A MACHINE LEARNING-BASED FRAMEWORK FOR DELAY RISK MITIGATION IN BUILDING PROJECTS

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DEDICATION

This thesis is dedicated to my late father (Alhaji Mas'ud O. Sanni-Anibire), who taught me to value knowledge, and showed me how to relentlessly pursue my dreams;

And mother (Engr. Muslimat O. Sanni-Anibire, MNSE, FNIEE), my teacher and mentor, who inspired me to become an engineer and always encouraged me. As well as my late aunt (Alhaja Idiat Adefunke Adelugba) for her motherly role and support.

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"BACK OF EVERY GREAT WORK, WE CAN FIND THE SELF-SACRIFICING DEVOTION OF A WOMAN" – *Plaque on the Brooklyn Bridge*

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ABSTRACT

The construction industry is lagging behind the service and manufacturing industries in terms of efficiency and productivity; though the industry continues to boom, as demonstrated in the rapid growth of tall buildings in urban centres across the globe. The rise of tall buildings is partly in response to the need to create more urban space for an impeding global population explosion and urbanization; however, this building typology is notorious for being delayed and uncompleted. The research domain is saturated with numerous studies on construction delays across continents and project types. These studies only make modest contributions in dealing with the inherent problem. An inadequate effort has been channelled towards the development of prescriptive tools with the potential to mitigate construction delays. The desired solution would employ innovative methods to arrive at problem-solving strategies for the ultimate purpose of delay mitigation. Furthermore, the current mantra of the construction industry is to embrace the fourth industrial revolution (IR 4.0), and leverage the capabilities of digital technologies such as artificial intelligence and machine learning. Thus, the aim of this study was to develop a delay mitigation framework based on the application of machine learning, with a focus on tall building projects. The proposed framework is dependent on three key areas of delay mitigation, including “reliable cost estimates”, “reliable duration estimates”, and “delay risk assessment”. This was achieved in two phases of data collection and model development. The first phase identified the causes of delay in the global construction industry, and subsequently determined the delay risk factors in tall building projects. Likewise, historical data on completed tall building projects featuring the total cost and duration of the project was obtained. In the second phase, machine learning models were developed based on Multi Linear Regression Analysis (MLRA), Artificial Neural Networks (ANN), K Nearest Neighbours (KNN) and Support Vector Machines (SVM). This stage also involved combining models to develop ensemble models/multi classifier systems to investigate the possibility for improved predictive performance. The developed models were evaluated by standard performance metrics used in machine learning for classification and regression problems (i.e. Classification Accuracy, Correlation Coefficient (CC), Mean Absolute Percentage Error (MAPE), and Root Mean Squared Error (RMSE)). The performance of the selected model for the duration was characterised by a CC of 0.69, MAPE of 0.18 and RMSE of 301.76, while for cost by a CC of 0.81, MAPE of 0.89 and RMSE of 6.09, and for delay risk a classification accuracy of 93.75% was achieved. The final visualization of the delay mitigation framework was conveyed with the most prevalent analytics model: the Cross-Industry Standard Process for Data Mining (CRISP-DM). Finally, the proposed framework was reviewed and validated by industry professionals. The significance of the proposed framework can be seen in its potential as a decision-making tool for proactive delay risk mitigation at the planning stage of tall building projects. Although the development of delay mitigation framework concentrated on tall building projects, a similar approach can also be extended to other types of construction.

ABSTRAK

Industri pembinaan ketinggalan berbanding industri perkhidmatan dan pembuatan dari segi kecekapan dan produktiviti; walaupun industri ini terus berkembang, seperti yang ditunjukkan dalam pertumbuhan pesat bangunan tinggi di pusat-pusat bandar di seluruh dunia. Peningkatan bangunan tinggi sebahagiannya sebagai tindak balas kepada keperluan untuk mewujudkan lebih banyak ruang bandar untuk penghambatan ledakan dan pembandaran penduduk global; namun, tipologi bangunan ini menjadi terkenal kerana kelewatan dan tidak siap. Domain penyelidikan dipenuhi dengan banyak kajian mengenai kelewatan pembinaan di seluruh benua dan jenis projek. Kajian-kajian ini hanya memberikan sumbangan sederhana dalam menangani masalah yang wujud. Usaha yang tidak mencukupi telah disalurkan ke arah pengembangan alat preskriptif yang berpotensi untuk memitigasi kelewatan pembinaan. Penyelesaian yang diinginkan adalah sesuatu yang menggunakan kaedah inovatif untuk mencapai strategi penyelesaian masalah untuk tujuan utama mitigasi kelewatan. Selanjutnya, mantera industri pembinaan sekarang adalah mendakap revolusi industri keempat (IR 4.0), dan memanfaatkan kemampuan teknologi digital seperti kecerdasan buatan dan pembelajaran mesin. Oleh itu, objektif keseluruhan kajian ini adalah untuk membangunkan kerangka mitigasi kelewatan berdasarkan penerapan pembelajaran mesin, dengan fokus terhadap projek bangunan tinggi. Kerangka kerja yang dicadangkan bergantung pada tiga bidang utama mitigasi kelewatan, termasuk "anggaran kos yang boleh dipercayai", "anggaran jangka masa yang boleh dipercayai", dan "penilaian risiko kelewatan". Ini dicapai dalam dua fasa pengumpulan data dan pembangunan model. Fasa pertama mengenal pasti penyebab kelewatan dalam industri pembinaan global, dan seterusnya menentukan faktor risiko kelewatan dalam projek bangunan tinggi. Begitu juga, data sejarah mengenai projek bangunan tinggi yang siap dibina yang merangkumi jumlah kos dan jangka masa projek tersebut diperolehi. Dalam fasa kedua, model pembelajaran mesin dikembangkan berdasarkan *Multi Linear Regression Analysis* (MLRA), *Artificial Neural Networks* (ANN), *K Nearest Neighbours* (KNN) dan *Support Vector Machines* (SVM). Tahap ini juga melibatkan penggabungan model untuk mengembangkan model ensembel/sistem pengkelasan pelbagai untuk menyiasat peningkatan prestasi ramalan. Model yang dikembangkan dinilai oleh metrik prestasi standard yang digunakan dalam pembelajaran mesin untuk masalah klasifikasi dan regresi (iaitu Klasifikasi Ketepatan, Pekali Korelasi (CC), *Mean Absolute Percentage Error* (MAPE), dan *Root Mean Squared Error* (RMSE)). Prestasi model untuk jangka masa dicirikan oleh CC 0.69, MAPE 0.18 dan RMSE 301.76, sementara untuk kos oleh CC 0.81, MAPE 0.89 dan RMSE 6.09, dan untuk risiko kelewatan ketepatan klasifikasi 93.75 % telah dicapai. Visualisasi akhir kerangka mitigasi kelewatan disampaikan oleh model analitik yang paling lazim: *Cross-Industry Standard Process for Data Mining* (CRISP-DM). Akhirnya, kerangka yang dicadangkan telah dinilai dan disahkan oleh profesional industri. Kepentingan kerangka yang dicadangkan dapat dilihat melalui potensi sebagai alat membuat keputusan proaktif mitigasi risiko kelewatan di peringkat awal projek bangunan tinggi. Walaupun pembangunan kerangka mitigasi kelewatan tertumpu kepada projek bangunan tinggi, pendekatan sama boleh diperluaskan kepada jenis pembinaan lain.

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LIST OF ABBREVIATIONS

AI	-	Artificial Intelligence
AACEI	-	Association for the Advancement of Cost Engineering International
ANN	-	Artificial Neural Network
BIM	-	Building Information Modelling
BOQ	-	Bill of Quantities
BOT	-	Build-Operate-Transfer
CBR	-	Case Based Reasoning
CPM	-	Critical Path Method
CRISP-DM	-	Cross Industry Standard Process for Data Mining
CTBUH	-	Council on Tall Buildings and Urban Habitat
FL	-	Fuzzy Logic
GA	-	Genetic Algorithm
GCC	-	Gulf Cooperating Council
GDP	-	Gross Domestic Product
ICT	-	Information and Communications Technology
IR4.0	-	Fourth Industrial Revolution
KBES	-	Knowledge-Based Expert Systems
KNN	-	K Nearest Neighbours
MAPE	-	Mean Absolute Percentage Error
MCS	-	Multi Classifier Systems
ML	-	Machine Learning
MLRA	-	Multi Linear Regression Analysis
PERT	-	Program Evaluation and Review Technique
CC	-	Correlation Co-Efficient
RII	-	Relative Importance Index
RMSE	-	Root Mean Squared Error
SME	-	Subject Matter Experts
SVM	-	Support Vector Machines
SVR	-	Support Vector Regression

LIST OF SYMBOLS

α	-	Cronbach's alpha
r_s	-	Spearman's rank correlation coefficient
$	-	Dollar sign
μ	-	Arithmetic mean
σ	-	Standard deviation

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CHAPTER 1

INTRODUCTION

1.1 Problem Background

The exponential rise in global population, expected to range between 9 and 11 billion by 2050; coupled with a breakneck pace in technological advancements has led to a rapid transformation of the built environment. The United Nations projects that urbanization will add 2.5 billion people to urban populations by 2050, and consequently 66% of the world's population will inhabit urban centres (UN, 2014). The combined trends of urbanization and population growth will thus place an added stress on already limited urban housing and infrastructure. From this perspective, the safety and comfort of the world's future population will depend on how fast engineers are able to solve inherent problems of the built environment. Tall buildings have been viewed as a viable solution to creating urban space in areas where there exists concentrated population, scarcity of land, and high land costs. Thus, the current trend is to take advantage of the urban skyline, and as a result, urban centres around the world now feature a huddle of tall building structures (Zisko, 2008). The predominance of tall buildings in urban centres across the world is sufficient evidence that there is a paradigm shift in the configuration of the built environment. Despite its exponential rate of growth, tall buildings have suffered from delayed completion times, a productivity loss which has plagued the construction industry for many decades. Remarkably, the Council on Tall Buildings and Urban Habitat (CTBUH) in its report "Dream Deferred: Unfinished Tall Buildings" noted the alarming rate of increase of "never completed" tall buildings, and further provided a list of 50 projects of 150m or taller that were never completed (CTBUH, 2014).

1.2 Problem Statement

The 21st century is witnessing a rising complexity in its construction projects. The construction industry continues to soar higher with the astronomical growth of tall buildings, notably in Asian and Middle Eastern skies (Moon, 2015). Interestingly, the Council on Tall Buildings and Urban Habitat (CTBUH) suggests that there is an alarming rate of increase in never competed tall building projects across the globe (CTBUH, 2014). Table 1.1 illustrates examples of abandoned tall building projects across the world, along with the supposed causes of delay. Previous studies suggest that the first step in resolving delay problems is to identify the main causes of delay (Assaf and Al-Hejji, 2006; Yang and Ou 2008). Therefore, the research domain is saturated with an abundance of literature on the causes of delay in the construction industry. On the subject of tall buildings, few studies have dealt with the subject matter of construction delays (Ogunlana et al., 1996; Kaming et al. 1997; Suksai et al., 2015; Bhangale, 2017; Haslinda et al., 2017; Kog 2017; Aaditya and Bhattacharya, 2018). These studies are however limited in addressing the problem due to their exploratory nature and lack of a constructive methodology. Moreover, studies that sought to propose delay mitigation frameworks do not consider the complex interplay among multiple delay factors holistically (Love et al., 2000; Abdul-Rahman 2008; Motaleb 2014; Khair et al., 2018). Effective strategies for delay mitigation should cover three main aspects including the project's timeframe, estimated costs, and performance in terms of identified risks (Galway, 2004; Meyer, 2015). Furthermore, Construction 4.0 has ushered in the potential to adopt digital technologies such as machine learning to solve problems such as construction delay. Despite the industry's determination to modernize, as demonstrated through Construction 4.0, it is still lagging behind other industries in adopting digital technologies such as machine learning. Though there are few applications of machine learning in construction and civil engineering (Deka, 2019; Adeli, 2020), there is a lack of its clear application to proactive delay mitigation in construction. The current study hopes to fulfil the research need for a digital and holistic delay mitigation framework.

Table 1.1 Unfinished Iconic Tall Building Projects across the World, based on CTBUH Data, 2014 (Modified from: Al-Kodmany, 2018)

S/N	Name of project	Finish date		Causes of delay (source)
		Date Started	Date Ended	
1	Nakheel Tower, Dubai (1000+m)	2008	2009	Financial problems (https://en.wikipedia.org/wiki/Nakheel_Tower)
2	India Tower, Mumbai (700m)	2010	2011	Dispute between the tower's developers and Mumbai's civic authorities (https://en.wikipedia.org/wiki/India_Tower)
3	Russia Tower, Moscow (612m)	2008	2008	Global Financial Crisis of 2007-2008 (https://en.wikipedia.org/wiki/Russia_Tower)
4	Chicago Spire, Chicago (610m)	2007	2008	Financial crises (https://en.wikipedia.org/wiki/Chicago_Spire)
5	Doha Convention Center Tower, Doha (551m)	2007	2012	Impact on flights to and from Doha International Airport (https://en.wikipedia.org/wiki/Doha_Tower_and_Convention_Center)
6	Burj Al Alam, Dubai (510m)	2009	2009	Global Financial Crisis of 2007-2008 (https://en.wikipedia.org/wiki/Burj_Al_Alam)
7	Palace of Soviets, Moscow (495m)	1937	1941	German invasion in 1941 (https://en.wikipedia.org/wiki/Palace_of_the_Soviets)
8	Fairwell International, Xiamen (397m)	1996	2018	Financial problems within China Post (https://en.wikipedia.org/wiki/Xiamen_International_Centre)
9	Faros de Panama Torre Centra I, Panama City (346m)	2008	2008	Financial problems (https://en.wikipedia.org/wiki/Faros_del_Panam%C3%A1)
10	Skycity, Mandaluyong (335m)	1997	1997	Lawsuit filed by homeowners' association from nearby village (https://en.wikipedia.org/wiki/Skycity_(Mandaluyong))

1.3 Research Aim

The aim of this research is to develop a machine learning-based framework for delay mitigation in tall building projects. The framework is based on the premise that the first step towards mitigating delays is identifying the causes, and further controlling the risks of occurrence of the identified causes. Additionally, the framework entails the use of predictive models developed based on machine learning to estimate construction cost, duration and delay risk. Specifically, the objectives of this research are as follows:

1.3.1 Research Objectives

1. To carry out a systematic literature review of studies on the causes of delay in the global construction industry.
2. To identify and rank the causes of delay in tall building projects according to various stakeholders across the project life cycle.
3. To develop models for estimating the cost, duration and delay-risk of tall building projects based on machine-learning techniques.
4. To develop and validate a delay mitigation framework based on the results obtained from the previous research objectives.

1.4 Research Scope

The scope of this research is project specific i.e. it focuses on tall building projects. In this research, tall buildings are considered as per the definition of The Council of Tall Buildings and Urban Habitat (CTBUH). CTBUH defines a tall building as one exceeding 50m in height, while supertall buildings exceed 300m in height, and mega-tall building exceeding 600m in height (Chew, 2017). The study is also limited in terms of data collected on delay causes to the Gulf Cooperating Council (GCC) countries (Saudi Arabia, United Arab Emirates, Bahrain, Kuwait, Oman and Qatar). Countries in the GCC have drawn up ambitious development plans in infrastructure and facilities with billions of US Dollars in investment (Abdelhadi et al., 2018). This rapid growth in the region has positioned the GCC as a global leader in tall building construction. Thus, Subjected Matter Experts (SMEs) were consulted in this region covering three main stages of the project life cycle (Consultants, Contractors, and Clients' Representatives/Facility Managers). Furthermore, the source of the dataset on cost and duration used in this research is the Mega Project Case Study Center of China, corroborated with information from CTBUH's skyscraper center. Remarkably, China according to CTBUH (2018) accounts for 61.5% of 200-meter-tall buildings in the world in 2018, and has maintained its role as the most prolific country in tall building construction for over two decades.

In developing the models in this research, the choice of machine learning algorithms was based on two factors: (1) methods commonly used in the problem's domain i.e. construction research; (2) based on Benz´ecri (1973)'s idea to "let the data speak for itself", i.e. experimenting with a suite of algorithms and determining what works best for the dataset. This study considered Multi Linear Regression Analysis (MLRA), Artificial Neural Networks (ANN), k Nearest Neighbors (KNN), Support Vector Machines (SVM) and Ensemble techniques. These methods have been adopted in similar construction research (Attal, 2010; Czarnigowska and Sobotka, 2014; Peško et al., 2017).

1.5 Methodology of the Study

The methodology adopted in this doctoral thesis is detailed in chapter 3, this section however provides an overview of the research methodology. This research work would be based on primary and secondary sources of data.

1. Primary sources of data: consultations with Subject Matter Experts (SMEs) by way of providing them with questionnaires to obtain their professional feedback on various research issues. Professionals will include consultants, contractors, and clients' representatives/facility managers.

2. Secondary sources of data: the extant published literature in the research domain, and historical records of completed tall building projects.

The approach to be employed in achieving the objectives of this research are summarized as follows:

(a) Objective 01: A systematic literature review and meta-data analysis of the causes of delay reported by influential research studies across the global construction industry was carried out. This was used to establish the main factors causing delay in the global construction industry, to be carried over for further research.

(b) Objective 02: The various factors causing construction delay identified in (a) was used to develop a questionnaire. The developed questionnaire was administered to construction SMEs across a project life cycle (Consultants, Contractors, and Clients' Representatives/Facility Managers). A Likert scale of importance from (1) to (5) was used to design the questionnaire in line with previous studies that investigated the causes of delay, and the Relative Importance Index (RII) was therefore computed. To test the reliability of the questionnaire, the standardized Cronbach's alpha (α) test was employed. Also, Spearman's rank correlation coefficient (r_s) was employed to determine the level of agreement between various respondent categories.

(c) Objective 03: Historical data on the construction duration and costs of tall building projects were obtained. Similarly, the questionnaire survey developed in "Objective 02" was used to obtain the consequence of the delay causes, along the importance ratings. The obtained information was further processed to obtain risk ratings, and to develop a dataset structure suitable for machine learning application. The Waikato Environment for Knowledge Analysis (Weka 3.8.3) has been used in this research for pre-processing of the dataset. Weka is an open source machine learning software written in Java, and developed at the University of Waikato, New Zealand (Witten et al., 2011). Predictive models for cost, duration and delay risk were developed based on machine learning techniques such as Multi Linear Regression (MLRA), k-Nearest Neighbors (KNN), Support Vector Machines (SVM), Artificial Neural Network (ANN) and Ensemble techniques/Multi Classifier Systems. The performance of the developed models were evaluated by standard performance metrics used in machine learning for classification and regression problems (i.e. Classification Accuracy, Correlation Co-efficient (CC), Mean Absolute Percentage Error (MAPE), and Root Mean Squared Error (RMSE)).

(d) Objective 04: A graphical representation of the proposed delay mitigation framework was developed based on the most prevalent analytics model: the Cross-Industry Standard Process for Data Mining (CRISP-DM). The framework was further validated by highly experienced construction professionals as regard its applicability, appropriateness, practicability, and reliability.

1.6 Significance of the Study

The significance of this study is firstly reflected in addressing a current problem in the construction industry, which is the increasing number of delayed tall building projects. This trend deserves a call for research into traditional construction issues that may affect tall building projects, including delays. Additionally, this study has significant implications for research and practice. The study presented a thorough analysis on the causes of delay in the global construction industry, which will form the foundation for developing risk mitigation procedures in construction management, especially in global construction projects. The study further provided an assessment and identification of major delay causes in tall building projects. Understanding the causes of delay in tall building projects is necessary as the first step to mitigating the occurrence of these delays. This will be instrumental in the development of guidelines and recommendations, as well as project control and monitoring strategies for tall building projects. Furthermore, real estate investors could use the causes of delay identified to carry out financial risk assessments in project feasibility studies. As for the research implications, it would be interesting to see how the results of this study will compare with future delay studies in tall building projects from China and the USA, where there has been rapid development of tall buildings in the past few decades.

Furthermore, this study demonstrates the adoption of machine learning in solving an inherent problem in the industry. Thus, it promotes the current aspiration of the construction industry for digitization and automation under the umbrella of Construction 4.0. This study has proposed machine learning models to support a reliable estimation of cost, duration and delay risk. With due consideration for the limitations of data-driven models, the developed models could serve as decision making tools at the preliminary stages of tall building projects. Construction professionals in tall building projects will find it useful in establishing initial estimates, and in risk-based project planning to avoid issues related to time overrun, cost overrun, dispute, arbitration and litigation, total abandonment and dissatisfied stakeholders. Ultimately, the main contribution of this research is in its conceptualization and validation of a framework as a problem-solving strategy to mitigate construction delays in tall building projects. The framework developed in this study can be extended by other researchers to other project types. It could also serve as the basis for the development of ICT tools to be incorporated in existing project management tools for mitigating construction delay.

1.7 Structure of the Thesis

The structure of the thesis consists of five chapters. Chapter 2 presents the relevant background literature on tall buildings, construction planning and scheduling, construction delay causes, effects and mitigation, as well as Industry 4.0 and machine learning. Chapter 3 describes the various research methodologies used in achieving the objectives of the study. Chapter 4 discusses the results of the four objectives of the study. Chapter 5 presents a conclusion of the overall research study. The contents of the various chapters are described in more detail as follows:

Chapter 2 presents an overview of global urbanization trends as well as the evolution of tall building projects in the urban context. It highlights the historical reasons for the existence of tall building projects, as well as the need for such buildings in the 21st century, citing triggers such as urbanization, population increase, and limited land space. Additionally, an overview of construction planning and scheduling was discussed, while highlighting traditional and modern methods used in construction cost and duration estimation. This was followed by a discussion on issues related to productivity in the construction industry, and the desire for modernization and digitization. Subsequently, an extensive review of construction delay including definitions, types, causes, effects and mitigation was presented. A systematic tabularization of past studies on construction delays was made based on geographic location and project types. Finally, a brief narrative on Industry 4.0 (IR 4.0) was made, including machine learning techniques; as well as applications in construction duration and cost estimation.

Chapter 3 presents a detailed illustration of the research methodology adopted in the study. It describes in detail the approaches used to achieve the four objectives of this doctoral thesis. Firstly, the procedure for executing the meta-analysis was described. This entailed the extraction of data from the referenced literature and the formulae used to compute the effect summaries-the main result of the meta-analysis. Subsequently, the procedure used in achieving the second objective was described. This entailed the questionnaire survey design and administration, alongside the analysis approach and accompanying formulae, including procedures for computing the Relative Importance Index (RII), Cronbach's alpha (α) test and Spearman's rank correlation coefficient (r_s). Next, a detailed description of the steps used to achieve the third objective was provided. This involved dataset establishment, pre-processing, investigation of various views of the dataset, feature sub-set selection, hyperparameter optimization, and performance measurement. A description of the procedure used to develop Multi Classifier Systems (MCS) was also presented. Finally, the procedure used for the development and validation of the framework was presented –which is the fourth and final objective of this doctoral thesis.

Chapter 4 presents the results of various issues investigated in the course of this research. Firstly, the RII values extracted from selected influential studies were presented. This information was used for a meta-analysis, and the results including the effect summaries, confidence interval, in-group and overall ranking were presented and discussed. Subsequently, the results obtained from the assessment of the causes of delay in tall building projects in the GCC countries were presented. Initially, the demographics of respondents were presented, followed by the RII values calculated from the importance ratings, which were categorized according to the respondents' groups (Consultants, Contractors, and Owner Representative/Facility Managers). Similarly, results of Cronbach's alpha (α) test and Spearman's rank correlation coefficient (r_s) were discussed. The discussion also entailed a comparison of the top ten causes of delay in tall buildings from various geographic regions. This chapter also presented the results of the developed models for cost, duration and delay risk of tall building projects. The unique results presented include an investigation of various views of the dataset, feature sub-set selection, and the configuration of the developed models. A comparative analysis of various models was made to determine the best performing model based on standard performance metrics (Classification Accuracy, CC, RMSE, MAPE), as well as cross plots of the actual and predicted values. Finally, this chapter described the validation results of the proposed delay mitigation framework, highlighting the qualifications of the professionals consulted as well as their feedback in terms of the applicability, appropriateness, practicality and reliability of the framework.

Chapter 5 presents the conclusions of this doctoral thesis, summarizing the main findings according to the four objectives of this research. Additionally, contributions to theory and practice, limitations of the research, as well as suggestions for further research are discussed.

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LIST OF PUBLICATIONS

S/N	Research output	Type	Publication
1	Estimating Construction Duration of High-Rise Buildings: Comparing the BTC Model to KNN	Conference paper	*International graduate conference of built environment and surveying, GBES 2019, Universiti Teknologi Malaysia*
2	Forecasting Construction Delay Times in High-Rise Building Projects	Conference paper	*International Structural Engineering and Construction Conference, ISEC 2020, Cyprus.*
3	Causes of Delay in Tall Building Projects in GCC Countries	Conference paper	*The 8th International Conference on Construction Engineering and Project Management Dec. 7-8, 2020, Hong Kong SAR. ICCEPM 2020*
4	Causes of Delay in the Global Construction Industry – A Meta Analytical Review	Journal paper	*International Journal of Construction Management*
5	Developing a Machine Learning Model to Predict the Construction Duration of Tall Building Projects	Journal paper	*Journal of Construction Engineering, Management & Innovation*
6	Developing a Preliminary Cost Estimation Model for Tall Buildings based on Machine Learning	Journal paper	*International Journal of Management Science and Engineering Management*
7	Machine Learning Model for Delay Risk Assessment in Tall Building Projects	Journal paper	*International Journal of Construction Management*
8	Development of a Delay Mitigation Framework for Tall Building Projects	Journal paper	*Journal of Information Technology in Construction (ITcon)*