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ASSESSMENT OF SOLAR OUTPUT INTERMITTENCY THROUGH DOMESTIC ROOFTOP SITE DATA FOR 2017-2021

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ABSTRACT

Rooftop solar photovoltaic (PV) systems are commonly used in homes to supply excess electricity to the grid. Although, the variation of the average energy supplied during a given month shows a regular behaviour to a certain extent, not only is the generated power intermittent but sometimes varies drastically from day to day, even within a given week. These hourly and daily variations, although well known in the solar industry are not readily available to the public, are quite often not taken into account in studies on solar generation. These can also lead to the supply authority having to plan without detailed knowledge of the likelihood of such loss of energy. This paper analyses the known concepts considering the power output of a 4 kWp solar rooftop system, in a site in Mount Lavinia Sri Lanka. It allows the public to envisage rooftop solar, to understand the fluctuations of solar energy and the chance of daily and seasonal output energy variations.

KEYWORDS: *Solar PV, Power Fluctuations, Rooftop solar, Intermittency, Daily variations, Monthly variations, Database*

1. INTRODUCTION

With Sri Lankan Government incentives, many rooftop solar PV installations have come up throughout the country, not only in large industrial installations but also in domestic installations. Most owners of these installations do not have any guide to the probable solar energy that can be collected and are at the mercy of the solar system vendors. While these producers would like to maximize the amount of energy harvested over the year, they would like to have minimum operation or maintenance costs for the installation. As most of Sri Lanka is located at a latitude of around 7°N (with Colombo 06.927°N) the rooftop installation should preferably be facing South with the tilt angle of the PV panels being approximately 7° to optimize energy yield. However, the slope of a domestic roof is generally much higher, at around 30°, and the solar panels would probably be laid parallel to the slope. Although steeper angles would give a slight decrease in solar energy harvested, they would facilitate self-cleaning of panels, which is an advantage to domestic users.

The daily energy harvested would vary due to cloud cover, monthly variations [1], [2] due to the position of the Earth relative to the Sun, or monthly weather variations [3], [4]. The decrement in output energy other than due to the position of the Sun, is the clearness of the sky, temperature, wind speed, precipitation, and the number of wet days [5].

This paper aims to provide a multitude of solar fluctuation information, especially for the general public who wish to become rooftop solar electricity producers by producing electricity daily, and are probably paid monthly.

2. MAXIMUM AVAILABLE SOLAR ENERGY

It is now generally accepted that the total solar irradiance at the top of the Earth's atmosphere, or extra-terrestrial radiation is around 1361 W/m^2 [6]. However, due to the transparency of the atmosphere, defined by a clearness index [7], the maximum direct beam irradiance reaching the Earth's surface is around 1050 W/m^2 [8], and the maximum global irradiance on the horizontal Earth's surface is around 1120 W/m^2 including the effects of diffused sunlight, which would occur in a cloudless sky when the Sun is at its zenith. The direction in which the Sun falls on the Earth depends on the location and how near it is to the equator. Further, the path the radiation takes to reach ground level changes as the day progresses with maximum radiation at noon. Thus, near the equator, the Sun's beams reach the Earth's surface from 6 a.m. to 6 p.m. and only diffused light can reach it at other times. When looking at it in a different way, some part of the Earth receives sunlight 24 hours a day while the Earth's surface is approximately spherical with a surface area of 4πR^2, as shown in Figure 1.

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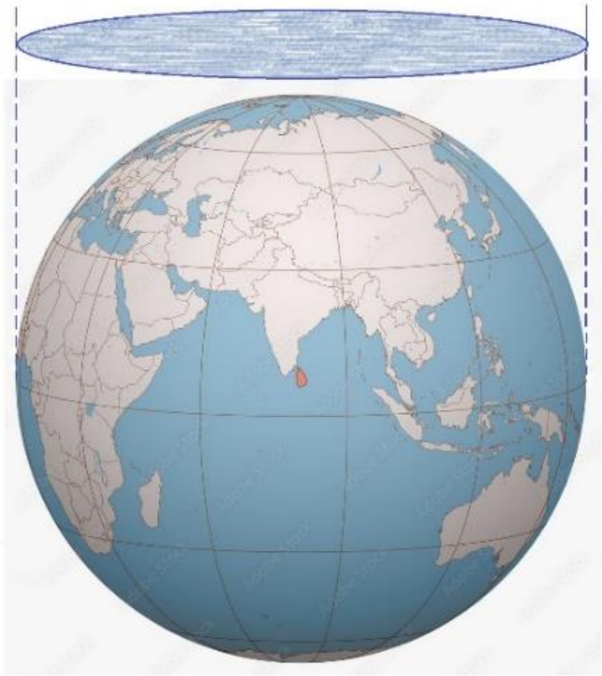

Figure 1: Surface area and projected area

The projected area (corresponding to that falling on the horizontal surface) is πR^2, giving a maximum of one-fourth of the energy falling on the horizontal area on which the sunlight falls. Thus, the maximum energy that could even theoretically be harvested from a given site would be 8.17 kWh/m^2/day (=1.361 × 24/4) including any harvested diffused radiation. Solar panels have at present a typical maximum efficiency of 18.6% at standard test conditions (including a nominal cell temperature of 25° C). Thus, the maximum realisable solar power generation is 0.253 kWp or 1.52 kWh/m^2/day.

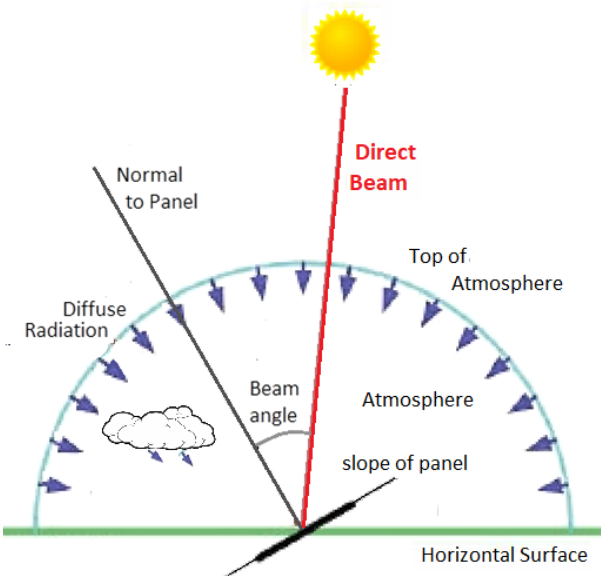

Figure 2: Composition of Irradiance

Figure 2 shows the direct beam component normal to the panel, and the diffuse radiation of the Sun. While maximum electricity is produced during noon time, the cell temperature of the panel would also be highest at this time; typically, it can rise to 30°C above ambient temperature.

Monocrystalline solar cells have a temperature coefficient of -0.4%/°C [9]. Thus, for a 30°C rise in cell temperature, there would be a drop of 12% in power output, reducing the effective panel efficiency to 16.4%. Since most of the solar power produced is when the solar panel is hot, around 1.34 kWh/m^2/day will be produced with what is normally considered a clear sky. A typical monocrystalline solar panel would be of size 1 m × 1.65 m so that 2.21 kWh can be expected per panel per day.

For a 12-panel installation, this would mean a maximum of around 26.5 kWh/day. The daily solar electricity production depends both on seasonal variations as well as cloud cover in addition to the variation of sunlight from sunrise to sunset.

3. MONTHLY VARIATION OF SOLAR INSOLATION

Due to the tilt of the Earth on its axis of rotation and the elliptical rotation of the Earth around the sun, there is a declination angle that varies seasonally as shown in Figure 3.

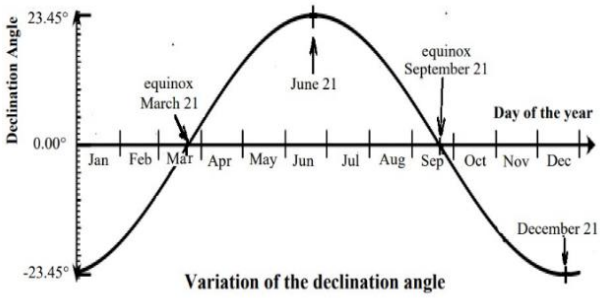

Figure 3: Monthly variation of the declination angle

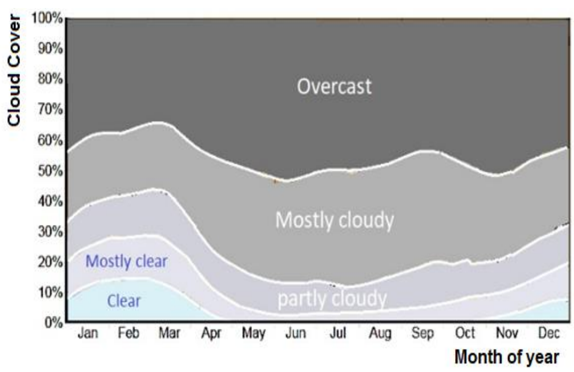

Figure 4: Cloud cover categories

Figure 4 shows a typical categorization of the percentage of time the sky is covered by clouds on a monthly basis in Dehiwala-Mount Lavinia in Sri Lanka

[3]. These are categorized in 20% steps as clear, mostly clear, partly cloudy, mostly cloudy, and overcast conditions which greatly affect the solar output.

A study [10], considering the period 2017-2021 for Mount Lavinia, has shown that for any month, 90% of the maximum solar energy yield can be guaranteed only on 17% of the days. However, 70% of the possible energy can be supplied on 60% of the days. It has also shown the rare possibility, on less than 2% of the days of less than 10% of the possible energy yield.

4. SELECTED SITE IN MOUNT LAVINIA

The data of a domestic site in Mount Lavinia Sri Lanka has been considered for detailed analysis. This site has 12 monocrystalline panels of size 1.65 m × 1.0 m installed with a total capacity of 4.16 kWp. Based on the current study, this site can be considered to generate a maximum of 3.3 kW (based on a nominal 80%) at around noon on a clear day with corresponding maximum energy of 26.4 kWh/day.

5. SOLAR OUTPUT MEASUREMENTS

Solar output measurements have been recorded online at the Mount Lavinia site from August 2017 to July 2021. Near ideal conditions have been recorded on 1st February 2018 and are shown in Figure 5 with a peak power of 3.332 kW and energy of 26.27 kWh/day. These correspond very well with the theoretically anticipated values.

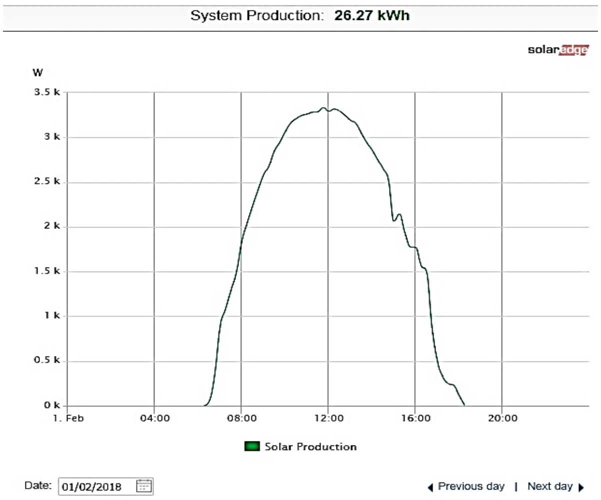

Figure 5: Peak solar energy day (1st February 2018)

It has been observed that the sky is relatively clear with nearly cloudless skies in January and February.

However, ideal days do not last the whole week-long. The best week for solar production during the 4-year period occurred from 3rd to 9th January 2019 as seen in Figure 6. However, the peak solar energy was observed on a different day on 1st February 2018.

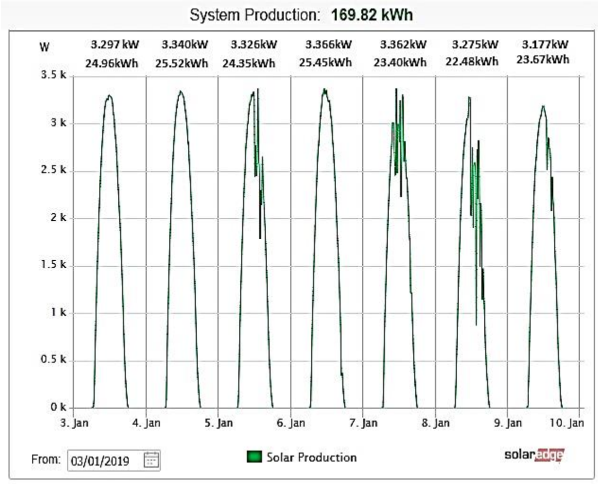

Figure 6: Solar output in a good week in January

It is seen that during this week, the peak power is virtually the same, but the daily energy produced varies slightly from 22.5 kWh to 25.5 kWh with a mean of 24.3 kWh.

On the other extreme, May and June are very unproductive months, with the lowest recorded during the 4 year period being on 3rd June 2021, just 0.324 kW peak power, but with the peak energy being just 0.807 kWh as shown in Figure 7.

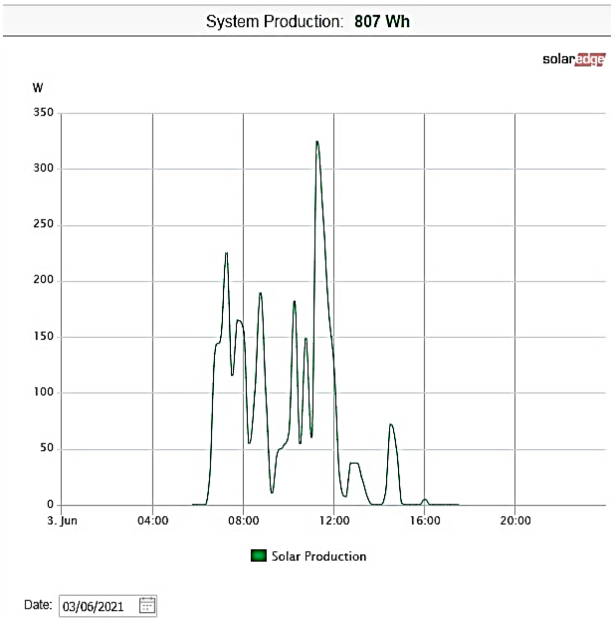

Figure 7: Minimum energy day in June 2021

Further, during this period the power and energy varied substantially from day to day as shown in Figure 8.

The overall solar output energy from month to month is shown to be somewhat consistent as in Figure 9. This is also consistent with the variations from month to month due to changes in declination angle and cloud cover as expected theoretically.

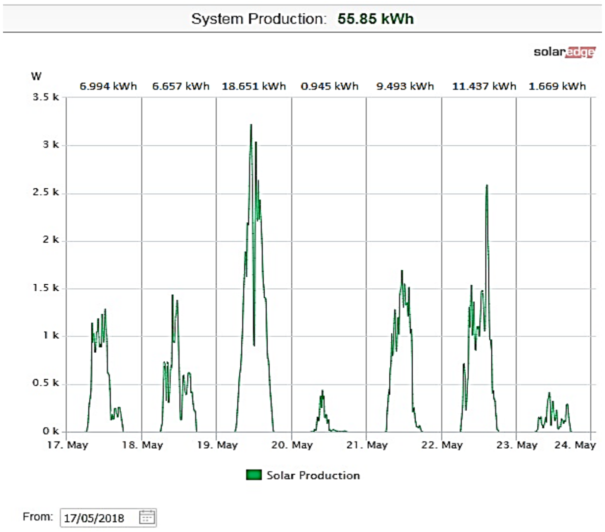

Figure 8: Solar output on a highly fluctuating week

6. SOLAR OUTPUT FLUCTUATIONS ANALYSIS

To understand the solar output behaviour, the intermittent output on 25th September 2017 has been compared with that of the maximum energy day and a maximum power day in September as shown in Figure 10.

It is seen from the figure that while the peak power for a clear day was 3.332 kW with energy of 26.27 kWh/day, the pattern did not completely match the pattern for September. Thus, a peak day in September was found where the peak power corresponds to 3.055 kW. It might be surprising that the peak power on a cloudy day like 12th September 2018 with 13.42 kWh/day, was much higher at 4.436 kW, compared to what could have been expected as 3.055 kW for even a clear day.

While it seems strange, the detailed analysis gives the reason for this apparent discrepancy. Studying the curves of 12th September 2018 with a clear day in September shows that there are many points which are above the clear day curve. Further examination of each of these points shows that each higher point occurs just after a very low point just before that instant.

For example, for the 4.436 kWp, moments before the power stood at 1.188 kW, and moments later falls to around 0.3 kW, seems very strange, but it is just due to the movement of relative clouds above the panel.

While a solar panel normally operates at around 30ºC higher than the ambient temperature at mid-day, the temperature would fall to near ambient during cloud cover. Thus, soon after a cold session for the panel, when the sun suddenly appears, the solar panel efficiency is high giving a value very close to the nominal value of 4.16 kWp.

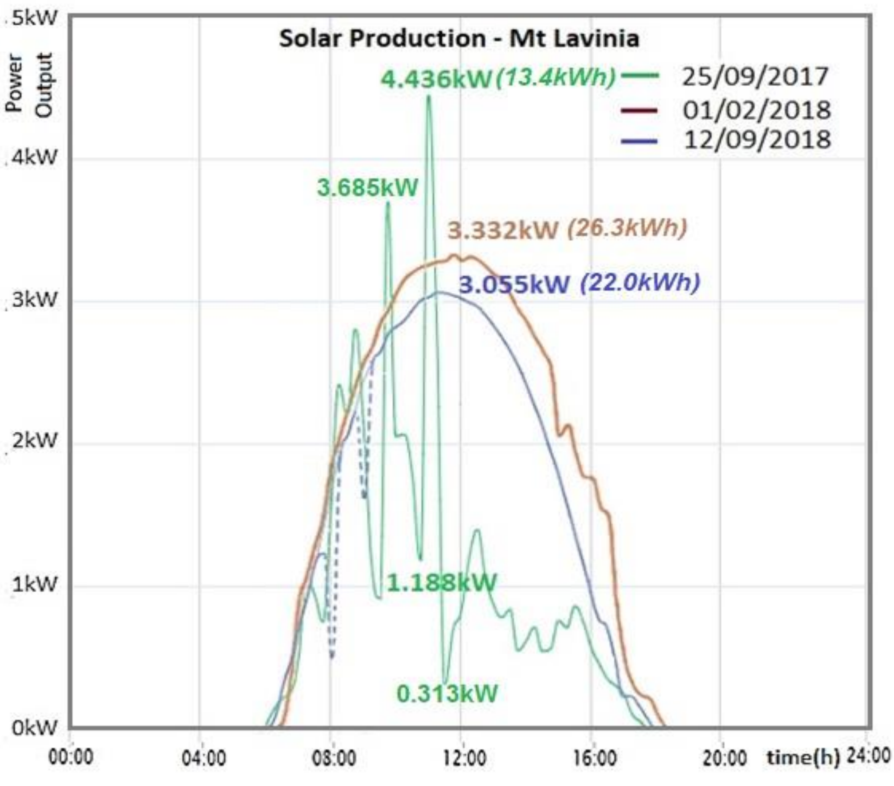

Figure 9: Average monthly solar output over the 4-year period

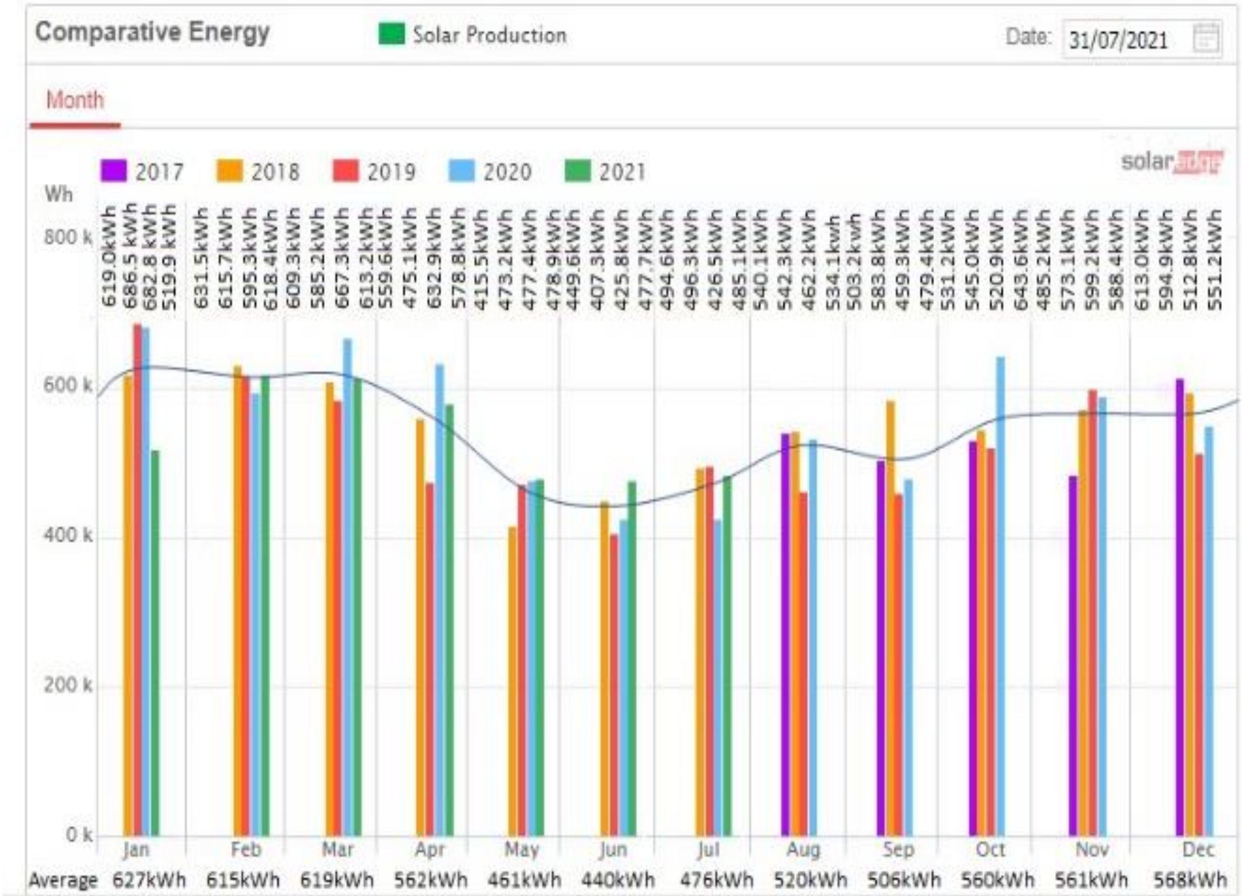

Figure 10: Analysis of solar output during fluctuations

7. CONCLUSION

The paper has presented an analysis of solar output for rooftop solar PV systems in the presence of both daily and seasonal fluctuations. Statistics represent how the generated power sometimes varies drastically from day to day, even within a given week. The review of analysis has been presented with respect to a 4.6 kWp monocrystalline solar rooftop system, on a site in Mount Lavinia Sri Lanka. Solar output patterns are analysed, and reasons for even higher power outputs during high fluctuations are explained to enable domestic solar roof-top owners to effectively utilise the power.

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LABOUR PRODUCTIVITY OF LARGE-SCALE BUILDING CONSTRUCTION PROJECTS IN SRI LANKA: PERSPECTIVE OF PROJECT MANAGEMENT STAFF

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ABSTRACT

As construction projects play an important role in a country's economy, it is vital to improve their productivity. Labour productivity is considered one of the major measures of construction productivity. Therefore, improving labour productivity in construction industry is recognized as critical for the national economy of Sri Lanka. This research is conducted to identify the critical factors affecting labour productivity of large-scale building construction projects in Sri Lanka. Thirty-nine factors that affect the construction labour productivity were identified from reviewing the literature. These factors were modified and thirty-two factors were short listed to match the Sri Lankan context with the help of experts in the industry. In order to collect the data required for the study, a questionnaire was distributed among the selected sample of project management professionals in the Sri Lankan construction industry. The Relative Importance Index (RII) method was used to analyse the data and to identify the critical factors affecting labour productivity. The top five critical factors were identified as shortage of experienced labourers, insufficient skill level of labourers, shortage of materials, rework, and unavailability of suitable tools and equipment. The main recommendations of the study include enhancing training and development opportunities for workers, developing policies to improve the skill levels of the workforce, focusing on target-based wage system instead of a daily wage system, maintaining continuous information sharing among stakeholders, and providing the appropriate tools and equipment for construction work through effective equipment management plans. The recommendations of this study are expected to contribute to improving the labour productivity of future building construction projects in Sri Lanka.

KEYWORDS: *Labour productivity, Construction projects, Critical factors, Relative Importance Index*

1. INTRODUCTION

The construction industry is one of the most significant industries that impact the economy of a country. This scenario is even more relevant for a developing country like Sri Lanka. Therefore, developing the Sri Lankan construction industry is very important for reinforcing the national economy and social development. Improving productivity plays a vital role in developing the construction industry.

In general, "productivity" is defined as the ratio of input to output [1]. Among various measures of construction productivity, "labour productivity" is crucial as it considerably impacts the overall productivity of a construction project. Labour productivity mainly concerns the direct labour force and in most countries, the cost of construction labour is found to be 30% to 50% of the total project cost [2].

This study aimed at investigating the factors affecting labour productivity of large-scale building construction projects in Sri Lanka and providing recommendations to enhance the labour productivity of building construction projects.

2. LITERATURE REVIEW

The poor productivity of construction labour was found to be the main reason for cost and time overrun in a construction project as it directly affects the performance and cost effectiveness [3]. Although there are many studies conducted globally on construction labour productivity, only a limited number of such research can be found in the context of Sri Lanka.

Much research is currently available on construction labour productivity [4], [5], [6], [7], [8]. A study carried out in Trinidad and Tobago identified the top five factors for poor labour productivity as lack of labour supervision, unrealistic expectations for labour performance, shortage of experienced workers, lack of leadership skills of construction managers, and low skill level of workers [4].

Hughes and Thorpe [5] identified the top ten critical factors affecting construction productivity in Australia from the perspective of project managers and developing a formal structure responsible for improving construction productivity was recommended. A similar study conducted in the USA suggested improving labour

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productivity through appropriate and continuous training. Also, identifying a planned approach to overcome conflicts during the construction process was recommended [8].

Durdyev and Mbachu [7], in a study carried out in New Zealand recommended conducting further studies to investigate the factors affecting construction labour productivity during all phases of a construction project. Further, it was recommended to consider the views of clients, designers, and other stakeholders of the projects as well as those of consultants, contractors, and subcontractors. A study conducted in UK identified the need for conducting further research taking into account the perceptions of project management personnel such as designers and engineers [6].

A number of studies on construction labour productivity are available in the context of developing countries. In India, many such studies have been conducted [9], [10], [11], [12]. One study identified the critical factors for low labour productivity as poor decision making, improper planning, poor logistics and supply chain management, ineffective site coordination, and lack of labour skills. A detailed study to further investigate these critical factors and to identify the appropriate measures for improving labour productivity was recommended [9]. The need for extending the scope of research to include different regions of the country was emphasized [10].

Dixit et al. [11] pointed out that construction productivity can be improved by comprehensively revising the management process for project execution and appropriately changing the organizational environment. Further, they identified that insufficient time allocation for project planning as one of the main factors which lead to poor labour productivity. A study conducted in Pakistan [13] identified rough outdoor environment during project execution, poor management, as well as unskilled and inexperienced workers as the main causes for low labour productivity. In another study, the factors influencing labour productivity in construction projects in Pakistan were investigated and ranked based on severity level [14].

A study conducted in Iraq from the perspective of construction contractors highlighted that most of the issues related to labour productivity can be mitigated by proper planning of construction work [15]. In a similar study based in Yemen, it was identified that one of the main reasons for cost and time overrun in construction projects is poor labour productivity, which significantly affects the performance and profitability [16]. In a study conducted in Ethiopia, the top five factors affecting construction labour productivity were identified [17].

A similar study conducted by Howlader and Rahman [18] identified the most critical factors affecting construction productivity in Bangladesh. The findings of this research can be used to guide the stakeholders of construction projects in enhancing construction productivity. According to a study carried out in Indonesia, the overall performance of a construction project can be improved by developing a detailed understanding of various factors affecting construction labour productivity [19]. It was recommended to identify the critical factors affecting construction productivity in both positive and negative aspects and thereby, to formulate suitable strategies to improve construction productivity. In a study conducted in Thailand, the five most significant factors affecting construction productivity were identified as shortage of materials, incomplete drawings, incompetency of supervisors, shortage of tools and equipment, and absenteeism [20].

A limited number of research studies have been conducted related to the construction labour productivity in Sri Lanka. These research mainly focused on identifying the factors affecting labour productivity [21], [22], [23]. In his study to identify the critical factors affecting the motivation of construction workers, Halwatura [3] found out that enhancing worker motivation significantly contributes to improving labour productivity. Another study highlighted the importance of factor ranking in order to identify measures to improve worker productivity [21]. The critical role of skilled labour in improving construction labour productivity was emphasized and the need for providing training focusing on productivity improvement was identified as an appropriate strategy for Sri Lankan construction industry [22].

In their study, Santoso and Gallage [23] identified the vital role played by the contractors in effective project performance when compared to the clients. They highlighted the limited efforts taken so far to study the labour productivity in Sri Lankan construction industry as a main reason for labour productivity remaining a critical issue [3]. Many of the previous research identified the need for further studies on construction labour productivity in the Sri Lankan context.

3. METHODOLOGY AND DATA

The methodology of the research is summarized in Figure 1.

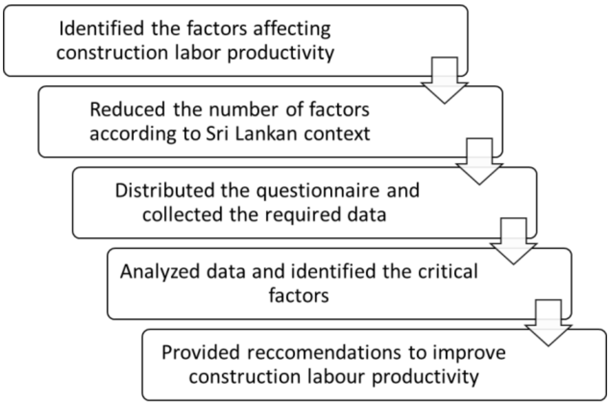

Figure 1: Summary of research methodology

3.1 REVIEW OF LABOR PRODUCTIVITY FACTORS

Initially, a total of 39 factors affecting labour productivity were identified from literature [4], [8], [14], [15], [16], [17], [21]. These factors were modified to match the Sri Lankan context and a total of 32 factors were identified for the current study. This was done based on the views of experienced professionals from the Sri Lankan construction industry. These factors were then classified into four groups: (1) technological related factors, (2) human/labour related factors, (3) management related factors and (4) external factors. This categorization was done based on previous research studies related to construction labour productivity [4], [15], [16].

3.2 SAMPLE SELECTION

The minimum sample size required was estimated statistically by using the Cochran formula considering the confidence level and margin of error for which Equation 1 and Equation 2 were adopted from past studies [4], [16].

$$n = \frac{m}{1 + \left(\frac{m-1}{N}\right)} \qquad \text{Equation 01}$$

$$m = \frac{z^2 \times \hat{p} \times (1-\hat{p})}{e^2} \qquad \text{Equation 02}$$

where:

n = Minimum sample size

m = Sample size of the unlimited population

N = Sample size of the available population

z = Statistical value for the confidence level

e = Margin of error (Sampling error)

$\hat{p}$ = Population proportion

The population of the study was the total number of project management professionals in large-scale building construction projects in Sri Lanka including project managers, civil engineers, quantity surveyors, construction supervisors, and technical officers. In determining the sample size, a 90% confidence level was considered. Further, previous studies suggested the value of $\hat{p}$ as 0.50 for estimating the minimum sample size [4], [16]. Therefore, by using the above values in Equations 1 and 2, the minimum sample size was estimated as 36 for the study.

3.3 DEVELOPMENT OF QUESTIONNAIRE

The questionnaire was developed using relevant references and guidelines [24]. The structured questionnaire consisted of three sections A, B, and C. Section A included background information of respondents such as job title, experience in construction, experience in large-scale building construction projects, and educational qualifications. This section was used to justify the suitability of the selected sample and to ensure the reliability of the results.

Section B included the identified factors affecting construction labour productivity in Sri Lanka. The respondents were asked to rate these factors according to a Likert scale. This section was used to obtain data, in order to identify the critical factors affecting construction labour productivity in Sri Lanka.

Section C was used to gather suggestions from respondents including the proposed improvements to enhance construction labour productivity. The purpose of this section was to incorporate the practical experience of respondents in recommending improvements for construction labour productivity.

3.4 DATA COLLECTION

A pilot survey was conducted to identify the practical issues that can occur in responding to the questionnaire and to improve the relevance of questions before distributing the final questionnaire.

In order to ensure the data collection from the required minimum sample size, a total of 135 questionnaires were distributed to the project management professionals through email, LinkedIn, and also using direct personal contacts. A total of 51 completed questionnaires were received, from which nine were rejected and 42 questionnaires were used for the study.

3.5. DATA ANALYSIS

For data analysis, the Relative Importance Index (RII) was used. This method was selected because it can be used to identify the critical factors affecting construction labour productivity [21], which is one of the objectives of this research. Furthermore, Cronbach's Alpha coefficient was calculated using Statistical Package for the Social Sciences (SPSS) software in order to ensure the internal consistency of the collected data and the reliability of the questionnaire. To determine the RII values, the calculations were performed and the data was compiled using Microsoft Excel spreadsheet software. RII for each factor was calculated using Equation 3 adopted from previous studies [4], [16], [17].

$$RII = \frac{5n_5+4n_4+3n_3+2n_2+1n_1}{N} \qquad \text{Equation 03}$$

Where:

n = Number of responses for each scale

N = Total number of responses collected

In Section B of the questionnaire, a Likert scale was used to rate each of the factors affecting labour productivity considering a scale of 1 to 5 (1 representing very low effect and 5 representing very high effect). The factors were ranked and critical factors affecting construction labour productivity were identified by considering the RII values. The factors were ranked for each category, the overall ranking of factors and overall ranking of productivity categories were determined and the top five critical factors affecting labour productivity were identified. As the final objective of this study, improvements to enhance the construction labour productivity were recommended.

4. RESULTS AND DISCUSSION

This study investigated the factors affecting labour productivity in large-scale construction projects in Sri Lanka. Initially, a total of 39 factors affecting labour productivity in global building construction industry were identified from the literature. Then, these factors were screened and short listed to match the Sri Lankan construction industry, by considering the views of professionals in the field. Hence, 32 factors were incorporated into the questionnaire for data collection.

4.1. COMPOSITION OF RESPONDENTS

A total of 135 questionnaires were distributed to the professionals in the construction industry and a total of 42 responses were used for the data analysis, as shown in Table 1.

The composition of respondents was analysed considering the job titles, educational level, and experience. Figure 2 illustrates the composition of respondents based on job titles.

Table 1: Details of data collection

	Total Number
Questionnaires sent	135
Questionnaires received	51
Rejected responses	9
Selected for the study	42

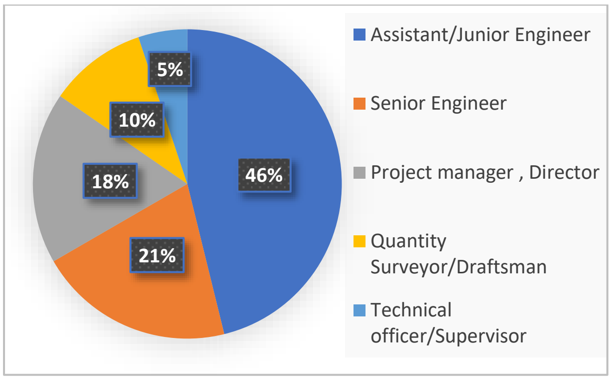

Figure 2: Job titles of respondents

The number of respondents based on their work experience and education level are shown in Figure 3 and Figure 4 respectively.

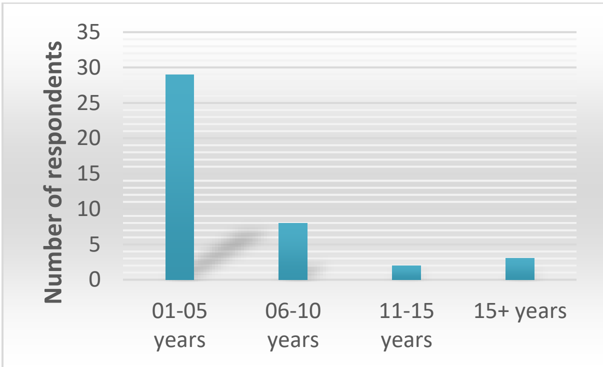

Figure 3: Work experience of respondents

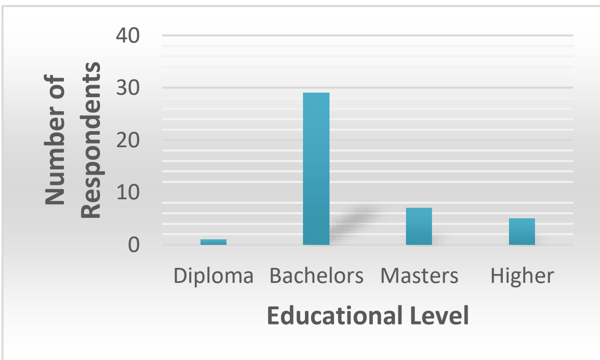

Figure 4: Educational level of respondents

Reliability analysis was done by calculating the Cronbach's Alpha coefficient in order to measure the internal consistency between responses collected for the study. This test was done by using SPSS and the value of Cronbach's Alpha coefficient was found to be 0.814. Therefore, the reliability of the questionnaire was considered sufficient for the study.

4.2. OVERALL RANKING OF FACTORS AFFECTING LABOUR PRODUCTIVITY

The overall ranking of 32 labour productivity factors investigated in this study, which were ranked based on their Relative Importance Index (RII) are given in Table 2. The top five factors that affect construction labour productivity in Sri Lanka were identified as the critical factors. These are (1) shortage of experienced labourers, (2) low skill level of labourers, (3) shortage of materials, (4) rework, and (5) unavailability of suitable tools.

Table 2: Overall ranking of factors

Category	Factor	RII	Overall Rank
Human/Labour	Shortage of experienced labourers	4.3095	1
Human/Labour	Skill of labourers	4.2855	2
Management	Shortage of materials	4.2145	3
Technological	Rework	4.1905	4
Management	Unavailability of suitable tools	4.1430	5
Human/Labour	Motivation of labourers	4.0715	6
Management	Unrealistic scheduling and expectation of labour performance	3.9760	7
Management	Payment delays	3.9525	8
Technological	Poor site layout and organization	3.9050	9
Human/Labour	Physical fatigue	3.9050	9
Management	Lack of labour supervision	3.9050	9
Management	Construction manager’s lack of leadership	3.9050	9
Management	Communication problems between site management and labourers	3.9050	9
External	Extreme weather conditions (rainy/dry seasons)	3.9050	9
Technological	Coordination level among design disciplines	3.8810	15
Technological	The extent of variation/change orders during execution	3.8810	15
Technological	Clarity of technical specification	3.8570	17
Management	Inspection delay by site management	3.7855	18
Management	Lack of training offered to operatives	3.7620	19
Technological	Delay in responding to requests for information	3.7380	20
Technological	Design complexity level	3.7380	20
External	Delays in getting service approval	3.6905	22
Management	Lack of incentive scheme	3.6665	23
Technological	Inspection delay by the engineer	3.6190	24
Management	Accidents as a result of poor site safety program	3.6190	24
External	Site location, environment around project site and the neighbourhood	3.5475	26
Management	Proportion of work subcontracted	3.5240	27
Management	Lack of periodical meetings	3.5000	28
External	Extreme temperatures in the working environment	3.4050	29
Management	Lack of suitable rest area offered to labourers on site	3.2855	30
Management	Working over time	3.2620	31
Human/Labour	Education level of labourers	3.1905	32

4.3 RANKING OF PRODUCTIVITY CATEGORIES

The ranking of productivity categories was determined based on their average RII values as shown in Table 3.

The results demonstrate that human/labour group was ranked first with the highest average RII value of 0.7905. This reveals the impact of experience, skill, motivation, and individual characteristics of workers to the productivity at the work site. The technological group was ranked second with an average RII value of 0.7702, illustrating the significant effect of construction practices and equipment to the labour productivity.

Table 3: Ranking of productivity categories

Group	Average RII	Rank
Human factors	3.9525	1
Technological factors	3.8510	2
Management factors	3.7605	3
External factors	3.6370	4

5. CONCLUSION

This study investigated the factors affecting labour productivity of large-scale building construction projects in Sri Lanka. The factors were ranked according to their RII values and the critical factors were identified as: (1) shortage of experienced labourers, (2) low skill level of labourers, (3) shortage of materials, (4) rework, and (5) unavailability of suitable tools. Shortage of experienced labourers may occur due to the lack of a proper employment hierarchy for the experienced workers within local construction companies in Sri Lanka. Therefore, experienced workers tend to move to other companies in the expectation of better prospects. Lack of appropriate material management system, the economic condition of the country as well as the contractor related factors can be identified as the main reasons for the shortage of materials at the site. This can result in time and cost overrun and increase the workers' unproductive time. Rework is caused by various reasons including inexperienced labour, poor workmanship, and poor construction methods. The main reasons for the unavailability of suitable tools at construction site can be identified as lack of proper maintenance, poor handling of tools, and ineffective tool and equipment planning.

The following measures are recommended in order to enhance the labour productivity of building construction projects in Sri Lanka. These are expected to contribute in improving labour productivity of future building construction projects in Sri Lanka.

1) Organizations should focus on providing more training and development opportunities for workers, in order to enhancing the necessary skills of construction labour force.

2) Necessary steps should be taken to improve the existing National Vocational Qualification (NVQ) system of Sri Lanka by developing appropriate policies to enhance the skill levels of workforce, focusing on maximizing access to assessment and evaluation at work site.

3) Organizations should focus on target-based wage system for the workers, instead of a daily wage system.

4) A suitable combination of skilled and unskilled labour should be maintained in order to ensure a smooth and effective workflow.

5) Organizations should identify strategies for improving the quality of life of the construction workers.

6) Supervisors should be advised to assign daily targets to workers and to review the worker performance on site. Individuals with necessary skills, knowledge, and leadership qualities should be assigned for work supervision.

7) A systematic approach should be implemented for the registration of construction workers in Sri Lanka. This should include providing them with job security and lifelong benefits such as ETF and EPF, which will lead to attracting youths of the country to the construction industry.

8) Project managers should focus on maintaining continuous information flow among the stakeholders. This would support minimizing rework during the construction.

9) The necessary measures should be taken for effective planning and scheduling of material, by paying extra attention to material availability at site in order to avoid idling of labourers.

10) Organizations should provide the required number of necessary tools, equipment and machinery for construction work through effective planning. Further, necessary steps should be taken to maintain tools, equipment and machinery in good working condition as well as to prevent poor handling of tools.

6. FUTURE DIRECTIONS

This study was limited to large-scale building construction projects in Sri Lanka. Therefore, future studies can be conducted focusing on small-scale and medium-scale projects as well as the other areas of the construction such as the roads, bridges, and hydraulic structures.

Only the perspective of project management personnel was considered in the study. As the input of labourers is extremely important in identifying the current issues related to labour productivity, focusing on construction workers in future studies is recommended.

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MARINE ENGINEERING UNDERGRADUATES' PRACTICAL SKILL DEVELOPMENT: AN ANALYSIS OF ENGINE PARAMETERS BY A HYBRID MARINE ENGINE SIMULATOR

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ABSTRACT

Diesel engines are widely used for industrial applications and predominantly in maritime transportation as a propulsion source for ships and power generation. Accurate handling of propulsor onboard has become vital to meet a high degree of operationality of a vessel and effective functioning of the machine. This paper describes an approach for analyzing parameters simulated by a Hybrid Marine Engine Simulator (HMES), which has been established as a skill development tool for engine room watchkeepers onboard ships. The design is based on a microcontroller-based platform that can create simulated operational disturbances for the main engine and makes opportunities to rehearse remedial actions for situations. Further, hands-on experience on starting – loading – unloading a medium speed 4-stroke diesel engine and respondents for emergencies, are facilitated through the system by providing separate consoles for respondence in simulation and general operation of the main engine. Moreover, the developed model can simulate possible main engine malfunctions based on operational parameters. Therefore, it is possible to obtain the engine response to failures without having to invite them to a real engine and develop fault identification skills by following an accurate analysis of data.

KEYWORDS: *Hybrid Marine Engine Simulator, Niigata 6M26AGT Marine Diesel Engine, Exhaust temperature, Peak pressure, Engine parameters, Engine room watch keeper*

1. INTRODUCTION

Four-stroke diesel engines are commonly used in maritime transportation both as propulsors and auxiliary generator sets, being the most critical equipment in onboard ships. Therefore, the reliability optimization of marine diesel engines has a significant impact on operation and cost. [1] The most trending reason for the installation of a diesel engine as propulsors in the maritime sector is due to its high-power density, efficiency, reliability, and better response to load changes compared to other solutions such as gas turbines and steam engines [2]. Simulator-based learning programs were initiated in the 1970s with the evolution of computers and software, which has become an effective academic orientation compared to traditional teaching. Engine diagnostic systems proposed in the literature can be classified among statistical, physical, and hybrid/ semi-physical systems [3]. Hybrid Marine Engine Simulator (HMES) is designed and developed with a large-scale marine diesel engine and a microcontroller based on an embedded controlled environment to conduct realistic engine room scenarios and to evaluate the performance of the current technical state of engines and devices.

Accordingly, this system facilitates fault finding by analyzing simulated parameters which develop skills in detection and diagnosis of failures that occur in a diesel engine before they become a catastrophic failure in actual conditions. Further, timely respondence for a simulated emergency is a powerful tool available for users in developing reliable skills in watch keeping.

Literature divulges that 90% of engine room breakdowns occur due to operator's negligence or human errors [4], [5] which comprehends the necessity of seeking more reliable training aids to educate ship's crew. The realistic engine room operation scenarios generated in the HMES contribute invaluably to driving away operational fear among the users and improving decision-making traits, preparing them for unforeseen hardships and emergencies at sea.

Most common analytical techniques are based on limit values and trending monitoring. Statistical systems are more accurate when improvised with advanced statistical and Artificial Intelligence-based algorithms. However, such models require a large amount of data for system validation to ensure reliable operation.

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The HMES of General Sir John Kotelawala Defence University is developed with two main consoles for responding and simulation which is operated by the trainee and an instructor respectively, where all scenario-based working conditions and operational disturbances are created by the instructor, manually. Disturbances are generated by the parameters entered by the instructor once the main engine is in simulation mode. Students are monitored and evaluated as per the respective decisions/ conclusions made by them [6].

2. METHODOLOGY

A. OUTFIT

Basic engine data implemented for the HMES are given in Table 1.

Table 1: Main engine parameters

Parameters	Value	Unit
Type	Inline, single acting, 4 strokes, diesel engine	
Make	Niigata	
Model	6M26AGT	
Weight	12,700	kg
Cylinder Bore	260	mm
Piston Stroke	400	mm
Cylinder Number	06	
Idle rom	245	rpm
Max rpm	510	rpm
Max continuous output	850	HP
Rotation	Clockwise	
Starting System	Compressed Air	
Governor	Hydraulic	

Source: Operation manual of Niigata 6M26AGT Marine Diesel Engine

The HMES comprises several subsystems (Figure 1) and several exercises based on engine systems are designed under the sub-system of parameter simulation. Further, it integrates Microcontroller based workstations inside the machinery Control Room which is comprised of two workstations; one is controlled by the instructor and the other is operated by a trainee during simulations.

Students are given time to familiarize themselves with all engine systems such as coolant system, fuel system, exhaust system, lubricating oil system, and high-pressure air system by preparing characteristics for each system, visual inspection, and starting/ stopping the main engine manually.

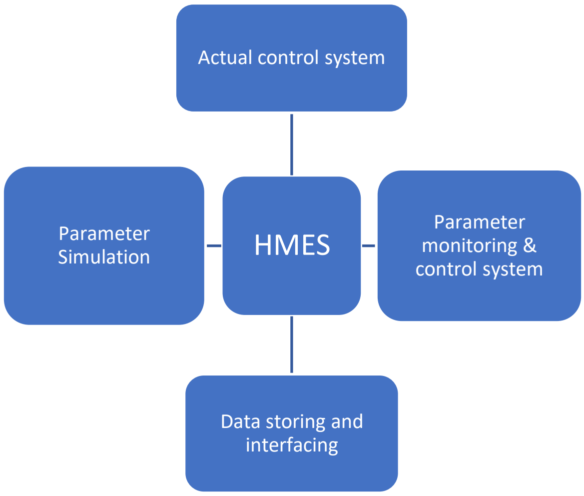

Figure 1: Subsystems of HMES

B. EXPERIMENTAL MEASUREMENTS

Initially, the main engine is started by the students and all system data is uploaded to the system on activation of simulation mode. Subsequently, the engine is virtually loaded 20%, 40%, 60%, and 80%, out of the total BHP of the engine, allowing a settling time of 15 – 20 minutes in each stage.

Accordingly, as such the key parameters registered for the analysis are engine load (%), peak pressure of each cylinder (bar), charged air pressure (bar), exhaust air pressure (bar) and exhaust temperature (°C) of each cylinder.

Apart from the above, the following parameters are also logged as a practice for analysis.

- Peak pressure of units
- Engine power output
- Exhaust gas temperature
- Coolant temperature
- Lubricating oil pressure and temperature
- Fuel oil pressure
- Ambient air temperature
- Charged air pressure

The main engine is only virtually loaded in this set up, software program itself generates corresponding values for specific fuel consumptions, power output, and other parameters against the engine loading percentage, once the instructor enters abnormal dependently varying parameters for the exercise.

Accordingly, the analysis of data obtained from the above activity revealed that abnormal exhaust temperature rises in No. 02 & No. 05 units which are shown in Figure 2.

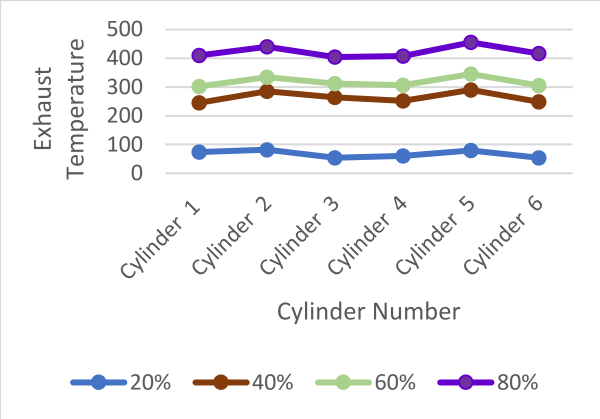

Figure 2: Exhaust gas temperature analysis

In the same situation, the peak pressures of each unit were shown in Figure 3.

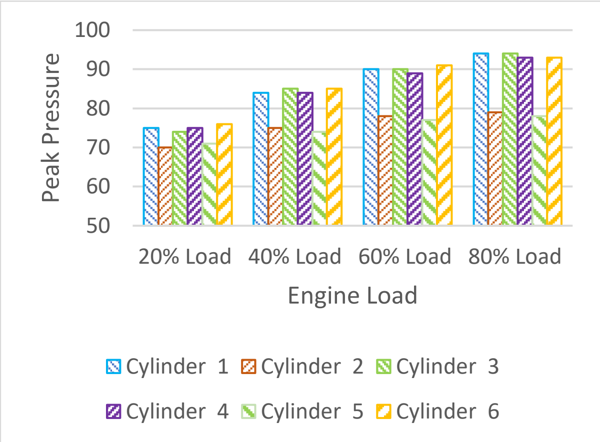

Figure 3: Peak Pressure of units for loading conditions

According to Figure 4, it can be perceived that peak pressures of No. 02 and No. 05 units display a significant drop compared to other units, with the increase in engine load. Therefore, the above condition of malfunction has to be compared with a selected cylinder unit that operates in perfect condition. Accordingly, the following analysis was done comparing with No. 01 cylinder which was observed to be normal compared to No. 03, No. 04, and No. 06 units.

It is apparent that No. 02 and No. 05 units comparatively produce less amount of peak pressure. Further, the peak pressures of the same cylinder units have not increased compared to the engine load.

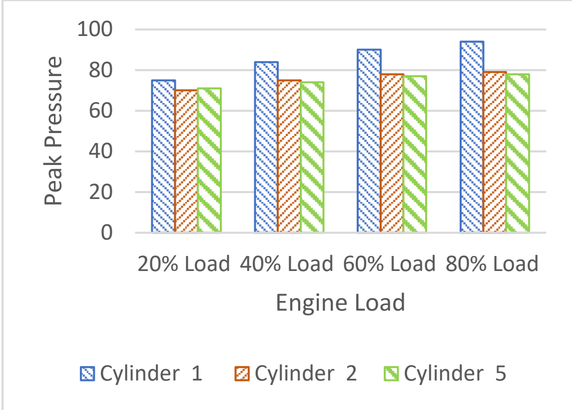

Figure 4: Comparison of faulty peak pressures

Concerning the above situation, Figure 5 shows the comparison of the engine load curve against the existing loading Vs engine rpm as a further study.

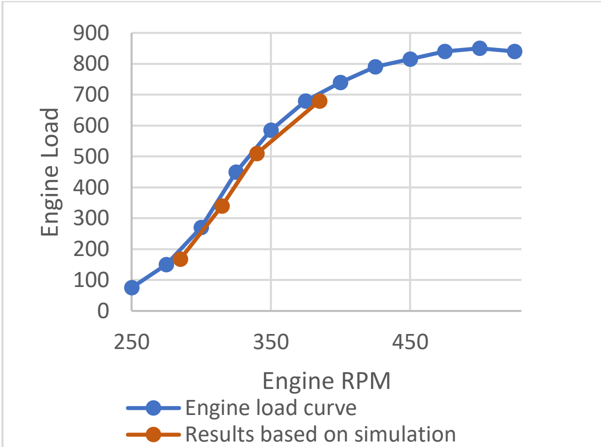

Figure 5: Comparison of Engine load curve and simulated results

3. DISCUSSION

According to the above analysis, the temperature upswing of No. 02 and No. 05 units was observed. Further, it is comprehended that relatively low levels of peak pressures of said units have a relationship with the observed malfunctioning situation.

General variation of peak pressures against the engine load can be taken into the discussion, reasoning out an escalation of reduced peak pressure that would cause severe blow–by conditions, as discussed in [1].

As per the results obtained from the simulation, loss of peak pressure has caused low performance as indicated in Figure 2. The engine has increased rpm to meet the same engine load of 20%, 40%, 60%, and 80% from total loads which has reduced the efficiency of the engine. It is taught that this fact can be further verified by obtaining readings of specific fuel consumption and fuel rack position reading in the real-time environment, which has not been implied in this simulator design. Accordingly, students can clearly understand the effects caused by high exhaust temperature in units. Further, students have a chance to analyze data with the existing, to find out possible root causes and remedial actions.

The acquired knowledge from the exercise is evaluated through a written report including the following content

- Introduction to the exercise
- Procedures followed
- Parameters considered
- Data analysis and presentation
- Identification of root causes and remedial actions

Consequently, the reports will be evaluated based on the descriptive writing adhered to the above criteria.

4. CONCLUSION

Teaching through this simulator broadens the student's knowledge and experience in the marine engine room environment before performing onboard. Activities conducted through this facility prepare the students to face such conditions and timely react to even harder situations at sea. Therefore, the training of marine engineers utilizing the HMES is the least expensive and the safest training method in the present day context.

5. ACKNOWLEDGEMENT

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FORECASTING AIR POLLUTION: CASE STUDY INVESTIGATING THE TRUE IMPACT OF COVID-19 LOCKDOWNS ON AIR QUALITY IN SOUTH ASIA

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ABSTRACT

Air pollution is a modern anthropological catastrophe faced by all humanity. Most of the world's pollution hotspots are located in the South Asian region where most countries are recognized as developing countries. Management of air quality in the region is directly linked to the insufficient infrastructure in the region to monitor and analyse air pollution. Regional air pollution studies are limited and excessively focused on analysing the current pollution landscape rather than developing forecasting tools suitable for the region. The study has focused on the analysis and development of an air pollution forecasting model to predict air quality variations based on the Auto Regressive Integrated Moving Average (ARIMA) method. The model was developed and validated using available historical PM2.5 pollution data from the region. Additionally, the model was used to analyse the true impact of COVID-19 lockdowns on regional air quality. The analysis includes investigations of PM2.5 pollutant levels in Colombo, Chennai, Dhaka, Delhi, Kathmandu, Islamabad, and Hyderabad. The developed model performed well with RMSE values of less than 12% in all instances relative to the pollutant concentration ranges for each city. Forecasted and historical data comparison identified that the impact of COVID-19 lockdowns is underestimated in cities such as Kolkata, Colombo, and Chennai by more than 10%. Vice versa was observed for Delhi, Islamabad, and Hyderabad where the pollution trend is decreasing. Traditional time series analysis will certainly underestimate or overestimate the impact of COVID-19 lockdowns as expected.

KEYWORDS: *Air pollution, COVID-19, Pollution forecasting*

1. INTRODUCTION

South Asian countries such as India, Pakistan, Nepal, Bhutan, Bangladesh, and Sri Lanka are considered to be low-income or middle-income, developing nations. According to air quality surveys, 18 out of the top 20 most polluted cities in the world, are in this region [1]. Poor environmental protection regulations, poor availability of legal and scientific infrastructure, and excessive biomass burning are observed to be common attributes in the region.

Increased pollution landscapes in the region are largely assisted by industrial emissions, vehicular emissions, and biomass burning [2], [3]. Particulate Matter (PM) has been identified as the prominent pollutant in the region [4], [5], [6]. Particulate Matter pollution and its effects were first studied in the early 19th century, especially during the London Smog events [7]. According to regional research, weaker emission controls and environmental regulations, use of low-quality fuel, and inaccessibility to reliable energy sources have led to the increase in particulate matter levels in South Asia [8], [9].

India is considered the largest economy in the region. India has heavily invested in air quality monitoring, after being exposed to serious pollution episodes in major cities. Though similar circumstances are observed in the other countries, most South Asian countries lack the required technical infrastructure for effective monitoring and regulation of air quality. Due to the alarming conditions, numerous attempts have taken place recently in the region to manage air quality and minimize severe pollution exposure. Positive signs of these attempts are already visible through the collected data from previous research [10], [11], [12].

Air Pollution Forecasting can be divided into two main branches. The first is modelling pollutant dispersion patterns and forecasting behaviour of air pollution over time in a specified region. This approach requires significant data on emission landscape, meteorological conditions, and chemical aspects of the pollutant mix. The second approach is analysing the past and present pollution trends to forecast pollution behaviour over time. This approach requires considerably less historical data for forecasting.

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and is comparatively less complex than the first method. Due to the complexity and lack of data, research into pollutant dispersion modelling is less frequent [05], [06], [13].

Air pollution trend analysis is conducted using either traditional statistic related regression methods or using machine learning algorithms. With the increased popularity of data science, machine learning and other computer-based algorithms are now widely used for most forecasting approaches. These methods can consider either the trend alone or other influencing factors such as meteorology [14].

Severe meteorological events result in considerable changes to air quality as observed in previous research [15], [16].

When analysing and forecasting time series data, there are key factors that contribute to choosing a suitable machine learning algorithm. The selection of machine learning algorithm is based on whether the time series is univariate or multivariate. Then, depending on the number of historical data points and the availability of the seasonality effect, the complexity of the model can be decided. The most common models used for time series forecasting are the Auto-Regressive (AR) models [17].

The basic AR model uses the correlation between the time lags of the data points to predict future values. Another similar model is the Moving Average (MA) model, which uses the mean of residual errors as a linear function. The Auto-Regressive Moving Average (ARMA) model is developed by combining these two models for better accuracy. However, all three of these models are suitable for a univariate time series without seasonality or visible trend. Therefore, making them unsuitable for air quality forecasting when used separately. However, this issue was resolved by the Auto-Regressive Integrated Moving Average (ARIMA) model. It combines the AR and MA models and adds an integration step in between to make the series stationary. This allows using the ARIMA model for univariate time series data with a trend but without a seasonality effect. The SARIMA model which is also called the Seasonal ARIMA, is the next step in the AR model path, where it includes a parameter that considers the seasonality [18].

However, the ARIMA model can be used for seasonal data by removing the seasonality effect and using the remainder for forecasting. This is done when the seasonality is a regular cyclical pattern and not an irregular pattern. After the forecasting is done using ARIMA, to get the final result, the seasonality values should be added back [19]. When the series is multivariate, the Vector Auto-Regressive and Moving Average (VARMA) models can be used [18]. As for time series with large amounts of data showing irregular seasonal patterns and more advanced climatic changes, machine learning techniques like neural networks can be used.

Donnelly, Misstear, and Broderick [20] used a similar approach for predicting the behaviour of NO_2 concentration levels and forecasted pollution trends for 48 hours with considerable accuracy.

Gourav et al., [21] also used a similar approach in the short-term prediction of NO_2 and SO_2 levels with considerably satisfactory results. However, both of these studies focus on a single parametric analysis. A hybrid method was experimented by Díaz-Robles et al., [22] using both Artificial Neural Networks (ANN) and Multi Linear Regression (MLR) on forecasting particulate matter pollution in Chile. Meteorological elements and seasonality were considered for the study. It was observed that the method used in the study generated reliable and accurate forecasts while including extreme pollution events. The authors of this study aimed to evaluate the applicability of an ARIMA based method considering seasonality, for the purpose of trend forecasting in different regions in South Asia. Novelty of the study is based on the evaluation of the applicability of an ARIMA forecasting model considering regional seasonality over several cities in South Asia.

Available studies on regional air pollution primarily utilize various monitoring methods and instruments to arrive at the data required for the study. Variations in instrumental sensitivity result in non-homogeneous data. A variety of accuracy-related complications arise when data from different sources are used in congestion. Kandari and Kumar [23] investigated the variation of air quality over eight Asian countries using data from variety of sources including websites (aqicn.org; worldometers.info; iqair.com, etc.), World Health Organization, United Nations Environment Programme, National Aeronautics and Space Administration. Using a range of sources creates non-uniformity in the collected data. Manikanda et al., [24] only used data from Central Pollution Control Board, India (CPCB) to overcome this and study air quality over 10 Indian cities comparing reference years 2017 to 2019 against 2020 on an annual average. Authors of this study, as a novel approach utilized data from the network of Automated Air Quality Monitoring Stations (AAQMS) located in the United States Embassy and Consulates in the region (airnow.gov) as a novel approach. These raw data from AAQMS provided access to homogeneous data to train and evaluate the developed ARIMA forecast model over different backgrounds.

Worldwide, the air pollution trend was significantly affected by the COVID-19 lockdowns. The decrease in industrial activities and the travel restrictions resulted in a phenomenal decrease in pollution levels during lockdowns [25], [26]. It was also observed that air pollution steeply reduced during the period [26]. The upper atmosphere and the Ozone layer also illustrated improvements due to reduced pollution [27], [28]. A reduced number of cases of respiratory illnesses on the ground was also evident [29].

Vikas Singh et al. [30] used data from 134 different calibres of measurement devices belonging to CPCB to analyse the decrease in air pollution over several cities of India and isolated the effects of lockdowns on pollution reduction. In a novel attempt, the authors of this study compared the forecasted pollution trend and actual pollution during the lockdowns and isolated the actual impact of COVID-19 lockdowns on decreasing air pollution.

2. METHODOLOGY

Data Collection and Pre-processing

As the first step, the impact of meteorological events during 2017 to 2020 was analysed in a lower resolution using data from the MERRA-2 programme as suggested by Vikas Singh et al. [9], Sharma, S. et al. [28], who believe that Air Quality Index (AQI) better reflects the change in air quality than any other individual parameter when actual exposure conditions are concerned. However, the study considered Particulate Matter as the focus parameter.

The granularity of the raw dataset is in hourly averaged intervals. The raw data was cleaned and pre-processed to ensure quality and consistency. Data from the AQQMS archives were observed to contain outliers and Instrument codes (for when the measuring device was in calibration or non-functioning). Data cleaning and transformation methods were applied to remove the outliers and smoothened by the quantile clipping method. “Quantile clipping” is an anomaly smoothing method that replaces the data points with values higher or lower than the 95th or 5th percentile respectively to the percentile point value. Data cleansing was done by first replacing the instrumental codes with missing values strings (NaN) and then using linear interpolation to fill in the said missing value strings. Python data analysis and modelling libraries including pandas, matplotlib, and stats models were used for the process. The processed data were then resampled into daily averages before being used for the study.

Time Series Analysis of the Air Quality

Pre-processed data, averaged per day were used to study air quality in selected cities. This initial analysis was done through a time series analysis in the form of a graph. Air quality in eight locations in five South Asian countries was graphed separately for 2018, 2019, and 2020. Macro investigations of the trend were concluded by using combined 2018 to 2019 monthly data as reference and the data from 2020 as a comparison.

Quantitative values of the variation were obtained through the Equation 1 in terms of percentage. M_c refers to the 2020 data set, while M_r refers to the reference data set. It was expected that a significant decrease in air pollution would occur, overlaying the lockdown period.

$$Change\ in\ Air\ Pollution = \frac{M_c - M_r}{M_r} \times 100 \qquad \text{Equation 01}$$

Time Series Forecast and Comparison

The time series forecast was obtained by training an Auto-Regressive Integrated Moving Average (ARIMA) model. ARIMA is a statistical model used for non-seasonal, time-series data analysis and forecasting based on the behaviour of past values. The observed values from January 2018 to December 2019 (Reference Dataset) were considered the training dataset of the model. The forecast was done for the next six months in daily granularity, that is, from January 2020 to June 2020.

Seasonal decomposition was performed on a complete dataset to identify the availability of a seasonal effect. Time series data can be divided into the components of Equation 2 according to additive decomposition.

$$Observed\ value = Trend + Seasonality + Residual$$

Equation 02

Decomposition results indicated seasonality to be present in the data set. Therefore, seasonality should be removed before the training data is fitted into the ARIMA model. This was done by differencing each data point by the previous value.

The next step involved selecting the model parameters. In order to decide the AR factor for the model, the autocorrelation plots were obtained for each city. A general AR factor of 5 was decided after observing the plots through the trial and error method.

The developed model needed to be trained and validated before applying the reference dataset to measure reliability and accuracy. Therefore, the reference dataset was again divided into train and validation sets on the ratio of 60:40, respectively. Table 1 shows the root mean square error (RMSE) between the predicted and expected values of the validation data of each city. The dataset range is given in Table 1 to understand the effect of the RMSE on the data.

Finally, the complete reference dataset was fitted to the developed ARIMA model, and forecasts were obtained for the next six months. The complete dataset was plotted, including the forecasted and actual trends. Through the comparison of forecast data and observed data, the study aimed to better understand the impact of lockdown on regional pollution scenarios.

3. RESULTS & DISCUSSION

Time Series Analysis

An apparent decrease in air pollution levels was observed in early 2020. It was clear that this occurred due to the impact of the COVID-19 lockdown. In most countries, the earlier half of the year was recognized as the most concerning period when it comes to air quality due to seasonality. This enabled the comparison to be more fruitful.

When 2018/19 combined reference data was compared against the 2020 data, the highest reduction of pollution levels were recorded from cities with a history of severe air pollution complications such as Delhi, Kolkata, Dhaka, and Colombo. Figure 01 to 07 illustrates the behaviour of the daily median pollution during the combined reference years and 2020.

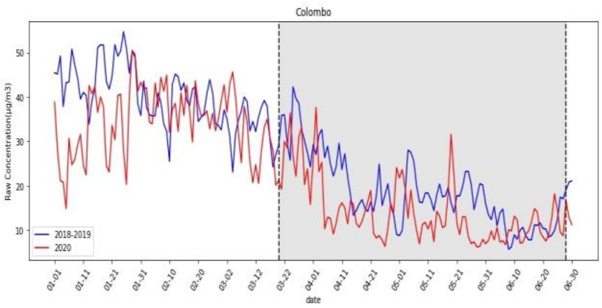

Figure 1: Air pollution variation in Colombo

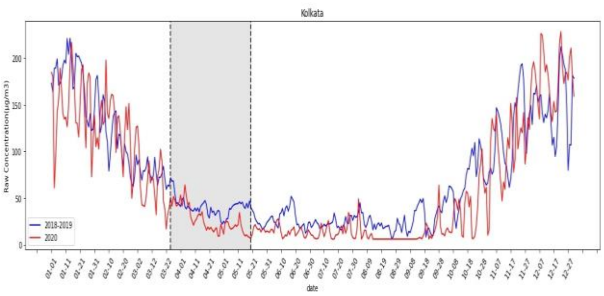

Figure 2: Air pollution variation in Kolkata

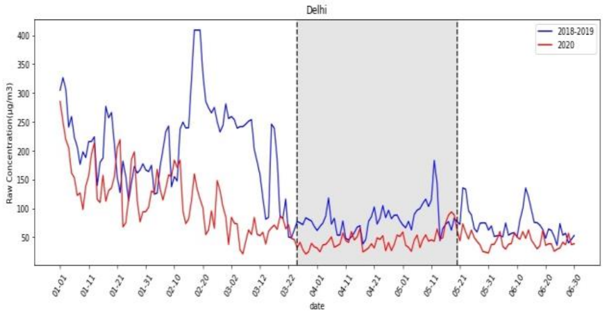

Figure 3: Air pollution variation in Delhi

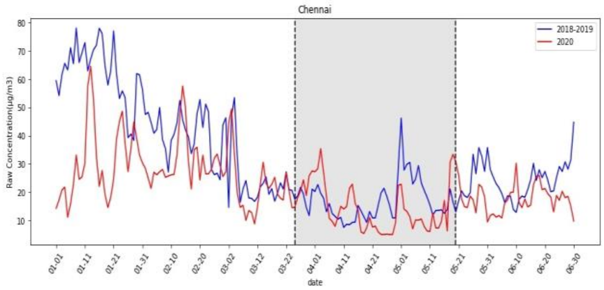

Figure 4: Air pollution variation in Chennai

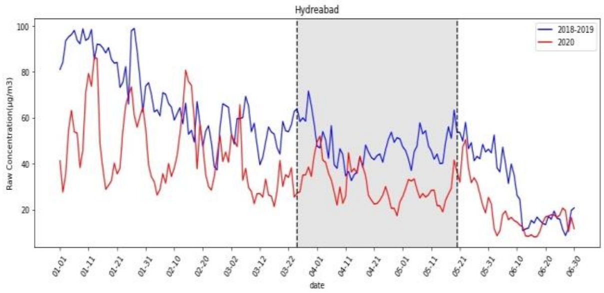

Figure 5: Air pollution variation in Hyderabad

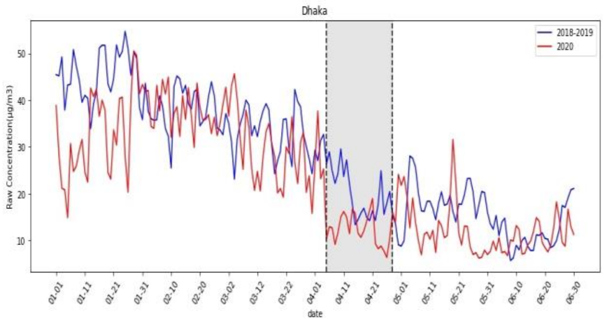

Figure 6: Air pollution variation in Dhaka

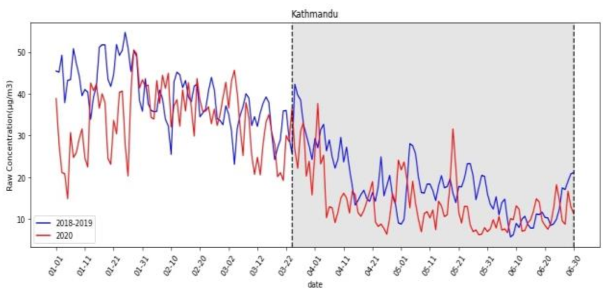

Figure 7: Air pollution variation in Kathmandu

Accuracy of the Developed ARIMA Model

Root Mean Square Error (RMSE) between the predicted and expected values of the validation data of each city is included in Table 1 with the range of the dataset to understand the effect of the RMSE on the data.

Table 1: Test RMSE details for the ARIMA model

City	Data Range	RMSE
Colombo	0-50	5.440
Kolkata	0-250	21.093
Delhi	0-400	34.958
Chennai	0-80	8.107
Hyderabad	0-150	8.513
Dhaka	0-55	5.443
Kathmandu	0-50	5.455
Islamabad	0-120	12.369

As per the above results, the forecasts of the model seemed to be within the acceptable range. In most cases, the value did not exceed 12% of the original data range from the sample. During the additive decomposition of the data set, significant seasonality was observed in most major cities in Bangladesh, India, and Sri Lanka. Apart from the seasonality, the trend was also isolated from the data set. Kathmandu, Chennai, Kolkata, and Colombo were observed to illustrate an increasing pollution trend while Delhi, Islamabad, and Hyderabad demonstrate a decreasing pollution trend.

When a trend is present, the assumption made by most previous research on pollution behaviour, especially related to COVID-19 lockdowns can be understated or overstated. The impact of the lockdown can be only accurately measured by comparing forecasted data against observed data.

Time Series Forecast and Comparison

The observed data and reference data were first compared with each other to identify the observable impact of the lockdown. This simple analysis ignored the presence of trend and seasonality in the data set. Secondly, observed data was compared with the forecasted data in order to obtain more accurate measurements of impact of the lockdown on regional air pollution.

An apparent variation in the decreased levels was identified when the forecasted values were used in the comparison. The decrease in pollution levels even surpassed the previously investigated levels on some occasions. Table 2 illustrates how the levels of pollution have decreased between the results obtained through the two methods.

Table 2: Decrease in pollution levels – Comparison between the results of the two methods

City	Month	Comparison with historical data (Percentage Decrease)	Comparison with forecasted data (Percentage Decrease)
Kathmandu	June	61.98	71.25
	May	53.33	52.06
	April	15.30	29.95
Delhi	June	35.75	29.56
	May	42.86	32.52
	April	44.39	34.59
Chennai	June	26.53	36.62
	May	33.57	24.79
	April	5.08	12.87
Colombo	June	10.65	33.51
	May	30.32	50.62
	April	28.03	37.86
Kolkata	June	50.39	66.52
	May	49.98	57.29
	April	25.69	38.39
Dhaka	June	0.04	24.50
	May	47.32	8.30
	April	26.76	15.61
Islamabad	June	8.17	13.59
	May	33.77	8.09
Hyderabad	June	38.34	-7.97
	May	37.96	26.58
	April	29.67	28.37

Results from the above table verify the observed trend over the years. Based on the results, most previous research on the impact of COVID-19 lockdowns undermined the actual impact.

While most cities indicated a variation in pollution levels over the three months considered, a decrease in pollution levels in Kathmandu significantly occurred only in June. The unique topographical characteristics of

Kathmandu have largely contributed to this. The city of Kathmandu is located in the Kathmandu valley, surrounded by the Himalayan Mountains range. This bowl-like topography surrounding the city traps pollution and negatively affects the air quality [31]. This clearly explains the observed variation in pollution behaviour.

Delhi and Kolkata have been considered pollution hotspots in India [32]. Research links paddy field burning across northern India to the significant seasonality air pollution behaviour found in these two cities [9], [33]. Forecast data illustrated that the pollution behaviour in Delhi is improving. Yet, the decrease in pollution levels was staggering as soon as the lockdown was enforced. However, the pollution trend in Kolkata has increased significantly and this led to the observed increase in the perceived impact of lockdowns on air pollution.

Pollution behaviour of Colombo between historical and forecasted has a significant difference. Premasiri *et al.*, [35] suggest that the visible pollution in the city is lower than the reality because most of the pollution is carried inwards through the strong coastal winds, away from the city. It was identified that the dominant pollutant in the region is particulate matter, and traces of transboundary pollution is visible in Colombo's atmosphere [3]. Observations made by Gunasekara and Waraketiya, [26] also provide evidence of transboundary pollution. European studies into Long-range Transboundary Pollution have proven that the upper atmosphere could transfer pollutants over long distances [37]. The results of time series analysis from the study show similarities between the pollution behaviour in Delhi, Kolkata, and Colombo.

According to previously conducted research, Pollution in Dhaka is caused by two significant pollutants, PM2.5 and Lead [5]. Literature information also confirmed that the primary source of pollution in Bangladesh is Brick Kilns and Vehicular Emissions [5]. Lockdown was only enforced in April, hence significant pollution decrease was only recorded in April and May. The historical trend indicates that the pollution level in the city is decreasing. However, as Table 2 illustrates the effects of the lockdown are largely visible only in June. The air quality improvement was contradictory to the observed trend. 10% variation between historical and forecast comparisons is clearly influenced by the topography of the city.

Pollution levels in Hyderabad decreased similarly over the lockdown period from both perspectives. Compared to Delhi and Kolkata, Hyderabad reported lower pollution values throughout the years [24]. Since these are not industrial cities, pollution levels are quite low and illustrate high seasonality levels, suggesting that transboundary pollution is a crucial aspect.

4. CONCLUSION

In conclusion, the ARIMA based forecasting model developed for the purpose of predicting air pollution seemed applicable in lower-resolution air quality forecasts. Recorded RMSE values during the verification process were less than 12% for all cities, indicating that the model can be considered accurate. This simple method is beneficial in low-resolution air pollution forecasts for measuring the actual impact of air pollution mitigation strategies and estimating pollution events influenced by seasonality.

Observations from the time series analysis indicate that industrial cities such as Kolkata, Delhi, and Dhaka significantly improved air pollution compared to non-industrial cities such as Colombo, Hyderabad, Islamabad, and Chennai in 2020. Availability of seasonality in pollution trends, especially in non-industrialized cities, is evidence of transboundary pollution being present in the region.

Observations indicate that the pollutant concentration has been underestimated by 5% to 20% in Chennai, Colombo, and Kolkata when only historical data is used for comparison ignoring the pollution trend. The situation is reversed when cities with decreasing pollution trends are concerned. The trend is identified as a determining factor when low-resolution pollution forecasts are made. Studying the impact of COVID-19 lockdowns without considering the pollution trend will result in inaccurate results.

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OPTIMIZATION OF REGULAR PICK AND PLACE TASKS VIA PARALLEL MANIPULATORS AND MODELLING

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ABSTRACT

Small-scale product handling industries are at the cusp of increasing their efficiency and effectiveness, where optimization is largely a considerable factor. Though regular pick and place tasks are nonvalue added steps, they can replace expensive manual labor and thereby increase efficiency by reducing idle times. Hence, this paper discusses the optimization of regular pick and place tasks using parallel manipulators. By evaluating alternative manipulators, the 3-link parallel manipulator which is the delta robot was taken for presenting the model given in this paper. A simulation and a real-time operation were conducted for comparison of 2 designs of the delta robot, in relation to the robot workspace and the component stress-strain analysis. The robot kinematics were derived to define the robot workspace and for the dimensions of the mechanical components which were equally designed and tested. Fabricating was done using lathe machining and 3D printing. The servo and visual systems were decided accordingly for the generalized pick and place application. Control and functionality with the input visual system and kinematics model were mapped and generated in a programming platform and were transferred to the controller in order to drive the motors of the manipulator. This makes the robot end effector activate and perform the picking and placing using the solenoid gripper. An accurate result in object detection, mapping, picking, and placing by the delta robot is thereby achieved which is presented in the paper. The presented model is feasible to be used in an industry which can accommodate regular pick and place tasks. An example application would be picking and placing screws as mentioned in the paper.

KEYWORDS: *Delta robot, Visual-servo system, Workspace, Pick and place, MATLAB®*

1. INTRODUCTION

The requirement for automation is in the verge of being an industrial necessity due to various challenges faced by modern day industries. Labor shortage, complex customer orders, cost of labor, idle times, inaccuracies, and compliance standards are a few instances that promote the need for automating various processes in a regular production flow. Automating the task of pick and place products from assembly lines shares a common interest in multiple industries mainly due to it being a nonvalue added task and with no direct effect to the quality standards of the production.

Different industrial manipulators with the required DOF are quite sufficient to handle the demanding tasks of the industry. The current automation solutions of utilizing robotic manipulators to achieve this task consist of major drawbacks such as space limitations, energy consumption, speed, and feasibility to cooperate with workers. However, the recent advancement of parallel robots has shown greater potential for finding better solutions to this problem.

Because parallel manipulators are of higher precision, stiffness, dynamic capacity (due to closed links), lower maintenance cost, efficiency in attaining higher accelerations (due to lower inertia), and lower space taken up in comparison to serial robots for pick and place applications. Some of these have also been discussed from comparisons in the review paper [1]. Furthermore, the trade-off as per the requirement for a series robot manipulator is mostly not viable for industries with small scale product categories mainly due to the aforementioned factors.

The above challenges were the main motivation for this study on optimizing general pick and place tasks commonly available in the small-scale product category industry. Pick and place objects on a moving conveyor, which is a commonly seen application, has been selected. The task was to detect the object via a web camera through image processing and to pick and place the item accurately with a considerable speed of operation. The proposed method with mathematical modeling also considers planning minimum cost paths.

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The main objective was the designing and development of a prototype of a parallel robot manipulator for optimizing a regular pick and place task with the implementation of a visual servo system for detecting and mapping the objects. Furthermore, testing and validating the proposed model for a generalized regular pick and place task was done using the developed prototype. Additionally, the comparison of the two designs was done to minimize the manipulator workspace for more compact and limited space requirements. These results and comparisons are presented in Section 5 of this paper.

2. LITERATURE REVIEW

A design has been proposed in [2] for a 4-DOF delta robot in SimMechanics environment of MATLAB software, by studying the performances of the Sliding Mode Control (SMC) mechanism and the PID control based on the Inverse Kinematic Problems (IKP). A simulation study of optimizing for delta robots is given in [3]. That is for the improvement of pick and place route based on lame curves to smooth the right angles of transitions. Thereby they have established the overall trajectory in the cartesian plane with good performance in comparison to the virtual prototype in ADAMS software and MATLAB. An algorithm for the forward kinematics method with one root for delta robots is given in [4] where the conventional method is to solve forward kinematics by 3 sphere method and find the intersection point out of which one is selected. But their calculation algorithm, only one solution is given. They have verified the method, by doing an analytical substantiation and a numerical experiment with the results obtained. The thesis [5] describes the modelling of the kinematics and forward dynamics for the IRB340 FlexPicker parallel robot and the implementation control through software and hardware by the B&R Automation company. A new approach has been utilized in [6] to design a delta robot with the desired workspace by using a technique known as inscribed workspace. Two kinematics calibration models have been proposed in [7] and it shows that the accuracy of the parallel robot can be improved by means of calibration. The mechanical development, kinematic analysis along with simulation for the training of the delta robot Caertec rk 2010 have been proposed in [8] using CATIA software. A vision servo-based delta robot was developed [9] to pick and place objects on a moving conveyor with a vacuum suction clamping method where Canny and Sobel edge detection methods was used for object recognition in a C++ based program. By the proposed algorithm, only when the object is fully present in the screen, the coordinates of the object is calculated and communicated to the delta robot via TCP/IP protocol. The fundamentals and mathematics for modelling series and parallel robots given in [10] and [11] describe the manipulator DOF, parallelogram theory for closed chains robots, and the manipulator forward inverse kinematics and dynamics.

3. EXPERIMENTAL DESIGNS

Through comparison of serial and parallel robots, another comparison was done to select 3-link parallel manipulators among 2-link and 4-link manipulators. The 3-link delta robot satisfied the minimum requirements to complete a regular pick and place task with 3-DOF for X,Y, and Z translation. Based on this, a further study was done to improve the optimization and workspace of delta robot.

To optimize in relation to workspace, conceptual designs were created with a new configuration by altering the motor orientation relative to the base plate. Motors were placed parallel to the tangent of the circumference of the base plate as shown in Figure 1 (a). The other design is where the motor is mounted so that the arm is perpendicular to the circumference of the circle, which is shown in Figure 1 (b). In both the designs, the motor shafts were placed at 120° apart. This is considered the standard configuration of the delta robot. Both configurations were fabricated to implement real-time kinematics along with manipulator workspace simulation for the end effector and for the 3 robot arms.

Figure 1: Design 1(a) Design 2(b)

The unique advantages and disadvantages of each design are presented in Section 5.

4. SYSTEM OVERVIEW

The specific application selected was, pick and place screws through a vision-based system which additionally requires an operation of sorting based on the color or size of the screw or both. The presented system uses a direct operating solenoid as the gripping mechanism. Sections mentioned under A, B, C, D, and E discuss the phases followed in developing the model.

A. Modeling of Parallel Manipulator

In pick and place, the delta robot changes its 3 motor parameters to move the end effector to the desired position where either the angles of the motors or the coordinates of the end position are to be decided. In inverse kinematics, if the desired position is known, the motor angles can be generated. In forward kinematics, if joint angles are known, the end effector position can be generated. One general observation is that for serial chains or open loop configuration robots, the forward kinematics is generally straightforward while inverse kinematics may be complex and for parallel mechanisms or closed loop configuration robots, the inverse kinematics is generally straightforward while forward kinematics may be complex.

The calculations required to determine the manipulator kinematics and motor torques were done based on the design criteria. A thorough calculation of the forward and inverse kinematic, and dynamics regarding parallel robots and series robots were studied and compared. The forward and inverse kinematic model given in [12] was referred in building up the inverse kinematics model. These kinematic model parameters and dimensions of the design were simultaneously taken into account when determining the most practical design parameters.

B. Design Specification and Simulation

Evaluation of alternative serial and parallel robots was done and conceptual designs were brought up prior to finalizing on design specifications. By designs 1 and 2, a calculation procedure was followed to arrive at the final machine designs. The calculations and the simulated material analysis acquired the final design parameters and verified if the design system can withstand all loads and deformations acting on the design parts. The material stress analysis, bending moment analysis, and twist analysis for components were done prior to selecting material and with the availability of materials, aluminum was selected as the most suitable material for almost all components. With the obtained designed values, 3D modeling and product simulation were done. The components were drawn partwise and assembled to form the required design which has given a visual representation of the system designed. A motion study was performed to depict the complete motion of all the components of the system.

After finalizing the structure of the base plate and the type of rod end ball bearings, the length of the robot arms and links were decided according to the required workspace of the robot. The required workspace of the robot was decided upon the requirement of the application. Accordingly, it was decided to come up with the following workspace of the robot in the 3 axes to suit the requirement: X: -135 mm to 135 mm, Y: -135 mm to 135 mm, and Z: 600 mm to 300 mm. Using the kinematics models with the above values, the length of the arm and link (forearm) was designed: Length of the arm = 200 mm and length of the link (forearm) = 450 mm. The intermediate shaft used to join the arms with the links was designed to be 6 mm in diameter and a length of 70 mm, to suit the bearing shell. The base plate was decided according to the design proposed in the preliminary design and its diameter was chosen in a way that it can comfortably accommodate the 3 motors chosen. Finally, it was decided to design the base plate with a diameter of 300 mm and 6 mm thickness. 3 motor brackets to hold the motors were also designed. A structure was designed to hold the whole robot vertically.

C. Fabrication

After finalizing the design parameters and dimensions, the fabrication of the project was initiated part by part. The robot base plate, 3 robot-arms of 200 x 6 x 4 mm (l x b x h), 6 robot-links (forearm) of 6 mm diameter, motor brackets of 3 mm thickness, and 6 intermediate rods of 10 mm diameter and 70 mm length were fabricated in aluminum. The three arms were drilled with holes of 6 mm diameter for the intermediate shaft to pass through. The other end of the arm was drilled with 5 holes with a diameter of 3 mm to hold the motor coupling. Threads were made in robot-links (forearms) on both ends to a suitable length to attach the rod end ball bearings. For the base plate, a set of 4 holes each were drilled 120 degrees apart at the edge of the plate for smooth, fast, and error free operation of the robot. Finally, the end effector was 3D printed using Polylactic acid (PLA) polymer which is light weighted and even has high strength. The end effector holds the object and also performs the required task. The delta robot end effector, holds all the 3 links together at the ends or from the corners of the end effector as it is shaped similar to an equilateral triangle. The appropriate electromagnetic gripper for the end effector was selected for the application.

The mounting structure is used to hold the manipulator in place for its functioning. The main consideration of it was that the mounting structure needed to be designed to withstand the jerks and inertial effects caused by the movement of the links. As per the requirement, it needed to be portable and withstand the movements of the robot. It was designed and fabricated using 1.5 x 1.5 inch aluminum box bars. This cuboid structure comprised the dimensions of (65 x 65 x 70 cm) (l x b x h) and had extra two cross bars at the top to mount the robot. Finally, the fabricated components were assembled with the camera module mounted to the mounting structure and the solenoid gripper was attached to the middle of the end effector for the completion of the delta robot.

D. Image Processing

For the image processing task, a web camera with 720p resolution with 30 fps and as per the required specifications a minimum of 60° viewing angle was selected. The camera input is taken directly to MATLAB for image processing. Initially, surf features were used to detect the object. However, according to the experiments done, the surfing feature was not strong enough in identifying the same object among other objects and mixed up the relative points. Hence, the color of the object was taken as the next approach with the use of color thresholding tools. A lab color scheme was used for this, and it was successful in identifying the object based on its specific color.

To move the end effector, the system requires the location of the object. The robot was programmed to locate the center of mass based on the area of the image with the given color. The web camera connected to the system sends a 640 x 480 pixel frame from the video output to the model for detecting and locating the object. The model calls another function for processing the above-mentioned task and the output video stream is given from another function model. The frame was mapped to the physical dimension of the manipulator working area via a predefined scaling. The images were converted from RGB to Lab color scheme images for further processing. Locating this object was done through blob analysis technique for computing information for connected regions using computer vision system tools by creating a persistent variable. Hence initial steps were the trial sessions done for object detection.

For the application, to detect screws of varying lengths, morphological operations were used. The RGB image was first converted to binary. This image was then subjected to morphological erosion and dilation through the construction of a structuring element. The number of screws laid was correctly detected. All the object detections were done by capturing a snippet of the video stream. Finally, the center points of the screws and the length of each of the screws were obtained accurately from this procedure. The programmed model showed the exact x and y locations of the center of the object in pixels. The pixel coordinates were then mapped to the real x and y coordinates of the plane. With the increase in resolution of the image, a more accurate object locating can be done. The GUI (Graphical User Interface) shown in Figure 2 explains the centroid of the object in pixels as well as the converted value in meters via the mapping. These coordinates were then passed on to the kinematics model for generating the motor angles.

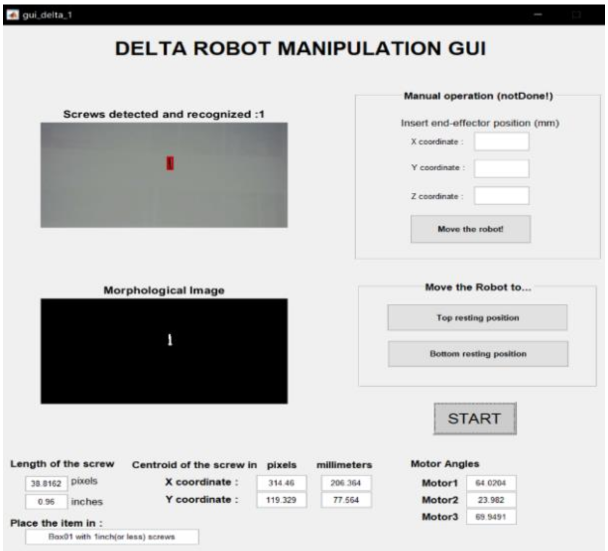

Figure 2: Graphical User Interface (GUI)

E. Control and Functionality

Position based and Model based control methods are the two available control strategies for robotic manipulations. In position-based control, each joint is separately considered in motor controlling whereas in model-based control the complete system dynamics are considered. Therefore, the model-based controller yields higher positional accuracy without the use of additional sensors. By considering the computational capacity of this process, the following physical components were required: PC, Microcontroller, Motor Driver, and software for programming and controlling. As initial testing, Robot Operating Software (ROS) was used as the communication medium for MATLAB and the Arduino controller. The image processing and kinematics are done by taking the input of the camera to the model and the generated motor angles are next passed on to the controller where the motors are connected via motor drivers.

The kinematics model given in [7], [13], and [14] was referred for controlling this robot as in our previous work [15]. The mathematical model for inverse kinematic computation utilized the robot dimensions and the characteristic features: robot arms (L) and base plate revolute joints relative to the fixed base plate, revolute joints relative to the end effector, and the end effector location relative to base plate {x,y,z} were taken to derive the vector loop closure equation for the delta robot. Eventually, the kinematic equations for the legs of the delta robot were derived.

These are the intersections of 3 spheres of radii of the length of links and arms in the geometrical aspect.

Where,

SB = radius of the base plate and, In an equilateral triangle of the end effector, where revolute joints are at the edges:

VE = distance from the reference point of the end effector to a vertex,

ES = side length of the equilateral triangle,

SE = distance from reference point of the end effector to revolute joint, where

$a = SB - VE$ Equation 01

$b = (ES/2) - (\sqrt{3}/2)\,SB$ Equation 02

$c = SE - (1/2)\,SB$ Equation 03

$$2L(y + a)\cos\theta_1 + 2zL\sin\theta_1 + x^2 + y^2 + z^2 + a^2 + L^2 + 2ya - l^2 = 0 \quad \text{Equation 04}$$

$$-L(\sqrt{3}(x + b) + y + c)\cos\theta_2 + 2zL\sin\theta_2 + x^2 + y^2 + z^2 + b^2 + c^2 + L^2 + 2xb + 2y - l^2 = 0 \quad \text{Equation 05}$$

$$L(\sqrt{3}(x - b) - y - c)\cos\theta_3 + 2zL\sin\theta_3 + x^2 + y^2 + z^2 + b^2 + c^2 + L^2 - 2xb + 2yc - l^2 = 0 \quad \text{Equation 06}$$

Hence, the three independent scalar inverse position kinematics are of the form,

$E\cos\theta_i + F\sin\theta_i + G_i = 0$ Equation 07

Where,

$E = 2L(y + a)$ Equation 08

$F = 2zL$ Equation 09

$G = x^2 + y^2 + z^2 + a^2 + L^2 + 2ya - l^2 = 0$ Equation 10

$t_i = \tan(\theta_i/2)$ Equation 11

Thereby, using tangent half angle substitution, the 3 theta values can be obtained for the motor parameters. The prior measurements of extreme values for arm angles avoided singularities.

The weights were calculated through simulation software by giving the proposed material. The simulation was done to examine the motion study of the robot, with weights and gravitational force. This motion study was done for the modelling; the motor torques were calculated. Since servo motors are more precise and accurate compared to stepper motors, a DC servo motor of 20 kilograms per centimeter was selected as the motor for the delta robot.

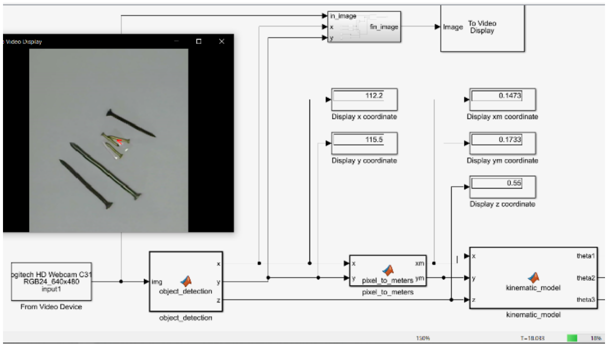

Figure 3: Image processing and kinematics model

F. Testing and Optimization

For testing the system with the mathematical model, the controller facilitated computational capacity and multi-sequential PWM signal generation for the 3 motors in the delta robot were used. Simulations and the fabrication of both designs 1 and 2 were conducted aiming at comparing and generating an accurate motion profile.

Ensuring the reachable area of the robot, the camera is mounted and pointed out to the area where the screws are located. The written program executes image processing and kinematics model to generate the coordinates. This data is then sent to the controller to actuate the motors thereby achieving the picking task by the delta robot as shown in Figure 3. Image processing and predefined locations determine the placement of the object by the delta robot.

The customized GUI created allows some basic operations for the user and to run the algorithm for sorting operations making it more user-friendly. However, this is a feature to which further improvements can be done. The real time captured image used for processing is also shown.

5. RESULTS

Workspace from the ground level of a parallel robot is less compared to a serial type of robot since a parallel robot is mounted from the top. When the system is running, unlike in serial robots, the positional error gets averaged without accumulating in the parallel robot. Parallel robots can achieve higher accelerations and is the ideal system for pick and place tasks when a quicker response is required and also when a limited workspace is available.

As the creation of kinematics code for Design 1 is complicated, workspace simulation was conducted in real time analysis for Design 1 and Design 2. This was due to the complexity of creating the kinematics code for Design 1. Both designs showed similar workspaces.

Table 1. Results from the mathematical model

Description of placement of screws (using 640x480 pixels video stream)	Location in pixels (x, y)	Location in mm (x, y, z)	Computed motor angles		
			ϑ_1	ϑ_2	ϑ_3
On a side of the delta robot	(362.0, 83.0)	(237.6, 53.9, -550)	66.9°	25.8°	78.2°
Underneath the delta robot	(282.6, 125.4)	(185.5, 81.5, -550)	60.9°	23.5°	64.7°
Underneath the delta robot	(314.5, 119.3)	(206.4, 77.6, -550)	64.0°	23.9°	70.0°
Underneath the delta robot	(283.6, 88.4)	(186.1, 61.8, -550)	71.2°	26.3°	81.6°

Design 1 has a better advantage over Design 2 when considering the robot arm workspace, which is the ideal solution for a system that has a limited area for tasks within a limited space, which will cut out lengthy conveyors and the time taken for a process to finish the entire task. But when the robot-end effector workspace is considered, Design 2 is more flexible since that orientation gives the minimum strain on bearings.

From the motion study simulation of both the designs, it was seen that the intermediate rod of Design 1 is affected by an additional force component when in motion. It is the twisting effect that occurs due to the tangential placement of the arms at the base plate as shown in Figure 4.

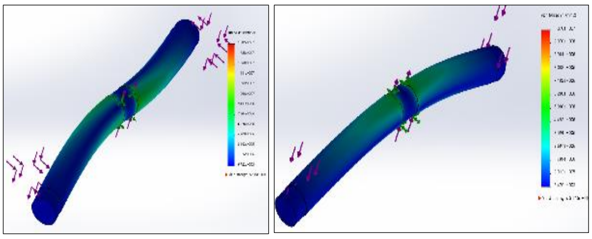

Figure 4: Stress strain analysis of intermediate rod

The amount, lengths, colors and coordinates of the screws and mapping were accurately done using the created image processing model, thereby generating the motor angles via the kinematics model. The results taken through computation of the model are given in Table I. The center of the detected object from the 640 x 480 resolution video stream were taken initially in pixel coordinates. Giving these coordinates to the kinematics model, the dimensions in real physical quantities were mapped in deriving the resulting motor angles given in Table I.

The fabrication and the testing were done according to the method discussed in this paper. This produced accurate results in object detection, mapping, picking, and placing by the delta robot following the sequence of operation mentioned in Figure 5.

6. DISCUSSION

The intermediate rods shown in Figure 4 are passed through the shell of the rod end ball bearings freely. Therefore, once the robot is in operation, the length of all the shafts will not be equal unless fixed. The intermediate shafts started to fall off the bearings and due to the shaft being passed into the bearings functioning. Thereby, more robots can be placed in line within the production system achieving more freely. Hence, intermediate shafts of 10mm diameter were taken and were threaded at the ends to a lesser diameter. By this, it was able to pass through the bearings freely and then they were tightened with a nut to achieve equal length.

The initial decision was to undergo the manufacturing of links using carbon fiber due to its light weight and strength. Due to availability, cost, and fabrication, Aluminum was selected as the alternate material because of its lightweight and strength as shown in Figure 6. However, the material stress analysis, bending moment analysis, and twist analysis done for each component for both carbon fiber and aluminum yielded well above the required value.

Singularities were common at the initiation of the system. Also, the strength of the end effector solenoid should withstand the acceleration of the system.

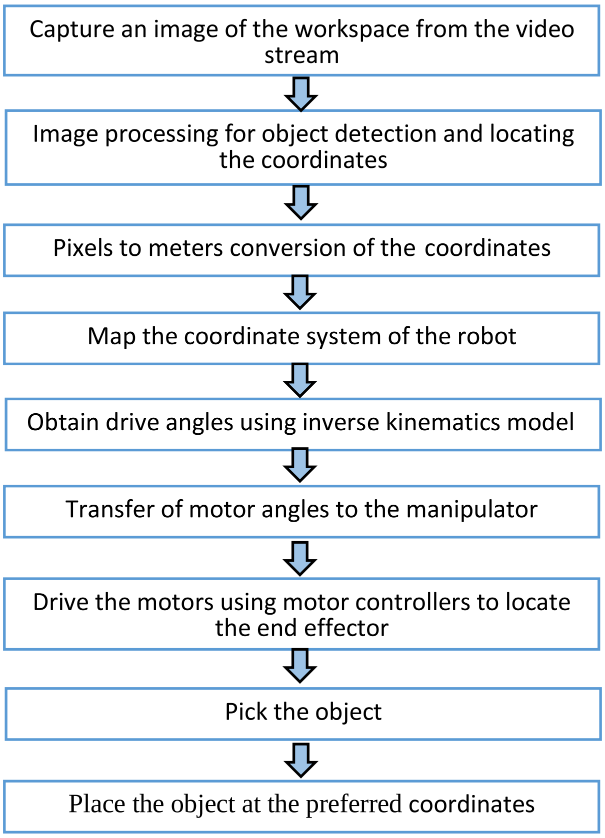

Figure 5: Control Flow

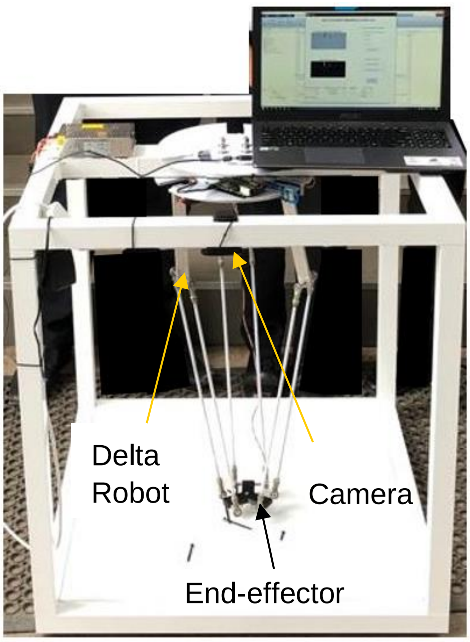

Figure 6: Fabricated, visual servo delta robot for sorting screws

7. CONCLUSION

As of the objective, a prototype was designed and developed by testing and validating to optimize regular pick and place tasks in the industry via parallel manipulators. Together with a comparison of two delta robot designs, with the aim of minimizing manipulator workspace for requirements on space constraints. Since the functionality and the objectives of the prototype model were to their expected level, a scaled-up model is feasible to be used in the industry to accommodate regular pick and place tasks such as stacking, sorting, packing, and palletizing.

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IDENTIFICATION OF MODERN COST REDUCTION TECHNIQUES FOR CONSTRUCTION PROJECTS IN SRI LANKA

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ABSTRACT

Cost is a basic criterion that measures the success of a construction project. Projects rarely meet the pre-estimated budget. There are many techniques available in current practices to control the cost of a project. However, there is still poor cost performance in the construction industry. Thus, this paper aims to identify the modern cost reduction techniques for construction projects in Sri Lanka. The data collection was conducted through a detailed questionnaire survey and interviews. The respondents are industry professionals and the response rate was 88%. The industry experts suggested a broad range of solutions based on their experience regarding the cost of a project. The Effectiveness Index analysis and content analysis were used to analyze the collected data. The findings are expected to bridge the gap in the current cost control practices by implementing modern techniques which are found as selecting appropriate value management approaches, implementing modern construction technologies, risk management, and sustainable construction. It was recommended to have construction risk assessments, continuous training programs on project cost control, and introduce a course module regarding modern cost reduction techniques at the academic level. While this research focused on the cost control of private sector projects, research can be extended to validate the conclusion of this study considering the public sector projects and categorise the modern techniques to reduce the time overruns in construction projects in the future.

KEYWORDS: *Cost overruns, Cost control, Cost reduction techniques*

1. INTRODUCTION

Construction Industry plays a significant role in the development of a country. It is the engine of the national economy of Sri Lanka where the overall physical improvement of the country is achieved. Construction Industry is one of the prominent sectors in the Sri Lankan context which has contributed approximately 6.8% to the GDP (Annual Report 2018, Central Bank of Sri Lanka). Due to different issues, the main problem that the Sri Lankan construction industry is currently facing is identified as "poor cost performance".

Every project aims to finish on time within the budget, with the required quality by consuming the available resources [1]. Cost performance is one of the significant criteria which measures the success of a project because the performance of a specific project is expressed in terms of actual cost and its adjustment to the budget. This is a challenging task for Project Managers considering the necessity for measuring and evaluating the progress and taking required corrective actions when it is needed.

In most construction projects, the cost at completion is almost always higher than the anticipated cost which is pre-estimated at the initial stage. Cost overruns arise when the actual cost of the project is more than the estimated cost. Factors affecting cost overruns differ from country to country depending on economic, political, cultural as well as internal and external factors of the industry. Cost estimated at the initial stage is the most important factor [2]. It carries far more monetary value than just a normal idea about cost performance. The real cost estimate is so dynamic because it determines the financial competence of the project and provides a baseline for cost control of the project.

In some situations, acceleration of a project is required, which results in increasing of the project cost. In addressing this, monitoring of each phase of the construction is important. Controlling project cost is not an easy task which involves applications of different cost reduction methods. Hence experts in the industry need to have theoretical as well as practical knowledge of

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cost control techniques. Insufficient cost control may lead to project failures and it emphasizes the need for proper control over the construction cost in the Sri Lankan construction industry.

There are diverse techniques and project management software available for cost optimization, but still they are insufficient to accomplish the desired cost parameters completely within the projects. Even with various cost control techniques, cost overrun is not uncommon all over the world. It does not sufficiently explain why the cost overrun keep happening though adequate understanding has been already shared by the industry professionals. The excess construction cost will lead to additional investment burden, negatively affect the investment related decision-making and cause wastage of national funding and ultimately bring negative impact on the overall economy of the country.

It is common to see a construction project failing to achieve its' objectives within the pre-estimated cost. None of the studies have improved on this and the cost overrun undertaken over the last 70 years [3] highlighted the need for modern cost reduction strategies. In the lack of related research in Sri Lanka, this study targets to fill a significant knowledge gap by identifying the specific modern cost reduction techniques which can be practically implemented in construction projects in Sri Lanka.

2. LITERATURE REVIEW

A. Construction Cost Overruns

There is a need for understanding the factors affecting cost overrun and identifying the mitigation measures. The public usually underestimate the costs which lead to negative impacts for the project and overestimated the benefits of the same action. It has been observed that delay and cost overruns are habitually occurring in developing countries [4]. Further Azhar [5] confirmed that poor cost performance is a shared problem worldwide.

The cost overrun of a project depends on project size, type, and location. It was emphasized by Dlakwa and Culpin [6] that the requirement of proper management of projects is greater at large scale construction projects than the smaller ones. Cost and time are inseparable since the extension of time leads to cost overrun [7]. Usually clients expect high quality and better service performance at a minimum cost. Malkanthi [8] interpreted that the main problem is not in the techniques, but in the familiarity regarding poor management of methods and more over inadequate control. "*Without keeping an eye on the real costs while in progress, the successful completion will not be possible*" [9].

Cost overrun has been a topic discussed in many previous studies which is considered problematic in projects. It is required to be addressed as early as possible. However, there is a significant lack of related literature in Sri Lankan context which address the causes and mitigating measures of cost overrun. Thus, there is an urgent need to find the best cost reduction techniques for successful project completion in the Sri Lankan context.

B. Cost Reduction Methods

The cost reduction techniques were identified and proposed through different studies. Management should take necessary steps on controlling human resources. Value and change management approaches, reducing errors in estimations, and inventory control are also beneficial to minimizing cost overrun. Further, the importance of training on cost management was emphasized, through brainstorming sessions [10]. It was further stated that a well-defined plan is necessary for the effective completion of a project with fewer disputes. It is recommended that contractors, clients, and consultants should work as a team and take collective decisions whenever necessary.

The total cost should be carefully assessed in the initial stage before signing a contract [3]. The tight control among projects can limit variations which directly affect the cost overrun. Aljohani [1] suggested controlling the cost of projects by applying effective resources and improving proper communication between internal and external stakeholders. Tam [11] highlighted the importance of procurement management and the availability of required material at the site on time. Sri Lankan authorities should inspire construction professionals to use cost reduction techniques by conducting awareness programs [8].

Durdyev [12] recommended spending more time on the pre-contract stage to clearly define the scope of the project. Further, attention is necessary to the quality of construction materials to minimize wastage and a detailed schedule of material supply should be provided. If they were properly managed the extra cost would be reduced [13]. Kaming et al. [7] recommended maintaining a cost database of materials based on research in Indonesia. According to Hafez, et al. [14], cost control can be easily attained through recruiting the right person for the right job function which is the responsibility of the project manager by delegating the responsibilities with proper understanding. The authors further recommended that contractors should have the necessary knowledge of cost control.

3. RESEARCH METHODOLOGY

The aim of the research is to identify the modern cost reduction techniques in building construction projects in Sri Lanka. To evaluate the mitigation techniques in construction projects, a large range of communities attached to the construction industry in Sri Lanka was targeted covering the professionals and other stakeholders in the Sri Lankan construction industry. The research was completely evaluated through a questionnaire survey (quantitative) and interviews (qualitative) with the concerned authorities. The combinations of qualitative and quantitative methods are highly appreciated because it gives a comprehensive picture and enhances the study of the research area.

A. DATA COLLECTION METHODS

A web-based detailed questionnaire (Google forms) was circulated among professional groups in the construction industry in Sri Lanka, through e-mails sent to the construction firms. Questionnaires were distributed among professionals to obtain suitable responses to the questionnaire and different viewpoints were ranked accordingly on the "Likert Scale". The total number of questionnaires distributed was 60 (selected by stratified random sampling), and the response rate was 88.33% including 13 Contractors (C), 18 Quantity Surveyors (QS), 10 Engineers (Eng), 07 Consultants (CR), and 5 Project Managers (PM).

Semi-structured interviews provided the freedom to discuss numerous areas widely [15]. A purposive sample was selected for the semi-structured interviews since the objective wass to select the partakers who had better knowledge and industry experience in the area of the research study. A total number of interviews conducted was eight including one Contractor, three Quantity Surveyors, two Engineers, one Consultant, and one Project Manager.

B. DATA ANALYSIS METHODS

Data analysis was done with the use of the Effectiveness Index (EI) analysis (data gathered through a questionnaire survey) which expressed the effectiveness of each cost reduction method towards the cost overruns [16], and the content analysis was done to analyze the data which were gathered through the interviews.

The presentation was in the form of graphs, charts & tables. A coding system was used to identify the factors separately for the convenience of understanding and discussion. The Effectiveness Index was calculated by using Equation 1.

$$Effectiveness\ Index(EI) = \frac{\sum_{i=1}^{5} a_i \times e_i}{H \times N} \qquad \text{Equation 01}$$

Where:

i = Score of the factor ranging from "Unimportant = 1" to "Very Important =5"

a_i = Weight of the response for the ith response

e_{is} = The frequency of the ith response from all respondents

H = Highest ranking available, which is 5 in this survey

N = Total number of respondents who have answered the question

4. DATA ANALYSIS

A cconstruction project is a complex endeavour that needs the contribution of different parties who specialize in a wide range of areas. Construction ccost is a main component that affects the life cycle of a project, hence all parties must have sufficient knowledge of cost items in different degrees according to their job specifications. Therefore, it is important to get the ideas of different parties involved in a construction project regarding the "Cost" factor. The general information of respondents including their profession and experience in the industry was assessed

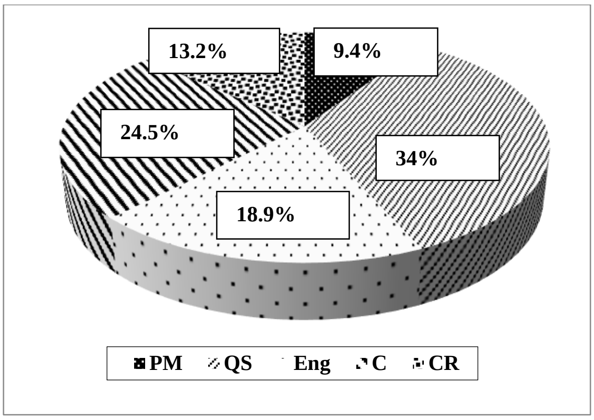

Figure 1: Respondents based on profession

as the responses may vary based on the perspective of different people due to their thinking capacity, knowledge and experience. The professions of the respondents are shown in Figure 1.

It was targeted to find out whether these professionals, experienced project cost overruns. More than 90% of respondents experienced cost overruns at construction projects as represented in Figure 2, which highlighted it as a serious problem in the construction industry and emphasizes the need for actions to mitigate the cost overrun in projects.

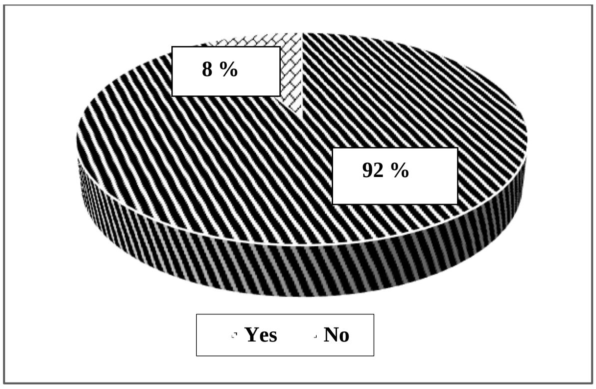

Figure 2: Experience in cost overruns on construction projects

A. EFFECTIVENESS OF CURRENT COST CONTROL PRACTICES

According to the opinion of the respondents cost control techniques can be used most effectively in pre-contract and post-contract stages. The project participants are not much focused on cost in the pre-contract stage due to the limited time allocation. Most team members of the project are going for easy and short-term plans without identifying the long-term risks. The post-contract stage is the longest period in a construction project where a series of different and complex activities take place. Controlling costs at that stage with appropriate strategies leads to reducing cost overruns.

The cost reduction techniques are identified from the literature survey and ranked according to the effectiveness of the strategy in the practical scenario of projects. The scores gained by the respondents in the questionnaire were summed up for each method of cost reduction. The Effectiveness Index was computed based on the agreement of the respondents. The cost reduction methods are noted based on a coding system as represented in Table 1 and Table 2. The main cost reduction strategies were evaluated separately in two main categories. They are Pre-Contract Management Stage-related (A) and Post-Contract Management Stage-related (B).

A.1 Pre-Contract Management

According to the analyzed data, as shown in Figure 3, A2 is the best way to control costs in pre-contract management.

A preliminary estimation will be prepared by an experienced quantity surveyor at the early stage of the project to predict the project budget [17]. It should be a properly detailed estimation based on accurate quantity take-off. Documentation including accurate drawings, specifications, and Bill of Quantities (BOQ) is to be maintained to reduce discrepancies (A6). There is a need of providing sufficient time allocation for this documentation and to cross-check the data to avoid arithmetic errors in the estimation which is also highlighted in the study done by [4]. The proper time allocation also helps to clearly define the project scope of work and reduce complexity levels which leads to reduce variations and control of the costs (A7).

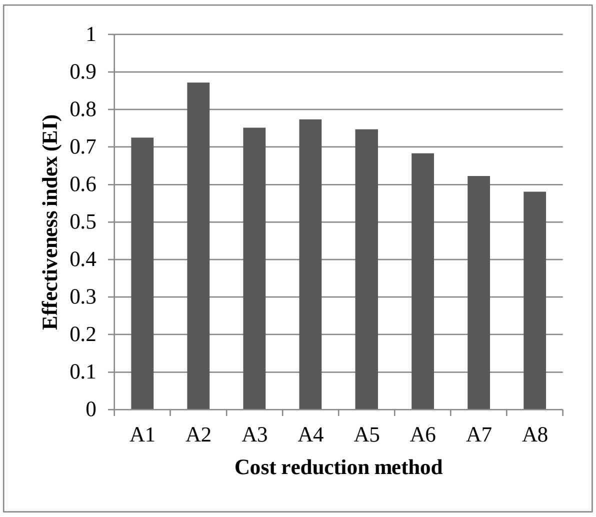

Figure 3: Ranked cost reduction methods according to the effectiveness index analysis based on "A"

Code	EI	Rank	Opinion
A1	0.725	05	Risk assessment at the tender stage
A2	0.872	01	Proper detailed and accurate estimation is done with the use of accurate quantity take-off by experienced estimators and provides sufficient time for cross-check
A3	0.751	03	Allocate adequate contingency plans for unforeseen future circumstances
A4	0.774	02	Pre-qualification assessment for selected bidders to confirm that contractor is eligible enough for the work
A5	0.747	04	Change the old-fashioned contract awarding from first lowest to the most accurate bidder
A6	0.683	06	Proper tender documentation including accurate Drawings, Specifications and BOQs to reduce discrepancies
A7	0.623	07	Proper time allocation in the pre-contract stage to clearly define the scope of the project and complexity levels
A8	0.581	08	Proper site investigations and feasibility studies to mitigate future risks

Table 1: List of cost reduction techniques based on "A"

A4 comes as the 2nd important cost reduction method which is assessing the pre-qualification of bidders at the tender stage. This will ensure the contractors' eligibility to work with the necessary resources. Selecting the most appropriate bidder through a pre-qualification assessment will mitigate the risk of future terminations and suspensions of the contractors which save cost.

Allocating adequate contingency amounts for unforeseen future circumstances (A3) come as the 3rd most effective strategy to reduce the cost of a project. To determine the contingency amount, there should be a proper risk assessment at the initial stage (A1) which ranks as the 5th factor of cost reduction. Identification of future risks will lead to construction work on a better completion of the project on time, and within the budget [18]. The risk assessment can be done with the use of proper site investigations and feasibility studies of the proposed project (A8).

Construction projects are awarded to the selected contractor through a tendering/bidding process. Tendering process totally depends on market conditions and there is a need to have a framework for the tendering mechanism. The current practice is to award the contract to the lowest bidder. It was highlighted that there is a need of changing the old-fashioned contract awarding method from the first lowest to the most accurate one (A5). Sometimes bidders purposely bid for the lower prices (front and back-end loading) with the intention of only winning the bid. The selection of the wrong contractor for a project will make a negative impact on project cost.

A.2 Post-Contract Management

Post contract stage is the longest stage in which more cost overruns could happen. There is a need to have better cost reduction strategies at this stage.

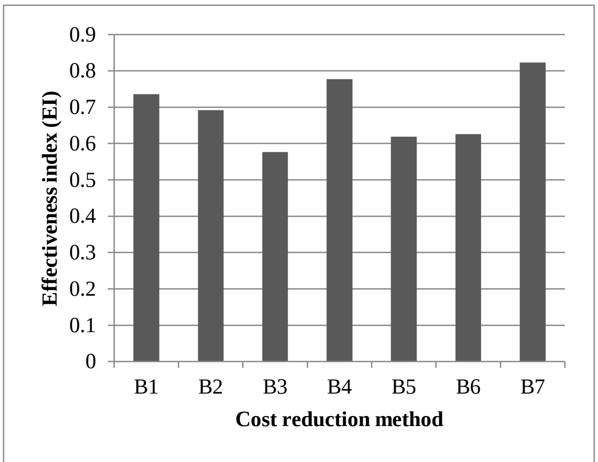

Figure 4: Ranked cost reduction methods according to the effectiveness index analysis based on “B”

Table 2: List of cost reduction techniques based on “B”

Code	EI	Rank	Opinion
B1	0.736	03	Contractors’ financial stability with the availability of sufficient funding plans
B2	0.692	04	The client should prepare available funds for the project to make payment on time for the contractors & the laborers as well as to reduce delayed works & labor strikes
B3	0.577	07	Allocate flexible funds/loans by the Government with minimal interest rates on behalf of the construction industry
B4	0.777	02	Make ICTAD documents concerning the project cost control a mandatory requirement
B5	0.619	06	Proper monitoring & evaluation of site work done by conducting inspection meetings & keep necessary reports & records
B6	0.626	05	The quick decision made to reduce the chance of increasing the time of project delivery led to cost overrun
B7	0.823	01	Regular update of cost data & maintain a properly updated cash flow.

According to the analyzed data, as shown in Figure 4, B7 the best way to control cost at post-contract management is the regular update of cost data and maintaining an updated cash flow which will lead to project success. The finding was confirmed by Karunakaran et al. [15] by identifying the main reason for cost overrun as not updating the cost plan regularly. If these documents are in order, it can filter the errors easily and necessary actions can be taken accordingly. The documents reviewed based on actual project data revealed that most projects are currently practicing this method of updating cost data.

An interviewee highlighted an experience as, “*One of my projects which is at its’ completion stage goes along with the estimated cost parameters due to properly detailed documentation of cost along with ICTAD guidelines*”. This statement is further confirmed as making ICTAD documents related to project cost control a mandatory requirement (B4) was ranked the 2nd most effective cost reduction method. It was further stated that the site at the finishing stage was almost overrun by the budgeted amount. It was found out that though the project is not complete at that stage, still the cost overrun happened due to not updating the cost documents well. This confirmed that B7 is an essential cost reduction method in the post-contract stage.

Contractors'-and clients' financial stability comes as 3rd and 4th effective cost reduction methods on ranking factors. The contractor must have a positive cash flow with available funding backups to make the construction work flow smoothly (B1). The client should also prepare available funds for the project to make payment on time for the contractors and for the labourers to reduce delayed work –and labor strikes (B2). For this, the government also can make adjustments by allocating flexible loans for construction projects with minimal interest rates which ranks the least weight under B3.

The other cost reduction techniques which were revealed from open-ended questions in the questionnaire were proper project formulation, applying new methods of construction with modern technology to save time, coordination among all the stakeholders, ensuring that proper planning strategies, proper time allocation for the completion of work, selecting the appropriate procurement methods by deep analysis on the type of the project and availability of resources strict to the procurement method of the project and quantity surveyors' involvement with proper cost documentations.

An interviewee stated that the cost control techniques currently practiced in the Sri Lankan construction industry were feasibility studies to check whether the work can proceed within the available budget, control expenses, monthly check-ups on actual expenses (invoices, material delivery notes), and update documents and inform management on behalf of adding additional funding plans. He further stated that "*Re-measure the quantities of projects of any procurement path (lump-sum contracts, measure & pay contracts, design & build contracts) will lead to finding the arithmetic errors in pricing of documents. This will take more time than expected at the initial stage. But it's better to eliminate the risk of cost overrun rather than take strategies to control when estimated budget exceeds the limit*".

Another interviewee highlighted the importance of controlling material cost by updating material reconciliation reports which identify the excess or fewer quantities and finding comparatively goes along with the finding of a similar study done by Holt et al. [19]. It was identified that updating the daily works with the planned program, properly maintaining the site, minimizing construction wastage, creating competition among labourers and ensuring site safety which reduces damages as cost reduction methods.

B. MODERN COST REDUCTION TECHNIQUES

The causes for cost overruns were identified and the study covered the current cost control practices in the industry. Though industry has been practicing different techniques for cost control, still cost overrun happens. The need for "Modern Cost Reduction Techniques" was identified by open-ended questionnaires and interviews with industry experts. The identified modern cost reduction techniques are discussed below.

- **Select the appropriate procurement path & suitable contractor**

There are different types of procurement strategies for projects. Main procurement methods are Traditional, Design and Build, Management and Partnering. The successful completion of any project will be highly dependent on the decision of selection procurement method [20]. An interviewee stated that engaging in more lump sum projects keeps the budget within limits than other contracts. In this type of project, the estimated budget at the initial stage is fixed. So the overrun of cost is limited. The selection of the procurement strategy for the project has to be carefully done. Further it was highlighted the importance of selecting suitable contractors at the tender stage. Pre-qualification assessment of contractor (A4) is an effective cost control method at the pre-contract stage which comes as the 2nd highest rank according to Table 1. This allows changing of the perception of selecting the lowest bidder and replacing it with the most accurate one (A5). This will affect the process of construction work positively in the future.

- **Cost planning**

Preliminary estimation is the basic, initial cost document in a project [17]. Proper detailed and accurate estimation done with the use of accurate quantities by an experienced estimator/QS (A2), is marked as the highest effective cost control method in the pre-contract stage (refer to Table 1). The importance of monitoring data by regularly updating cost data and cash flow (B7) was revealed by the study findings, which was also marked as the most effective cost control method at the post-contract stage (refer to Table 2). When the project commenced, proper cost planning have to be implemented. An interviewee stated that the use of modern estimation techniques will help to reduce cost overruns in construction. Elemental cost planning, Target cost, Activity-based cost, Earn Value Management (EVM) theory, Cost To Complete (CTC) and Cost Value Reconciliation (CVR) are some of the modern techniques identified.

- **Value management (VM)**

Value Management is a new approach to increase the value of the project by minimizing the additional unnecessary cost and reducing the time for completion. The concept of VM is becoming more applicable to the Sri Lankan construction industry [21]. Value Engineering (VE) is the best method for value management and it is a decision-making tool [22]. VM is considered from a strategic point while the VE is considered from a technical point. An interviewee stated that the value engineering team analyzed the project and identified the areas which consume high costs and selecting the best alternatives from different ideas which minimize cost and maximize the quality of function.

- **Modern construction technologies**

With the advancement of technology, there are modern techniques in building construction that can be used to complete projects in lesser time. If the time is saved, the cost overrun will be mitigated. An interviewee listed modern construction methods as off-site construction, modular construction, precision manufactured construction, pre-manufactured construction and digital/ smart construction. Holt et al. [19] confirmed this as the use of high technology machinery, plants–and developed materials also saves excess cost exchange of projects. The interviewee further stated that "The use of modern techniques in designs also help to reduce time and save cost. Some of the design methods are post-tension structures in place of typical reinforced techniques, reinforced retaining walls -and soil nailing". The use of modern techniques in mechanical –and electrical service systems in buildings for less power consumption will benefit in Whole Life Cycle Costing (WLC).

- **Sustainable construction**

With sustainability practices, more natural energy resources are used which minimizes the cost to increase the use of renewable energy systems [23]. An interviewee revealed that converting to sustainable construction will reduce the life cycle cost of the project. It was suggested to go for sustainable development, towards lean construction with low-cost housing, at affordable cost parameters and eco-friendly building which save future cost and environment itself. The concept of Lean Construction would be able to gain a substantial cost advantage by eliminating cost-consuming flow activities [24].

- **Modern software**

With the development of technology now there is new modern software which is specially designed for the construction field to ease the complex activities. The initiative of these methods was high in cost at the beginning, but beneficial during the whole construction process. An interviewee listed some software which are highly appreciated at the site as Primavera, MS Project, ERP system–and BIM. BIM has a great potential for integration into construction projects' life cycle which will lead to cost savings for construction projects [25]. This software can be used to update the project schedule along with which the cost data of the project can be updated (B7). This is the top most rank effective cost control method at the post-contract stage (refer to Table 2). With the use of new software, the project program can update and can check the actual expenses of the project along with the estimated project budget.

- **Risk management**

Risk is known as an unforeseen future event that causes significant consequences on construction, especially on the cost factor. Allocating adequate contingency plans for unforeseen circumstances (A3) is marked as the 3rd effective cost control method in pre-contract management according to Table 1. An interviewee classified construction risk areas as physical, technical, legal, contractual, financial and environmental. These can impact various types of cost, time and quality of construction. Risk management has to be done at the initial stage of a project as the main requirement to reduce future negative impacts [18]. An interviewee stated that "Most of the projects don't make a priority of the risk management at design stage and a proper approach is needed for this". This statement was confirmed by marking risk assessment at the tender stage (A1) as the highest rank among effective methods of cost control according to Table 1.

- **Research** and **Development (R&D) method**

R&D is a new strategy to control the cost of a project. This is a modern technique of cost controlling which needs training of people and changing their minds to think beyond the traditional methods. In this method, it identifies one activity of work -and researches on it to get the best option out of it with minimum cost. An interviewee explained an example, "This method was experienced at a proposal of constructing pile foundation. The feasibility study was done to identify the risk which can caused to the nearby neighborhood. This initial research process eliminates compensation amount which can be given to the people after the damage". This is a better way to reduce the cost of a project by minimizing future extra costs.

- **Proper dispute resolution**

According to Baccarini [26], disputes are a common phenomenon in construction due to the complexity and involvement of different parties. Dispute resolution is a process that consumes a large amount of money. It is essential to mitigate those to reduce cost overruns. If the dispute resolution was not practicable for a problem, then the parties have to go for litigation which consumes a considerable amount of time and consumes a lot of money. It is better to mitigate arising of disputes by maintaining better communication among members of the project, having better management approaches and clearly defining the scope of the project. Making a quick decision on this kind of event is essential to avoid time overruns (B6) which directly affect the cost of the project, which is also marked as a top rank effective method of construction according to Table 2.

- **Government involvement**

Institute of Construction Training and Development (ICTAD) is the Sri Lankan authority governed by the Construction Industry Development Authority (CIDA) on behalf of construction involvement for a better unique framework. The government could make amendments and general arrangements to control costs at the site. Proper documentation regarding cost data has to be maintained with ICTAD guidelines to reduce cost overruns. It is confirmed with the statement "Make ICTAD documents with reference to the project cost control as a mandatory requirement (B4)", by ranking 2nd most effective method of cost control according to Table 2. Government can involve with funding plans for both clients (B2) and contractors (B1), which is also effective in the long term. Though these methods are highlighted as the most effective methods according to Table 2, allocating flexible funds/loans by the Government with minimal interest rates on behalf of the construction industry (B3), is marked as the least effective method of cost control from the listed methods.

5. CONCLUSION

Based on a questionnaire survey, current practices of cost control were identified. It was found out that though there are practicing types of cost control techniques, still cost overruns happen, and it highlighted the need for modern cost reduction techniques which were also confirmed by [8]. According to an interviewee, "*Time, cost and quality are the main pillars of the construction, and change of those one parameter will effect on the other two*". As per the key intention of the research, when controlling the cost of the project, one has to think about the other *two* factors as well because Le-Hoai [16] stated that cost control is not effective if the time exceeds and it damages the quality of the product.

The main objective of the research was to identify the modern cost reduction techniques for construction projects in Sri Lanka. When considering the data gathered and analyzed above, it emphasized the need for monitoring the current practices of cost controlling and identifying modern methods to reduce cost overruns. There may be barriers when implementing those trends in practical scenarios and precautions have to be taken against them. Corrective cost controlling is a critical requirement in the Sri Lankan construction industry [8].

Karunakaran [15] mentioned the need of studying the mitigation of cost overruns. This gap was filled by the objective of the research by identifying modern cost reduction techniques for the Sri Lankan construction industry. The research study reviewed different techniques, including various mathematical methods (estimations) and software-based models (planning) to optimize the cost of projects. Risk management, research and development method, applying proper procurement management systems, value engineering approaches and government involvement are among the key findings of modern cost reduction techniques.

6. RECOMMENDATIONS

According to the study, although there are traditional techniques available to control cost, the parties of the construction projects have not properly implemented those. The problem of cost control was not the techniques being used, but rather the poor management of techniques and practical adaptability of those in the industry. Project cost needs an efficient and effective control process and corrective actions where necessary to ensure the successful accomplishment of the estimated budget [20]. Based on the results of the study, the following were recommended for the management of cost performance in the construction industry.

Applying better risk management plans for the construction projects and having an adequate contingency plan, which is calculated with pre-feasibility studies will help to reduce the cost of unforeseen events. A well-defined budget, based on the accurate plan of the project, at the initial stage, is essential. The project managers should have tight control over the project budget.

There should be continuous training programs and awareness programs on the importance of project cost control to update the knowledge of the project partake (top-level to middle level). Introducing a course module regarding modern cost reduction techniques for construction projects at the academic level will increase the importance of the cost factor at the very basic level. Involvement of the Government sector with flexible loans regarding construction work and allocating proper funding plans for the project stakeholders will also help to conduct construction work along with the forecasted cash flow.

7. FUTURE RESEARCH DIRECTIONS

While this research focused on the modern mitigation methods of cost overruns in Sri Lankan private sector projects, a study can be done to validate the conclusion of this study considering the public sector projects. A similar study can be done to categorize the most vital causes of cost overruns in construction projects, and also a study can be done to identify the modern techniques to reduce the time overruns in construction projects. Further research can be done to measure the cost of training against the cost of saving from proper training on the subject matter of "Cost Control".

8. ACKNOWLEDGMENT

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