenance	7.032
1.	Soil hardness	6.931	***B. Operation zones***		
2.	Change of cut depth	7.111	1.	Using improper lower gear speed	6.060
3.	Operator skills	7.852	2.	Using improper higher gear speed	6.676
4.	Excavated soil particle size	7.204	***C. Improve Operation Cycle***		
5.	Power of machine	6.958	1.	Least waiting durations	7.824
II. Hauling and Access Roads Conditions			2.	Considering equipment balance	7.227
1.	Loosely soil road	7.255	3.	Skilled drivers and operators	7.574
2.	Rutty road	7.056	4.	Strict supervision	6.894
3.	Congested road	7.704	5.	Good road conditions	7.542
4.	Road with up or downhill	6.884	**IV. Weather Conditions**		
5.	Muddy road	7.347	1.	Rain	7.560
6.	Snowy road	8.028	2.	Humidity	4.745
III. Equipment and Operational Conditions			3.	Wind	6.760
A. Fuel Consumption			4.	Temperature	5.800
1.	Tire pressure	6.532	5.	Fog	8.020
2.	Age of equipment	7.491	6.	Sunshine	4.140
3.	Operator skills	6.972	7.	Duration of daylight	7.984

3.6 Prioritization of Influencing Factors

The factors that are related to the same influencing category have been ranked based on their respective scores as shown in Figures 6 to 10. Where the higher score, the higher priority the factor has. Figure 6 presents the prioritization of the factors related to the soil properties of the excavated soil. Figure 7 shows the prioritization of the factors that could affect the BFF (Bucket Fill Factors) of the excavated soils. Figure 8 presents the prioritization of the factors related to hauling and access road conditions that might affect the productivity of earthmoving operations. Equipment and operational conditions have been categorized into three (3) sub-groups, where, the factors related to each group have been ranked from higher to lower scores to determine the factors with higher priority to be detected using the proposed customized data acquisition system. Figure 9, Figure 10, and Figure 11 show the fuzzy-set-based ranking of factors that have an impact on fuel consumption, operational zone and improving operational time respectively. Where, Figure 9 illustrates a group of 10 factors related to equipment and operational conditions that might influence the equipment fuel consumption where, excessive loads, equipment age, and bad road conditions represent the factors that lead to uneconomic fuel consumption. The same demonstration philosophy applied to factors depict by Figure 10 and Figure 11, where the usage of an equipment gear speed higher than the appropriate diminishes the equipment utilization efficiency as shown in Figure 10. Figure 11 indicates the ranking of factors that contribute to the improvement of the operation cycle time. Finally, Figure 12 presents the ranking of the factors related to the weather conditions.

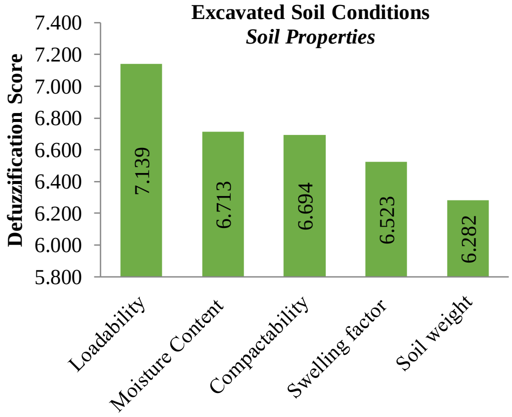

Figure 6: Ranking Scores of Excavated Soil Conditions- Soil Properties

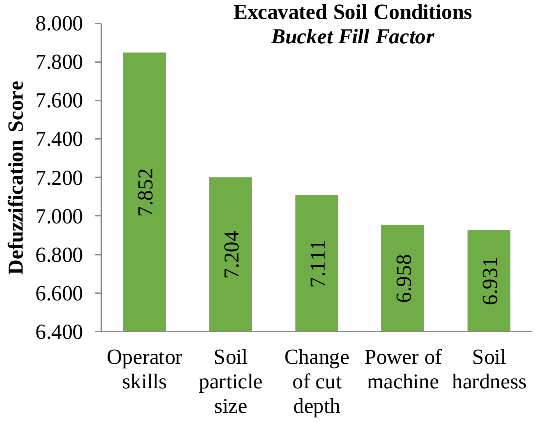

Figure 7: Ranking Scores of Excavated Soil Conditions-Bucket Fill Factor

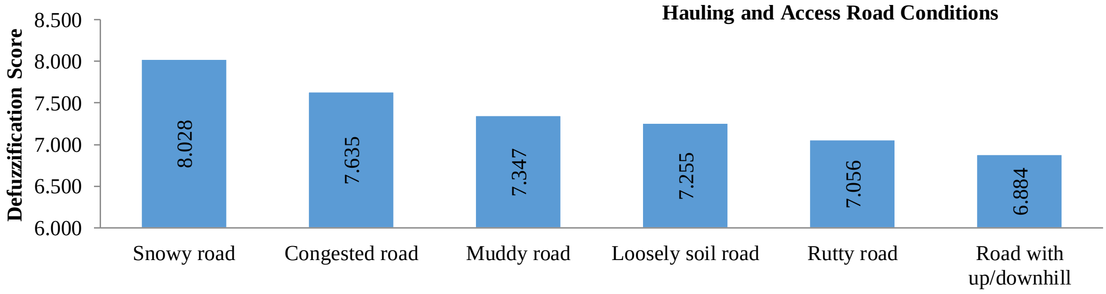

Figure 8: Ranking Scores of Hauling and Access Road Conditions

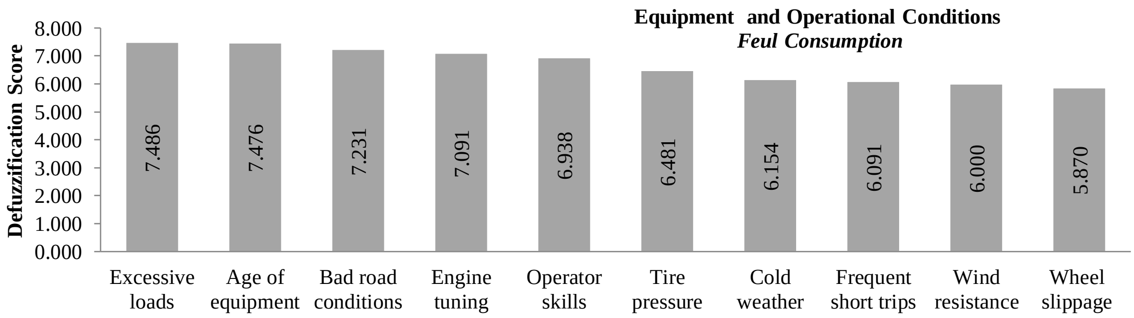

Figure 9: Ranking Scores of Equipment and Operational Conditions - Fuel Consumption

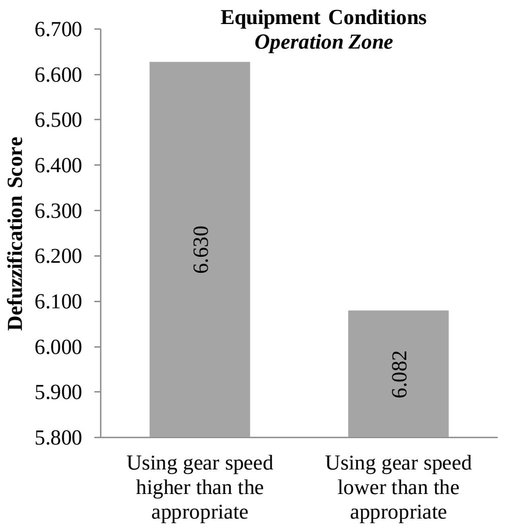

Figure 10: Ranking Scores of Equipment Conditions- Operation Zone

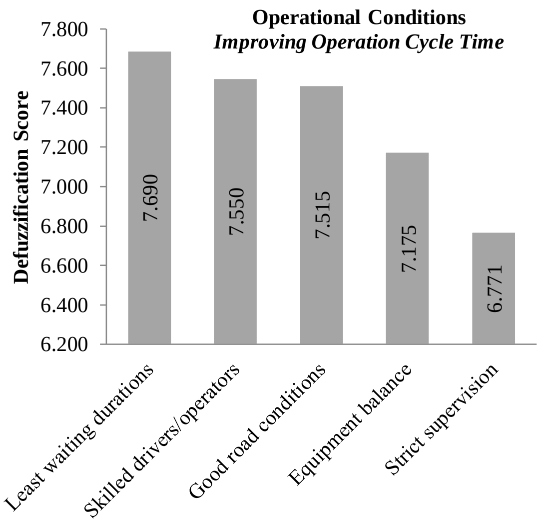

Figure 11: Ranking Scores of Operational Conditions - Improving Operation Cycle Time

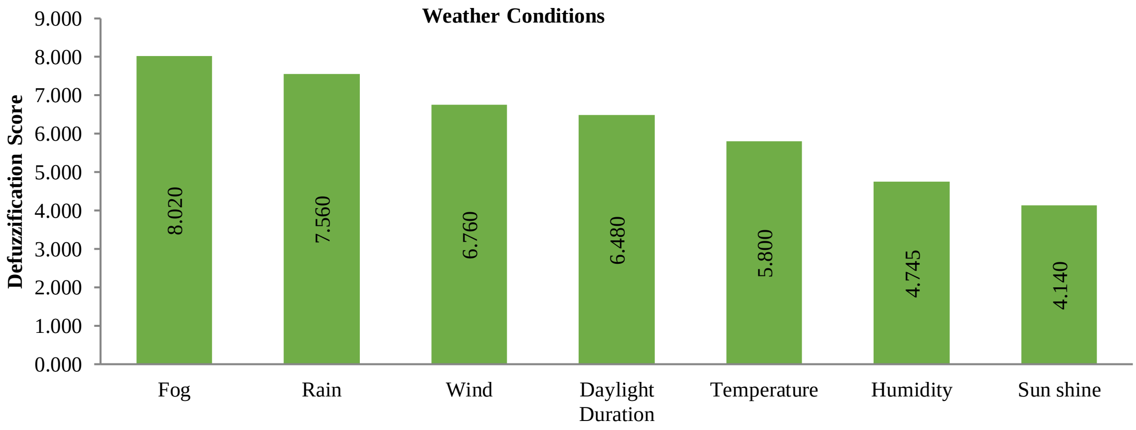

Figure 12: Ranking Scores of Weather Conditions

4. DISCUSSION AND ANALYSIS OF RESULTS

Ranking results identify the factors that have the higher priority to be recognized as compared to other factors. The first group of factors related to excavated soil condition includes two subgroups. First, the soil properties influencing factors subgroup, in which, loadability (a measure of the difficulty in excavating and loading a soil), and soil moisture content have come in the first and second positions. This analysis is genuinely compatible with the logical engineering sense, where, the deficient loadable soil, the longest required duration to be loaded, and hence the less production of the fleet. Also, soil water content has a significant share from the actual loaded quantities perspective, where, in soils with high water content, trucks might reach their payload capacity before reaching its commonly usable volumetric capacity. Such consideration contributes to avoiding unintentional abuse of hauling trucks, consequently, less time out of the fleet for maintenance, and then more production. Second, the factors of excavated soil that impact the bucket fill factor, in which, operators' skills, the size of particles and depth of cut were respectively the most three important, affecting factors. The second group of factors influencing productivity of earthmoving operations is the hauling and access road conditions. The different road conditions have been ranked, where, snowy and congested roads have come in the first and second state respectively. Snowy roads result in higher rolling resistance, excessive torque, wheel slippage and hence slow speeds and long durations for hauling and returning trips. Similarly, the top-ranked factors in other groups are the most recommended factors to be recognized to detect as early as possible their respective influence on productivity. Hence, this early detection of factors influencing productivity of earthmoving operations permits the management personnel in charge to take the necessary actions in a timely and prioritized manner. Also, it helps in selecting the most appropriate configuration or customization of on-site data acquisition system to collect the data related to the selected significant influencing factors.

5. CUSTOMIZED CONFIGURATION

Over the last decades, automation technology market made noticeable advancements, in both hardware and software. In particular, is the advancement in remote sensing technologies, Wireless Sensing Networks (WSN) and data communication, which all provide an opportunity to detect these prioritized influencing factors and communicate their relating data sets using automated data acquisition and transmission systems. The majority of the existing data acquisition systems are off-the-shelf, expensive and in a black box format in both perspectives of software and hardware, such as On-Board Instrumentation Systems (OBIS). Those commercial data acquisition systems have traditionally been used, where, the user has no right either to configure the hardware nor to access the relevant algorithms and modify it as they see fit, where the stored data is often difficult to be accessed without using the seller specific software.

Open-source technologies allocate a minute portion in data acquisition systems' marketplace. There are two pioneers in the domain of the cost-efficient available technologies, Arduino and Waspmote. Although Arduino has older existence than Waspmote, both platforms are using typical coding syntax. Arduino is considerably purposeful to learn how to use electronics and to do cheap, and simple projects (e.g., home automation projects), while Waspmote is a device specially designed to create long lifetime wireless sensor networks which expected to be installed in a real scenario like a city, agriculture farm or construction job site.

A detailed comparative study has been done to select the most suitable open source technology for automated data acquisition and communication, Both Arduino and Waspmote are certified open source, so all the source code libraries are released under the Lesser General Public License (LGPL). Moreover, Both Waspmote and Arduino boards are FCC and CE certified. However a Radio certification is needed in case of using a communication module (e.g., WiFi, GPRS, ZigBee ......etc.). Only Waspmote has the Radio Certification for all the possible combinations of the communication modules (802.15.4, ZigBee, 3G, ZigBee + 3G,... etc.), while, Arduino doesn't. **Error! Not a valid bookmark self-reference.** summarizes the different comparison aspects for both Arduino and Waspmote including the cost of various modules.

Table 6: Detailed Comparison between Arduino and Waspmote

Technology / Feature	Arduino		Waspmote
	UNO	**Mega 2560**	
Compiler/IDE	Same compiler and core libraries		
Code	Same code is compatible in both platforms		
Suitability	Automated home projects		Wireless sensor networks Long lifetime real scenarios
RTC (Real Time Clock)	Separate module		Built-in
3D Accelerometer	Separate module		Built-in
Data Logging	Separate module		Built-in SD card slot
Frequency	16 MHz	16MHz	14MHz
RAM	2 KB	8 KB	8 KB
External Storage (SD card)	No	No	Yes, 2GB
Consumption ON	50 mA	50 mA	15 mA
Sleep mode	No	No	Yes, 55µA
Hibernate mode	No	No	Yes, 0.7µA
Board	22,00 €	41,00 €	155.00 €
Arduino Xbee 802.15.4 + 2dBi antenna	45,00 €	45,00 €	
Triple axis accelerometer	7,75 €	7,75 €	
On Board Programmable LED + ON/OFF Switch	1,00 €	1,00 €	
RTC DS3234 + Button Battery	16,00 €	16,00 €	
uSD Adaptor	20,00 €	20,00 €	
Solar Panel Socket 6600mAh Battery	47,00 €	47,00 €	30,00 €
Total	**158,75 €**	**177,75 €**	**185,00 €**

The proposed data acquisition system is configured to be fully automated, accurate, reliable and cost-effective. The system is customizable to include a variety of sensors that able to detect the most important factors influencing performance and production of earthmoving operations. The customized selection of these sensors depends on the fuzzy-set-based application of the proposed questionnaire. Although the selection of the required sensors depends on the realized ranking, this selection could be prioritized by giving higher priority to a sensor which covers more than an influencing factor over another sensor which covers just one factor. The factors which have been come in the top ranks of each influencing category or sub-category are the base for selecting the appropriate sensor. The sensors have been selected to capture the reading related to these factors directly or indirectly to their indicators. The chosen sensors should mainly and to satisfy the following configuration criteria: (1) cost-effective, (2) reliable, (3) open-source based. In the light of this configuration criterion and the above-stated results of the proposed fuzzy-set-based ranking method, Table 7 shows the highly-recommended, and top-ranked influencing factors and their relevant associated selected sensing technology. Figure 13 illustrates the architecture of the proposed customized data acquisition system.

Table 7: Highly Recommended Top Ranked Influencing Factors and Their Relevant Selected Sensors

Top Ranked Influencing		**Relevant Selected Sensors**
Excavated Soil Properties		
Loadability	Indicator: Number of buckets	Pressure Atmospheric sensor
Soil Moisture Content		Moisture Content sensor
Bucket Fill Factor		
Operators Skills	Indicator: Number of buckets	Pressure Atmospheric sensor
Soil Size Particles		
Change of Cut Depth		
Hauling and Access Road conditions		
Snowy Road	Indicator: Wheel slippage	OBDII Scanner
Congested Road	Indicator: Frequent Delays	GPS
Muddy Road	Indicator: Wheel slippage and Excessive torque	OBDII Scanner
Loosely Soil Road		
Rutting Road	Indicator: Frequent excessive vibration with distinct zones	3D Accelerometer
Road with Up / Down Hills		3D Accelerometer
Equipment and Operational Road Conditions		
Excessive loads		Load Cell
Bad Road Conditions		3D Accelerometer
Tire Pressure		OBDII Scanner
Weather Conditions		
Fog		Humidity sensor
Rain		Automated Weather Station
Wind (Speed and Direction)		
Daylight Duration		Luminosity sensor
Temperature		Temperature sensor
Humidity		Humidity sensor
Sunshine		Luminosity sensor

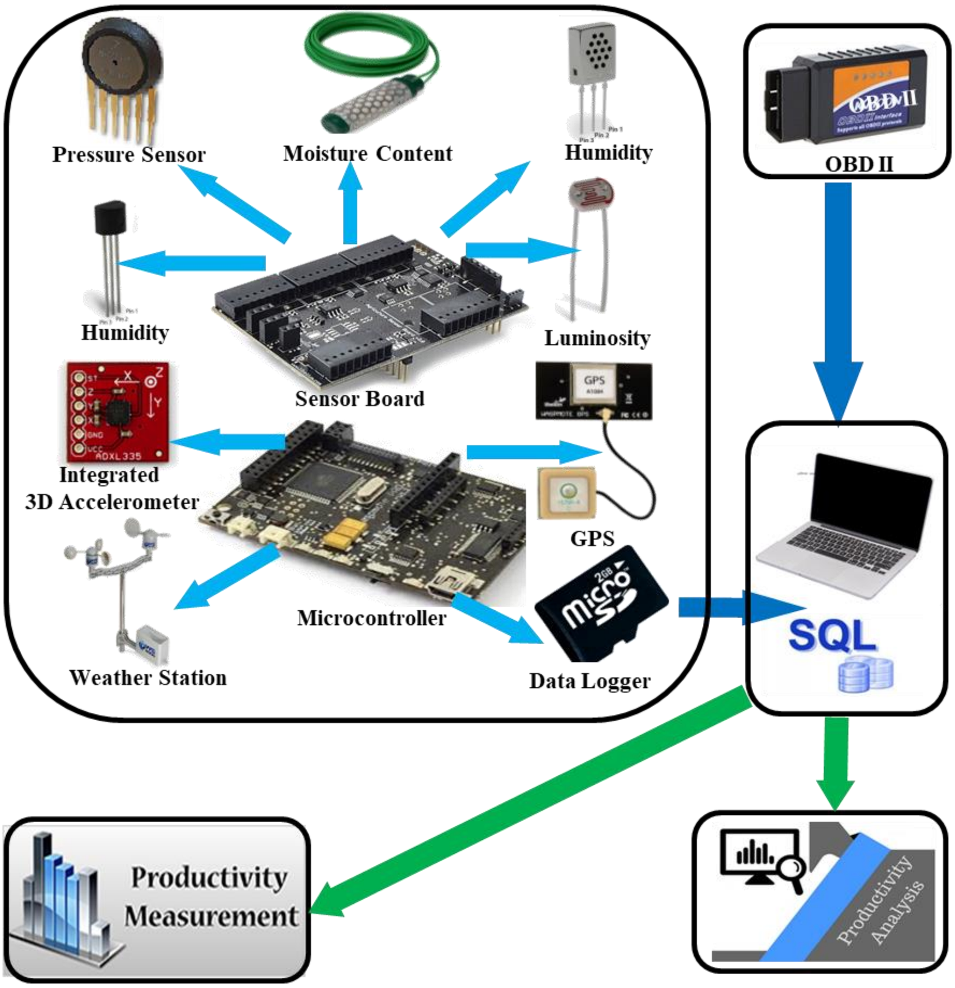

Figure 13: The Architecture of the Proposed Customized Data Acquisition System

6. CONCLUSION

This paper introduced a new method for customizing the configuration of on-site automated data acquisition systems for earthmoving operations. The method is efficient and less costly compared to other black box market available technologies. The data needed for the study was collected using a questionnaire survey, after that, the questionnaire responses have been analyzed using fuzzy set theory. This approach identifies, categorizes, evaluates and prioritizes vast scope of factors affecting productivity of earthmoving operations. The influencing factors have been ranked based on scores calculated as the defuzzified values of fuzzy numbers representing those factors. The highly scored factors that belong to the same influencing category are selected to be measured using proper sensory tools to measure those factors. Then, the selected sensory tools are combined into one particular customized data acquisition system for automating the monitoring and tracking process in a manner that improves the performance of earthmoving operations. In this paper, the linguistic-numeric conversion was performed based on the answers of 27 experts, and the results were reflected in the prioritization of influencing factors. The utilized linguistic-numeric conversion is updatable, where the opinions of more experts should are reflected. Hence, the combined fuzzy numbers, defuzzification output, and prioritization of influencing factors change. The developed method represents a proactive decision support assistive tool that helps owners and contractors to identify the most influencing factors. And, accordingly, allow them to cost-efficiently select the technologies that need to be included for customizing an automated data acquisition system that augments the productivity and elevates the utilization efficiency of equipment in earthmoving operations. The developed methodology is expandable and more factors that affect the productivity performance throughout the various cycles of earthmoving operations can be investigated and included in a way that increases the effectiveness of the proposed method in tracking and monitoring productivity in earthmoving projects. This study is a part of ongoing research on automated data acquisition and productivity analysis of earthmoving operations.

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