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Editorial

About This Issue

The ongoing impact of COVID-19 pandemic has brought many challenges to many people and activities in the past year. With the unexpected constraints, the Editorial Sub-committee has continued to plan and review the work for the Journal. We could sustain this publication Volume 43 Number 2, including seven (7) research/ technical articles. The relevance and usefulness of respective articles are summarised below.

O. Kamiyo, "Airflow and Heat Transfer Analysis within Flat-top Roofs Heated from Below", investigated natural convection in attic of non-conventional rooftops. In this study, a finite-volume numerical investigation of laminar fluid dynamics and heat transfer of air within the attic of a flat-top roof structure has been predicted for bottom isothermal heating at varying pitch angle. The heat transfer between the walls results in multiple thermal plumes and multi-cellular flow structure with the number, size and strength of the counter-rotating cells reducing with increasing pitch angle. The results show that the peculiar shape of the roof has significant effect on the fluid flow and heat transfer. Particularly, the truncated triangular architecture of the roof prevents the formation of large, dominating and upper-row cells at the midsection of the attic. At low pitch, the intensity of the vortices results in thorough mixing of air and, hence, uniform temperature distribution within the attic. In modern pitched-roof buildings, heat loss to the attic is minimised when the roof pitch is relatively high due to the peculiarity of the flat-top roof structure.

In the article, "Improving the Lighting Project Executions with Light-Emitting Diodes (LED) in Trinidad and Tobago: A Value Engineering Approach", **M. Ramrose** and **K.F. Pun,** explored the current issues and challenges faced with adopting LED lighting in projects and provide a value-based solution in Trinidad and Tobago (T&T). The study identified the factors affecting LED adoption in lighting projects and acquired empirical data via interviews and a survey with industry practitioners in T&T. 60% of practitioners agreed that they lacked the knowledge of adopting LED lighting. The collation of findings was used to develop 2-phase LED adoption approach incorporating the principles and tools of value engineering (VE). These two phases are constituted to overcome the barriers and challenges currently being faced in lighting projects. A post-evaluation survey was undertaken focusing on acquiring practitioners' views on the applicability of the proposed approach in lighting project executions in T&T. Future work would include testing of the VE-LED approach on a wider scale using lighting projects in the public- and private-sectors separately and collectively in T&T to decrease the current issues and challenges faced with adopting LED lighting across the country.

R. Ramjattan, D. Ramsook and **P. Hosein,** "Cybersecurity Threat Analysis for an Energy Rich, Small Island Developing State", determined the level of threats and the source of such threats for educational and industrial web sites for one such country. The authors deployed a network honeypot with File Transfer Protocol (FTP), Secure Shell (SSH), Hypertext Transfer Protocol (HTTP) and Industrial Control System (ICS) on a fake educational institution server. Besides, a network honeypot with server message block (SMB), FTP, HTTP, and ICS was set up in a fake oil company server. Honeypot events were recorded and locations of the potential intruders were determined using source IP addresses. It was found that the oil company site's SMB server had the most honeypot events and the highest repeat attacker rate. This information can be used to better detect potential attacks and defend against them.

L. Wright J-M. Tangwell, and **A. Dick,** "Public Transportation in the Caribbean: Dominance of Paratransit Modes", presented the types of modes in the public transportation system in five Caribbean countries; Jamaica, St. Lucia, Barbados, Guyana, Trinidad and Tobago. The paratransit systems have developed similarly in each country and share identical cultures around these modes. In some countries, the paratransit modes are the only form of public transportation available. These modes are more reliable than government-owned buses and more frequently used. This paper focused on the paratransit modes of six Caribbean countries, and provided some factual analysis of the current public transportation system. This study would contribute to provide a foundation to future studies aiming to establish a general methodology framework that could assist in solving some of the transportation issues the Caribbean faces, through a system using paratransit modes and policy development.

In the fifth article, "Supply Chain Evaluation for the Plant Extracts Industry in the Eastern Caribbean", **D.R. McGaw** and **S. Maharaj** investigated the potential of the expansion of the industry using an in-depth evaluation of the 5 stages of the complex supply chain in the small island states. The potential for introducing new products has identified the additional crops which could be considered for commercial exploitation: root crops (turmeric, vetiver), shrubs (basil, hot peppers), trees (ylang ylang). The authors recommended based on the analysis that management of agricultural production is key to the success of the operation. Besides, steam distillation extraction can only produce essential oils, whereas supercritical fluid extraction can extract both essential oils and oleoresins, but at a rather higher capital cost. There would be a move towards major production and distribution of commercial products after the new businesses are established. These new businesses would contribute to the fulfillment of a sustainable supply of crops to the process plant.

R. Bachoo and **J. Bridge**, “Flow Induced Vibrations of for Oil and Gas Piping Systems: Wall Pressure Fluctuations and Fatigue Life Assessment”, developed a procedure for incorporating the underlying wall pressure fluctuations in a finite element model for the purpose of determining the fatigue life of a piping system. Numerical simulations were used to determine the fatigue life for a flowline transporting natural gas at three different flow velocities; 65 m/s, 130 m/s and 170 m/s. The authors also experimentally investigated the wall pressure fluctuations associated with single phase flow in a geometrically complex manifold. Extensive wall pressure fluctuation measurements associated with water flowing at 1.6 m/s and air flowing at 3 m/s were investigated. It was found that the pressure fluctuations associated with a fully developed turbulent flow are significantly greater than that observed at an undisturbed position, owing to the dramatic changes in geometry. Unlike the simple 90º elbow or mitre bend, the fluctuations within the manifold remain pronounced with no decay in amplitude.

The seventh paper, “Hydraulic Model Study of Arena Dam Spillway Works, Trinidad”, by **H.O Phelps (late), H. Md. Azamathulla,** and **G.S. Shrivastava**, is a special paper. The work was carried out by the late Professor Phelps (1929-2018) - in the Fluid Mechanics Laboratory of the Department of Civil and Environmental Engineering at The University of the West Indies at St. Augustine in 1975. This physical model study was not published in the lifetime of Professor Phelps. For the sake of preserving the integrity of original work, it is essentially unaltered for publication. The publication would add to the history of landmark hydraulic engineering structures built in Trinidad, and indeed in the Commonwealth Caribbean, and equally to Professor Phelps’ legacy investigated.

On behalf of the Editorial Office, we gratefully acknowledge all authors who have made this special issue possible with their research work. We greatly appreciate the voluntary contributions and unfailing support that our reviewers give to the Journal.

Our reviewer panel is composed of academia, scientists, and practising engineers and professionals from industry and other organisations as listed below:

The views expressed in articles are those of the authors to whom they are credited. This does not necessarily reflect the opinions or policy of the Journal.

KIT FAI PUN, *Editor-in-Chief*

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Airflow and Heat Transfer Analysis within Flat-top Roofs Heated from Below

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Abstract: *Natural convection in attic of non-conventional rooftops has received considerable attention in recent years due to its importance in thermal management of modern pitched-roof buildings. In this study, a finite-volume numerical investigation of laminar fluid dynamics and heat transfer of air within the attic of a flat-top roof structure has been predicted for bottom isothermal heating at varying pitch angle. The heat transfer between the walls results in multiple thermal plumes and multi-cellular flow structure with the number, size and strength of the counter-rotating cells reducing with increasing pitch angle. The results further show that the peculiar shape of the roof has significant effect on the fluid flow and heat transfer. Particularly, the truncated triangular architecture of the roof prevents the formation of large, dominating and upper-row cells at the midsection of the attic. At low pitch, the intensity of the vortices results in thorough mixing of air and, hence, uniform temperature distribution within the attic. The averaged Nusselt number for the hot ceiling wall which depicts the rate of convective heat transfer into the attic is in negative-gradient quasilinear relationship with the roof pitch. The practical significance of the predicted results is that, due to the peculiarity of the flat-top roof structure, heat loss to the attic is minimised when the roof pitch is relatively high; particularly not less than 300 and made as low as possible if the attic is to be used for drying of food crops.*

Keywords: *Flat-top, triangular, roofs, heated below, pitch angle, heat transfer*

Nomenclature

AR	*Aspect ratio*
G	*Gravitational acceleration, m/s²*
h	*Heat transfer coefficient, W/m²K*
H	*Height of enclosure, m*
k	*Thermal conductivity, W/m K*
L	*Length of enclosure, m*
Nu	*Nusselt number*
p	*Pressure*
Pr	*Prandtl number*
Ra	*Rayleigh number*
T	*Temperature, K*
Th	*Temperature at the hot wall, K*
Tc	*Temperature at the cold wall, K*
u	*Velocity in x-axis, m/s*
v	*Velocity in y-axis, m/s*
x, y	*Cartesian coordinates, m*

Greek letters

α	*Thermal diffusivity, m²/s*
β	*Coefficient of thermal expansion,0K*
θ	*Dimensionless temperature*
ν	*Kinematic viscosity, m²/s*
ρ	*Density, kg/m³*
ϕ	*Pitch angle, degrees*

subscripts

h	*hot wall*
c	*cold wall*

1. Introduction

In most residential, commercial and industrial buildings, the thermal characteristics of the attic space have significant influence on the cooling or heating load of the space directly below it. Therefore, for effective energy management, the roof attic is designed based on the heat transfer principles. For instance, in rural areas in Sub-Saharan Africa, agricultural produce are stored in the attics for accelerated drying. To obtain the expected uniform drying of these produce, it is imperative to have knowledge of the actual temperature distribution and the flow field in the attic which is influenced by the roof frame configuration. Over the years, temperature distribution and flow field within the attic and natural convective heat transfer across the ceiling have been subjects of investigation, more importantly, with the advent of unconventional roof designs.

The development of robust computational fluid dynamics (CFD) packages has made using them to obtain near-accurate numerical solutions of natural convection in enclosure problems. Comprehensive review on natural convective heat transfer across triangular enclosures carried out by Kamiyo et al. (2010) revealed extensive studies on regular pitched roofs and some complex-shaped roofs such as gambrel, gable and trapezoidal. Thereafter, investigations on heat transfer within attics of regular and complex shapes under different boundary conditions have continued.

Using two-dimensional (2D) unsteady CFD model, the impacts of roof pitch and ceiling insulation on the cooling load of gable-roof residential buildings were investigated by Wang et al. (2012) for attic spaces with roof pitches from 3/12 (14º) to 18/12 (60º) combined with ceiling insulation levels from R-1.2 to R-40. The results show that an increase of roof pitch from 3/12 to 8/12 results in a decrease in the cooling load by about 9%. The team further considered the effects of roof pitch on airflow and heating load of both sealed and vented attics for the same buildings in Wang and Shen (2012) and reported that airflow pattern in the sealed attics is steady and asymmetric, while that of the vented attics is a combination of symmetric base flow and a periodical oscillating flow.

Kamiyo et al. (2014) reported the flow structure and temperature distribution in asymmetric triangular enclosures heated from below in which they analysed the effects of the Rayleigh number and the pitch angle. The natural convection flow in an isosceles triangular enclosure subject to non-uniform cooling from the inclined surfaces and uniform heating from the base is investigated numerically by Saha and Gu (2015). The numerical simulation is performed using a finite volume method for a range of aspect ratio $0.2 \leq AR \leq 1.0$ and Rayleigh number $5 \times 10^4 \leq Ra \leq 1 \times 10^6$.

Sieres et al. (2016) reported an analytical and numerical computation of laminar natural convection in vertical upright–angled triangular cavities filled with air for angles 15º, 30º, 45º and Rayleigh number range: $0 \leq Ra < 10^9$. The vertical wall is heated with a uniform heat flux, the inclined wall is cooled at a uniform temperature while the upper horizontal wall is thermally insulated. At low Ra, heat transfer rate increases for lower angles but remains the same for high Ra. In a CFD modeling of a right-angled triangular enclosure, Mirabedin (2016) formulated a correlation for Nusselt number in terms of its aspect ratio and Rayleigh number and found that the Nusselt number increased with increase in aspect ratio.

In recent times, Amrani et al. (2017) numerically studied natural convection with surface radiation in a gabel roof for hot climates. Also, using 3D numerical model approach, Cui et al. (2019) carried out transient free convection heat transfer in a section-triangular prismatic enclosure with different aspect ratios and Ra range from 10^0 to 10^7 under top-cooled and bottom-heated boundary conditions to determine the critical Rayleigh numbers for the transition of the flow.

Archival literature has shown that knowledge of airflow and thermal characteristics of attic space is important and that knowledge could reliably be obtained using numerical simulation techniques. Many complex roof shapes have been studied but there are still some common ones that investigations have not covered sufficiently. The flat-top attic configuration shown in Figure 1 is one of such. In this study, a finite-volume CFD package is employed to better understand the steady airflow and temperature fields, and natural convective heat transfer into the attic of a flat-top roof heated through the ceiling.

Figure 1. Atypical Flat-top Roof House

2. Methods

Simply, the physical geometry of the attic of a pitched roof could be represented by a 2D triangular shape provided the roof extension in the direction perpendicular to the cross-section is more than double its width (Penot and N'Dame, 1992). Therefore, the physical geometry of the flat-top roof considered in this study, which coincides as the computational domain, is as shown in Figure 2. The horizontally truncated triangular structure of the geometry makes it appear like a low aspect ratio rectangle with inclined vertical sides. This peculiar shape is expected to affect the thermal performance of the roof in comparison with conventional roof shapes.

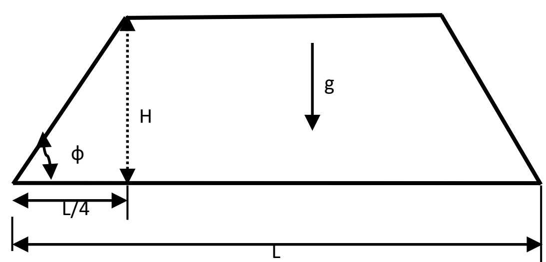


Figure 2. Computational Domain

The enclosure is filled with air. The base wall is heated isothermally; assuming the conventional hearth-heating method. The upper cold inclined and the flat-top walls (assumed made of aluminum) are set at a temperature difference of 20K with that of the hot ceiling (assumed made of gypsum board). There is no internal generation of heat. Being insignificant, the effect of the heat stored by the roof frame is neglected. The flow is assumed steady. Bousinessq approximation is applied;

the validity of which is corroborated by Gray and Giorgini (1976) and Ridouane et al. (2005). Actual roof size and real life weather conditions vary, hence, the domain dimensions and boundary conditions are normalised.

The governing equations for buoyancy-driven, laminar natural convective flow under steady-state conditions are conservation of mass, momentum and energy, expressed in dimensionless forms, subject to Bousinessq approximation, as:

Mass:

$$\frac{\partial U}{\partial X} + \frac{\partial V}{\partial Y} = 0 \quad (1)$$

X-momentum:

$$U\frac{\partial U}{\partial X} + V\frac{\partial U}{\partial Y} = -\frac{\partial P}{\partial X} + \Pr\left(\frac{\partial^2 U}{\partial X^2} + \frac{\partial^2 U}{\partial Y^2}\right) \quad (2)$$

Y-momentum:

$$U\frac{\partial V}{\partial X} + V\frac{\partial V}{\partial Y} = -\frac{\partial P}{\partial Y} + \Pr\left(\frac{\partial^2 V}{\partial X^2} + \frac{\partial^2 V}{\partial Y^2}\right) + RaPr\theta \quad (3)$$

Energy:

$$U\frac{\partial \theta}{\partial X} + V\frac{\partial \theta}{\partial Y} = \left(\frac{\partial^2 \theta}{\partial X^2} + \frac{\partial^2 \theta}{\partial Y^2}\right) \quad (4)$$

Using the following non-dimensional variables:

$$X = \frac{x}{H},\ Y = \frac{y}{H},\ U = \frac{uH}{\alpha},\ V = \frac{vH}{\alpha},\ \theta = \frac{T - T_c}{T_h - T_c},$$

$$P = \frac{pH^2}{\rho\alpha^2},\ Pr = \frac{v}{\alpha}$$

$$Ra = \frac{g\beta(T_h - T_c)H^3}{\alpha v}$$

Boundary Conditions:

Temperature: $\theta_c = 0$; $\theta_h = 1$

(isothermal roof and ceiling walls respectively)

Velocity: U = V = 0

(no-slip condition along the walls)

Four pitch angles, selected arbitrarily within the standard roof pitch range, are considered in the study. Computational parameters are as indicated in Table 1, indicating that the study is restricted to steady, laminar flow conditions.

Table 1: Computational Parameters

Pitch Angle (ϕ)	14^0	18^0	30^0	45^0
Aspect Ratio, AR = 4H/L	0.250	0.325	0.580	1.00
Rayleigh Number (Ra)	3.98 x10^4	8.75 x 10^4	4.97 x 10^5	2.55 x 10^6

The governing partial differential equations, with the associated buoyancy quantities, were discretized and solved using ANSYS FLUENT© (V18), a finite volume CFD package. SIMPLE algorithm as applied in the code was employed for the pressure-velocity coupling alongside a QUICK scheme adopted for spatial discretization of the momentum and energy equations. Convergence criteria were fixed at 10^{-5} for the continuity residual, and at 10^{-7} for the residuals of the momentum and energy equations. No slip condition was employed for velocity at the walls.

A combination of uniform and non-uniform meshes arrangement is implemented to capture the rapid changes in the dependent variables. To test grid independence of the solution scheme, many numerical runs were performed and the result of the Nusselt number variation for the 45° -pitch enclosure (see Figure 3) is as shown in Table 2.

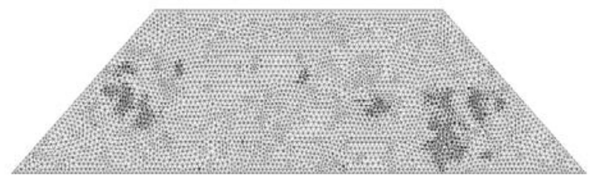


Figure 3. Computational Grid for the 45^0 Pitch Enclosure

Table 2. Grid Independence Study for the 45^0 Pitch Enclosure

Number of elements	41,113	46,921	50,744	54,536
Mean Nusselt number	17.736	19.134	19.665	19.710

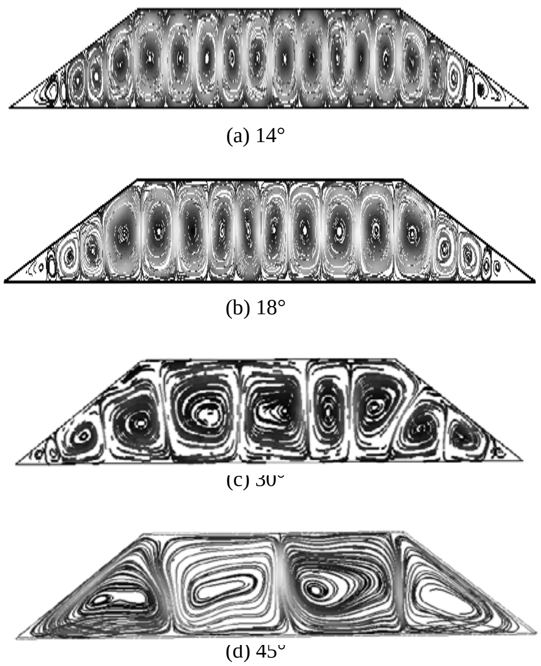
Converged results show that the mesh with 50,000 elements was sufficient to produce grid independence.

3. Results and Discussion

The results of the simulations are presented in forms of predicted steady streamlines, velocity and temperature distributions within the attic alongside the local and averaged Nusselt number variations along the hot wall for the roof pitches considered. The velocity and temperature are scaled using $U = \sqrt{g\beta(T_h - T_c)H}$ and $\theta = (T - T_c)/(T_h - T_c)$ respectively; hence, range from zero to one.

3.1 Flow Field Analysis

The predicted streamlines in Figure 4 generally show that hot air rising from the hot, horizontal base wall hits the upper walls almost perpendicularly, then divides in either directions and returns to the base wall, thereby forming counter-rotating, recirculating cells. The flattop nature of the enclosure has peculiar influence on this flow structure. The closeness of the top and bottom walls constrained the cells to the lower part of the truncated triangle in a form similar to a low-height rectangular enclosure resulting in the classical Rayleigh-Bernard convection. In a regular triangular enclosure with the upper vertex, there are upper rows of cells formed as the pitch angle and Ra increase (Kamiyo et al., 2014). However, in the present study, the truncated nature of the enclosure prevents the formation of such upper cells.



(a) 14°

(b) 18°

(c) 30°

(d) 45°

Figure 4. Streamlines for Different Pitch Angles

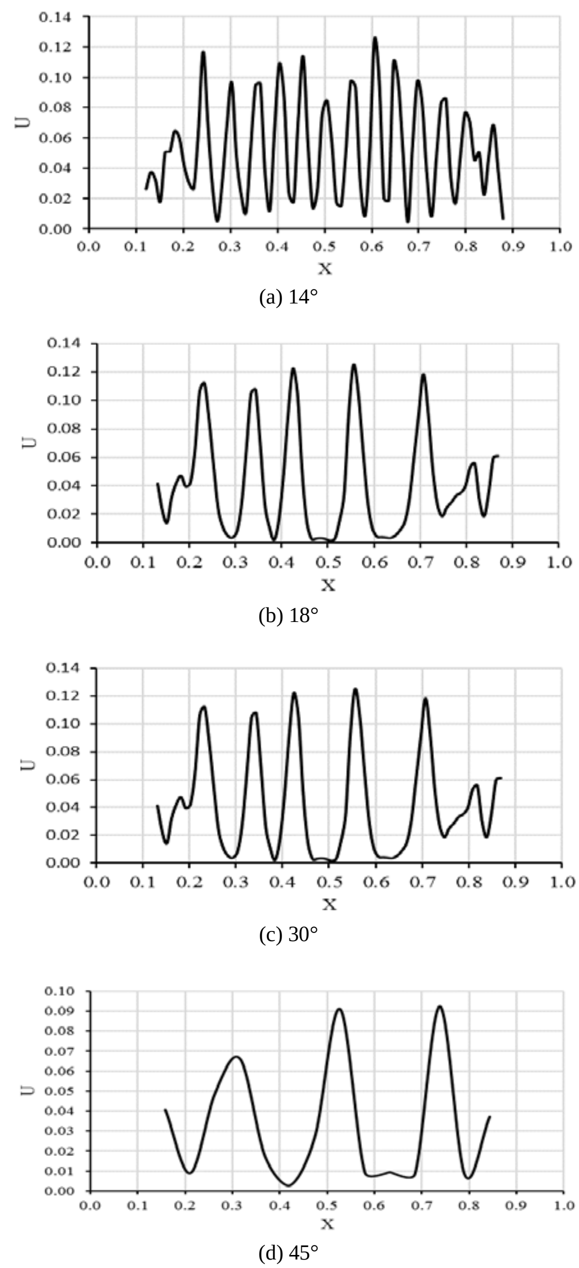
As the attic aspect ratio increases, the location of the counter-rotating vortices changes and their number also decreases. The strength of the vortices decreases with increase in pitch angle and from the midsection towards the bottom corners. This is due to the reducing effect of heat from the base wall (which is the same for all angles) as the pitch increases.

In the 14°-pitch enclosure, Figure 4(a), there are twenty counter-rotating cells moving with different levels of intensity. While the size and the strength of the vortices under the flattop are relatively the same, those under the inclined walls naturally reduce in size towards the bottom corners. The strength of each cell reduces from the outer circumference towards the core; setting up regions of highest intensity where adjacent cells rub on each other. Near the intersections of the hot and cold walls, a very small region dominated by pure conduction exists. As the roof pitch increased to 18°, Figure 4(b), thereby creating more space height to roam, the cells becomes larger and their number reduced to eighteen.

However, in Figure 4(c) for the 30°-pitch, with almost double increase in the pitch angle, the central cells in the 18°-pitch cavity merged to form larger cells. Also, the conduction region has become smaller. In the 45° pitch cavity, Figure 4(d), there are just four counter-rotating cells as two cells in the 30°-pitch enclosure appeared to have merged to form one. The formation of the vortices depends largely on the Rayleigh number, which at the same temperature difference and length of base wall, depends solely on the characteristic length, H which increases with the pitch angle.

Counter-rotating vortices obtained in this study is similar to that reported by Holtzman et al. (2000) who presented flow visualisation results from experiments performed in a smoke-filled isosceles triangular enclosure heated from the base wall, to show that, as Ra increases for a given geometry, the flow pattern becomes multi-cellular and the number of counter-rotating cells increases.

Figure 5 gives the variation of the predicted velocity at the mid height (Y= 0.5H) of the attic for different roof pitches. The velocity value has peaks at the point where adjacent cells rub on each other and low values at the core of the cells. The distance between two peaks therefore corresponds to the diameter of a cell.



(a) 14°

(b) 18°

(c) 30°

(d) 45°

Figure 5. Velocity Variations at Mid height (Y= 0.5H) for Different Roof Pitches

Velocity value is relatively high in major part of the cavities with an average value of about U = 0.06 but low in the 450-pitch where it is 0.045. The latter is due to low heating effect of the base wall on the cold volume of air within the cavity. Velocity variation plot at a cross-section in the enclosure is useful for predicting the convection currents that could guide in the proper ventilation of the attic space and on the best arrangement of food crops for uniform drying.

The air velocity profiles at the centerline (X = 0.5L) for different roof pitches are presented in Figure 6. It is observed that, in the 14^o and 45^o roof pitches, the centerline coincides with where two vortices at the midcentre rub on each other. The value of the air velocity increases gradually from the base wall as hot air rises and peaks at the midheight. It then gradually reduces to almost zero as the air dissipates most of its heat content to the cold flat-top wall. On the other hand, in the 18^o and 30^o pitches, the centerline coincides with the diameter of the midcentre cell rotating within the lower and upper boundary layers at $Y \leq 0.1$ and $Y \geq 0.9$ respectively. The air velocity value changed sharply within the boundary layers while its lowest value is at the core of the cells.

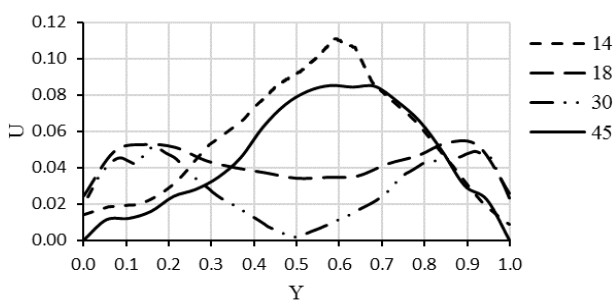
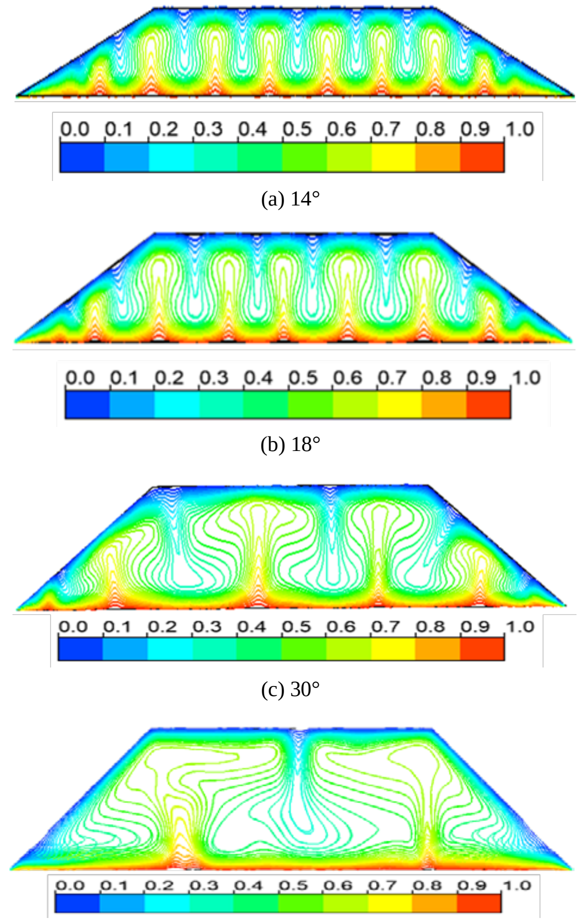


Figure 6. Velocity Profiles at Centre line (X = 0.5 L) for Different Roof Pitches

3.2 Temperature Distribution

The results of the predicted thermal field show domination by convection in all the roof pitch and Ra range considered. The predicted isotherm contours in Figure 7 indicate the presence of thermal plumes of hot air rising from the hot ceiling towards the cold roof walls and of cold jets leaving the cold roof walls downward. These correspond to regions between two counter-rotating vortices. Also, temperature gradient is very high at the thermal boundary layers along the walls. The strength and number of the vortices is observed to have strong influence on the transport processes within the enclosures. Analogous to the convection currents, the number of thermals progressively reduces as the roof pitch increases. Also, the isotherms in between the plumes become more spatial indicating reducing average temperature.

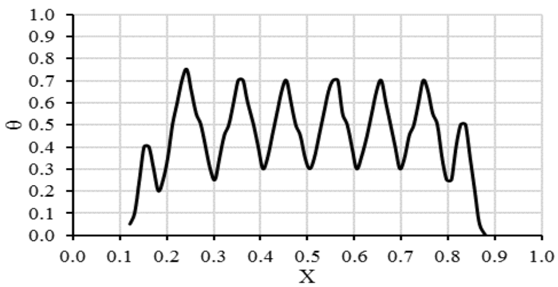


(d) 45°

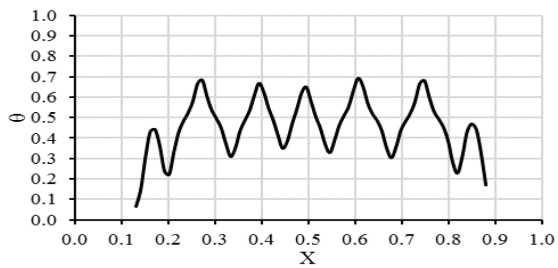
Figure 7. Isotherms for different roof pitches

What started as ten rising plumes in the 14^o-pitch cavity, Figure 7(a), reduced drastically to two in the 45^o-pitch in Figure 7(d). The multi-cellular flow within the 14°-pitch enclosure reported in Figure 4(a) results in a thorough mixing of the fluid to which corresponds a relatively high value of the mean temperature. Generally, the temperature distribution within an enclosure becomes progressively more uniform as the attic aspect ratio and the Rayleigh number increase. This effect is directly related to the formation of big vortices whose central part remains practically isothermal. Thermal boundary layers are formed along the hot and cold walls. The thickness of boundary layers increases with the roof pitch. At the bottom corners, heat transfer is very high due to the closeness of the hot and cold walls. It is suggested that insulation around that region of the ceiling should be reinforced to reduce heat loss into the attic while the locations are well suited for crop drying.

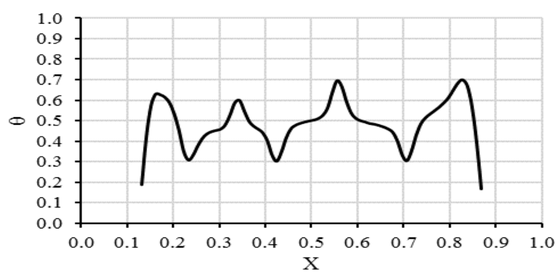
The variation of the predicted temperature at the midheight (Y = 0.5H) of the attic for different roof pitches is presented in dimensionless form in Figure 8. The peaks correspond to the centres of the hot plumes while the valleys are at the middle of the cold jets. The distance between two peaks gives the thickness of a cold jet while the thickness of a plume is determined by the distance between two valleys. The plot is useful to determine the location and degree of hotness of plumes which could guide in the arrangement of agricultural produce on the ceiling for proper drying.



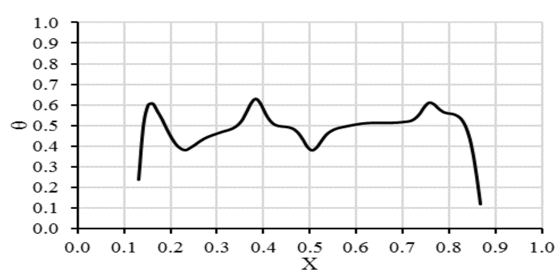
(a) 14°



(b) 18°



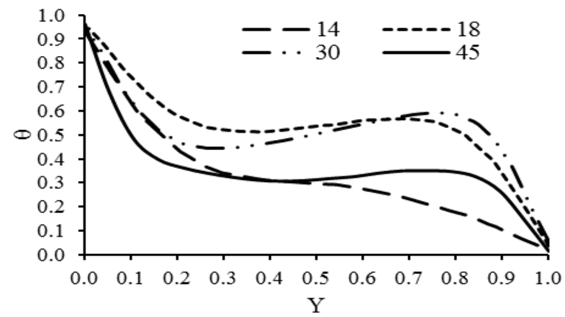
(c) 30°



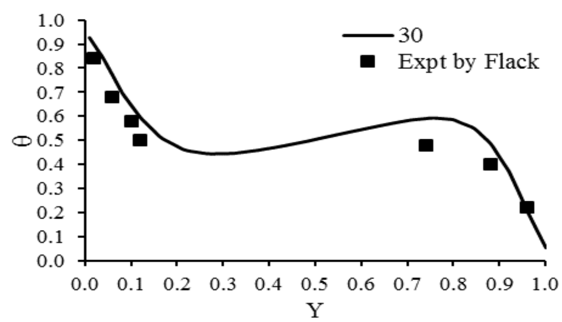
(d) 45°

Figure 8. Temperature Variation at Mid height (Y= 0.5H) for Different Roof Pitches

The temperature profiles at the centerline (X = 0.5L) of each roof pitch are presented in Figure 9(a). Generally, the profiles indicate two distinct regions: the lower and upper thermal boundary layers at $Y \leq 0.2$ and $Y \geq 0.8$, respectively, where air temperature drops sharply and a practically isothermal core. The predicted air temperature for the 30° roof pitch with Ra = 4.97 x10^5 is compared with a closely related experimental data of Flack (1980) at Ra = 4.5 x 10^5 in Figure 9(b). The agreement is good and adequate.



(a)



(b)

Figure 9. Temperature Profiles at the Centre line (X = 0.5L) for, (a) Different Roof Pitches, and (b) 30° Roof Pitch (Ra = 4.97 x10^5) and Flack Experiment (Ra = 4.5 x10^5)

3.3 Heat Transfer Analysis

The heat transfer pattern within the enclosures is reported with the plots of the values of the local Nusselt number along the walls and mean Nusselt number along the hot wall in Figures 10 and 11, respectively. In this study, the local Nusselt number is defined as:

$$Nu_x = \frac{h_x L}{k} \tag{5}$$

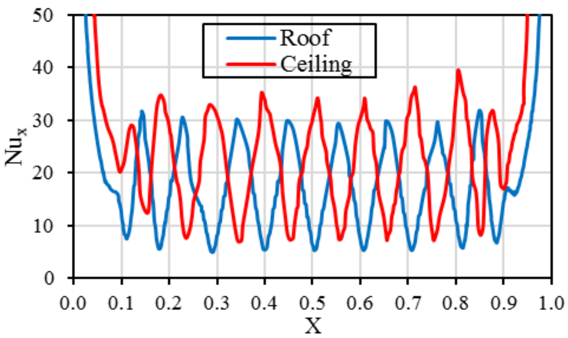
and, the mean Nusselt number as:

$$\overline{Nu} = \frac{\bar{h} L}{k} \tag{6}$$

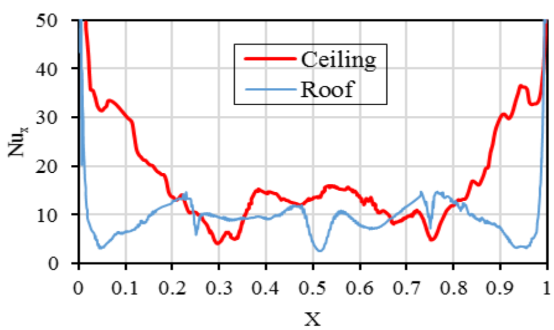
where the ceiling length L, common to the enclosures, is chosen as the characteristic length.

The order of variation of the Nu_x along the hot ceiling and cold roof walls corroborate the fact that the rate of heat transfer from the walls synchronizes with the pattern of attachment and detachment of the thermal plumes at the walls. Particularly, in Figure 10, the upper values in the local Nu plot for the 14°-pitch cavity directly correspond to thermal plume crash and separation points on the walls. The relatively sequential wavy Nu_x lines indicate uniform heat flow across the enclosure.

In the 45°-pitch, this is no longer the case. The trends become irregular and the relatively low values of Nu_x under the flattop wall show that heat transfer from the base wall, at that roof pitch, is quite low; the average temperature within the cavity tends towards that of the upper cold wall. Similar result was obtained by Haese and Teubner (2002). In all the roof pitches considered, high Nu-values are found in the vicinity of the bottom corners, mainly due to the closeness of the hot and cold walls. In solar drying in the tropics, the agricultural produce is contained in an enclosed space and the air in contact with it is heated by solar radiation. By heating the air, its capacity to attract moisture from the environment increases. Therefore, grains dry faster and better when placed in the high temperature region near the bottom corners.



(a) 14°



(b) 45°

Figure 10. Variation of Local Nusselt Number along the Walls for (a) 14^0- and (b) 45^0- Pitch Enclosures

In order to predict the effect of pitch angle on the rate of heat loss from the heated space through the ceiling into the attic of a flat-top roof, the plot of values of the mean Nusselt number against roof pitch is presented in Figure 11. The plot shows that the $\overline{Nu}$ is in negative-gradient quasilinear relationship with the roof pitch. That is, the heat transfer rate reduces as the roof pitch increases; specifically $\overline{Nu}$ varies inversely with $\phi^{1/3}$.

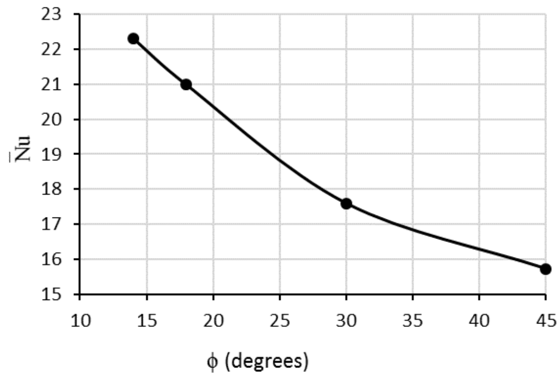


Figure 11. Variation of mean Nusselt number on the hot wall for different enclosures

In other words, the higher the roof pitch, the longer the length of the cold wall, the higher the distance between the hot and cold walls and the higher the volume of attic air to heat. Therefore, for the same length of the ceiling and same heating rate, the heating effect reduces. It is then concluded that due to the peculiarity of the flat-top roof structure, to minimise heat loss to the attic, the roof pitch should be relatively high; particularly not less than 30°. On the other hand, if the attic is to be used for effective drying of food crops, as in sub-Saharan rural villages, the roof pitch should be as low as possible.

4. Conclusion

The fluid dynamics and heat transfer of air within the attic of a flat-top roof structure at varying pitch angles has been predicted for bottom heating condition using numerical technique. The results show that the peculiar shape of the roof has significant effects on the fluid flow and heat transfer. Particularly, the truncated triangular architecture of the roof prevents the formation of upper-row counter rotating cells in the attic. Also, the number of the cells formed reduces as pitch angle (or aspect ratio) increases. At low roof pitch, the high intensity of the vortices causes uniform flow field and temperature distribution within the attic.

The averaged Nusselt number for the hot ceiling wall which depicts the rate of convective heat transfer into the attic is in negative-gradient quasilinear relationship with the roof pitch. For the range of pitch angle considered, the heat transfer rate is higher near the lower base corners than any part of the flow area. The practical significance of the predicted results is that, due to the peculiarity of the flat-top roof structure, heat loss to the attic is minimised when the roof pitch is relatively high; particularly not less than 30° and made as low as possible if the attic is to be used for drying of food crops.

This work will be useful to building designers in their choice of insulation material for controlling heat losses through flat top attic spaces. Also, knowledge of the flow pattern of the hot air within the attic enables agriculturalists in a tropical environment to predict the most appropriate positions for placing farm produce especially when the control of drying- and moisture-removal rates is important.

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Improving the Lighting Project Executions with Light-Emitting Diodes in Trinidad and Tobago: A Value Engineering Approach

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Abstract: *Light emitting diodes (LED) are being used increasingly to provide lighting solutions for domestic and commercial lighting. This paper reports the findings on a recent study on the current issues and challenges faced with adopting LED lighting in projects and provides a value-based solution in Trinidad and Tobago (T&T). It identifies the factors affecting LED adoption in lighting projects. It then relates the challenges of LED adoption and the improvement of lighting efficiency in projects by acquiring empirical data via the conduct of interviews and a survey with industry practitioners in T&T. Compared to traditional lighting, LED lighting has superior qualities in various ways such as being energy efficient; has a long lifespan, durable, and is environmentally friendly. As evidenced from the empirical findings, 60% of practitioners agreed that they lacked the knowledge of adopting LED lighting. There have been needs to eliminate the cost barriers and to educate the public on the potential use of LED lighting in T&T. The collation of findings was used to develop 2-phase LED adoption approach incorporating the principles and tools of value engineering (VE). Phase 1 is concerned with lighting solutions analysis with DIALux in the planning phase of a project, whereas Phase 2 is an integrated VE policy for transitioning efficient lighting solutions in projects. These two phases are constituted to overcome the barriers and challenges currently being faced in lighting projects. A post-evaluation survey was undertaken with those who had participated in the previous stage of data acquisition. The post evaluation focused on acquiring practitioners' views on the applicability of the proposed approach in lighting project executions in T&T. Subject to further verification of empirical and case evidence, future work would include testing of the VE-LED approach on a wider scale using lighting projects in the public- and private-sectors separately and collectively in T&T to decrease the current issues and challenges faced with adopting LED lighting across the country.*

Keywords: *Light emitting diodes (LED), lighting projects, Value Engineering, Trinidad and Tobago*

1. Introduction

Energy efficiency practices are greatly increased due to the issues with climate change and high energy pricing (Edirisinghe, 2012). Light emitting diodes (LED) has entered the market and is constantly developing new methodologies and technologies that can be utilised in lighting designs and practices. LED lighting technology has numerous advantages over traditional lighting. It is more energy efficient, has a longer lifetime, has less maintenance requirements, and contributes to reduced climate control costs. LED lighting reduces heat and UV emissions, and it contains no mercury ((Energystar.gov, 2018)). Many projects are aiming for the implementation of cost-saving solutions that are energy efficient. LED lighting is one of the most cost-effective products for achieving this aim (UN Environment, 2017).

In Trinidad and Tobago (T&T), projects undertaken in the public and private sectors require a lot of lighting sources. Traditional lighting has been used in preference to LED lighting. However, traditional lighting fixtures would require high maintenance costs, and produce less lumens per watt. LED lighting would have been used in projects, but sometimes with the wrong application and quantities. There is also an issue that the public is not aware of determining which quality and 'value' of LED lighting to purchase (Ramrose, 2019). Value resides in a sort of appreciation towards a product, service, event or item. The extent to which the client needs to be satisfied and the cost of achieving it will be subject to various risks, making the value calculation uncertain.

Lighting plays an important role in increasing a building's total value, due to its impact on comfort, productivity, and health, to the extent that it is considered on par with energy efficiency (Dehoff, 2012, 2014). Value Engineering (VE) is a systematic study of a project, process or system that seeks the most favourable solution that would prevent any unnecessary cost (Tosca, 2018). This paper investigates the current situations and issues of lighting inefficiency in projects undertaken by the public and private sectors, and incorporates VE into fostering the adoption of LED lighting in T&T.

This paper has seven (7) sections. After the introduction, Section 2 describes the key problems currently faced in lighting project executions in T&T. Section 3 discusses the incorporation of VE into the planning and executions of lighting projects. Section 4 outlines the study methodology and presents the findings. Section 5 shows the development of a proposed VE-LED adoption approach, whereas the results of a post-evaluation survey on the applicability of the approach are presented in Section 6. The paper concludes in Section 7 by underlining the applicability of the approach with some recommendations for future work.

2. LED Lighting and Challenges of Its Adoption in Projects

LED stands for light emitting diode. An electrical current passes through a microchip, which illuminates the tiny light sources we call LEDs and the result is visible light (Energystar.gov, 2018). Appearing as practical electronic components in 1962, LED's have been and are used in applications as diverse as aviation lighting, automotive headlamps, advertising, general lighting, traffic signals, camera flashes, lighted wallpaper, horticultural grow lights, and medical devices (Peláez and Villegas, 2007). As compared to traditional light sources (like incandescent, compact fluorescent lamps (CFLs), tungsten, sodium, and other forms of lighting), LED lighting has many advantages, including lower energy consumption, longer lifetime, improved physical robustness, smaller size, and faster switching (Energystar.gov, 2018).

Several lighting design software (e.g., DIALux, AutoLUX, RELUX, Ulysse, Calculux, etc.) were developed and have been used for analysing photometrics, building information modelling (BIM), and 3D modelling (Wikipedia, 2020). Despite that LED lighting solutions have become one of the cost-effective products and are energy efficient, several challenges are identified for adopting LED lighting in projects (Yu, 2015; UN Environment, 2017). Table 1 depicts a summary of common reasons and types of these challenges.

The challenges of LED adoption apparent in T&T (Ramrose, 2019) are elaborated as follows:

1) *Lack of Policies and Standards* – At present, no national standards have been published for the use of LED lighting in T&T. There have also been a lack of activities and programmes aimed at encouraging the uses and purchases on energy efficiency labelling of lighting and associated products.
2) *Skepticism towards LED Products* - LED is an emerging technology to many industry practitioners who would face many uncertainties to adopt it. There has been no product performance testing standard, leading to poor quality LED products flooding the market in T&T. Many practitioners might have bad experiences with sub-standard LED products leading to a loss of confidence and trust in them.

Table 1. Challenges in adopting LED Lighting in Projects

Challenges	Descriptions	Reasons
Financial	The size of the initial cost compared to other traditional lighting	• Lack of sustainable financing schemes. • The higher cost of LED creates an initial investment hurdle even though there will be favourable payback periods. • Lack of incentives to promote or use LED lighting.
Awareness and Information	Lack of awareness and exposure to information about the benefits of LED lighting.	• Specifications such as lumens and Correlated Colour Temperature (CCT) are new to customers and are difficult to understand. • Purchasing officers, managers, and maintenance personnel lack knowledge of LED lighting. • There is a poor promotion of LED lighting benefits • The public is not aware of the benefits of the LED versus traditional lighting.
Technical	Infrastructure and resources are lacking to promote LED lighting	• Limited resources to develop and implement regulations. • Cheap low quality lighting is available which disrupts customer's choice in selecting the efficient lighting. • Poor power supply affects the performance and longevity of all lighting.
Market	Market structures and constraints that prevent the investment into LED lighting	• High import costs. • Negative impact on local industries. • Limited availability of low costing LED lighting with high quality. • No agreement within the company to change to LED.
Environmental Risk Perception	Concerns of safety towards the environment	• Lack of recycling companies that takes the LED lighting at the end for proper disposal.
Regulatory and Institutional	Political and legal systems not implemented	• Lacking policies that encourage the adoption of LED lighting. • There is no regulatory, verification, monitoring or enforcement of LED lighting in projects.

Source: Abstracted from UN Environment (2017)

3) *Misconception of High Cost* - Installing LED lighting faces challenges in projects due to the project budget restrictions and austerity measures. Many practitioners are reluctant to install LED outdoor lighting because of the high initial cost which clashes with their budget even though it could reduce their maintenance cost in the future.
4) *Insufficient Knowledge and Awareness of LED Applications* - LED has many benefits other than cost and energy savings such as visual comfort, increased productivity and even chronic diseases prevention. The public puts LED lighting as a technical subject even though lighting includes other criteria such as comfort, productivity, health and well-being. Practitioners are not fully knowledgeable in the technicalities, and are also not aware of the use of any lighting design software and LED lighting solutions.

3. Incorporating Value Engineering into Lighting Projects

The generation of values in a building happens when there are different processes connected, which consists of a number of sub-systems such as heat, air conditioning and lighting. In improving the executions of lighting projects, VE aims to reduce the costs and increase the quality of products being used. Benefits include a reduction in the life cycle cost, improvement in quality, and a reduction of environmental impacts. Figure 1 shows a value-generation network in building design. Davoodi (2016) advocates a 5-step scheme for VE modelling of lighting projects. Individual steps are elaborated as follows:

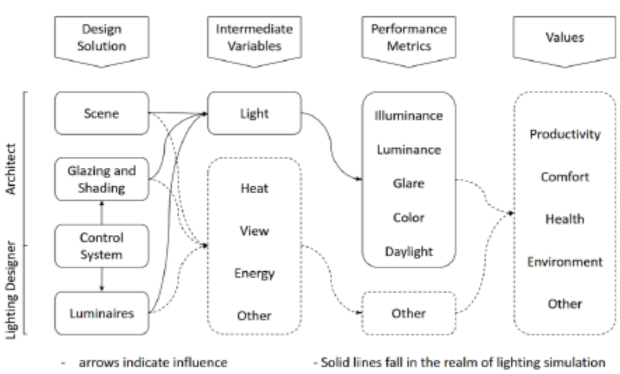

Figure 1. Value-generation network in building design

1) *Problem and System Definition* - Value of lighting should be assessed relative to the needs of the user which makes it quantification complicated. From a quantifiable perspective, values can be classified into four categories: financial, quantifiable, measurable, and observable. Currently, engineers and architects are increasingly using simulation software tools to assess and optimise their design solutions. Lighting simulation tools can be used to calculate the various categories of performance metrics in the value-generation network in building design (Davoodi, 2016). Moreover, it is necessary to define boundaries, depending on what lighting is being studied, and different boundaries can be drawn, for example, for visibility, glare or energy efficiency.
2) *System Analysis* - Lighting can be categorised into 2 subsystems: physical and human. The physical refers to the objective phenomena and the human system concerns the subjective experience of the system user. Although there are a lot of problems that concern the visual effect of lighting, there has been a growing increase on the focus of the non-visual effects of light, such as the circadian effect. Figure 2 shows the systems involved in lighting and how it is analysed.

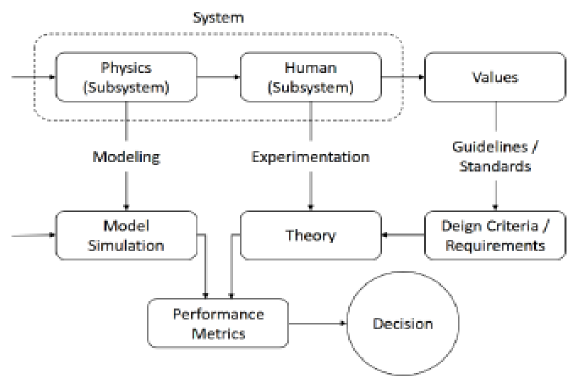

Figure 2. Analysis of systems in Lighting
Source: Abstracted from Davoodi (2016)

3) *Modelling* - Using computer models for obtaining information about a system is advantageous as there is no need to experiment with the original system. There is no threat posed to the system so investigations can be done in broader terms than on the actual system. Hence, results can be generated quickly and alternative paths can be studied and compared before implementation.
4) *Simulation* - One advantage of using computer simulation is lower marginal cost of model construction and simulation. It has an ability to shorten or lengthen the time course of dynamic behaviour (Davoodi, 2016).
5) *Validation* - Validity can be established by comparison of the model results and experimental data. This data can come from literature or from specific experimentation that has been designed to validate the model (Davoodi, 2016).

There are various factors (such as, productivity, comfort, health and environment) that would create value for the customer. There are also intermediate variables (such as light, heat, energy consumption and visual), and other performance indicators (such as luminance, glare and colour of the lighting). In order to evaluate lighting design solution(s) with respect to value, incorporating VE into lighting projects would focus on the physical light and those factors, intermediate and performance variables that would contribute to creating value for the customers/stakeholders. The VE analysis and modelling has been advocated for lighting projects in many studies with recorded success (e.g., Iturbide-Jimenez et al., 2016; Kenall, 2017).

4. Acquiring Empirical Evidence of Lighting in T&T

4.1 Study Methodology

In T&T, traditional lighting is mostly used in preference to LED lighting (Ramrose, 2019). Records showed that the amount of imported fluorescent lamps during the period of January 2011 to August 2016 was some 8.2 million fluorescent bulbs (Batchasingh, 2016). Hence, many industry practitioners have been aware of need to improve the lighting efficiency by adopting efficient LED lighting in projects in both private and public sectors. Many companies would not use LED lighting as they perceived high costs of and/or lacked the knowledge of the benefits of LED lighting.

An attempt was made to acquire empirical data via a 2-step process, using the client database of a leading lighting project company in T&T. The process was composed of interviews and a survey with industry practitioners. It aimed 1) to identify different challenges associated with adopting LED lighting, and 2) to improve the lighting efficiency by adopting the correct usage of LED lighting in projects executed in T&T. The data would be diagnosed and then used to develop a VE-LED adoption approach.

In the initial stage, semi-structured interviews were undertaken to acquire practitioners' opinions on LED lighting adoption and the associated barriers in T&T. These practitioners are of knowledge and experience in LED lighting and holding positions as Procurement managers, Engineers, Quality Managers, Business Development Leads, Contractors and Project Managers in respective clients of the lighting company. The participants are from commercial and industrial companies. They all have given verbal consent to take part in the interview. These companies are located in different parts of Trinidad and the clients were selected based on their buying history of LED lighting within the past 5 years from the lighting company.

A convenience sampling method was chosen. Interviewers were persons who worked for the lighting company where the interviewees were met at their company at their convenience for the interview. Questions were developed to investigate 1) the key components, criteria and/or attributes/parameters of the VE-LED approach, and 2) how to execute/ implement VE-LED initiatives as a sustainable option for lighting project executions in Trinidad and Tobago.

The interview session duration varied for each client between 30 to 40 minutes. The research period was from February 2019 to April 2019. The sessions were not videotaped and only physical written notes were taken. For the second-stage survey, a study instrument was designed with modification of the interview instrument. It was aimed specifically to acquire views from the practitioners of respective client companies on 1) whether the traditional lighting would have met their requirements in projects, 2) how to determine the lighting specifications and quantity, and 3) what challenges would have been faced with the adoption of LED lighting. Amongst the respondents were those who had expressed their willingness to participate but could not make it via the initial step of interviews.

4.2 Results and Analysis

4.2.1 Profile of Representatives

Out of the 100 representatives invited for interviewing, 73 agreed to take part in the study via either face-to-face interview or the survey method. The overall response rate was 73%. Most representatives had busy schedules. Of them, 44 were able to meet face-to-face whereas 29 did the survey. The results depict a combination of the results gathered from the survey and face-to-face.

4.2.2 Satisfaction of the Traditional Lighting Used

It was found that all participating client companies have some type of traditional lighting being used either fluorescent tubes or halogen bulbs or incandescent. Some clients have already bought LED lighting from the lighting company either on a small scale or large scale but not all clients were using LED lighting on their projects (as seen in Figure 3). However, the main factor that affects the selection of traditional lighting over LED lighting is cost. 60% of the clients agreed or strongly agreed that cost was the main factor that affected the selection of LED lighting.

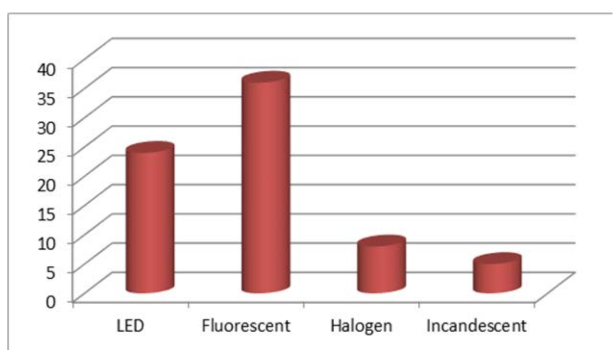

Figure 3. Types of Lighting Products Currently Used

Besides, more than half of the participants said 'no'. Hence, those participants saying 'yes' were the ones that already used LED lighting, and even a few said they were satisfied with the traditional type of fixtures (see Figure 4).

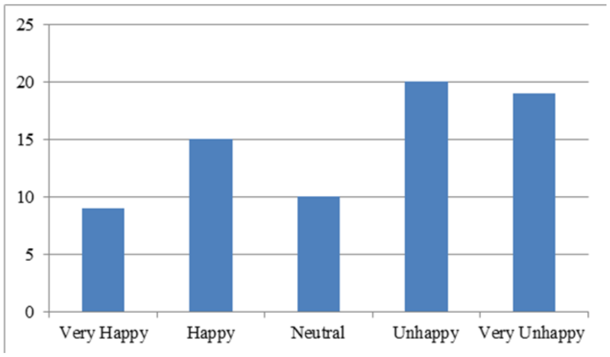

Figure 4. Number of Participants on the Level of Satisfaction of Lighting Products

4.2.3 LED versus Traditional Lighting Used in Projects

Clients were asked about the projects their company has undergone that needed lighting. When asked if they knew how many lighting fixtures a project needed, some participants said 'yes' but could only provide a rough estimate. Some were almost certain as they had their lighting drawing but not 100% sure if it would give the amount of brightness required. The participants indicated that in order to estimate how much lighting their project needed, their method was to ask an expert, hire a firm to do the lighting plans, or just try to follow past projects. Besides, participants shared views on the current needs of LED versus traditional lighting in projects. These include:

1) Cost, as traditional lighting is cheaper.
2) Most familiar with traditional lighting; LED is new to some.
3) Persons are not aware of the dangers of traditional lighting.
4) Persons are not educated on the benefits of LED lighting, and
5) Traditional lighting is more readily available.

4.2.4 Experience with LED lighting and DIALux

All participants claimed that they were familiar with LED lighting. The main benefit they were aware of that LED lights are environmentally-friendly. Most participants did not know any other additional benefits that would be brought to the project. They were also asked if they ever used LED lighting in past projects. Some claimed that their companies have used LED in projects to their satisfaction. Others implemented LED lighting, but did not take into consideration the correct amount of lighting and the suitable wattage to use.

Another question asked was if their respective companies preferred using LED lighting. 67% claimed that their organisations would take the cheapest lights upfront which would usually be non-LED lighting. Many participants have not realised that traditional lighting would fail faster than LED lighting, and more money would have to be spent to replace it. Some said that they were not aware of the benefits of using LED lighting. Once the advantages were explained to the company, this would increase the chance of using LED. Some stated that education and training would help promote the use and benefits of LED lighting in projects.

Some eighty percent (i.e., 59 participants) were not aware of the use of the DIALux programme in planning and design of lighting products (see Figure 5). Many clients and practitioners have requested for a DIALux analysis before they buy and install any lighting. DIALux is a free software developed by DIAL for professional light planning (Dial, 2019; Airfal, 2019). In addition, some were aware of what lux was required for some projects but were not sure of the exact quantities of lighting fixtures. A total of 24 participants (i.e., 20 percent) had experience with the DIALux programme that could work out the number, style and wattage of lighting needed. It would be helpful to show participants the exact number of fixtures to buy, and the costs and benefits before any decision to be made on the purchase of lighting fixtures.

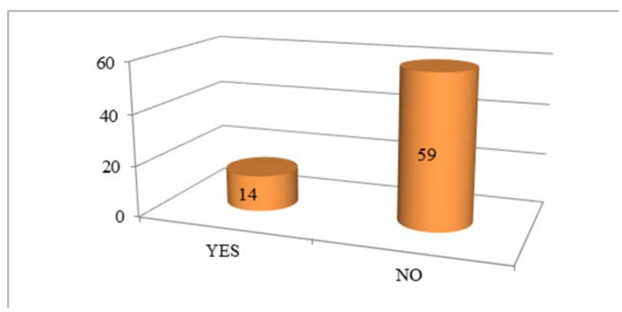

Figure 5. Number of Participants Used DIALux

Some participants saw the need, but others did not see it necessary. Those who said 'yes', their companies are involved in a green initiative (i.e., to implement LED lighting) as they knew it would be environmentally-friendly. These participants were also concerned about what T&T should do to preserve the environment. Moreover, these participants argued that there must be some sort of standards or regulations for selling LED lighting. According to the clients and practitioners, this would be helpful to ensure a high standard of quality lighting on the market which would make a major impact and improvement on the lighting efficiency in projects.

4.3 Discussion of Findings

Compared to traditional lighting, LED lighting has superior qualities in various ways such as energy efficiency, long lifespans, durability, and being environmentally friendly. However, LED lighting was not the main type of lighting used in T&T. The present status of the application of LED lighting is that either it is not being used at all, or if it is being used then the wrong application would have been installed. This would be attributable to a lack of proper tools and methods that should be used before the actual purchasing of LED lighting for a project. Some client companies also lack the knowledge of LED lighting and long-term benefits of using LED products.

As evidenced from the empirical findings, 60% of the clients and practitioners agreed or strongly agreed that the cost prevented them from using LED lighting. More than half of the respondents said they were unhappy with the traditional lighting. There have been needs to eliminate the cost barriers and to educate the public on the potential use of LED lighting. One initiative was to develop some sort of policies and standards that could ensure good practices of quality lighting in projects across the country.

Moreover, the use of the lighting design software was not known to the majority of participants. Many participants suggested that lighting design software (like DIALux, among others) should be introduced and be a crucial step in the planning phase of a project. Based on the DIALux results, benchmarking and cost-benefit analyses would be done to compare the costs and benefits of the LED lighting solution as compared to that of traditional lighting.

5. A Proposed VE-LED Adoption Approach

There have been many obvious challenges and barriers faced by many clients, companies and practitioners. This necessitates the initiative to explore an energy efficient LED lighting as a sustainable option in T&T. A VE framework was adopted, with an aim to reduce cost, improve quality, increase reliability and availability, enhance customer satisfaction, improve organisational performance, identify further issues and develop recommended solutions. With incorporation of VE concepts and principles, a 2-phase VE-LED adoption approach was developed to facilitate lighting project executions.

5.1 Phase 1: Lighting Solutions Analysis with DIALux Software

For designing and proposing any project solutions that need lighting, a thorough analysis and diagnosis of lighting requirements and fixtures are to be performed with the aid of DIALux and/or other lighting design software. The DIALux analysis could rectify issues in determining the number and style of lighting, the installation position, and the most suitable lux range of the lighting. The system could also be useful to do simulations of lighting need (Ramrose, 2019).

Phase 1 follows the VE methodology to achieve the best results for the clients/practitioners in the phase of the product design and development (see Figure 6). There are procedural elements to be executed for DIALux analysis (Ramrose and Pun, 2020) as follows:

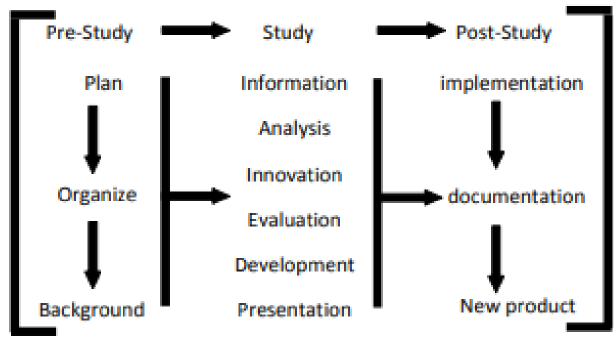

Figure 6. Lighting (Product) Design and Development Process
Source: Abstracted from Iturbide-Jimenez et al. (2016)

1) *Information Step*: Information is to be gathered from the project practitioners and/or clients. This includes, for instance, specifications, standards, and demands/needs (e.g., the layout, installation and maintenance conditions);
2) *Analysis Step*: Information and requirements of the project are to be analysed and the functions to be diagnosed. This would address the required lux with conditions (like quantities, colour and furnishing), the luminaires, lighting system and sources, and the controls needed to increase comfort and improve energy usage.
3) *Creative Step*: Ideas are to be generated in different ways to accomplish the required function needed from the light, which is the lux or how many fixtures are needed, and the style or wattage;
4) *Evaluation Step*: Synthesise the ideas and concepts and select the most suitable lighting design with the DIALux lighting system. Financial evaluation is to be made by calculating the entire life cycle cost from the investment to operation to maintenance and a Function/Cost Analysis is to be done to ascertain the purpose(s) and determine value versus cost of the lighting solution.
5) *Development Step*: Select and prepare the best alternative for improving value, where the correct number of fixtures is chosen, the position of each light is determined and the most appropriate style and wattage is selected to achieve the needed lux value; and
6) *Presentation Step*: Document the results of lighting analysis, solutions and recommendations and present them to stakeholders (e.g., project

practitioners and clients). This entails documentation of the selected lighting solution prepared to include installation drawing, control and assembly instructions as well as the list of the amount of lighting needed to achieve the objective(s).

5.2 Phase 2: Instituting Integrated VE Policy into Lighting Project Executions

Phase 2 focuses on developing standards and policies that should be implemented, as well as the testing criteria which would ensure quality LED lighting products be offered on the market. Its core components constitute developing standards, policies, processes, and getting and managing resources (Ramrose, 2019). Figure 7 shows these five (5) components that are listed and elaborated, as follows:

1) Standards and regulations,
2) Supporting policies,
3) Financing schemes,
4) Monitoring, verification and enforcement, and
5) Environmental health and safety.

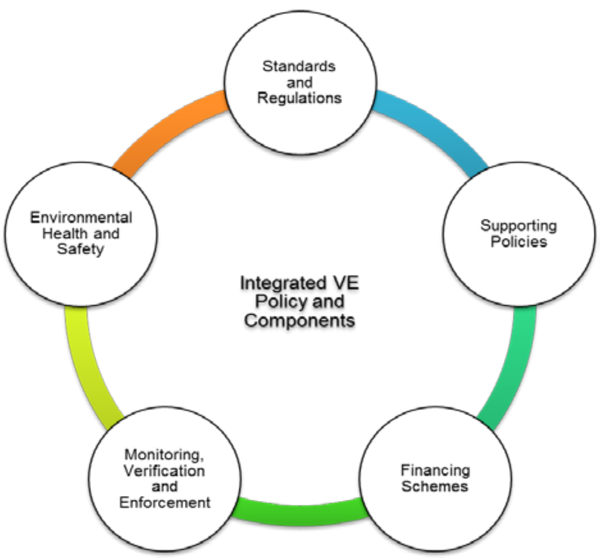

Figure 7. Components of Integrated VE Policy
Source: Abstracted from Ramrose (2019)

5.2.1 Standard and Regulations

Standards and regulations are policy measurements that a product must meet. Through effective policies and enforcement, they would ensure quality lighting products are being implemented into the market in a controlled way. The Government should look into what is deemed high quality lighting products and set a standard which includes the energy requirement, lifetime, power and lighting quality. Figure 8 depicts a set of the lighting regulatory requirements.

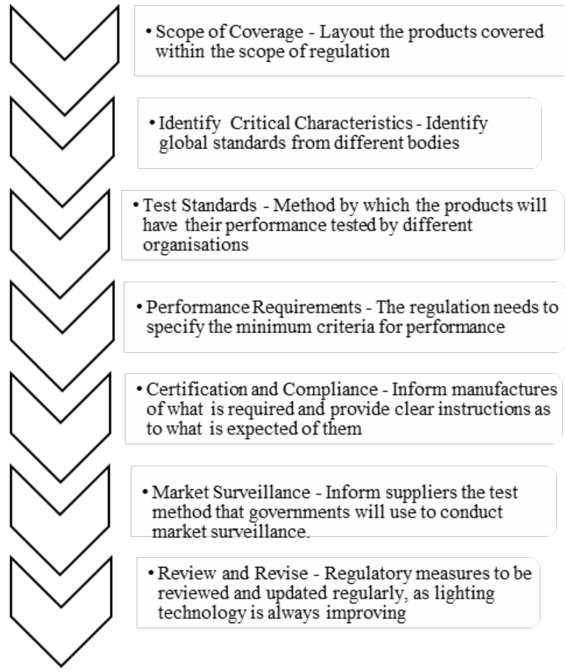

Figure 8. Lighting Regulatory Requirements

Moreover, a sequence of processes for establishing the requirements are:

1) *Establish a legal framework* - Review Legislation and develop a framework to have a legal basis and political commitment for mandatory standards and labelling.
2) *Appoint an agency* - Develop standards and labelling plan and assign an agency responsible for implementing the plan.
3) *Create a stakeholder group* - Identify the relevant persons who are interested and invite them to take part in the process.
4) *Data collection* - Establish what data are needed and develop a plan for data collection.
5) *Economic analysis* - Use cost analysis to determine the resources needed.
6) *Testing* - Sync testing with international protocols.
7) *Set levels* - Determine the technical feasibility and economically regulatory level, invite stakeholders to comment and refine, get political endorsement, publish regulatory notice, and specify a date it would be in effect, and
8) *Review and update* - Periodically review and update the levels to ensure it is updated and relevant.

5.2.2 Supporting Policies

These are concerned with product labelling, communication, and education. Product labelling is one of the cost-effective energy efficient measures. There are different types of labels, for instance:

1) *Informative labels* – To provide data on the lighting fixture and its performance,
2) *Endorsement labels* – To meet or surpass specific criteria and would be recognised as a premium, and
3) *Comparative labelling* – To facilitate the comparison of products and show their ranking.

The education and communication focus on providing stakeholders with information and enabling them to be aware of the benefits. Public awareness and education campaigns would help LED lighting be understood and faster adopted as changes in end user behaviour would help them. This would provide clients/practitioners with the knowledge about efficient lighting and the benefits would help promote a general acceptance and create a positive public environment for energy efficiency. The main objective is to bring across the message that should be simple and relevant to the stakeholders (including businesses, end-users, media, government and institutions). Table 2 shows the target groups of stakeholders and the topics for discussion that would help with their involvement in promoting energy efficiency.

5.2.3 Financing Schemes

This entails the financing of energy efficient light and overcoming the cost barrier of adopting LED lighting. There are two (2) main sources of financing, including:

1) *Government Financing* - Source of financing would be created to help support energy efficient educational programmes, and
2) *Private-sector Financing* – This offers an incentive to invest in energy efficient lighting.

Both public and private sectors would be assisted through financial schemes and repayment mechanisms. For instance, a loan could be made to individual utility customers for enabling the purchase of energy efficient lighting and solutions (such as energy audits, system designs and lighting designs). The public-private-partnership (PPP) mechanism would allow the government to fund and operate services through contracts with private companies. This would offer an opportunity to take on large scale projects with private sector expertise and financing while still being in charge of key decisions.

5.2.4 Monitoring, Verification and Enforcement

The legal framework for an energy efficient enforcement is dependent on the national governance structure and the monitoring, verification and enforcement process. Figure 9 depicts a typical model of the process. This framework must have detailed responsibilities to ensure smooth transition. It could give the authority for an agency to issue fines and block the sale of products that are not legitimate from entering the market. It is anticipated that benefits would be attainable for the three (3) main categories of stakeholders, as follows:

1) *Consumers* – To have the products that are legitimate,
2) *Businesses* – To provide a level playing field which encourages investment and technological innovation, and
3) *Policy Makers* – To help achieve economic and environmental objectives.

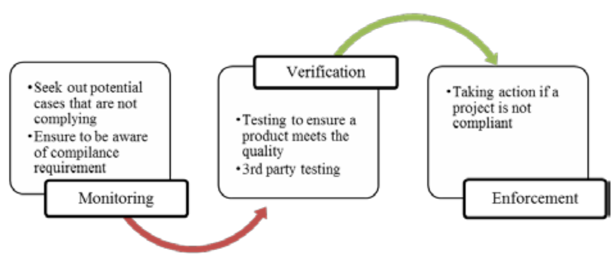

Figure 9. A Process Model of Monitoring, Verification and Enforcement

Table 2. Target Audiences, Topics and Areas of Involvement

Target Audiences	Topics	Areas of Involvement
Institutions/ Government	• Ensuring efficient standards and product quality	• Provide support to any regulatory and legislative initiative • Support policy implementation • Evaluate and monitor processes • Review which tariff should be used to clear LEDs and enforce its consistent use.
Business	• Promoting LED • Corporate responsibility • Reducing electrical consumption	• Key players in promoting sustainable policies • Provide best products to customers
End Users	• Acquire information to make informed decisions about the savings when using LED lighting • Promote LED lighting	• Acceptance and utilisation of LED based on first-hand experience and affordability • Provide information about buying habits • Increase the consumption of LED lighting
Media	• Increase awareness and develop knowledge about LED lighting among customers and businesses	• Share information on LED to consumers. • Assist governments in implementing policies • Publish formal and informal educational and training materials

The government must monitor, verify and enforce regulations and standards to ensure the policies and programmes for the adoption of LED lighting. This contains having products registered, testing products and verifying/enforcement of standards and policies, as follows:

1) *Product Registration* - Suppliers would register products that are compliant with the regulatory authority. Test results are submitted on the product which are used to certify that the product performance meets regulations before placing on the market. The registration is designed to meet the needs of various stakeholders.
2) *Testing* - LED lighting must be tested and measured in order to certify its compliance. This would ensure good quality products are being used in projects and encourage persons to adopt LED lighting. Their uncertainty would be decreased as providing proven results of the LED lighting would eliminate any misconceptions.
3) *Regulatory Enforcement* - There are different levels of regulatory enforcement, and actions must be taken for non-compliance. These penalties and powers of enforcement authority should be set out in law.

5.2.5 Environmental Health and Safety

This initiative is concerned with issues of environmental health and safety (EHS). It focuses on the life cycle of the lighting from production to its usage to the end of its life. The material could be recycled, recovered or reused to ensure the full value of the light is used. Raising consumer awareness includes, for instance, 1) no mercury in lighting products that would minimise health and safety risks, 2) no glare and flicker which would not affect users' vision, and 3) no effects that would disrupt their circadian rhythms. This initiative allows proper collection of LED lighting that needs to be disposed of in an environmentally safe way. Hence, by assuring good quality lights and verifying the lighting compliance, the customers' buying decision would gravitate more towards the selection of LED.

Moreover, several EHS parameters are determined to facilitate a smooth LED adoption. These are listed and elaborated as follows:

1) *A Policy and Legal Framework* - There must be a legal framework for waste in terms of electronics, hazardous substance and mercury levels to encourage the use of LED lighting. Once these limits are strictly upheld the use of traditional lighting, in particular, the mercury contained ones would be significantly reduced.
2) *Collection Schemes* – These allow for proper collection of used LED lighting that needs to be disposed of properly as it contains electronic waste. Specific areas are to be assigned for the collection of these items.
3) *Awareness Activities* - A continuous educational campaign to encourage the use of LED and its proper disposal is to be done on a regular basis. The process on how to do it should be explained to the public on all forums such as social media, public campaigns, flyers, brochures, newspaper articles, and TV and radio stations.
4) *Recycling Programmes* - Regulators would explore and adopt methods that are in line with national procedures to encourage the collection and recycling of lighting. Using LED lighting would make it easy to recycle as mercury would no longer be a factor of concern. The recycling programmes would be funded in various ways which are dependent on the nation's condition and resources.
5) *Financing Environmentally-Sustainable Lighting Solutions* - To ensure that used LED lighting is sustainably collected and recycled, the regulations should account for the economy to minimise the cost to user. One method would be that customers get some sort of refund when they return their used LED to encourage the recycling of the products (UN Environment, 2017).

6. Evaluation of the Approach

6.1 Conduct of Post-Evaluation Survey

A post-evaluation survey was undertaken with the stakeholders who had participated in the previous survey and personal interviews. The post evaluation focused on acquiring their views and comments on applicability of the 2-phase VE-LED adoption approach to lighting project executions in T&T.

6.2 Response Rate and Views from Respondents

Out of the 73 practitioners who did the initial stage of face-to-face interviews and survey, 51 persons responded, yielding a response rate of 69.9%. It was found that over 60% (i.e., 31 respondents) agreed that the approach could help remove barriers and bring benefits of LED lighting solutions to users in T&T. The main findings and their implications are summarised as below:

1) *On Standards and Regulations* - Most respondents agreed or strongly agreed that implementing standards and regulations would assist in assuring proper installation of lighting solutions. Most respondents considered product testing and registration as very beneficial and would reduce the availability of poor-quality LED lighting products on the market.
2) *On Supporting Policies* - Respondents agreed on the importance of product labelling with information, endorsements and comparisons to assist in encouraging the adoption of LED lighting, while some disagreed that practitioners in the country would break the law and companies would lie on the labels.

3) *On Public Awareness and Campaigns* - Most respondents agreed with the benefits of the VE-LED initiative and regarded this as a sound idea to promote the use of LED lighting solutions. If the public is exposed to the dangers of traditional lighting, they would gravitate to buying LED lighting. However, respondents thought that it would not make a difference to persons who refuse to change and would stick to traditional lighting.
4) *On LED Lighting Enforcement* - When it concerns matters of health and saving money and the environment, all respondents agreed on this. These factors would be major players driving the use of LED lighting solutions in the country. Benchmarking is to be made to ensure comparison with traditional lighting practices. The majority agreed upon educating the public as the main strategy to encourage and enforce the use of LED lighting.
5) *On the Use of DIALux* – Respondents were made aware that the DIALux software would accurately determine the necessary specifications and quantities of the lighting in projects. The DIALux would show how it could save on cost with the concerns on purchasing accurate lighting fixtures. Most respondents indicated that they would use the tool to aid with making decisions on purchasing or installing lighting solutions. They shared that their company would increase their LED adoption in projects with the use of DIALux.

7. Conclusion

This paper aimed to investigate the current issues and challenges faced with adopting LED lighting in projects and to provide viable value-based solutions in T&T. As evidenced from the empirical findings, 60% of the clients and practitioners agreed or strongly agreed that the cost prevented them from using LED lighting. Many participants suggested that lighting design software (like, DIALux, among others) should be introduced and be a crucial step in the planning phase of a project.

Therefore, a proposed 2-phase VE-LED adoption approach was developed. Phase 1 is concerned with lighting solutions analysis with DIALux in the planning phase of a project. It follows a VE methodology that guides the generation of a viable value-based lighting solution. Phase 2 is an integrated VE policy for transitioning efficient lighting solutions in projects. It consists of 5 major components that include development of standards and regulations, supporting policies, finance schemes, and then the monitoring, verification and enforcement of the practices with EHS initiatives.

Evaluations of the proposed approach were done via the post-evaluation survey with stakeholders. It was ascertained from the practitioners' views of the importance and benefits of the DIALux system and the need for standards, regulations and policies. The majority of respondents were in agreement with the VE-LED adoption approach in overcoming barriers and challenges. Planned adoption of the proposed VE-LED approach would help achieve the optimum balance between quality, function, performance, cost and safety. This would also balance results in the maximum value for any given project without affecting the quality of the LED light, but rather focused on reducing expenses, improving quality and protecting the environment.

For demonstrating the generation and applications of LED lighting solutions, lighting projects of varying nature could be selected and then diagnosed with the DIALux system. Despite that it is anticipated that energy efficient LED lighting would provide a sustainable option for lighting project executions, the components and procedural elements in the two phases of the VE-LED approach would be verified subject to further empirical and case evidence. Future work should include testing of the approach on a wider scale using lighting projects in the public and private sectors separately and collectively in T&T.

This paper demonstrates what society can implement to save on money in lighting projects in both the private and public sectors. It indicates the need for educating the public so that they can implement the correct lighting required to improve their quality of life, as accurate application creates value where it increases comfort for the user while decreasing cost.

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Cybersecurity Threat Analysis for an Energy Rich, Small Island Developing State

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Abstract: *With the ever-increasing use of the Internet by people of all walks of life and the storage of their personal and financial information, attacks on web sites have been rapidly growing. Unfortunately, many do not take sufficient precautions and some even significantly underestimate the potential threats and the associated costs of an intruder. In particular, Small Island States (SIDs) lack the resources to monitor and repel attacks, even those rich in energy and natural resources. We determine the level of threats and the source of such threats for educational and industrial web sites for one such country. We deployed a network honeypot with File Transfer Protocol (FTP), Secure Shell (SSH), Hypertext Transfer Protocol (HTTP) and Industrial Control System (ICS) on a fake educational institution server. Besides, a network honeypot with server message block (SMB), FTP, HTTP, and ICS was set up in a fake oil company server. The ICS used was above ground storage tanks (AST) and a programmable logic controller (PLC), mostly utilised in the Oil and Gas industry. We recorded honeypot events and determined locations of the potential intruders using source IP addresses. We found that the oil company site's SMB server had the most honeypot events and the highest repeat attacker rate. We also determined the countries that hosted the most attackers. This information can be used to better detect potential attacks and defend against them.*

Keywords: *Threat Analysis, Cybersecurity, Honeypot, OWASP, Dionaea, Conpot*

1. Introduction

The recent growth in worldwide internet users, means a similar growth in web applications and services globally. Developing countries also share in this rapid growth rate as there are people becoming connected to the internet, due to increased availability and lower costs for a connection. In the case of South America, the average internet accessibility rate per person is tied with a positive trend in economic growth measured through gross domestic products (GDP) (Ochoa-Jimenez et al., 2018).

This general trend in developing countries would also indicate that proper cybersecurity measures are put in place, but this is not always the case. Developed countries have had the time and capability to fully develop Critical Information Infrastructure Protection (CIIP) Systems, unlike developing countries. In turn, these countries are becoming a haven for cyberattacks due to the weaker cybersecurity measures in place (Ellefsen and Solms, 2010). Relevant persons in these countries are sometimes unaware of the attacks due to insufficient groundwork conducted on target identification or the general inability to detect cyberattacks.

Significant research has been reported on the design, use and results of Honeypots. There are specialised honeypots for IoT (Internet of Things) devices (Pa et al., 2016) and even ones for detecting ransomware (Moore, 2016). An exhaustive survey of the software available for deploying a honeypot can be found in Nawrocki et al (2016) and the number of options indicate the interest in using such devices. Work on preventing honeypot detection and compromise is contained in Tsikerdekis et al. (2018). Design of honeypots is also an area of interest and patents are also being led such as the one led on a Cognitive Honeypot (Saikawa and Klyuev, 2019).

To properly design and create customised dynamic network security systems, groundwork on attack characteristics and patterns must be conducted. A network honeypot can be used to gather such information. A network honeypot is defined as a security resource whose value lies in being probed, attacked or compromised (Spitzner, 2003). Honeypot systems are traditionally deployed in controlled environments that lure attackers, which in turn, generate valuable information about the network (Zhang et al, 2002).

We present a framework that was used to capture intruder information using three honeypots. We then analyse this data to determine the extent and frequency of attempts, and determine the nature of the attackers. This work will form the basis for policies on protecting important sites such as those deployed by the Government and those Companies that are attractive targets.

Honeypots are classified on the environment that they are implemented within as well as the level of interaction associated with the honeypot. On the basis of implementation a honeypot can either be a Research or Production honeypot, while on the basis of its environment, a honeypot can be a low, medium or high interaction honeypot (Nagpal et al, 2015).

Low Interaction honeypots (LIHs) is defined as a system designed to attract attackers by emulating an operating system or networking features on a host system. The attacker is only allowed access to the services and files as defined by the honeypot software, meaning that there will be no direct interaction with the attacker and the host system (McGrew, 2006). These types of honeypots offer easy installation and maintenance primarily due to the low risk associated with the "sandbox" environment provided to the attacker, however present the least amount of information on the attack.

Medium Interaction honeypots (MIHs) allows for more data collection than LIHs. MIHs does not simulate the network protocol stack by itself, but rather binds to sockets and utilises the Operating System to do this (Fan et al., 2018). MIHs allows for a better illusion of a computing system through the use of the Operating System meaning there will be more potential information that can be logged from the attackers' actions (Mokube and Adams, 2007). MIHs typically have higher risk associated due to operating system being used as part of the honeypot.

High Interaction honeypots (HIHs) is a normal functioning system where there is no restriction to the attacker. This allows for the most amount of data to be extracted from different types of attacks and is typically used to find the full intentions of attackers. HIHs provide the most amount of risk, as they allow the attacker the most amount of control.

Production honeypots are typically utilised by organisations and is part of a protection system for that organisation. They are integrated into a larger system that eliminates threats on a given network (Spitzner, 2003). Production honeypots involve a higher level of risk due to its deployment environment. Research honeypots are designed with the intention to track and monitor behaviour with no scheduled secondary action. They are used purely as a data collection tool to create information on new defensive techniques (Campbell et al., 2015).

A Virtual Private Network (VPN) is an encrypted connection over the internet that can mask the true source of an experienced attacker. However, location information of script-based attackers, victim machines that perpetuate automated attacks and the VPN servers used for attacks can still be useful.

2. Research Objective

The susceptibility of developing countries to cyberattacks compared to developed nations can be attributed to many factors, namely, commonness of software piracy, inadequate awareness of cybersecurity practices and a lack of cybersecurity strategies, laws and regulatory frameworks (Elkhannoubi and Belaissaoui, 2016). The resulting weakness of infrastructure can be improved upon efficiently by evaluating the attacks being currently made to high priority targets within the SID, including critical infrastructure, Governmental sites and educational sites. Information like common origins of attacks and the most frequently targeted server types and systems could help shape the policies and regulations that strengthen a SID's resilience to cyberattacks. For example, if an FTP server is most frequently targeted, an organisation could use the honeypot data to prepare IP blacklists, aid in risk assessments and prioritisation of security plans as well as calibrate firewalls or intrusion detection systems (IDS).

Honeypots are deployed on a network and used to lure attackers and generate data for these attackers. Moreover, one of the main reasons for deploying a honeypot is to get a better insight into attack methodologies used and therefore create more robust security systems (Rase and Deshmukh, 2015). Therefore, this paper is an attempt to provide such an assessment of educational sites and industrial sites by using honeypots. The Cybersecurity Threat Analysis for a SID purpose is to determine the attack surface on Trinidad and Tobago, an energy rich small island developing state. In the future we also plan to assess attacks on sites within the government domain.

3. Deployment of a Honeypot for an Educational Site

In the network setup utilised in this research, an isolated server was used and two real domain names were assigned for use with this server. The domains were real sub-domains of the domains used for educational institutions and commercial organisations of the country being evaluated. Low interaction level research honeypots were used for data collection as the intention of this paper that is to evaluate the types of protocols being targeted.

For the educational site, the OWASP Python Honeypot (OHP) was used to create the different application servers with varying levels of access security (OWASP, 2021). This honeypot utilises

Linux-Containers (LXC) to run multiple isolated Linux systems on a single host system and an overarching MongoDB database on the host system for data storage. This Honeypot deploys four different types of modules with varying security access on each module, resulting in 7 total access points. Traditional servers such as FTP, SSH and HTTP were used with both weak and strong passwords. Additionally, an Industrial Control System (ICS) for a Veeder-Root Guardian Above-ground Storage Tank (AST) was also deployed. Although such a server would normally not use an educational institution domain name we believed that it would still attract attackers.

The honeypot logs both honeypot related events as well as network related events. The honeypot related events are any events recorded on the various types of servers deployed, while the network related events is general network trac to the web server. The fields collected for honeypot events are shown in Listing 1, with redacted IP and country fields. The IP address associated with the event and their ISO 3166-1 A2 two letter country code are logged.

Listing 1 Fields for OWASP Honeypot Events

"_id":{"$oid":"5d932e04b0aa3067c9fa1f34"},
"machine_name":"127.0.1.1",
"ip":"xxx.xxx.xxx.xxx",
"country":"XX",
"date":"2019-10-01 10:44:20",
"module_name":"ftp/strong_password",
"port":21

Figure 1 depicts the collection of different entry points created by the Honeypot and its network architecture. The data used for this honeypot was collected over a 10-day period.

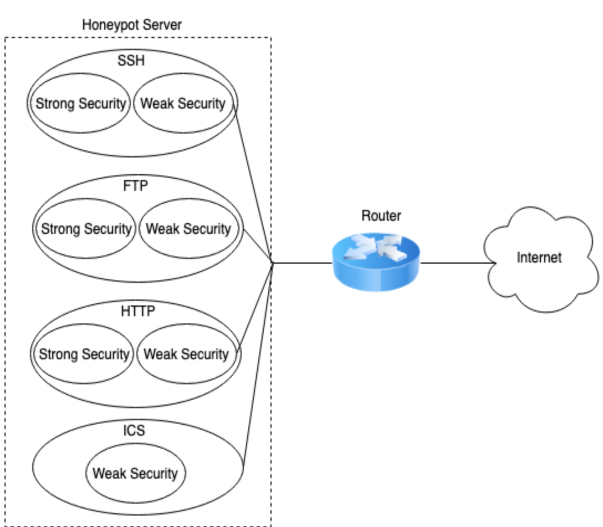

Figure 1 Network Architecture of OWASP Honeypot

Table 1 provides the number of events, unique IP addresses and Repeat Attacker Rates for the educational site sorted by server type and security level over the data collection period. A honeypot event is defined as an attempt to access a certain honeypot server. The repeat attacker rate is the average number of events per unique IP address for each server. This number indicates, on average, how many attempts were made from a particular IP address for a specific server. This repetition rate may indicate the level of automation of the attacks using scripts.

Table 1. OWASP Honeypot Results on Educational site

	Security Level	Events	Unique IPs	Repeat Attacker Rate
FTP	Weak	5912	846	6.99
	Strong	32368	1954	16.56
SSH	Weak	279	29	9.62
	Strong	448	41	10.93
HTTP	Weak	1656	43	11.19
	Strong	262	12	6.09
ICS	Weak	151	8	18.88

Domain Name Used: http: ths.edu.tt

4. Deployment of Honeypots for Industrial Sites

The industrial site represented a fake oil and gas company belonging to the country being evaluated. The Dionaea (Carnivore, 2021) and Conpot honeypots (Conpot, 2021) were used. The former deployed HTTP, FTP and SMB servers and logged their corresponding connection events to a SQLite database. Dionaea is a LIH used for capturing malware aimed at exploiting the vulnerabilities in its exposed services. Once an attacker successfully deploys a payload, the binary is downloaded, and Dionaea computes the file hash to avoid duplicates. We used MetaDefender and VirusTotal, online services that provide file scanning using various anti-virus engines, to scan and classify the obtained binaries. In addition to capturing malware, all connection events are logged including source IP and protocol. For each connection, the p0f (Zalewsk, 2021) passive TCP/IP stack fingerprinting tool is used to attempt to identify the system running on the machine that sent the network trac. For FTP events, any login attempts are also logged.

Since Dionaea does not support any ICS protocols and the purpose of the industrial site was to analyse threats in the Oil and Gas Industry, two instances of Conpot were also deployed. Conpot is another LIH honeypot but specifically provides ICS protocols emulating configurable industry systems. One instance once again, represented a Guardian AST system and the other was a Siemens S7-300 Programmable Logic Controller (PLC). Listing 2 details the fields collected per event by Conpot, with the addition of a country field determined using the source IP. Conpot events are any network events recorded on the server, for example, TCP connections and system specific events like querying the AST inventory data.

Listing 2 Fields for Conpot Events

```
"id":{"9b7296fa-0197-4d21-bd16-
   3cd5bceced08"},
"src_ip":"xxx.xxx.xxx.xxx",
"src_port":44796,
"data_type":"guardian_ast",
"country":"XX",
"request":null,
"response":null,
"timestamp":"2020-04-30
   05:21:29.092130",
"event_type":"NEW_CONNECTION"
```

The data used from Conpot and Dionaea were collected over 10 and 20 days, respectively. Table 2 presents the results obtained from Dionaea and Conpot for the industrial site, containing the number of events, unique IP addresses and repeat attacker rates.

Table 2. Dionaea and Conpot Results on Industrial site

	Service	Events	Unique IPs	Repeat Attacker Rate
Dionaea	FTP	2976	115	25.88
	HTTP	1850	728	2.54
	SMB	2117954	12007	176.39
Conpot	Guardian AST	27	11	2.45
	S7-S300 IEC104	75	25	3.0

Domain Name Used: http: oil.com.tt

4. Discussion

4.1 Educational Site

The FTP servers had the most attention on this site with 38,280 total events and the second highest repeat attacker rate, fourth across both sites. Figure 2 shows the rate of events for the site against the hours in the day, where most attacks occurred during the period of 8:00AM to 4:00PM UTC.

Figure 3 shows the top 5 country names and their percentage of contribution to the events of OHP. China has the highest number of events with 38.06% and United States of America was recorded as second with 8.55%. There was a large difference between the first and second countries and from there onward, the remainder of countries gently trend downwards with small intervals between them.

Similarly, Table 3 shows the percentage-wise top contributing countries, to events over each of the services for the educational site. It is seen that there are a few countries that constantly fell in the top contributing countries of the four services: United States with four occurrences, followed by China, Netherlands, Iceland and Seychelles all with two occurrences.

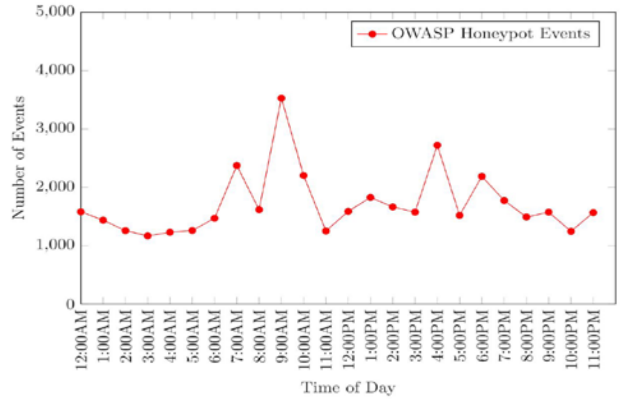

Figure 2 Educational Site OHP Attack rate dependence on time of day

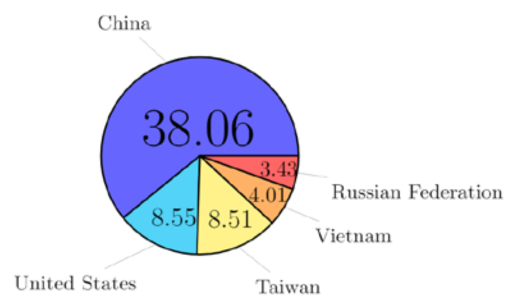

Figure 3. Top 5 Percentages of Total Educational Site OHP Events by Country

Table 3. Percentage of Educational Site Honeypot events by Service and Country

Server Type	Country	Percentage
FTP	China	40.54
	Taiwan	8.96
	United States	8.33
	Vietnam	4.01
	Russia	3.51
HTTP	Iceland	33.52
	United States	8.76
	Netherlands	8.6
	United Kingdom	7.46
	Brazil	6.1
SSH	Iceland	28.61
	United States	21.32
	Seychelles	16.92
	China	5.5
	Ireland	4.68
ICS (AST)	Netherlands	35.76
	Seychelles	35.76
	Spain	13.91
	Germany	5.96
	United States	2.65

4.2 Industrial Site

The results in Table 2 indicate that the industrial site SMB server under Dionaea is targeted the most across both sites with the highest number of events (2,117,954) and the highest repeat attacker rate (176.39), both by a significantly large margin. This repeat rate indicates the use of automated scripts or attacks being perpetuated by victim machines. Table 4 shows that 81.68% of the successful payload downloads were variants of WannaCry ransomware, further supporting the notion that the SMB attacks came from victim machines.

Table 4. Number of Malware Binaries Caught by Dionaea

Malware Family	Events
Wanna Cry	10017 (81.68%)
Small	2231 (18.19%)
Blackshades	11 (0.09%)
Trojan Downloader	5 (0.04%)

Tables 4 and 5 list the results of the scanned malware binaries and the most commonly used credentials of the 2,781 FTP login attempts. The FTP server was the second most targeted and Table 5 shows the most common attempted login credentials. The importance of strong passwords is one of the more well-established and commonly known security practices, but this information serves as a reinforcing example as to why this is the case.

Table 5. Most Commonly used Login Credentials on Industrial Site FTP

	Credential		Events
Username	anonymous		208
	test		184
	admin		184
	ftp		184
	user123		183
Password	anonymous		65
	admin		49
	test		48
	123		48
	admin123		48
Username/ Password Pair	anonymous	anonymous	23
	admin	admin	7
	anonymous	anonymous@	7
	test	test	6
	admin	admin123	6

In addition to the Industrial Control System (ICS) protocols deployed using Conpot on the industrial site, a similar ICS was set up on the previously mentioned OWASP Honeypot (OHP). The OHP ICS had the third highest repeat rate overall at 18.88. As it is an above ground storage tank, mainly used in the Oil and Gas Industry, this shows that attackers have a persistent interest in these devices or that specific automated scripts are being used. The Conpot services, a S7-S300 PLC and an AST, had the least events and were among the lowest repeat rates.

Considering the difference in results compared to the OHP ICS over the same time period and the similarity between the emulated ASTs, this could suggest that the Conpot services used have a higher degree of detectability as a honeypot, deterring attackers. Among those Conpot events, 3 from China and Netherlands queried the AST inventory data, while the rest were generally probing connections.

The rate of Dionaea and Conpot events on the industrial site are plotted against the hours of the day in Figures 4 and 5, respectively. This shows that most of the ICS attacks fall within the time frame of 8:00 AM to 4:00 PM UTC, similar to the educational site results whereas SMB, FTP and HTTP attacks were mostly during 8:00PM to 1:00 AM UTC.

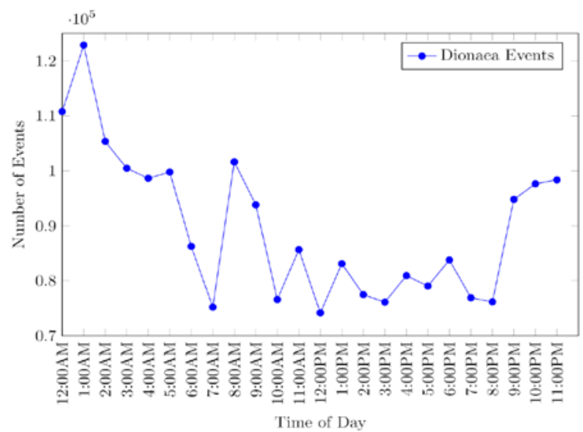

Figure 4. Industrial Site Dionaea Attack rate dependence on time of day

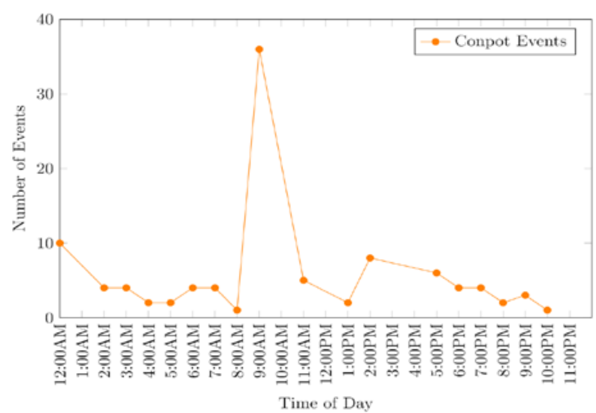

Figure 5. Industrial Site Conpot Attack rate dependence on time of day

Figure 6 shows the top 5 contributing countries to the Dionaea events and the Conpot ICS events. Among the ICS events, again China and United States were the top contributors with 51.96% and 35.29% respectively. However, neither country was present in the top 5 contributors to Dionaea events on the industrial site, where Vietnam at 10.87% closely followed by Russia at 10.16% had the highest number of events. The difference between the top 2 countries as well as the top 2 and second 3 countries were much smaller in Dionaea events when compared to Conpot and the previously discussed OHP. For both honeypots, the remainder of countries gently trend downwards with small intervals between them.

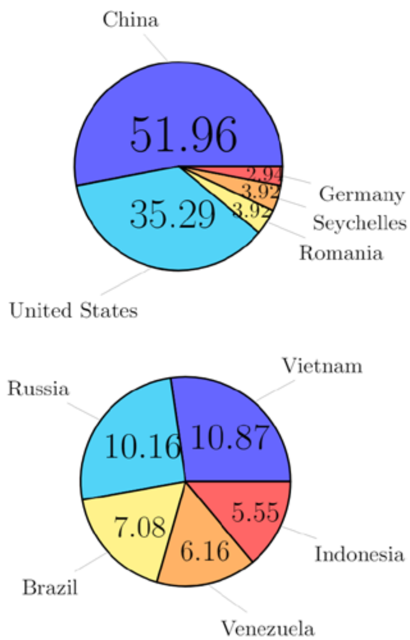

Figure 6. Top 5 Industrial Site ICS Events by Country: Dionaea (top) and Conpot (bottom)

The top countries per server type within the industrial site are shown in Table 6. China was amongst the top contributors for 3 out of 4 server types, followed by United States and Russia with 2 appearances. Seychelles was also a frequent occurrence, appearing in both the Conpot and OHP ICS services. Four out of the top 5 contributors to the industrial site's Dionaea attacks, Vietnam, Russia, Brazil and Indonesia, were also observed in the top 5 of the Japan based study (Saikawa, and Klyuev, 2019), suggesting some independence from victim region among these attacks.

4.3 Comparison of Sites

The similarities between the Conpot top contributors and that of the educational site's OHP, particularly the prevalence of contributions from China and United States, are not seen in Dionaea on the industrial site where those countries are ranked 17th and 18th. Furthermore, Table 7 illustrates the top 20 contributors grouped by region for each site and their server types. Both sites predominantly source from Europe and Asia, with the Educational site having Europe as the most represented region and the Industrial site having Asia.

Table 6. Percentage of Industrial Honeypot events by Service and Country

Server Type	Country	Percentage
FTP	China	31.89
	Japan	31.45
	Taiwan	31.32
	United States	3.33
	Romania	0.34
HTTP	Iceland	31.51
	China	9.89
	Russia	7.57
	Canada	4.11
	Germany	3.62
SMB	Vietnam	11.07
	Russia	10.34
	Brazil	7.2
	Venezuela	6.27
	Indonesia	5.65
ICS (AST & S7-300)	China	51.96
	United States	35.29
	Seychelles	3.92
	France	1.96

Table 7. Countries in Top 20 Contributors grouped by Region per Server Type

Site	Server Type	Region and Number of Countries in Top 20 Contributors				
Educa-ional	FTP	Europe 9	Asia 7	N. America 1	Africa 1	Oceania 1
	HTTP	Asia 9	Europe 8	S. America 2	N. America 1	
	SSH	Europe 7	Asia 4	Africa 2	N. America 1	
	ICS	Europe 4	Africa 1	N. America 1	Asia 1	
Indus-trial	SMB	Asia 9	S. America 4	Europe 3	N. America 2	Oceania 1
	FTP	Asia 9	Europe 5	N. America 4	Africa 2	
	HTTP	Asia 9	Europe 7	N. America 2	S. America 1	Africa 1
	ICS	Europe 2	Asia 1	N. America 1	Africa 1	

A noteworthy exception is South America, the second top region for the industrial site SMB server, the primary source of events and the source of the downloaded malware. This alludes to South America either having a higher presence of script based attackers since the WannaCry attack was first observed or a higher susceptibility to such attacks than other regions.

Table 8 shows the events per day of the common servers between the honeypots deployed on the two sites. For each OHP server type the security module with more events was chosen. The honeypots chosen for the industrial site were able to capture a wider variety of data including malware binaries, FTP login attempts and OS fingerprinting, however the educational site had a higher rate of events across all common services.

Table 8. Events per Day of Educational Site vs. Industrial Site

Server Type	Events/Day		Repeat Attacker Rate	
	Educational	Industrial	Educational	Industrial
FTP	3237	149	16.56	25.88
HTTP	166	93	11.19	2.54
ICS	15 (AST)	3 (AST) 8 (S7-300)	18.88 (AST)	2.45 (AST) 3.0 (S7-300)

The honeypots were released, according to the date their GitHub repositories were created, on July 2018 for OHP, December 2015 for Dionaea and March 2013 for Conpot, respectively. The difference in age and popularity over time resulting in a higher degree of detect-ability is likely a major contributor to the gap in rate of events. It is worth noting that the repeat attacker rates were also lower, with the exception of the FTP servers where the industrial site had a 56.2% higher repeat attack rate despite the aforementioned differences.

5. Conclusions and Future Work

From the honeypot data collected, there are many sources of attacks over FTP, HTTP, SSH, SMB and ICS servers. All geolocation data was evaluated through the use of the attackers IP addresses. However, one must keep in mind that such hackers tend to use VPNs to hide their origin. The total number of honeypot events was 2,155,855 over 20 days on the industrial site and 41,076 honeypot events with 294,623 network events on the educational site over 10 days.

China had the most honeypot events over the educational site (15,633) while Vietnam had the most on the industrial site (234,399). The United States had the most presence across all types of servers as a top-5 contributor in 7 out of 8. Moreover, certain locations were also, popular launching points for these attacks across the different types of servers, such as Seychelles, Netherlands, Iceland, Russia and Romania. There was a high repeat attacker rate for the SMB server (176.39) and 81.68% of malware payloads captured from this server were variants of WannaCry ransomware. Indicating the likely use of automated scripts and perpetuated attacks from victims.

Future work will analyse events over a much longer period and investigate other factors and log file records across a wider variety of sites including commercial and government sites. This can be done by using different types of honeypots, such as MIHs and HIHs. This information will be used to determine a plan for protecting sites and policies that should be put in place to ensure that valuable information is not being extracted from the country. Moreover, SIDs have a reliance on maritime ports as a key part of their national infrastructure. Considerations for other industries like those will be included in the future.

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Public Transportation in the Caribbean: Dominance of Paratransit Modes

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Abstract: *The use of paratransit modes is one important part of public transportation system in developing countries. Many studies have documented the different types, physical and operational characteristics of paratransit modes in African and Asian developing countries. However, there are few studies on paratransit modes in Caribbean developing countries and their significance in their transportation system. This paper documents the types of modes in the public transportation system in five Caribbean countries; Jamaica, St. Lucia, Barbados, Guyana, Trinidad and Tobago. Although these countries are different in geography, social culture and economic growth, the paratransit systems have developed similarly in each country and share identical cultures around these modes. In some countries, the paratransit modes are the only form of public transportation available. Despite there being a negative culture around paratransit modes in the Caribbean, these modes are more reliable than government-owned buses and more frequently used. This paper focused on the paratransit modes of six Caribbean countries, and provided some factual analysis of the current public transportation system. More studies are needed addressing the provision and development of these paratransit modes in the entire Caribbean. This study would contribute to provide a foundation to future studies aiming to establish a general methodology framework that could assist in solving some of the transportation issues the Caribbean faces, through a system using paratransit modes and policy development.*

Keywords: *Paratransit Modes, Public Transportation, Developing Countries, Caribbean*

1. Introduction

Public transportation is one of the few services that caters to an entire region, regardless of economic status and offers mobility and accessibility to everyone, especially captive public transportation users. Public transportation connects persons in far and rural areas to employment, leisure activities and necessary resources (Basuki Joewono and Kubota, 2008). Developing Countries tend to have unique transportation system characteristics separate from developed countries. One of the main differences is the prevalence of paratransit in the public transportation system. At their most basic form, paratransit modes are shared taxis or minibuses that operate on defined routes, stopping to collect or discharge passengers on demand. The concept of paratransit is intriguing and developed countries attempted to incorporate them into their own public transit system (Rimmer, 1984).

Studies on paratransit modes focused predominantly on Asian and African countries, though paratransit modes are prevalent in many other areas. These are the leading public transportation modes in some islands in the Caribbean region. Across the Caribbean, these modes of transport display many similarities to one another, and other paratransit modes in other developing countries. However, this is an unexplored area in transportation research.

This paper aims to bridge that gap by discussing the public transportation system and the various types of modes, specifically paratransit modes, in 5 Caribbean countries; Trinidad and Tobago, Jamaica, Guyana, St. Lucia and Barbados. These countries consist of 5 islands, and Guyana, which shares land with other countries (such as Venezuela, Suriname, and Brazil). These countries were selected to have representation in the Greater Antilles, Windward and Leeward Islands and Guyana, which has become one of the most dynamic oil producing countries in the 21st century and could drastically increase its GDP in years to come (Panelli, 2019). These countries vary in size, economy, and transportation system and give good depiction of the Caribbean. There is very limited documented data on the public transportation system in the Caribbean, thus the data for this paper was obtained predominantly from interviews and secondary sources.

Furthermore, an analysis of the similarities and differences of these modes and the culture surrounding public transportation in the Caribbean is discussed. The remainder of this paper discusses the background and historical development of the Caribbean, the state of paratransit modes in developing countries as well as the different modes and culture of public transportation in the Caribbean.

2. Background

Developing countries have certain characteristics differentiating them from their developed counterparts, such as extensive poverty and economic vulnerability (Teelucksingh and Nunes, 2010). Though Small Island Developing States (SIDS) are classified as developing countries, SIDS exhibit unique attributes due to geographic, social, economic and environmental characteristics. This is mainly due to their extremely small geographical size and population, insularity, remoteness and limited areas, and natural resources making them highly vulnerable to exogenous impacts (McElroy, Potter and Towle, 1990; Bass, 1993; Briguglio, 1995; Gay, Rogers and Shirley, 2018). Though Guyana is not classified as a SIDS, it shares similar culture and history to the Caribbean islands, and therefore is deemed part of the Caribbean region.

The Caribbean is mainly an arched-shaped group of islands (also includes the South American mainland such as Guyana) between North and South America, as shown in Figure 1.

Figure 1. Map of the Caribbean Archipelago
Source: Abstracted from Vidiani (2006)

The Caribbean is divided into the Greater Antilles and Lesser Antilles. The Greater Antilles consist of Cuba, Jamaica, the island of Hispaniola (that is divided into the Dominican Republic and Haiti) and Puerto Rico. The Lesser Antilles is further divided into the Windward and Leeward Islands. The Leeward Islands span from the Virgin Islands to Dominica, while the Windward Islands span from Martinique to Trinidad and Tobago.

Most of the Caribbean islands have mountainous terrain, which influences the type of road networks that are developed in those areas. Other islands, such as Barbados and Anguilla are not of volcanic origin, and are relatively flat. The Caribbean has influence from many different cultures from colonialism as far back as the 17th century and the early economy of the Caribbean focused on agriculture predominantly crops, such as tobacco, coffee, spices and sugar. At present tourism plays a major role in the economy of many Caribbean islands. The development of the economy in the Caribbean has tailored the public transportation systems to include paratransit modes (Gwilliam, 2008).

3. Paratransit Modes in Developing Countries

The existence of paratransit modes is a common characteristic of the transportation system in developing countries, including Caribbean countries (Pojani and Stead, 2015; Wongwiriya et al., 2016). Paratransit modes, also known as informal transit, are demand responsive, semi-public, locally generated, public transit services that are spontaneous unconventional modes, and in some islands, these modes are the only existing public mode available (Saltzman, 1976; Britton, 1980; Rimmer, 1980; Cervero and Golub, 2011).

Paratransit modes take many forms. They consist of shared taxis and minibuses as well as flexible transportation that offer on demand, door to door service for any origin and destination (Tangphaisankun, Nakamura and Okamura, 2009b; Owolabi and Akinwumi, 2011). These informal modes tend to share similar physical and operational characteristics, even though the origin countries of the modes differ. Paratransit modes are generally classified by two types; motorised and non-motorised. These modes have technical and culture adaptations and tend to dominate the public transportation system in their respective countries (Shimazaki and Rahman, 1996). Paratransit modes, usually fill a market void left by the absence, or lack of accessibility of a public transit service (Kerr, 2018). Despite the demand for paratransit modes, they usually have a poor perception from users. Most studies indicated that users perceive paratransit modes to be unsafe (Shimazaki and Rahman, 1996; Mutongi, 2006; Heinze, 2018). This issue contributes to the argument of eliminating paratransit modes from transportation systems.

Heavily subsidised transit companies were introduced, and they served as essential link in urban transportation. However, the increase in the individual automobile, and the irregularity of public transport operation has impacted the ridership in public transit (Poliak et al., 2017). Moreover, these transit companies do not operate on every route, and are scarce in more rural areas. Paratransit modes meet this void left by state-owned transit companies.

In developing countries, it is common for both government owned public transit and privately owned paratransit to co-exist. However there is a common debate about whether the bus or paratransit is superior and treat these modes as mutually exclusive systems within the public transportation (Silcock, 1986). Nonetheless, Rimmer (1984) highlighted case studies that showed when state-owned and privately owned paratransit operators ply for the same fare, the latter provides equivalent, if not better services, at no subsidy. Despite this, many travelers (both car users and public transportation users) rank public (bus) operators much higher than paratransit modes with respect to safety and comfort (Wright, 2018).

Though many are in favour of the phasing out of such modes, and incorporating more modern bus companies, it is possible for both modes to thrive together in an integrated system (Tangphaisankun, Nakamura and Okamura, 2009; Furlonge, 2016). This is a concept that was once attempted in the United States in the 1980s using the jipney, because they saw the benefits of paratransit modes (Rimmer, 1984). Though this initial attempt was unsuccessful, paratransit modes have re-emerged in developed countries using shared taxis in rideshare companies such as Uber and Lyft.

Rideshare companies are becoming more prevalent today, and have started to infiltrate into developing countries. There is a clear difference in the goal of rideshare companies using paratransit modes in developing versus developed countries (Phun and Yai, 2016). In developing countries, the platforms are developed to offer an affordable and efficient transportation service. The focus in developed countries is on convenience and environmental sustainability (Vayouphack, 2020). These companies share very similar characteristics to traditional paratransit modes. Though they boast door-to-door transportation, this is also a characteristic of some paratransit modes and the issue of safety is still a concern to users (Avula and Zou, 2019; Buruhanutheen et al., 2019).

Moreover, drivers for these companies share similar problems to paratransit drivers, that is, competition, safety and income security. These types of companies have proved their ability to disrupt traditional paratransit modes (Simmons, 2018), and thus negatively impact the system. Nonetheless, incorporating technology into traditional paratransit modes, could prove to be fruitful in improving mobility as well as the overall perception of modes (Mulley and Nelson, 2016).

4. Public Transportation Systems in the Caribbean

This paper looks at the public transportation system of six Caribbean countries; namely Barbados, Guyana, Jamaica, St. Lucia and Trinidad and Tobago. These countries consist of five islands, and Guyana, which shares land with other countries (such as, Venezuela, Suriname, and Brazil). These countries were selected to have representation in the Greater Antilles, Windward and Leeward islands and Guyana, which has become one of the most dynamic oil producing countries in the 21st century and could drastically increase its gross domestic products (GDP) in years to come (Panelli, 2019). These countries vary in size, economy, and transportation system and give good depiction of the Caribbean. There is very limited data on the public transportation system in the Caribbean, thus the data for this paper was obtained predominantly from interviews and secondary sources.

4.1 Physical and Economic Characteristics

Tourism is an important contribution to the GDP of these Caribbean countries, as shown in Table 1. Though the national economy of most Caribbean islands is heavily dependent on tourism, some islands are focused on areas such as agriculture, mining and oil and gas. These countries vary in size and population and have their own unique roadways and characteristics.

4.1.1 Barbados

Barbados has a relatively flat terrain, and thus is unrestricted by topography as it relates to roadway construction. There are approximately 1,750 km of roads of which 80% are paved. These roads are classified as Primary (25%), Secondary (14%), Local (41%) and Development (about 20%) (Travers Morgan International, 1996).

Table 1. Physical and Economic Characteristics of the Caribbean Countries

Country	Population /million (World Bank, 2020)	Population density person/km^2 (World Bank, 2020)	Surface Area (1000 km^2)	GDP/capita (USD) (World Bank, 2020)	Motor Vehicle/ 1000 people (NationMaster, 2020)	Main Economic Sector
Barbados	0.29 (2018)	668	0.431	17,949.28 (2018)	469	Tourism
Guyana	0.78 (2018)	4	214.9	4,979.00 (2018)	95	Mining and Farming
Jamaica	2.94 (2018)	273	11.00	5,354.24 (2018)	188	Aluminum oxides and ores
St. Lucia	0.18 (2018)	301	0.617	10,566.05 (2018)	166	Tourism

The transport network consists of seven radial highways, along with the Adams-Barrow-Cummins (ABC) Highway, opened in 1989, which consists of both two-lane and dual carriageway sections with at-grade intersections (typically roundabouts), which converge at Bridgetown. The radial highways are further linked to one another by secondary and tertiary roads. In addition, there are some 300 km of private roads. The roads in the public system are usually narrow, ranging from 5.5 to 6.5 meters in most areas (World Bank, 1984).

Additionally, because of increased traffic growth, lack of investment and limited maintenance, the quality of the road system has deteriorated, and large sections urgently need rehabilitation. Traffic volumes in and around Bridgetown are generally high, considering that the roads have only two lanes. The road network within the capital city consists of narrow roads which are restricted by existing buildings and allow limited space for pedestrian traffic. As a result of the high transport demand and the narrow roads, traffic congestion is common, particularly during morning and evening rush hours.

4.1.2 Guyana

Guyana is bound by Suriname, Venezuela and Brazil. Guyana has a relatively small population density as shown in Table 1. Its cities and towns mostly border the coast and the three largest rivers in Guyana; the Essequibo River, the Berbice River, and the Demerara River. This concentration of businesses and communities has influenced the existing road network. Guyana's road network is presently divided into highways, primary roads, secondary roads, tertiary roads, and trails (WFPGeonode, 2019). The Highways are the links from the villages and towns to the capital city, Georgetown, where most of the labour force commutes daily (Kaiteur News, 2015). The Demerara Bridge closes daily to allow for ships to traverse the river, preventing commute between the east and west banks to cross, thus creating queues of vehicles on either end (Demerara Harbour Bridge Corporation, 2020). Additionally, during peak hours, management of the bridge allows only for only one-way traffic flow with priority given to the higher volume along both lanes.

4.1.3 Jamaica

Jamaica has over 15, 000 kilometres of road (National Works Agency, 2012) that is densely configured. However, many of the nation's roads are not of a good quality. A 2005 study on the condition of the island's roadways, concluded that only 12% of the network could be categorised as "good" (Tarre and Persaud, 2019). Much of Jamaica's main arterial road network developed gradually from the era of horse-drawn carriages and bridle roads to the age of the motor vehicle (World Bank, 1983). Due to its genesis, a high proportion of the main road network was not originally constructed to specific engineering standards resulting in considerable variation in the standards of alignment, construction and drainage. Because of these inconsistencies, many of the roads have been maintained on a piecemeal basis, further accentuating the uneven, fragmented nature of the network (World Bank, 1983). Additionally, traffic volume has been steadily increasing over recent years. This has led to congestion problems in major towns and capitals across the island.

However, the Government of Jamaica undertook several projects to improve mobility and accessibility to urban, suburban and rural communities (Government of Jamaica, 2009). In 2009, it was reported that more than 75% of households in Jamaica, do not own a motor vehicle, emphasising the importance of public transportation in Jamaica. Nonetheless, Kingston Metropolitan Transport Region (KMTR) implemented different traffic management strategies, with proposals for congestion mitigation for the other parishes (Government of Jamaica, 2009). Highway 2000, planned as a public-private partnership, features a four-lane controlled-access, tolled motorway which consists of an East-West link and a North-South link that aims to establish and efficient motorway axis. The highway is the largest infrastructure project undertaken in the English-speaking Caribbean (NROC, 2020) and the only country on this list with an active toll road that can be accessed by both public and private vehicles. Also, there is a Northern Coastal Highway Improvement Project (NCHIP), which links Negril in the west to Port Antonio in the East (Government of Jamaica, 2007; Caribbean Development Bank, 2017).

4.1.4 St. Lucia

St. Lucia is a small island with relatively under-developed infrastructure which the government has gradually continued to invest in and modernise it since the mid-1990s. There are over 1,200 kilometres of roads, marred by unpredictability; particularly in the interior, where many may be narrow, curvy, steep, unpaved and vulnerable to landslides and storm damage. The rugged, mountainous topography has largely influenced the layout of its road networks (Mycoo, Griffith-Charles and Lalloo, 2017). The concentration of main roads and highways is focused along the coast and other lower lying areas, in an effort to avoid the mountainous interior that also holds several protected forest reserves. However, there are no alternative routes crossing the island between the coasts, which increases vulnerability to occasional hurricanes, landslides and flooding (Philogene-Mckie, 2019).

4.1.5 Trinidad and Tobago

Trinidad has two major transport corridors; the East-West Corridor and the North-South Corridor. Historically, these transport routes were influenced by the nation's sugar and oil industries for mining and shipping. The topography of the land was also important to where residential areas were developed, as the East-West corridor settlements lie on the flat land at the foothills of the Northern Range (Leung, 2009). Trinidad has the unique feature of having a restricted lane called the Priority Bus Route (PBR). The PBR is the main line-haul public transportation route for the East-West corridor. Emergency vehicles also have special preference along this route. The PBR can provide a designated, free-flowing stream of public transport vehicles, offering a time and fuel efficient route alternatives. Trinidad is the only country on the list with this type of road.

Tobago is the second island within the republic of Trinidad and Tobago, located 35 km north of Trinidad. Tobago has one highway, the Claude Noel Highway (CNH) that links many popular destinations and hubs in western Tobago (Anthony, 1997). The CNH and the primary roads to the east, west and south of the highway lie on relatively flat land around the coast. These lower capacity roads allow for multiple lanes to operate. However, the roads to the north of the highway, extend uphill and are usually described as narrow and winding.

4.2 Public Transportation Modes

There are 3 main types of public transportation modes in the countries listed; state-owned buses, minibuses and shared taxis. In this paper, the focus is strictly on shared taxis used for public transportation. Traditional private taxis that are metered, are not included. Excluding Barbados, the other islands have ferry systems. Ferries are sometimes used as an alternative to road transportation, and can be classified as a public transportation mode, in countries like Trinidad and Tobago and Guyana. In the island of St. Lucia, the ferry is used for inter-island transportation, to Dominica, Guadeloupe and Martinique. Trinidad and Tobago have a similar ferry. Jamaica and St. Lucia also use the ferry for tourism. While most ferries are privately owned, Trinidad has a government-owned ferry.

4.2.1 The Minibus

The most common, and widely used type of public transportation mode in the islands is the minibus. This type of paratransit mode, has a local variant amongst the different islands, as displayed in Table 2. This is a privately owned public transportation mode that is found in all six islands. This mode is referred to as the 'maxi taxi' in Trinidad and Tobago (see Figure 2), the ZR Van and the mini bus in Barbados, while Guyana, St. Lucia, and Jamaica identify the vehicle as the minibus (see Figure 3). Interestingly, similar vehicles types for the minibuses are used in these countries, and this shares a culture of 'naming' and decorating the vehicles for ease of identification.

Table 2. Physical and Operational Characteristics of Public Transportation Modes in the Caribbean

Common Terms	Local Variant	Country	Ownership	Vehicle Type	Seat Capacity	Route Options	Fares	Stops
Minibus	Maxi taxi	Trinidad and Tobago	Private	Jiangsu Joylong, Toyota HiAce, Nissan Urvan, Toyota Coaster, Mitsubishi- Rosa	15-24	Line haul	Varies by route/Fixed fare on given route	On Demand
	Minibus	Guyana		Toyota HiAce	15		Fixed fare	
	ZR Van Minibus	Barbados		Toyota Hi-Ace Hino Acme	11 24		Fixed fare	
	minibus	Jamaica		Toyota HiAce,	15		Varies by route/Fixed fare on given route	
	minibus	St. Lucia		Toyota HiAce	14		Varies by route/Fixed fare on given route	
Taxis	Route Taxi PH Taxi	Trinidad and Tobago	Private	Varied	4-8	Line haul Feeder routes	Varies by route/Fixed fare on given route	On Demand
	Taxi	Guyana				Line haul	Varies by supplier	
	Hackney Taxi/ Route Taxi	Jamaica				Line haul Feeder Routes	Varies by route/Fixed fare on given route	
Bus	PTSC Bus	Trinidad and Tobago	State	-City Champion, Higer Bus, Hino Acme, Mitsubishi Rosa, Thomas Cummins Bus, Volvo Caio, Zhengzhou Yutong	24-45	Line haul	Varies by route/Fixed fare on given route	Fixed
	Transport Board Bus	Barbados		Hino- Acme Mercedes- Marcopolo Mercedes- Caio	28-40		Fixed fare	
	JUTC	Jamaica		-Golden Dragon XML, Volvo VDL, Jonckheere			Varies by route/Fixed fare on given route	

(a) (b)

Figure 2. Minibus paratransit mode in Barbados:
(a) ZR Van, and (b) minibus
Sources: (a) Griffith, 2014, (b) Welchman Hall Gully Barbados (2016)

(c)

Figure 3. Minibus modes in (a) Jamaica; (b) St. Lucia, and (c) Guyana
Sources: (a) Caribya (2004); (b) Stephen (2017); (c) Guyanese Times Inc (2018)

In Trinidad and Tobago, there are six different route of maxi taxis in operation. These are differentiated by coloured bands on the maxis and link the main cities to residential communities. The ZR vans in Barbados are white with a maroon stripe and holds a maximum seating of 11, while the minibuses are yellow with a blue stripe and has a capacity of 24. Both ZR vans and minibuses are identified by a number displayed on them, specifying the route as well as a sign showing their route. In Guyana, the colourfully decorated minibuses do not have visually distinguishing characteristics specifying the route.

Similar to Barbados, the route numbers are displayed on the vehicle. St. Lucia identifies the minibus by an ‘M’ on their license plate, route bands that vary by colour and with the use of a number-letter combination or the name of the general area to identify their destination. The minibus in Jamaica carries a red license plate marked “PPV” (Public Passenger Vehicle). These vehicles can be colourfully decorated, with a unique name branded on the vehicle. The minibuses in these islands use similar vehicles, which is usually the Toyota HiAce. Additionally, most of the minibuses have a maximum seating capacity of 11-15 (see Figure 4).

(a) (b)

Figure 4. Maxi Taxi Trinidad and Tobago; (a) yellow band maxi, and (b) green band maxi
Sources: (a) NGV Journal (2016), and (b) Ghouralal, (2019)

Trinidad and Tobago, as well as Barbados are the only countries on the list that have reported minibuses with a larger capacity. The fares are usually dependent on the distance travelled. However, in Barbados the fare is fixed, for every route. These minibus vehicles are usually line-haul modes that run on specifically identified fixed routes and will pick up and drop off passengers anywhere along the route traversed.

4.2.2 Shared Taxis

Shared taxis are another form of public transportation mode found in different Caribbean islands. Trinidad and Tobago, Guyana and Jamaica, which are the main countries on the list that have shared taxis as a competitive mode of public transportation. In St. Lucia, there are a few registered private taxis that operate as public transportation modes on feeder routes, within the suburbs of the main town, however locals do not typically view these taxis as public transportation modes. These vehicles are usually 5-seater sedans or 9 seater small minivans. More recently, the 9-seater minivan is more prominently seen, since they can hold more passengers per trip. In Trinidad and Tobago, these shared taxis operate on either feeder routes, from the PBR, along the east-west corridor. Highway taxis in both islands operate as line-haul modes. In Tobago, the shared taxi service operates island wide, and also has the convenience of being available through phone call, through the taxi services (see Figure 10). Registered route shared taxis can be identified by the H on their license plate and have defined routes, and terminals in these areas. There is a growing number of illegally operating taxis, locally known as PH taxis that do not carry the H license, but are registered as private cars with the P license. These illegal taxis compete with registered taxis as well as operate along routes and in areas that the registered taxis do not. The absence of the H license, allows the PH Taxi to ply where taxis are restricted, which gives them more benefits than the legal service providers (Furlonge, 2016).

Shared taxis are very popular in Guyana. These taxis are hired from taxi services or have hubs at popular locations such as hotels, schools etc. These shared taxis, will transport a single group of passengers. There are cases of carpooling where a hired taxi will complete more than one job in a single trip, once given the consent of the passengers. The hired taxis do not have a specified route, and can actually be hired through phone call or text message, similar to international rideshare companies, without the app platform. The shared taxis are considered part of the public transportation system and are an alternative to the minibus.

Route shared taxis operate in almost every part of Jamaica. Like their local minibus, these taxis have the PPV license plate and will usually have 'Route Taxi' branded on the vehicle. These modes do follow a set route, like Trinidad and Tobago, and have defined terminals in the various towns. Similar to Trinidad and Tobago, these taxis wait until they are full to begin their journey. The fares are fixed (depending on the location) but are much cheaper than hiring a private chartered taxi. There are also cases of private vehicles, operating as route taxis without the regulated PPV license, like the PH in Trinidad and Tobago.

4.2.3 Bus

Barbados, Jamaica and Trinidad and Tobago have the highest GDPs and have state-owned bus companies in operation alongside the paratransit modes. These state owned bus companies are subsidised by the government and overall have a smaller fare than their paratransit competitors. These bus companies share similar features in that they operate along fixed routes and stop at fixed points, unlike the minibuses and shared taxis. These companies are The Public Transport Service Commission (PTSC) in Trinidad and Tobago, The Transport Board Bus Company in Barbados and The Jamaican Urban Transport Company (JUTC) in Jamaica (see Figure 5). In Trinidad and Jamaica, the PTSC and JUTC have legal rights to use the PBR and Toll roads respectively.

Figure 5. State-owned bus companies; (a) PTSC- Trinidad, (b) JUTC- Jamaica and (c) Transport Board- Barbados Sources: (a) PTSC (2020), (b) NICEPNG (2018), and (c) Alleyne (2019)

Though the countries have their unique history and culture, they share similar paratransit modes. Furthermore, in countries where both paratransit and public transit are available, the former is still more popular (Steer Davis Gleave, 2008; Johnson, Koebrich and Singer, 2019) despite being more expensive than the bus. Paratransit modes are valuable to the overall transportation system of those countries and have been for years. Given this, these modes have developed similar social behaviours and customs around them.

5. The Paratransit Mode Culture in the Caribbean

Public transportation is an important aspect of the livelihood and progression of a nation and in SIDS and developing countries, paratransit modes play an essential part of their public transportation. In countries such as Guyana and St. Lucia, where there is no government-owned public transit system, paratransit modes are the only alternatives to captive travelers. Travelers are therefore forced to tolerate the culture and behaviour of the paratransit modes. Islands such as Barbados, Jamaica and Trinidad and Tobago have state-owned bus alternatives, the paratransit modes in these systems are still preferred. Often times, the nonsubsidised paratransit, is used more frequently than the subsidised government bus, which has cheaper fare, but is often viewed as unreliable (Robinson, 2013). This may be due to the lack of available buses to service all the routes (Jamaica Observer, 2017; The Barbados Advocate, 2019). Though cheaper, the unreliability of the government owned buses, forces travelers to use the paratransit modes, even though they are not seen as the most comfortable alternative and makes the private car more attractive. This lack of confidence in the overall public transportation system can be linked to the constant increase in vehicle ownership (Furlonge, 2007; Government of Trinidad and Tobago, 2012; Robinson, 2013).

Paratransit modes are commonly criticised for being unsafe and dangerous. With the exception of Trinidad and Tobago and St. Lucia, the countries have reported that the minibuses in particular are constantly overcrowded, and this behaviour is encouraged by drivers and conductors. Vehicles can often be seen with passengers sitting on top of each other, with no seatbelts, and people standing in a packed vehicle. There have also been incidents of both drivers and passengers being robbed and physically harmed (St. Lucia Times, 2019). This further promotes the narrative that these types of modes are unsafe, and inevitably glorifies owning a private vehicle. The minibuses are known to drive competitively and recklessly, endangering passengers and other drivers. With no standard salary for minibus drivers or conductors, their income is dependent on the number of passengers carried in a day. This creates competition between drivers to obtain as many passengers as possible, perpetuating the reckless driving.

Many accidents have occurred with these modes, and some have caused fatalities (Barbados Free Press, 2012; Emanuel, 2020).

Moreover, there is a general culture of loud and offensive music, alcoholism and colourful vocabulary (Fenty, 2014; Guyanese Times Inc, 2018), again strengthening the unfavourable opinion of these modes. Nonetheless, these paratransit modes are a profitable system though the culture is viewed negatively. Despite the challenges and negative behaviour the paratransit community exhibits, its advantages cannot be disregarded and these modes are still frequently used in the public transportation system.

Paratransit modes have emerged and remain in the Caribbean due to their reliability being driven by profit and economic growth. This drives the operators to work longer hours, increase their frequency of operation and increase the vehicles that service a particular route, therefore reducing the waiting time for travelers on that route. Furthermore, the unscheduled nature of the system allows for the operation on routes, that are used by the paratransit service providers and are not serviced by the state-owned systems, giving a more demand driven approach for travelers (Salazar, 2015). As a result, areas that have a need for the service can be quickly addressed rather than waiting for governmental intervention. From the operator's perspective, it provides opportunities of employment to poor or low-skilled workers, thus stimulating socioeconomic growth.

Government-owned public transport in the researched territories is either non-existent, inefficient or struggles to provide comprehensive coverage to large sections of the population. Many residents live a significant distance away from the cities, which are typically focused on business activity. There may be few transfer hubs to provide ease of accessibility to communities further away from the city centres. The paratransit modes avoid the deficiencies of the main transportation system which does not service the less populated areas. Modes like the shared taxi in Trinidad and Tobago, Guyana and Jamaica are also more convenient for the elderly and disabled, as they offer more flexibility and comfort in reaching their final destination.

Captive travelers require a dependable mode of transportation to comfortably and safely conduct their daily activities. In some cases, the ridership of paratransit modes is more than double the ridership of the government bus company (Steer Davis Gleave, 2008; Wright, 2018; Dolcy, 2019). This has raised the question, whether the government needs to provide its own public transportation alternative. Both Guyana and St. Lucia have shown that their unsubsidised paratransit system can operate without a state-owned bus. Furthermore, the government buses tend to have low technical performance and output due to a lack of incentive (Salazar, 2015).

Rideshare companies have also become very popular in developed countries and their service is slowly trickling down to developing countries. Such platforms are popular in areas of Asia and Africa. Trinidad and Tobago, Barbados and Jamaica are the only Caribbean countries discussed in this paper that have local rideshare apps available for the public. There was a period of time when Uber was present in Trinidad and Tobago, but that was short lived. Though rideshare platforms are a relatively new concept to the Caribbean, Guyana has a similar system integrated into their public transportation system, by the means of their shared taxi public transportation service.

Though this is only a dial up system, where patrons pay with cash, there is capacity to digitise this service. In Trinidad and Tobago, Barbados and Jamaica these rideshare companies are used as an option when going to social gatherings, and as a cheaper alternative to hiring private taxis for these events. However these rideshare services have the potential to be alternatives to using the public transportation maxi taxi, route shared taxi service, ZR or minibus for every day travel. This new option in the transportation system, could supply travelers with a safer environment. Thus, rideshare companies can threaten the livelihood of the current and traditional paratransit operators.

In spite of the negative culture of the paratransit modes, the governments in these territories have acknowledged the pivotal role in the transportation system and their ability to pragmatically adapt to the local market, and thus have provided incentives to ensure that the paratransit system continues to thrive, by establishing transfer hubs, maintaining infrastructure such as the PBR in Trinidad, relaxing enforcement on infringements, such as speeding and overloading of passengers and giving subsidies on vehicular fuels (NGC CNG Company Limited, 2017; St. Lucia Times, 2018). Nonetheless, the issues of safety and comfort with the paratransit systems need to be addressed to create a more attractive alternative to captive travelers and private car users.

6. Conclusion

This paper has highlighted the essential role that paratransit modes play in some Caribbean territories. The islands in this study vary in size, population, GDP and yet, share similar physical and operational characteristics in the public transportation system, especially the paratransit modes.

Despite its many shortcomings, the paratransit systems evident in the Caribbean countries highlighted in this study can offer a solution to some of the transportation problems in those countries, and be an instrumental part of the public transportation system in developing countries. Without the financial aid necessary to construct and maintain an efficient public mass transit system; populations are forced to create their own solutions, restricted by available resources. The existing paratransit modes presented in this overview, form part of this solution. Nonetheless, people are still largely dissatisfied with the quality of service provided by them. While paratransit can provide a solution, it needs to be optimised; and properly integrated into the transportation system. It is necessary for governments to make the public transportation a priority and to invest in an efficient and well-planned system that can work in harmony with the organically growing paratransit system. An integrated approach utilising both the government-owned bus company and the paratransit modes can be a profitable and efficient and intervention by the government to skillfully manage this integrated system is necessary.

Future work should consist of research into different solutions to the problems faced by the transportation system, such as, the suitability of a bus rapid transit system, improving law enforcement around the public transportation system and improvement of public transportation transfer hubs. More studies could focus on possible policy changes to improve the system overall. However, in order to accomplish this, data is needed. In this manuscript, it is acknowledged that there is a shortage of readily available data in the Caribbean, particularly in the smaller islands. Data is not only necessary to make any relevant changes, but it is something that needs to collected regularly to see trends and understand changes.

While census data is already collected in the Caribbean, it is suggested that the data be collected more frequently, and information on transportation should be integrated in. Data such as amount, and cost of vehicles in a household, and average cost per trip of both car and public transportation users could be very useful. Cost of vehicles versus mean income of the population and vehicle ownership percentage can indicate how transportation choices are made, as well as how much people are willing to spend on the convenience of a private car and the quality of the public transportation system.

Transportation studies, such as travel demand studies, trip pattern data, and ridership data need to be conducted. Having a better understanding of how much trips people make per day, the amount of transfers from one transit mode to another can highlight inefficiencies within the system and where to focus on for improvement. Likewise, any proposed solutions should undergo a feasibility study to ensure that the solution is reasonable and sustainable. Attempts should be made to forecast potential conditions so that measures can be proactive rather than reactive.

Moreover, satisfaction surveys are important. Questions should be asked with the aim of determining the consensus on qualities like comfort; safety; travel times; costs; reliability; and accessibility. This information can guide improvement projects and give a view of why individuals make certain choices. Getting direct feedback from consumers can aid in ensuring that the investments made to the system are prioritised in the areas that are most highly demanded.

This paper provides a foundation of information for the public transportation system of five Caribbean countries. It can be viewed as an introduction for further research on public transportation in the Caribbean, focusing on policy and improving the quality of usage and of public transportation.

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Supply Chain Evaluation for the Plant Extracts Industry in the Eastern Caribbean

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Abstract: *Market research has shown that the demand for increasing essential oils, fragrances and flavours in aromatherapy, and food and beverages, is expected to remain a key driving factor in the global marketplace. This could effectively double to about US$15b by 2025 from about US$7b to US$8b as estimated in 2018. Additionally, the Oleoresin market was estimated to be about US$1.2b in 2014, increasing to US$1.7b in 2025. The Eastern Caribbean has a long history of essential oil production, specifically bay oil in Dominica, nutmeg oil in Grenada and anise oil in Trinidad. Unfortunately, the bay oil and nutmeg oil operations have been negatively affected by hurricanes and the anise oil operation has been closed down. Due to the buoyancy of global markets in both essential oil and oleoresin markets, it is appropriate to bring these traditional industries back into full production, and to expand the range of products to be marketed. The potential of this expansion was investigated using an in-depth evaluation of the 5 stages of the complex supply chain in the small island states, namely: 1) Agricultural production of raw material, 2) Extraction of the crude essential oil/oleoresin by steam distillation/supercritical fluid extraction, 3) Transportation of the crude extracts to a separation plant to recover valuable components, 4) Transportation of the valuable components for final consumer products to be produced and packaged, and 5) Marketing of the final consumer products. The potential for introducing new products has identified the additional crops which could be considered for commercial exploitation: root crops (turmeric, vetiver), shrubs (basil, hot peppers), trees (ylang ylang). The analysis has led to a number of conclusions. Firstly, management of agricultural production is key to the success of the operation. Secondly, steam distillation extraction can only produce essential oils, whereas supercritical fluid extraction can extract both essential oils and oleoresins, but at a rather higher capital cost. Finally, there would be a move towards major production and distribution of commercial products after the new businesses are established. These new businesses would contribute to the fulfillment of a sustainable supply of crops to the process plant.*

Keywords: *Essential oils, oleoresins, supply chain, techno-economic feasibility*

1. Introduction

Many plant species in the tropics secrete complex chemicals which are extracted and incorporated into various consumer products which may be classified under the following headings:

- Food Flavours
- Aromatherapy/Personal Care products
- Nutraceuticals/Pharmaceuticals
- Perfumes
- Various uses, e.g. security sprays, insecticides, dyes and colourings.

There are two basic types of plant extracts: essential oils and oleoresins. Essential oils are the volatile oils giving rise to the odour from the plant (Ríos, 2016; King, 2006; Turek and Stintzing, 2013). Oleoresins are natural resins often termed the fixed oils due to having much lower vapor pressures than the essential oils, melting at higher temperatures (Moyler, 1991; King, 2006).

Growing consumer preference for natural products has led to the development of novel applications in personal care and beauty products. Rapid industrialisation has resulted in increased disposable incomes, particularly in emerging economies such as China, India, Vietnam and Thailand. This is one of the macro factors steering growth (Maharaj et al., 2017). In addition, rising application scope on account of growing consumer awareness regarding health benefits, and negligible side effects associated with the use of essential oils and oleoresins, is expected to spur their demand in the medical industry. Growing demand for aromatic flavours and fragrances in cosmetics, perfumes, as well as spa and relaxation applications is also expected to fuel demand in the coming years.

2. Essential Oils and Oleoresins Market Projections

A number of market research companies (e.g., Fortune Business Insights, 2019; Global Market Insights, 2019; Allied Market Research, 2020; Grand View Research, 2020) have evaluated the current and projected global essential oils markets. There is reasonable agreement between their assessments indicating that the global market sales were $7.0b to $8.0b in 2018, with significant increases expected to give rise to a Compound Annual Growth Rate (CAGR) between 8.7% and 9.7% over the period to 2026, thereby projecting to virtually double the market size to about $15.6b in that period.

In terms of the supply chain, the Observatory of Economic Complexity stated that the major importers of essential oils were the USA 24%, France 14% followed by Germany and the UK both with 6.3%, and the major exporters were France 16%, China 14%, the USA 10%, Indonesia 8.2%, and India 5.1% (OEC, 2018). The numbers quoted for exports will, however, include re-exports of finished products particularly for the developed countries. The major production of basic plant extracts is from the developing countries, with Indonesia, India and Brazil being the major producers. In terms of the major market for essential oils. It was estimated that the United States essential oil market revenue would double from about US$2.0b in 2015 to more than US$4.0b in 2022, with breakdowns given for the top 10 oils (Grand View Research, 2020). The European market, comprising about 40% of the total, was estimated to increase at a lower rate.

As regards the specific essential oils which are commercialised, the top 10 in terms of output have been identified by the market research companies as oils from orange peel, eucalyptus, cornmint, citronella, lemon, lime, lavender, rosemary, tea tree and clove. Many of these are however not from tropical plants but, notwithstanding this, there are a large number of oils being produced from other tropical plants, which are marketed with lower volumes and often at higher unit prices (e.g. ylang ylang, jasmine, vetiver, bay leaf, basil, patchouli, and hot peppers).

In terms of application, about 40% of the oils go into the Food and Beverage market, about 30% into Spa and Relaxation, with about 15%, into Pharmaceuticals, and another 15% into Cleaning and Home (Grand View Research, 2020).

On the other hand, oleoresins have a high stability in storage with a reduced storage space (King, 2006). They are widely used as a natural means of lowering the risk of cancer, and also in treating stress and back pain owing to their natural antioxidants and anti-inflammatory properties (King, 2006).

According to Markets and Markets (2018), the global oleoresins market was estimated to be valued at US$1.2 billion in 2019 and is projected to reach US$ 1.7 billion by 2025, recording a CAGR of 6.0% from 2019 to 2025. The rising trend of using natural flavors in processed food and an increasing number of Quick Service Restaurants (QSRs) have led to a surge in demand for oleoresins. The rise in awareness regarding the side effects of synthetic products, and health benefits offered by phytomedicines and herbal extracts have significantly driven the growth of the market. Further, due to the increasing research and development (R&D) activities in the market and the rising popularity of health supplements, the demand for oleoresins in the nutraceutical industry remains high. The growing trend of offering "clean label" personal care products is also projected to drive the growth of the oleoresins market.

Major sources have been identified by Markets and Markets (2018) as paprika, capsicum, seed spices, turmeric, ginger, cinnamon, and herbs with various other materials (such as nutmeg, cardamom and garlic). All of these could be grown in the tropics. Moreover, applications were identified as Food and Beverage, Pharmaceuticals and Nutraceuticals and Personal Care Products. Estimated geographic market distribution was 42% the USA, 29% Europe, 18% Asia Pacific region, with 11% for the rest of the world.

Market data summarised above for both the essential oils and oleoresins market, which shows that both markets are buoyant with significant growth projected in the short to medium term. Many of the plants from which the essential oils and oleoresins are extracted are produced in the tropics. There is a history of essential oils production in the Eastern Caribbean, but the market projection shows that the opportunities for consolidation and expansion are significant. This paper would:

1) Evaluate the current situation for essential oils and oleoresin production in the Eastern Caribbean.
2) Identify areas for consolidation and expansion for essential oils and oleoresin production in Eastern Caribbean.
3) Analyse the Supply Chain Management with a view to identifying the issues which need to be addressed.
4) Make specific proposals as to how the industry can evolve in the short, medium and long term to the benefit of the local economies.

The overall market analyses summarised above relate to the total global situation. Much of the basic supplies are, however, from tropical sources. In terms of volumes, the major essential oils are from citrus peels as a byproduct from juice production, specifically orange oil, lemon oil and lime oil.

McMillan et al. (1991) have provided a listing of thirty tropical plants, other than citrus, from which essential oils can be extracted. Those that may be exploited in the Eastern Caribbean are listed below, together with additional plants with extractable oleoresins. The listing is initially classified under Root Crops, Herbs/Grasses/Shrubs and Trees, as the agricultural system for production and supply chain management will vary with these particular different classifications:

- Root Crops – turmeric, ginger, and vetiver.
- Grasses/Herbs/Shrubs – basil, lemongrass, jasmine, patchouli, hot peppers, and thyme.
- Trees – bay, ylang-ylang, cinnamon, clove, neem, nutmeg, and annatto.

In terms of final use, these plants have been reclassified by McMillan et al. (1991) in the areas below:

- Spices – bay, cinnamon, ginger, nutmeg, and turmeric
- Condiments and Seasoning – basil, lemongrass, thyme, and hot pepper
- Aromatherapy and Perfumes – basil, bay, cinnamon, clove, jasmine, lemongrass, patchouli, vetiver, ylang-ylang
- Drugs and Medicinal Plants – turmeric, hot pepper
- Natural Insecticides - neem
- Dyes and Tans – annatto

3. Essential Oils Industry in the Eastern Caribbean

3.1 History

The Eastern Caribbean has a long history of essential oil production, albeit limited in the range of products. Thus, bay oil has been produced in Dominica since the 19th century, and lime oil was produced in a number of the islands for many years (Co-operative Development Division, 2018). More recently, nutmeg oil has been produced in Grenada, anise oil in Trinidad and bay oil in Tobago (Forbes, 2020). Even though these industries are small by international standards, they have contributed significantly to the economy in the small islands. The anise operation has however since been closed down, and the operations in Dominica and Grenada have been negatively affected by hurricanes (Forbes, 2020).

In the Eastern Caribbean the leaves for bay oil extraction in Dominica and nutmegs for nutmeg oil extraction in Grenada were grown, harvested and processed through farmers' co-operatives. Apart from the production of small amounts of specific consumer products, the raw oils were then sold to brokers in North America and Europe, who sold them on to refiners and consumer product manufacturers. In the case of anise oil production in Trinidad, the production and initial processing of the raw material was carried out by the Pernod Company who took all the product for incorporation into its beverages. In each case, the value added was effectively exported.

3.2 Potential

Reference to Section 2 shows a significant number of potential plants which can be grown in the Eastern Caribbean from which high value products can be extracted in the form of essential oils and oleoresins. Markets are available and buoyant (CARICOM, 2007; Caribbean Export, 2019), with the expectation to expand significantly in the next 5 years. Reference to the history shows limited penetration by producers in the Eastern Caribbean. In fact, as all the process plants in the region employ steam distillation to extract the oils, only essential oils have been produced to date. Since there is much unused/underutilised land in the region, it is proposed that there be a significant expansion of output both in terms of the types of essential oils and oleoresins produced and also the quantum to be marketed. If labour costs are deemed to be excessive, however, it may be appropriate to concentrate on high value added products and materials, together with the introduction of a high level of mechanisation into agricultural production, where possible.

In terms of production, processing and marketing, a number of additional essential oil products can be considered probably the most promising from the point of view of ability to produce, process and market at a relatively high price being:

- bay *(Laurus nobilis)*
- basil *(Ocimum basilicum L.)*
- jasmine *(Jasminum sambac L.)*
- patchouli *(Pogostemon cablin Benth.)*
- vetiver *(Vetiveria zizanioides)*
- ylang ylang *(Canaga odorata)*

Orange oil is the most traded essential oil, this being produced by pressing the oil out of the peels, these being a by-product of orange juice production. Other citrus oils are similarly produced from grapefruit, lemons and limes. There is some citrus production in the Eastern Caribbean but it is not at the level appropriate for extracting and marketing the oils commercially at this time.

In addition, however, it may be appropriate to expand the plant extract offerings to include oleoresins, the most promising being:

- ginger (*Zingiber officinale)*
- turmeric (*Curcuma longa)*
- hot peppers (*Capsicum annum*)

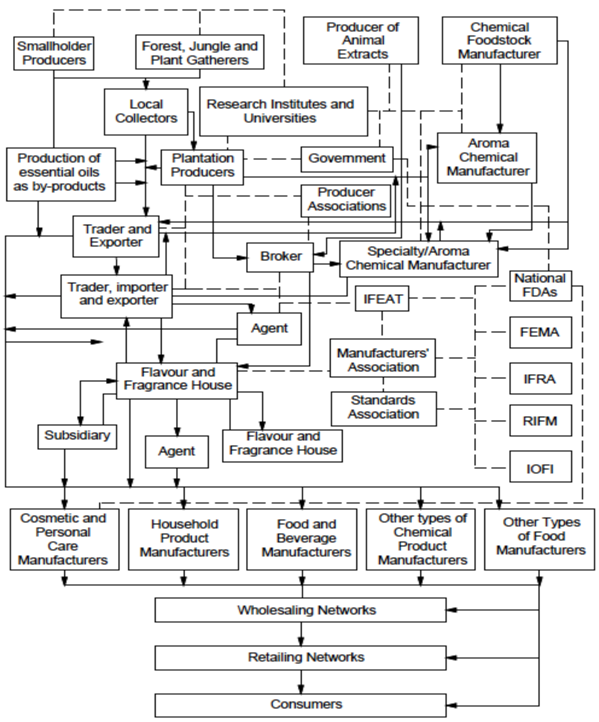
It must be recognised however, that whereas the production of essential oils may be carried by the simple process of steam distillation, the production of oleoresins will necessitate the introduction of either solvent extraction or supercritical fluid extraction.

The implications for consolidation of the current production and expansion into the production of new products is examined in the following Sections, with special reference to supply chain management; along the full supply chain from agricultural crop production to the marketing of consumer products. This will include the concept of producing more than one product from a single process plant, as well as the implications of moving down the supply chain to market final consumer products.

4. Supply Chain Management in the Plant Extracts Industry

Towards the realisation of this potential, it is important to have an in-depth understanding of how the industry works starting from crop production, through delivery to the extraction site and finally to the global distribution of the product. An understanding of various aspects of the supply chain is essential in ensuring that the continuation of existing businesses and the introduction of new businesses is organised to maximum benefit. The full supply chain is complex, as shown in the diagram of the supply chain which is specific to the flavour and fragrance industry by Hunter (1996), as quoted by Weiss (1997), and shown in Figure 1.

This supply chain analysis excludes certain products for other markets, particularly the nutraceuticals/ pharmaceuticals, insecticide, pepper spray, dyes and colourings markets, which will have similar structures, but varying in detail. They will also have their own controlling international bodies, particularly the pharmaceuticals markets.



Keys:
NFDA – National Food and Drug Administration
IFEAT – International Federation of Essential Oils and Aroma Traders
IFRA – International Fragrance Association
RIFM – Research Institute for Fragrance Materials
IOFI – International Organisation of Flavour Industries

Figure 1. Structure of the International Flavour and Fragrance Industry

As regards the analysis of the potential for expansion of the plant extracts industry in the Eastern Caribbean, the supply chain may be conveniently simplified to the following major steps:

1) Agricultural production of raw material and its delivery to the process plant.
2) Material preparation prior to extraction.
3) Extraction of the crude essential oil/oleoresin.
4) Transportation of the crude extracts to a separation plant where the valuable components are recovered. This may happen through an intermediary broker.
5) Transportation of the valuable components to the site where the final consumer products are produced and packaged.
6) Marketing of the final consumer products.

This is depicted in block diagram format in Figure 2. In fulfilling the above, it is recognised that all products must conform to the relevant international standards, as implied typically in Figure 1.

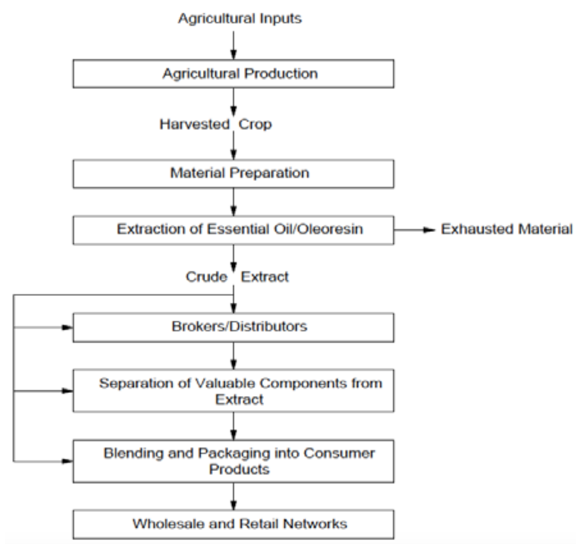


Figure 2. Block Diagram Format for the Supply Chain

5. Agricultural Production and Supply to the Process Plant

The aim of the agricultural supply system is to produce the appropriate plant materials to supply the extraction process plant. In essence, its establishment and management are key to developing a viable and profitable commercial operation, since it is at the front end of the Supply Chain. All the extraction processes are batch operated, generally on a 24 hour a day basis. There will be specific turn round times involving charging to the process, start up, extraction for a specified period, finishing with shut down and emptying of the spent charge. Typically, for a turn round time of 6 hours, there will be 4 batches processed per day per extraction unit. On-field loading of steam distillation vessels is also possible. However, the agricultural enterprise must of necessity have sufficient material available to keep the process plant operating throughout the year. This would therefore require planned storage of a few days' supply awaiting processing, and for high-moisture material, pre-drying to a moisture content of 75% or less is recommended to prevent mould growth.

Management of the different potential crop materials will vary significantly from crop to crop. Brief background to the selected crops within the classifications listed (see Section 2) is given below.

5.1 Crop Types

Three different crop types shall now be discussed namely, root crops, herbs/shrubs/grasses and trees.

5.1.1 Root Crops

Potential root crops that can be exploited for their extracts are:

- Essential oils – turmeric/ginger/vetiver
- Oleoresins – turmeric/ginger

Of these, both turmeric and ginger can be harvested mechanically, whereas vetiver has to be dug out manually because of the extent and depth of its root system. Since the agricultural system for ginger is similar to that of turmeric, only the background to turmeric and the summarised agricultural practices would be presented.

1) *Turmeric –* *Curcuma longa* (*Zingiberaceae*) is an erect herbaceous perennial which grows to a height of ~1m. The leaf sheaths form a pseudostem, but unlike ginger, has a distinctive thin petiole so that the leaf lamina is at a distance from the pseudostem. The rhyzomes which have a characteristic colour and taste, develop as a dense clump and are covered in scales, but are bright orange inside (Bhat, 1995; Prasath et al., 2018). Turmeric thrives on fertile soils with a loose texture. Well-drained alluvial sandy loams are ideal for growing turmeric (Das, 2016). It is very sensitive to waterlogging. Preparation of the land is to obtain a fine tilth that is essential for growing a good crop of turmeric. It requires heavy application of fertiliser. The crop is ready 7-9 months from planting. Extract composition from commercial turmeric grown in Trinidad has been reported to be ~11% of which around half is essential oil and half oleoresin (Maharaj et al., 2017). Yields are reported to be in the 10-20 tonnes per hectare under average conditions, although it has been shown that yields of up to 45 tonnes per hectare can be achieved with some high yielding cultivars. Mechanical harvesting can be achieved by a simple powered tiller or by use of a suitable device driven by a tractor.

2) *Vetiver –* *Vetiveria zizanioides* (*Gramineae*) is a densely tufted narrow leaved, perennial grass which grows to a height of up to 2m. The dense lacework of spongy aromatic roots is concentrated in the top 20-30 cm of soil, but individual roots can reach 100 cm in the soil profile. Luxuriant vegetative growth with moderate oil content is attainable when cultivated on well-drained sandy loam soils (Weiss, 1997). The highest oil yields are however obtained from crops grown on red laterite soils. Although plant multiplication by nature occurs both vegetatively and by seed dispersal, under cultivated systems it is usually propagated using slips obtained from the previous crop. The recommended spacing under tropical conditions is 60 cm by 30 cm. In the tropics the optimum stage of growth for harvesting of the roots is reached 15-18 months from planting. Oil quality is reported to be the best at this stage when a large percentage of the roots are thick, fleshy and carry fine rootlets. Oil contents from roots from cultivated crops reported in the literature vary widely from 0.1% to 4%. The oil content of vetiver grown in Trinidad has been reported to be 1.75% (Maharaj et al., 2020). During harvesting, the clumps are first cut or mowed at a height of 15-20cm above the ground and the clumps are uprooted manually from a minimum depth of 50 cm.

5.1.2 Herbs/Shrubs/Grasses

Potential herbs/short plants that could be exploited for their extract are:

- Essential oils – basil, coriander, lemongrass, jasmine, patchouli, thyme
- Oleoresins –hot peppers, paprika

Of the essential oil plants, jasmine flowers have to be hand-picked for perfume base extraction, whereas the other plants can be harvested mechanically. In terms of the oleoresins, the fruit has to be separated from the plant before forwarding for extraction. One example of each is chosen for summarising the background to agricultural production, specifically basil and hot peppers.

1) *Basil –* *Ocimum basilicum (Labiatae)* grows and thrives as a perennial in tropical climates. Generally, the plants have leafy stems, thin branching roots and reach a height of 60 cm at maturity (Weiss, 1997). It grows in well-drained loamy soils and should be harrowed as smoothly as possible, since the seeds must be drilled uniformly to obtain a good stand of plants. The plants should be placed 0.5-1.0 m between rows and 3 to 6 cm within 2 rows. Basil plants are unable to tolerate moisture stress and should be provided with a regular supply of water. When growing plants for oil production, large producers cultivate about 70,000 plants per hectare. Oil of high quality is obtained when the plants are at the flowering stage and are usually ready for harvest about 95 days after seeding. Leaf yields range from 15 to 25 tonnes per hectare. They should be trimmed frequently as this helps them remain bushy. A sickle bar type mower with an adjustable cutting height can be used to harvest the plants. They should be cut at least 15 cm above the ground to ensure a good second crop. Oil yield for the common variety grown in Trinidad has been determined to be about 0.3% (Maharaj, 2012).

2) *Hot peppers -* *Capsicum annum sp. L* is a variable herb, or sub-shrub, sometimes woody at the base, erect, much branched, 0.5 to 1,5m high, which is grown as an annual. The fruit is an indehiscent many-seeded berry, pendulous or erect, born singly at nodes and very variable in size, shape, colour and degree of pungency

(Weiss, 1997). Light loamy soil, rich in lime is best for their cultivation, but they can be grown on a variety of soils provided they are well drained. Spacing is usually up to 1 m apart. Flowering begins 1-2 months after planting and it takes a further month to the first picking of green peppers; and ripe fruits are picked at intervals of 1-2 weeks. After harvesting they can be dried in the sun to a quarter of their wet weight. The yield of dried peppers per hectare in India has been reported to be from 250 kg per hectare for rain fed crops to 2,500 kg per hectare for irrigated crops. There are a number of different varieties grown in Trinidad varying in the capsicum content. A typical capsicum content for scotch bonnet pepper has been measured to be ~2%. (Holder, 2008). Hot peppers are usually harvested daily by hand, but mechanical harvesters are available for a once-over harvest (Penn State Extension, 2020). A comprehensive Production Manual for hot peppers in Trinidad has been published by CARDI which can be utilised across the Eastern Caribbean (Adams et al., 2011).

5.1.3 Trees

Potential tree crops that could be exploited for their essential oils are:

- Essential Oils – bay, ylang ylang, nutmeg
- Oleoresins – cinnamon, clove, nutmeg

The three most promising tree crops for essential oil production are bay, nutmeg and ylang ylang. Since bay is already well exploited in Dominica and there is an unutilised bay tree plantation on Tobago, there is no need for additional production in the region. Similarly, nutmeg has already been exploited in Grenada. However, the essential oil from the flowers of ylang ylang does represent a significant opportunity.

Ylang Ylang – *Cananga odorata* (*Annonaceae*) is a fast growing medium to tall evergreen tree attaining a height of up to 35m in the wild state (Weiss, 1997). For ease of cultivation, the tree is kept at a height of 3m by topping as well as bending the branches downward, giving the tree a distorted appearance. Large yellow-green strongly scented leaves hang in clusters of 2-20 or more from the axils of alternate leaves. The flowers, found on the tree year round, spend 20-25 days maturing from smaller greenish-white flowers to larger flowers exhibiting a deep yellow colour. The tree thrives in a moist tropical climate near the sea coast and in rich volcanic or fertile sandy soil. It is propagated usually by seed rather than cuttings which may be sown directly into prepared pits where the tree is to be grown. The first flowers appear in sparse amounts after 1.5 to 2 years with full harvests produced by the third year. If properly attended and sheltered from the wind a plantation can last up to 25 years. On average, each tree can produce 6-8 kg per year in industrial plantations. The oil is usually extracted via steam and hydro-distillation with yields up to 2.0 to 2.5%. Oil from sources in Trinidad has produced yields of about 1.8% using Supercritical Fluid Extraction (Watson, 2005).

5.2 Ownership and Control of Agricultural Production

Turmeric, vetiver, basil, hot peppers and ylang ylang are probably the best five opportunities that worth investigating for commercial development. Similar backgrounds to those given above can be obtained from Weiss (1997). Reference to the summarised background data of the five identified exploitable crops shows significant differences between the agriculture, growing times, harvesting times, harvesting procedures, crop yields and extraction yields. In order to maximise the output from the extraction plant, management of agricultural output and supply to the process is crucial, in order to ensure a sustainable business. Thus the planting process has to be coordinated months, to even years, in advance to the time of harvesting, such that the process capacity is fulfilled on a daily basis, without too much time in prior storage.

This is a crucial factor in the supply chain management process. Crop production and supply to the process plant can be carried out in the following ways:

- from a plantation close to the extraction site and probably with the same ownership as that of the process plant.
- by a Cooperative of farmers who own the process plant.
- by farmers who supply their own small-scale still.
- by farmers who are contracted to supply to the process plant.

The background on the five specific crops shows a time lag between planting for each, starting from 3 months (hot peppers) through 18 months (vetiver) to 3 years (ylang ylang). Thus, start-up of any new business will require close synchronisation between agricultural supply and process plant commissioning, which will entail a delay of about 12 months after placing the order; and thereafter during subsequent production.

In terms of creating a sustainable supply thereafter, if the supply is from a plantation close to the process plant, management of the supply should be relatively straight-forward to plan and control. One such case in Trinidad was in anise oil production at the Orange Grove Estate.

Examples of Farmers Cooperatives in the Eastern Caribbean are the Dominica Essential Oils Cooperative Society (DEOCS) and Grenada Cooperative Nutmeg Association (GCNA). In the case of DEOCS, farmers supplied bay branches to their steam distillation plant at Petit Savanne, this having two stills. The supply often involved farmers placing their harvested branches on the side of the road to be picked up by the Co-Operative truck. Plant supply in the case of Co-Operatives was coordinated by the Factory Manager. The operation however was seasonal and the plant was unfortunately destroyed by a hurricane. In addition, around 100 small farmers process their own bay leaves in small crude stills, the oil being marketed through the Cooperative.

Supply by farmers contracted to supply to the process plant will be the most difficult to manage. Whatever system is used, daily operation of the plant requires an organised, sustainable, quantum of suitable raw materials, to supply the process.

6. Material Preparation and Extraction

The core of the supply chain is the extraction of the high value oils from the plant material. There are a number of extraction processes available (Lawrence, 1995; Tongnuanchan and Benjakul, 2014; Asbahani e al., 2015; Stratakos and Koidis, 2016; Aziz et al. 2018) in the context of the specific use in the Caribbean.

6.1 Pressing

The process of pressing is mostly applied to the production of citrus oils. In the process following juice extraction, either the spent fruits or peels are placed in a device that mechanically pierces it to rupture the essential oil sacs located on the underside of the rind. This is then centrifuged to separate the solids from the liquids and the immiscible oil is separated from the oil/water mixture by settling and siphoning off (Weiss, 1997; Tongnuanchan and Benjakul, 2014; Aziz et al., 2018).

Cold pressing is an inefficient process impractical for large-scale commercialisation in terms of the percentage of oil extracted, which can only be applied satisfactorily to peels, typically citrus peels. It is however a continuous process and suitable for high throughputs. It would only be utilised in the Eastern Caribbean if the citrus industry expanded to be able to incorporate oil extraction.

6.2 Steam/Hydro-distillation

Until towards the end of the 20th century (Guenther, 1961), separate batch operation technologies had to be used to extract essential oils and oleoresins. Thus, the extraction of essential oils was carried out mainly by either steam distillation or hydro-distillation.

A flow diagram of a typical steam distillation operation is shown in Figure 3. In steam distillation, the material to be extracted is charged into a basket, which is placed inside the distillation still, where it sits on a perforated grid. The top lid of the still is then clamped down and steam from the boiler is passed though the bed of material. The essential oil in the material vapourises and is carried off with the steam into the condenser where the oil/steam mixture condenses (Lawrence, 1995). This mixture then passes down into the separator where the immiscible oil and water separate. Once the bulk of the oil has been extracted, the supply of steam is shut off, the top lid opened and the basket removed. The spent material is then taken out of the basket, which is then refilled with fresh plant material from agricultural production for the next batch.

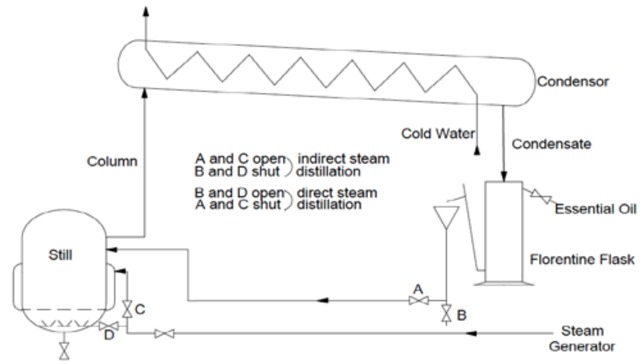


Figure 3. Steam Distillation
Source: Based on Weiss (1997)

An alternative to steam distillation is hydro-distillation, whereby the plant material is mixed with water and boiled to release the vapour/steam mixture to a condenser/separator system, similar to steam distillation (Lawrence, 1995). In terms of a standard operating procedure, the material is charged into the extraction chamber and covered with water. The system is then brought to the boiling point after which the bubbles of steam/vapourised oil mixture rise into the condenser section. When the bulk of the oil has been extracted, the supply of steam is shut off and the water/spent plant material is released from the base of the vessel. The vessel is then prepared for the next batch.

Steam/Hydro distillation are batch process which have been well established as the process for extracting essential oils from plant materials for well over 100 years. The major disadvantages in their use are that they use an elevated temperature of ~100°C causing potential degradation of the extracted oils, and relatively long distillation times up to 6 hours, in some cases (Lawrence, 1995).

The capital cost however is relatively low, this being offset by a high-energy requirement to produce the extracting fluid, steam. It cannot be applied for extracting oleoresins, which have much lower vapour pressures than the more volatile essential oils. They do however, have the versatility to process different materials at different times of the year. The main issue in that respect is in cleaning out the process plant between products to eliminate contamination.

One approach which can be applied where the crop is produced in the vicinity of the extraction process, involves transporting the distillation vessel into the fields where a mechanical harvesting system loads the vessel. Once full, the distillation vessel is returned to the process plant where it is connected to the steam supply for extraction (Lawrence, 1995). Once all of the essential oil is extracted, the spent charge is taken out of the distillation vessel and the cycle is repeated. This system was used very effectively for a number of years for Anise Oil production at the Orange Grove Estate in Trinidad.

6.3 Solvent Extraction

Oleoresins are not volatile, and have traditionally been extracted by solvent extraction using a suitable liquid solvent. Typically, the plant material is charged to a vessel containing the solvent e.g. ethanol which is then agitated to allow for thorough mixing (Watson, 2005; Tongnuanchan and Benjakul, 2014). After a suitable period of time, the vessel is discharged and the solvent/oleoresin solution is separated from the spent plant matrix. The solution is then distilled to separate the oleoresin product from the solvent which is then recycled.

Solvent extraction is a complex process with more processing steps than steam distillation. It relies on the preferential solubility of the product in an added organic phase (Weiss, 1997). Since a solvent is used to extract the oleoresin, the solvent/oleoresin mixture has to be subsequently separated by fractional distillation for product recovery and solvent recycle. This is not only expensive but it means that the oleoresin product will always be contaminated with the solvent. This can limit its use to a certain extent, particularly for food products.

6.4 Supercritical Fluid Extraction

In the last decade of the 20th century, the concept of supercritical fluid extraction (SFE) was promoted as a viable and more flexible alternative to both steam distillation and solvent extraction (Brunner, 1994; Mukhopadhyay, 2000). The extraction is effected by passing carbon dioxide at high pressure (up to 500 bar), and just above room temperature through a packed bed of the plant material charged to the extractor. The essential oil/oleoresin dissolves in the supercritical carbon dioxide and passes to the separator where the pressure is let down to release the extract. The carbon dioxide is then re-compressed to extraction pressure and recycled through the extractor.

A typical flowsheet for a three-extractor (Maharaj et al., 2017), two-separator commercial process is shown in Figure 4. Extractor volumes are usually limited to 1,500 L because of the high pressures involved. The critical temperature and pressure for carbon dioxide is 31.1°C and 73.8 bar. Such units usually operate in the range 30°C to 70°C and up to 500 bar pressure. The higher pressures will extract both essential oils and oleoresins as a mixture, but it is also possible to operate the system at sub critical conditions whereby only essential oils are extracted.

As shown in Figure 4, it shows that SFE, at the current state of development, is still a batch process. It is however usually operated with multiple vessels such that during a production operation, two of the vessels would normally be in their extraction mode with the third vessel being emptied after extraction and refilled for its next extraction. The extracted oil is collected from the base of the separators.

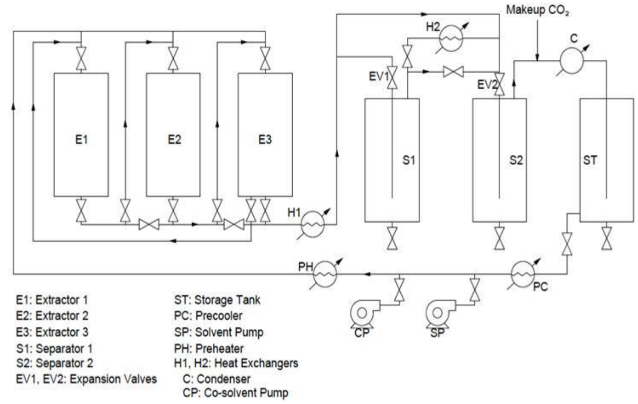


Figure 4. Flowsheet for Commercial Supercritical Fluid Extraction

The major advantage of SFE is that it can extract both essential oils and oleoresins, making it much more flexible in a multiproduct environment (Lee et al, 2020). The process also operates at temperatures not much above ambient, so that the chemistry of the extracted product is not modified significantly by the process. Extraction times are also shorter than those using the traditional techniques. The major disadvantage is capital cost. It is much more expensive than Steam Distillation. Its use however does necessitate a major supply of carbon dioxide. Carbon dioxide is recycled, but there will be small losses to replenish after the discharge/recharge operation.

6.5 Choice of Process

If the extracted product is to be an essential oil, there is a choice between steam distillation and SFE. Because of the elevated temperature associated with steam distillation, the extracted oils may have slightly different compositions than those from SFE. If the distillation product is commercially acceptable, the significantly lower capital cost will make the steam distillation process more economically viable.

If, however, the extracted product is an oleoresin, SFE would normally be used in preference to Solvent Extraction as the product is not contaminated with solvent. In addition, one of the major advantages of the use of SFE is that it can produce both essential oils and oleoresins. For instance, to produce both from a single source (e.g. turmeric), the initial extraction pressure is set near the critical pressure to extract the essential oil with little oleoresin contamination. Once the essential oil is depleted (usually after an hour of extraction), the pressure can be increased to about 200 bar to extract the oleoresin (Maharaj et al., 2017). SFE is therefore much more flexible than steam distillation, but at an increased capital cost and the need for a supply of carbon dioxide.

6.6 Material Preparation

Whichever extraction process is chosen, some form of preparation will often be necessary prior to charging the raw material to the process. This may involve washing, pre-drying and size reduction.

1) ***Washing*** **–** Root crops need to be washed to remove earth prior to processing.

2) ***Pre-drying*** – Most of the materials charged to the chosen process plant will require some pre-drying. Reducing the moisture content can have the following benefits (Vikaspedia, 2020; Jayas and Singh, 2011):
   - Increase in dry matter for each batch charge, and hence increase productivity.
   - Breakdown of internal cell structure to release oils for ease of extraction.
   - Excessive moisture in the charge can inhibit gas/particle contacting, thereby reducing extraction rates.
   - Ease of handling and size reduction.

   Pre-drying of flowers for perfume products however is not recommended. The major problem associated with pre-drying is the potential for oil loss during drying, such that over-drying must be avoided. The most appropriate pre-drying technique is natural or low temperature air drying, both of which will minimise oil losses (Dev and Raghavan, 2012). Pre-drying could be effected on a field site close to agricultural production, or close to the process plant.

3) **Size Reduction –** Many materials e.g. flowers, small leaves, will not require size reduction but others are typically milled on the process plant site to a size of less than 1 mm to increase extraction rate and reduce batch times.

6.7 Waste Disposal Issues

All of the processes described above require waste management, especially with respect to disposal of the spent plant material after removal of the valuable components. Operation of a composting operation close to the plant is an environmentally sustainable option. The space requirement will be significant but if designed and managed efficiently, the compost produced can be incorporated directly into the agricultural production system, or alternatively can be marketed separately.

Condensed water from steam or hydro-distillation - hydrosol - is also increasingly being recycled for irrigation or sold as hydrolats for aromatherapy (Price and Price, 2004). Carbon dioxide emissions from the SFE system emit only small amounts of carbon dioxide between batches and would not cause any major air pollution problem.

7. Distribution of Extracted Oils

The extracted essential oils/oleoresins are not generally appropriate for marketing directly as consumer products. It is therefore normal for the crude extracts to be further processed to extract specific components which are subsequently incorporated into the final products such as sophisticated perfumes, food flavourings or nutraceutical/pharmaceutical products.

Reference to the basic supply chain flowsheet in Figure 2 shows that the next link in the chain to be where the crude oils are introduced into the marketing system by selling to a broker. Brokers are intermediaries who buy crude oils from a wide range of producers and sell them on into the trade, or act as liaison between buyers and sellers. It is generally convenient for crude oil producers in developing countries to use this route, as the capital requirement and technological capabilities are inadequate to incorporate the process extension to the separation of the valuable components. Brokers are mainly located in Europe (like the UK, France, and Germany) and North America. They have very close relationships with the trade thereby facilitating the onward distribution towards the manufacturing of consumer products.

Besides, brokers will normally supply the next step in the supply chain whereby the crude essential oils/oleoresins are further processed to separate the various valuable components for product formulations. This process is usually one of fractional distillation, which could be carried out by the consumer product manufacturers or by an intermediary company.

The last stage in the supply chain is the blending of the isolated components, often with bulk fillers for specific user-applications prior to packaging for sale to consumers. There is considerable value added in by-passing the latter end of the supply chain, so it may be possible for companies involved in crude essential oil/oleoresin extraction to by-pass the broker system and carry out the subsequent steps on the main extraction site (see Figure 2).

In terms of the historical operations in the Eastern Caribbean to date, nutmeg oils from GCNA, and bay oil from DEOCS were mainly distributed through brokers, with the two cooperatives packaging and selling smaller amounts of consumer products that were formulated with the crude extracts. Anise oil production in Trinidad, by Pernod, involved direct transport and incorporation of the product into their beverage line in France, thereby bypassing the brokers.

8. Economic Feasibility

Notwithstanding the buoyant markets, the businesses must be financially viable. In 2004, an economic feasibility in respect of setting up a 200 hectare monocrop system geared towards the production of basil oil using steam distillation, showed that, with predicted yields and a conservative market price, an internal rate of return (IRR) of about 16% was possible (McGaw, 2004). Similar sized monocrop systems for patchouli, lemongrass and ylang-ylang were not viable. However, a multicrop system operating on more land (600 hectares) with mainly basil and shorter processing times for patchouli and ylang-ylang gave an IRR as high as 41%.

More recently, two economic feasibilities have been carried out to look at the feasibility of a SFE plant with 3 x 1000 L vessels. The first looked at the possibility of installing such a plant in Trinidad to process turmeric supplied by farmers to a mixture of essential oil and oleoresin (InvesTT, 2016a). The capital cost implication was determined to be about US$7.5m with an estimated payback of 5 years and an IRR of 21%. However, a sensitivity analysis on this economic feasibility showed that if the agricultural supply to the plant is reduced to 75%, i.e. 275 days per year, the IRR reduces to zero.

The second feasibility related to the installation of such a plant in Tobago to produce bay oil from an established 40 hectare plantation, this to be supplemented by processing vetiver from farmers (InvesTT, 2016b). The capital cost would be similar to that of the turmeric plant i.e. about US$7.5m again with an estimated payback time of 5 years and an IRR of 17%. These examples demonstrate that such ventures are worthy of further investigation towards investment and operation.

9. The Role of Research, Testing and Continual Business Analysis

If the plant extracts industry is to expand and thrive in the Eastern Caribbean it is essential that there be a R&D capability established to ensure that the industry remains at the cutting edge of technology, and is competitive in the global markets. This should involve:

1. Background research on the optimum growing conditions for the selected crops.
2. Research towards modifying the crop characteristics to maximise quality and/or yield of extract.
3. The capability to extract essential oils/oleoresins from trial plots of selected crops and crop varieties for quality evaluation and submission of samples to brokers for their evaluation.
4. Selection and testing of crop materials from which Nutraceutical/Pharmaceutical products could be extracted.
5. Determination of optimum extraction and other process conditions for both steam distillation and supercritical extraction for all of the selected products, both in terms of yield and quality.
6. Evaluation of the various techniques which may be used for separating the high value components from the crude extracts e.g., fractional distillation, and supercritical fractionation.

The Extraction Laboratory situated at the Department of Chemical Engineering at The University of the West Indies (UWI) has the capability of carrying out items 3 to 6 above with both bench scale and small pilot plant facilities for steam distillation and SFE in conjunction with product characterisation via Gas Chromatograph Mass Spectroscopy (GCMS). It is also equipped to investigate the relevant preparation methods of drying and size reduction.

The laboratory has had a successful research agenda with 5 Ph.D's to date, 2 M.Phil degrees awarded, and 5 M.Sc projects, together with a large number of B,Sc projects. Support was also given to the development of the bay oil industry in Dominica and in the initiation of the nutmeg oil industry in Grenada as well as the anise oil industry in Trinidad.

It is imperative however that the agricultural research and development work identified in 1 and 2 above be initiated in order to maximise supply of appropriate crops to the process plant. This could be through the Faculties of Agriculture and the university sector (The UWI and University of Trinidad and Tobago), in conjunction with the relevant Government Ministries of Agriculture.

10. Conclusions and Future Projections

There is significant potential for consolidating and expanding the plant extracts (essential oils and oleoresins) industry in the Eastern Caribbean to the benefit of the respective economies of the various islands, and the provision of employment opportunities. It is suggested that the approach adopted should be flexible, such that systems could be utilised to process more than one crop during any calendar year. The issues which have to be addressed are;

- The choice of crops to be exploited
- The agricultural system to be adopted
- Choice of extraction system
- Crude oil marketing
- Ownership
- Funding mechanism

Analysis of the supply chain shows that there must be a sustained and specified supply of the crop to the process plant for most of the year. The choice of extraction system will define the products for sale. Moreover, the marketing of products through brokers may be convenient, but bypassing the crude extract distribution chain through to producing consumer products can provide significant value added.

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Flow Induced Vibrations of Oil and Gas Piping Systems: Wall Pressure Fluctuations and Fatigue Life Assessment

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Abstract: *Engineers and analysts primarily rely on the Energy Institute's (EI) Guidelines for the Avoidance of Vibration Induced Fatigue Failure in Process Pipework to determine the possibility of a piping system failing due to flow induced vibration. Whilst the EI Guidelines provides a quantitative measure for the likelihood of failure and gives possible remedial actions, certain key parameters such as the fatigue life cannot be obtained. In this work a procedure for incorporating the underlying wall pressure fluctuations in a finite element model for the purpose of determining the fatigue life of a piping system is provided. Numerical simulations are used to determine the fatigue life for a flowline transporting natural gas at three different flow velocities; 65 m/s, 130 m/s and 170 m/s. The study also experimentally investigates the wall pressure fluctuations associated with single phase flow in a geometrically complex manifold. Extensive wall pressure fluctuation measurements associated with water flowing at 1.6 m/s and air flowing at 3 m/s are presented. It has been shown that owing to the dramatic changes in geometry, the pressure fluctuations associated with a fully developed turbulent flow are significantly greater than that observed at an undisturbed position. Unlike the simple 90^o elbow or mitre bend, the fluctuations within the manifold remain pronounced with no decay in amplitude. Specifically, for the case of water flowing at 1.6 m/s it is observed that the mean square pressure along the manifold falls within the range of 113 dB and 116 dB, whilst the undisturbed position had a mean square pressure of 104 dB. For the case of air flowing at 3 m/s, the mean square pressure ranged between 101 dB and 107 dB throughout the entire manifold.*

Keywords: *Fatigue Assessment, Flow Induced Vibration, Piping vibrations, Piping manifold, Random Vibration, Wall Pressure Fluctuation*

1. Introduction

The upstream and downstream oil and gas industries are major contributors to the Gross Domestic Product (GDP) of many Caribbean territories. One major asset that both upstream and downstream facilities have in common are the vast networks of process piping. Industrial plants, by their nature, transport fluids from one point to another and piping networks facilitate this core function. It is often the case that piping is responsible for 25% - 35% of the material in a processing plant, consumes 30% - 40% of the construction labor, and utilises 40% - 48% of the engineering man-hours in design, fabrication, and installation (Peng and Peng, 2009; Wu et al., 2018).

Flow induced vibration (FIV) is a common source of excitation in piping systems and occurs when the fluid being transported is forced to negotiate a change in geometry such as a piping bend or tee. The corresponding change in momentum creates strong pressure gradients beneath the turbulent boundary layer and results in a broadband excitation source. In particular, FIV can induce large fluctuating deflections and bending stresses on adjacent small bore piping connections (SBCs) potentially resulting in sudden and catastrophic failure (Garrison, 1998).

Several researchers have studied the effects of flow induced vibrations in simple and complex piping systems. Tunstall and Harvey (1968) experimentally investigated the flow in a mitre bend using flow visualisation. The work illustrated that flow downstream the bend was characterised by flow separation and a randomly switching swirling action. Bull and Norton (1981) later showed that the flow separation in the mitre bend acts as an excitation source that generates non-propagating pressure fluctuations, plane wave propagation and acoustically induced travelling waves. Bull and Norton (1981) further determined the associated wall pressure fluctuations of air with velocities between 0.2 to 0.5 Mach. In a later study, Norton and Bull (1984) reported the wall pressure fluctuations in other types flow obstructions: 90^o radius bends, 45^o mitred bends, a fully opened butterfly valve and a partially opened gate valve.

With respect to two-phase flow, Riverin (2006) measured the spectral density of the forces generated at a 90° elbow and impacting tee for different volumetric ratios of an air-water mixture. Belfroid et al. (2016) investigated the forces generated in large 6-inch diameter piping with a long radius bend when high velocity single phase and multiphase fluids were transported. Peltier and Hambric (2007) used a Reynolds Average Navier Stokes technique to predict the surface pressure power spectra in a 90° long radius bend. In a later study (Hambric et al., 2010) used the wall spectra information to calculate the structural and acoustical noise sources emitted by the piping.

Although it is evident that a wide range of research on FIV has been reported, the Energy Institute's Guidelines for the Avoidance of Vibration Induced Fatigue Failure in Process Pipework (Energy Institute 2008) is currently the only standard used to screen industrial process piping systems for potential failure due to flow induced vibrations. A major limitation of the guidelines (Energy Institute, 2008) is that it only provides crude estimates of the likelihood of failure and not detailed information such as fatigue life, which are critical for Designers and Engineers seeking to optimise the dynamic behavior of a piping system.

In this work a finite element based methodology is proposed to determine the fatigue life of a piping system subjected to flow induced vibration. The method incorporates the effects of the spatially distributed wall pressure fluctuations due to flow separation within the pipe. The efficacy of the method is demonstrated by performing numerical simulations on a flowline transporting high velocity flow streams. Comparisons are made between the results of the detailed finite element model and that of the recommendations proposed by the EI Guidelines (Energy Institute, 2008) for multiple flowrates.

Oil and gas piping networks are often routed to a piping manifold where flow is channeled and diverted to multiple locations. In the literature, flow induced vibration in piping manifolds have received little attention. Most of the studies to date, regarding piping manifolds, have focused on the hydraulic aspects of the flow as opposed to flow induced vibration and wall pressure fluctuations (Pigford et al., 1983; Bajura, 1971; Graber, 2010). As part of the work presented herein, extensive wall pressure fluctuations measurements on a complex piping manifold transporting single phase water flowing at 1.6 m/s and air at 3 m/s are presented. The key physical differences between the flow characteristics of the manifold compared to turbulent flow in a simple 90° bend are identified and discussed.

2. General Approach to Assessing Piping Vibrations

The methodology for undertaking a vibration assessment using the EI Guidelines (Energy Institute, 2008) consists of three stages. In the first stage, the section of the plant to be analysed is specified. Industrial plants often segment their entire operations into separate facilities based on the particular process or function taking place.

In the second stage, quantitative assessments of the mainline piping for each type of excitation identified in Stage 1 are carried out. The EI guidelines from the Energy Institute (2008) provides clear information on the parameters required for the flow induced vibration screening assessment. The input parameters are usually obtained from the PIDs, piping isometrics and knowledge of the operating conditions. Equations are provided to determine a parameter called the mainline Likelihood of Failure (LOF). The value of the LOF guides analysts on the actions that are required to minimise failure due to fatigue. The guidelines propose four categories of actions based on the LOFs as explained in Table 1.

Table 1. Proposed Recommendations based on the Energy Institute's Guidelines for the Avoidance of Vibration Induced Fatigue Failure in Process Pipework for Mainline Piping

Likelihood of failure	Recommendations
LOF< 0.3	The likelihood of failure of the mainline and SBCs are low. The guidelines, however, still advises that a field survey should be executed to ensure that the conditions specified in the assessment were achieved on the field.
0.5 > LOF ≥ 0.3	The likelihood of failure of the mainline is low, however, an additional assessment on the SBCs **should** be done. A field survey is recommended.
1 > LOF ≥ 0.5	The mainline **should** be redesigned or resupported to lower the LOF to an acceptable level. Small bore connections **shall** be assessed. Another alternative is to undertake experimental vibration measurements or detailed analysis to predict if the fatigue life of the piping and its branch connections are acceptable. A field survey is recommended.
LOF ≥ 1	The mainline **shall** be redesigned or resupported to lower the LOF to an acceptable level. Experimental vibration analysis or detailed modeling can also be used to predict if the fatigue life is acceptable. A field survey is recommended.

Source: Abstracted from Energy Institute (2008)

Notably, a separate assessment for SBCs on the mainline is suggested when the LOF is greater than 0.5. The SBC assessment is the third stage of screening, and considers the span-wise and cross-sectional geometry of the SBC, the type of fitting used to connect the SBC to the mainline, the number of valves on the SBC and the thickness of the mainline piping. This assessment produces a new set of LOFs with a separate set of actions as shown in Table 2.

The flowchart in Figure 1 illustrates how the screening process may be implemented for a typical industrial facility. A key feature in the recommendations includes a field visit to examine the mainline and small bore connections. Such examinations are necessary to ensure that the input data used in the screening analysis matches that which is on the field. For instance, often analysts may take credit for a piping-support only to realise that the pipe has lifted off its initial positon during the construction phase leaving the support completely inactive.

Table 2. Proposed Recommendations based on the Energy Institute's Guidelines for the Avoidance of Vibration Induced Fatigue Failure in Process Pipework for Small Bore Piping

Likelihood of failure	Recommendations
LOF< 0.4	The SBC has a low likelihood of failure. A field survey is still recommended.
0.7 > LOF ≥ 0.4	The SBC **should** be redesigned or resupported to lower the LOF to an acceptable level. Experimental vibration analysis or detailed modeling can also be used to predict if the fatigue life is acceptable. A field survey is recommended.
LOF ≥ 0.7	The SBC **shall** be redesigned or resupported to lower the LOF to an acceptable level. Experimental vibration analysis or detailed modeling can also be used to predict if the fatigue life is acceptable. A field survey is recommended.
LOF ≥ 1	The mainline **shall** be redesigned or resupported to lower the LOF to an acceptable level. Experimental vibration analysis or detailed modeling can also be used to predict if the fatigue life is acceptable. A field survey is recommended.

Source: Abstracted from Energy Institute (2008)

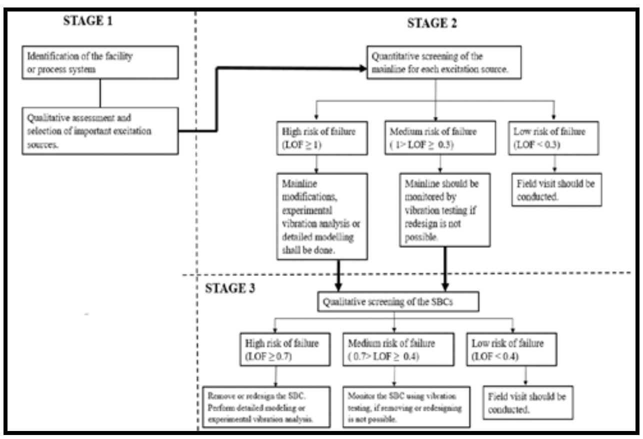

Figure 1: Flowchart illustrating the Qualitative and Quantitative Procedures of the Energy Institute's Guidelines for the Avoidance of Vibration Induced Fatigue Failure in Process Pipework

Source: Abstracted from Energy Institute (2008)

Engineers performing a field examination should pay particular attention to:

1. damaged and compromised piping supports and clamps,
2. the visible movement of lines and small bore connections,
3. the integrity of weldolets and sockolets connecting the SBC to the mainline piping, and
4. impact noises or tonal sounds and locate where they are emanating from.

Critical locations identified from the screening study combined with the points, piping spans or small bore connections that display symptoms of vibration issues from the field examinations are often then measured by using appropriate instrumentation and suitably qualified personnel. One other recommendation the EI guidelines alludes to in situations where the LOFs of the mainline or small bore are relatively large; is that a detailed analysis of the system can be conducted (Energy Institute, 2008). The EI guidelines offers this as a recommendation in recognition that a detailed analysis would provide a more accurate and informative description of the piping system's response. Such output information may include the frequencies of the natural modes that are excited, the output response in terms of velocity, stress and strain, and perhaps most importantly the fatigue life of the piping.

Inherently, a detailed analysis lowers the risk of implementing solutions to piping problems that are overly conservative or unknowingly risky. No information regarding the procedure to conduct detailed analyses for the specific excitation mechanisms are given in the EI guidelines, and in many cases upstream and downstream gas companies seek the help of specialists to perform such simulations.

3. Flow Induced Vibration

3.1 Wall Pressure Fluctuations and FIV

The response of a piping system can only be predicted if the sources of excitation are known. In the case of piping systems having a turbulent flow which is forced to navigate sharp geometric changes, one source of excitation is the underlying wall pressure fluctuation. As illustrated in Figure 2 the wall pressure fluctuation on the underside of the piping can be due to the occurrence of:

1. a naturally existing turbulent boundary layer generated on the internal piping walls,
2. low frequency plane waves traversing the piping circuit,
3. higher frequency acoustical modes, and
4. localised fluctuations occurring within the proximity of an internal disturbance due to flow separation and pressure gradients.

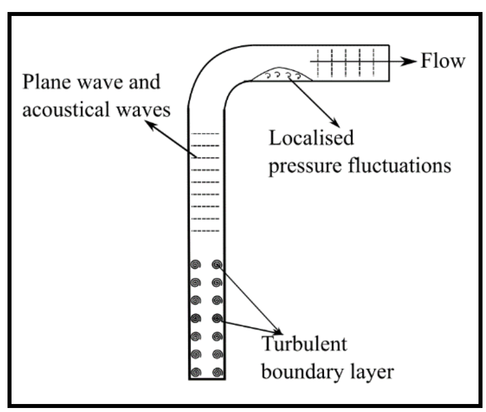

Figure 2. Sources of Wall Pressure Fluctuations due to Flow Induced Turbulence

The unsteady random nature of a fully developed turbulent flow results in pressure fluctuations in straight length pipes with no upstream internal obstruction of flow. These wall pressure fluctuations are the minimum excitation levels in a piping systems and forms a baseline signature to further understand the relative contribution of other excitation sources. The wall pressure excitations in straight piping with turbulent flow are statistically uniform along both the circumference and length of the piping system (Norton, 2003).

The acoustic field in a closed loop piping system behaves as an acoustic transmission line and is characterised by the generation, transmission, propagation and radiation of sound from the piping walls. This process can occur over the entire audible frequency range (0-20 kHz). At the lowest frequencies where the wavelengths generated are large compared to the cross sectional dimensions of the pipe only plane waves propagate and the system can be considered one-dimensional. At any instant in time, the acoustic parameters such as displacement, velocity and pressure are constant on any plane perpendicular to the direction of wave travel for a propagating plane wave. The one-dimensional acoustic theory of ducts dictate that plane wave propagation can occur at certain frequencies which are dependent on the working fluid, geometry and configuration of the piping (Jaconbsen, 2013).

3.2 Detailed FIV Analysis of a Natural Gas Flow-line with a Blind Tee

Natural gas flowlines are used on offshore platforms to connect the wellhead to a main production header or separator. Depending on the nature of the subsurface well, the flowline can transport mainly single phase gas at the early points in its history and multiphase liquid-gas mixtures at the latter end. Figure 3 shows the top view of a typical horizontal flowline that is connected on one end to the wellhead and on the other end to a pressure vessel or separator. The two major piping discontinuities on the flowline are the 90º blind tee and the small bore branch connection. A detailed finite element analysis model of the flowline will be used to determine the fatigue life of the critical locations on the mainline piping and small bore connection due to FIV. The internal diameter of the mainline piping is 78 mm and the thickness is 5.49 mm, whilst the internal diameter of the SBC is 26.7 mm with a similar thickness of 5.49 mm. A valve of mass 1.0 kg is connected to the end of the SBC. The span lengths of the mainline connection and SBC are as shown in Figure 3.

3.2.1 Wall Pressure Spectrum

The excitation mechanism for flow-induced vibration are the wall pressure fluctuations. The non-dimensional axial and circumferential wall pressure fluctuations provided by Bull and Norton (1981) due to a mitre bend can be used for the case of a blind tee since both fittings are similar geometrically. The non-dimensional power spectral densities (PSDs) and its variation along the axial length of the mitre are replicated in Figure 4.

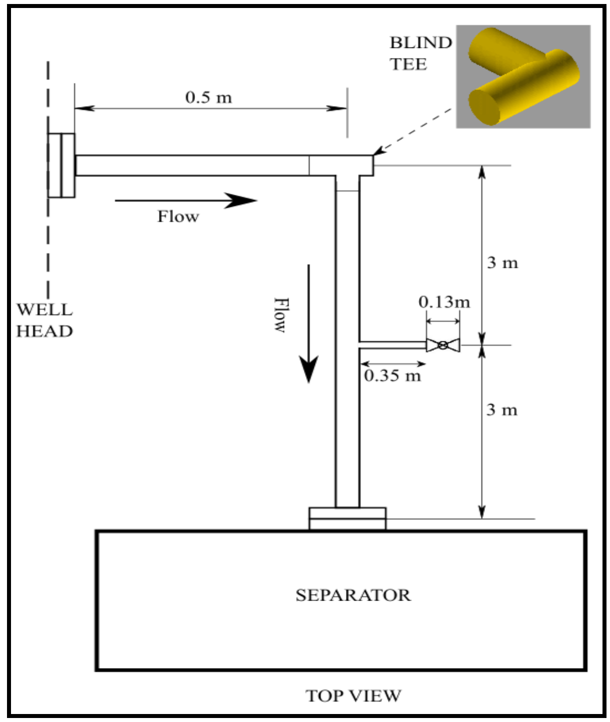

Figure 3. Flowline Connecting the Wellhead to the Separator on an Offshore Platform

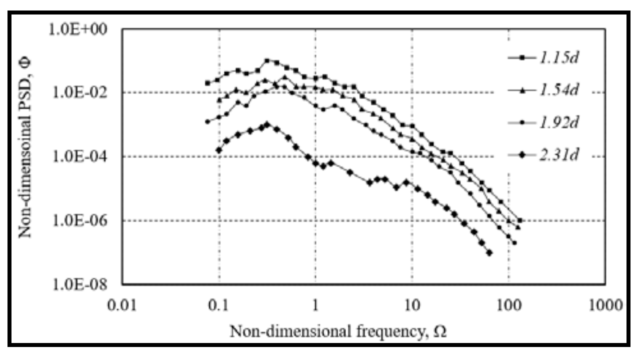

Figure 4. Non-dimensional Wall Pressure PSDs along the Axial Direction of a Mitre Bend

The non-dimensional PSD (Φ) is related to the dimensional or actual excitation PSD (ϕ) by the equation,

$$\Phi = \frac{4\phi}{\rho_f^2 U_o^3 a}, \quad (1)$$

where ρ_f is the density of the fluid, U_o is the centre line velocity of the flow, and a is the internal radius of the piping. Similarly, the non-dimensional frequency (Ω) is related to the radian frequency (ω) by the equation,

$$\Omega = \frac{\omega a}{U_o}. \quad (2)$$

Norton and Pruiti (1991) discussed how the non-dimensional PSD for the mitre can be scaled to obtain approximations for the actual wall pressure PSDs for different velocity flows and piping diameters. By comparing the magnitude of the PSDs, it is observed from the Bull and Norton (1981) study, that wall pressure fluctuations upstream of the mitre have a negligible contribution to flow induced vibration. A similar observation is made for the wall pressure fluctuations beyond 2.31 times the piping diameter downstream the mitre.

3.2.2 Finite Element Model of a Flowline

The finite element method is a useful tool for analysing the free and forced vibration characteristic of systems with complex geometry and loading conditions. A continuous structure is discretised into a contiguous set of elements and the equation of motion is given in the following matrix form:

$$[M]\ddot{q}+[C]\dot{q}+[K]q=\mathrm{F}(t) \tag{3}$$

where M, C and K are the mass, damping and stiffness matrices respectively. The term q is the displacement vector, $(\cdot)$ and $(\cdot\cdot)$ are the first and second derivatives with respect to time respectively and $\mathrm{F}(t)$ is the load vector. Owing to the complexity of large scale piping systems, finite element analysis is used to solve most dynamic problems and the basis for determining the response has its foundation in Eq. (3) above.

In this work a finite element model (FEM) was generated in the commercial software Ansys APDL 18.0 for the flowline in Figure 3. A total of 18,577 two dimensional SHELL281 elements were used with gradual refinement at the location of the mitre, small bore connection and end boundaries. The piping material was carbon steel having a density of 7,800 kg/m^3, a Young's Modulus of 200 GPa and a Poisson ratio of 0.3. The ends of the piping were treated as fixed owing to the large stiffness (and weight) of both the wellhead and separator. The valve at the end of the SBC was modelled as the same internal diameter and thickness of the small bore piping, however, the density of this piping-run was adjusted so that an equivalent mass of 1kg, similar to the mass of the valve, is obtained. The damping ratio of metallic piping is typically taken as 1% (Cremer et al., 2001; Mossou, 2003).

The first step to describing the response of the piping due to random excitation requires that the modes of vibration and the associated natural frequencies be calculated. This requires that the eigenvalue problem,

$$-\omega_n^2[M]\vec{q}+[K]\vec{q}=\vec{0}\,, \tag{4}$$

be solved. In Eq. (4), $\varpi_1,\varpi_2,\varpi_3\ldots$ are the natural frequencies with the corresponding eigen vectors, $\vec{q}_1,\vec{q}_2,\vec{q}_3....$. A modal analysis using the Subspace algorithm within Ansys extracts all modes and natural frequencies between 0.1 to 500 Hz for the entire piping system.

Conducting the modal analysis is necessary to apply the modal superposition technique to solve the inherent random vibration problem. Modal superposition characterises the piping response by linearly combining the undamped modes, usually within the frequency band of interest. Mathematically, this is represented as:

$$q(r,t)=\sum_{n=1}^{\infty}\psi_j(r)q_j(t) \tag{5}$$

where r is a spatial position vector, $\psi_j(r)$ is the undamped mode shape of order j and $q_j(t)$ is the modal coefficient. Therefore prior to conducting the random vibration or spectral analysis in Ansys 18.0, the modes are first expanded.

Random vibration theory shows that the response cross-spectral density $S_{qq}(r_1,r_2,\varpi)$ between two displacements $q(r_1,t)$ and $q(r_2,t)$ can be determined for a distributed excitation with cross spectral density, $S_{pp}(r_1,r_2,\varpi)$ from the expression

$$S_{qq}(r_1,r_2,\omega)=\int_R\int_R H^*(r_1,s_1,\omega)H(r_2,s_2,\omega)S_{pp}(s_1,s_2,\omega)\,\mathrm{d}s_1\mathrm{d}s_2\,, \tag{6}$$

where $H(r_1,S_1,\varpi)$ is the frequency response function for the response at position r_i due to a unit harmonic input at position s_i (Newland, 2012). In Ansys 18.0, a random spectral analysis was used to impose the power spectral densities of the underlying distributed pressure fluctuations. The correlations between pressure fluctuations from one point to the other decreases exponentially with axial and circumferential distance and can be considered to be uncorrelated (Durant, 2000). In conventional Finite Element packages such as Ansys APDL, uncorrelated pressures cannot be directly applied to a structure. Consequently, the wall pressure spectral densities must be transformed into uncorrelated nodal force spectral densities; a process described in Maymon (2008).

Bull and Norton (1981) gave the third-octave-band-averaged wall pressures at discrete axial locations and the magnitude of the PSDs decreased as the distance from the mitre increased. To use this information within the context of an FEM framework, the non-dimensional PSDs are converted to actual wall pressure PSDs for the fluid density and velocities of interest. In this study, the density of the natural gas flowing through the pipe is ρ_f = 4 kg/m^3 with a dynamic viscosity (μ) of 10^{-5} Pa.s. Three separate flow velocities, U_o = 65m/s, 130 m/s and 172 m/s are considered. For each velocity the four non-dimensional curves in Figure (4) are transformed to four dimensional wall pressure PSD curves at the locations, 1.15d, 1.54d, 1.92d and 2.31d downstream the mitre; where d is the diameter of the pipe and the units of the PSD is now in Pa^2/Hz.

Since the diameter of the flowline and velocities of the fluid are approximately equal to that used in Bull and Norton (1981) the scaled values are also approximately the same. The dimensionalised wall pressure PSDs are also third-octave-band-averaged values. One can approximate the time-averaged root mean square pressure in a particular frequency band, for a particular location, as

$$P_{rms} = \sqrt{\phi(f_c)\Delta f} \quad (7)$$

where $\phi(f_c)$ is the transformed wall pressure fluctuation (in Pa^2/Hz) at the centre frequency f_c and Δf is the third octave frequency bandwidth. Some lower centre frequencies and bandwidths are shown in Table 3 for different third octave bands.

Table 3. Third Octave Frequency Bands

Band	Bandwidth, Δf (Hz)	Centre frequency, f_c (Hz)
1	5.2	22.4
2	6.5	28.3
3	8.3	35.6
4	10.4	44.9
5	13.1	56.6
6	16.5	71.3
7	20.8	89.8
8	26.2	113.1
9	33	142.5
10	41.6	179.6
11	52.4	226.3
12	66.0	285.1
13	83.2	360.0

Exact knowledge of the wall pressure fluctuations at every axial position is impractical to obtain experimentally. Therefore, for the purpose of tractability we can assume that the time-averaged root mean square pressure P_{rms}, as obtained from Bull and Norton (1981), is constant both circumferentially and longitudinally in the region between measurement points. The justification for this assumptions is as follows: (1) it is inherently conservative since the amplitudes decrease with increasing distance from the mitre, (2) the number of positions measured by Bull and Norton (1981) in the axial direction is sufficiently refined to demonstrate a clear monotonic smooth trend in wall pressure fluctuations along the length of the pipe, and (3) Bull and Norton (1981) has shown for a wide range of operating conditions there is little to no variation of the PSD in the circumferential positions at any particular axial location.

The proposed regions for which the pressure is constant in the axial and circumferential directions are shown in Figure 5. Each of the four regions is associated with their respective PSD curve in Figure 4. It follows, an equivalent total force (F_{tot}) acting on a particular region in a specific frequency band (Δf) can be determined by multiplying the pressure, P_{rms} by the associated surface area it acts upon. This total force is now divided by the number of nodes in the region to produce an equivalent set of radially directed nodal forces (F_n). The nodes must be axisymmetrically distributed about the longitudinal axis of the pipe to permit an even distribution of pressure for each of the four regions.

A uniform PSD value for the force excitation acting on each node in a particular frequency band can then be obtained as $F_n^2/\Delta f$. Therefore, the power spectral density in terms of a nodal forcing function, where all the forces are uncorrelated within the excitation region $a < z \leq 2.31d$ is achieved, and the problem can be processed in the finite element software.

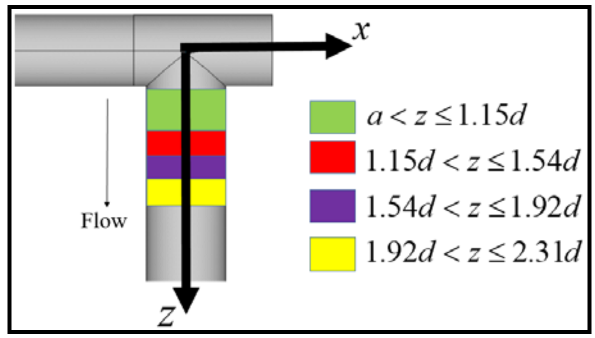

Figure 5. Regions of Constant Wall Pressure Fluctuation

3.2.3 Piping Response and Fatigue Analysis

The finite element solution generates the power spectral density (PSD) of the displacement at any node on the piping system according to Eq. (6) where the input excitation spectral density must be known. From the displacement PSD, the velocity and bending stress PSDs are important quantities that can be subsequently derived. Integrating the velocity PSD over the entire frequency band of interest leads to the temporal mean square velocity

$$v_{rms}^2(r) = \int_{\Delta\omega} S_{\dot{q}\dot{q}}(r,\omega)\,d\omega \quad (8)$$

which is a parameter that is used directly in several criteria to determine if the vibration levels are acceptable in a piping system (Moussou, 2003).

Since the piping is subjected to variable amplitude loading, a cumulative damage fatigue model is needed to determine the fatigue life of the system. The SN curve for the piping material is given by

$$N_F S^m = K, \quad (9)$$

where N_F is the number of cycles to failure, for a constant amplitude stress range S. The terms K and m are the fatigue strength coefficient and fatigue strength exponent respectively; both terms can be obtained from standards, such as BS7608 Guide to Fatigue Design and Assessment of Steel Products (BSI, 2014) and the American Bureau of Shipping's Guide for Fatigue Assessment of Offshore Structures (ABS, 2003). In this study, $K = 1.08(10^{14})$ and $m = 3.5$ as recommended for steel welded butt joints (Wirsching, 2006).

Due to its simplicity and wide range of application, Miners cumulative damage rule is the most prevalent model used to determine the damage fraction D, due to variable amplitude loading. The rule is given by:

$$D = \frac{1}{K}\sum_{i}^{M} n_i S_i^m \qquad (10)$$

where n_i is the number of cycles corresponding to the stress range S_i, and M is the number of stress ranges in the spectrum. When D is equal to unity, the cumulative damage is at 100% and the material fails. Experimentally, analysts obtain stress time histories and use techniques such as Rainflow counting to determine the number of cycles for specific stress ranges and subsequently use Eq. (10) to determine the damage fraction (Lee et al. 2005).

In analytical models, however, the damage fraction is often calculated in the frequency domain using the stress PSD. Dirlik's method is commonly used for calculating the cumulative damage based on the stress PSD from a narrow-band Gaussian process (Dirlik, 1985). Ragan (2007) provides a thorough review of the process involved in using Dirlik's method. The probability distribution function of the stress range (p(S)) in the Dirlik combines two Rayleigh and one exponential distribution functions,

$$p(\mathrm{S}) = \frac{\frac{D_1}{Q}\mathrm{e}^{-Z/Q} + \frac{D_2 Z}{R^2}\mathrm{e}^{-\left(Z^2/2R^2\right)} + D_2 Z\mathrm{e}^{-\left(Z^2/2\right)}}{2\sqrt{m_o}}. \qquad (11)$$

The terms in Eq. (11) are calculated as follows,

$$D_1 = \frac{2\left(x_m - \gamma^2\right)}{1+\gamma^2},\ D_2 = \frac{1-\gamma-D_1+D_1^2}{1-R},\ D_3 = 1-D_1-D_2,$$

$$Q = \frac{1.25\left(\gamma - D_3 - D_2 R\right)}{D_1},\qquad R = \frac{\gamma - x_m - D_1^2}{1-\gamma-D_1+D_1^2}$$

$$\mathrm{Z} = \frac{S}{2\sqrt{m_0}},\ x_m = \frac{m_1}{m_0}\sqrt{\frac{m_2}{m_4}},\ \text{and}\ \gamma = \frac{m_2}{\sqrt{m_0 m_4}}.$$

The n^{th} moment of the spectral density is given by $m_n = \int_0^\infty f^n P_s(f)\mathrm{d}f$, where P_s is the stress PSD. The expected damage fraction in time T seconds is given by,

$$E[D] = \frac{T}{K}E[P].E\left[S^m\right], \qquad (12)$$

where $E\left[S^m\right] = \int_0^\infty S^m p(S)\mathrm{d}S$, and $E[P] = \sqrt{\frac{m_4}{m_2}}$ is the expected number of peaks in the spectrum. Therefore, the time T when E[D] is unity represents the time to failure. A program, written in Matlab, is used to implement the Dirlik and calculate the estimated fatigue life of the piping system in Figure 3.

3.3 Assessment using EI Guidelines and Comparison with Detailed Analysis

Analysts screening the flowline in Figure 3 would generally follow the flowchart shown in Figure 6 to determine the LOF values from the EI Guidelines (Energy Institute, 2008). Table 1 provides guidance as to the recommended actions. The fluid viscosity factor (*FVF*) is only dependent on the dynamic viscosity of the natural gas and in this case the *FVF* = 0.1. The EI Guidelines first considers the means by which a span length of piping is supported, and then classifies it into one of four types: Stiff, Medium Stiff, Medium and Flexible (Energy Institute, 2008). The span length is defined as the distance between two fixed or partially fixed supports. As one moves from the Stiff to Flexible classifications the fundamental natural frequencies of the piping segment decreases.

Equations which are functions only of the outer diameter and span length are used to determine which classification is appropriate. For the case of the flowline, the span length is therefore 6.5 m and the calculation from the EI Guidelines (per Table 2-1 page 50) indicates that it falls into the Medium region (Energy Institute, 2008). A flow induced vibration factor (F_v) then needs to be calculated (as per Table 2-2 page 51 of the EI Guidelines). This factor depends on the span length classification, outer diameter and thickness of the piping. For the system under consideration, the $F_v = 10857$. One important point to note is that up until now in the screening analysis the momentum of the fluid was not considered; that is neither the density or the velocity. Specifically, the stiffness classification and flow induced vibration factor are only dependent on the geometry of the piping. The LOF as shown in Figure 6 only incorporates momentum of the fluid at the last stage of the calculation.

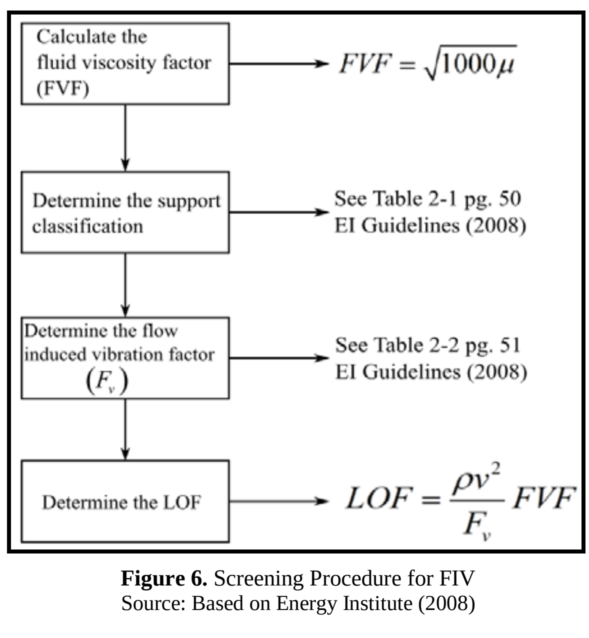

Figure 6. Screening Procedure for FIV
Source: Based on Energy Institute (2008)

The resulting LOFs of the mainline for the three separate flow rates considered are as shown in Table 4. Alongside the LOFs are the fatigue life in years predicted for the most stressed location on the piping system as obtained from the detailed analysis in Section 3.2 of this work.

Table 4. Results from the Screening Process and Detailed Finite Element Analysis for the Flowline

Velocity (m/s)	Likelihood of failure of mainline as per EI Guidelines	Likelihood of failure of SBC as per EI Guidelines	Fatigue life of most stressed position on the flowline with SBC/ Years to failure	Fatigue life of most stressed position on the flowline without SBC/Years to failure
65	0.09		665	
130	0.62	0.70	31	792
170	1.10	0.70	9	282

Source: Based on the Energy Institute (2008)

At 65 m/s the LOF is at its lowest value of 0.09 and from the EI Guidelines (Energy Institute, 2008), as per Table 1, only a field survey is required. The small bore connection is also deemed safe. The detailed finite element simulation indicates that the critical location is at the junction between the mainline and the small bore connection (see Figure 7). This position gave a fatigue life of 665 years. Typically, offshore piping is designed for a service life ranging between 10-40 years (Guo et al., 2005). Therefore, the FE model's prediction is in agreement with that of the EI Guidelines (Energy Institute, 2008).

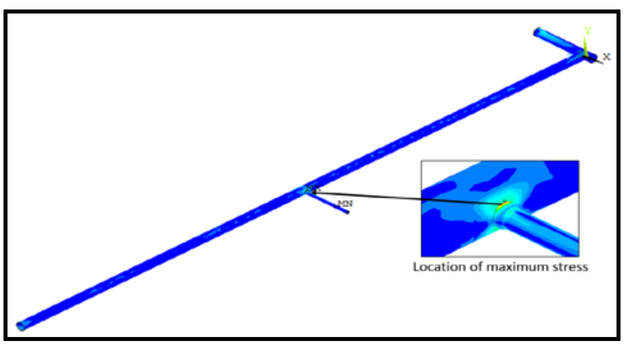

Figure 7. Detailed FEM shows that the largest stress occurs at the junction between the SBC and mainline piping. FEM Model show for $U_o = 65$m/s

Figure 8 shows the stress PSD at the critical location. The flow velocity for this case is $U_o = 65$m/s. The largest peak in the stress PSD occurs at 84 Hz which corresponds to a resonant mode where the SBC has a large displacement relative to the mainline piping. At 130 m/s the LOF is 0.62; and requires that either the mainline be resupported, redesigned or detailed analysis conducted. A screening on the small bore connection is also required in line with the procedures given on pages 73-80 in the EI Guidelines (Energy Institute, 2008). This screening process calculates one LOF based on the geometric configuration of the SBC and another separate LOF based on the location of the SBC on the mainline piping. It chooses the minimum value of the LOF citing that "both a poorly placed and poorly designed SBC need to be present to have a high LOF".

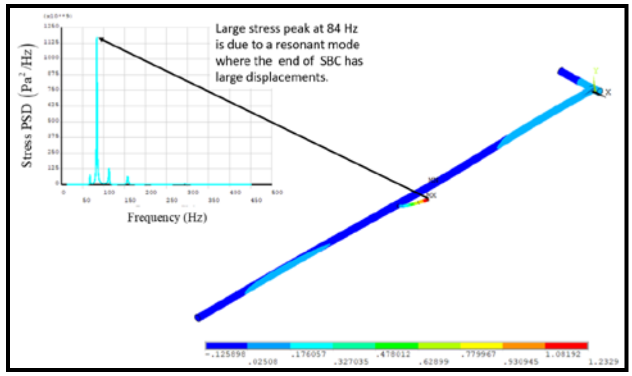

Figure 8. Stress PSD for the Critical Location on the Flowline

The SBC LOF is calculated as 0.7 for the mainline flow of 130 m/s, and therefore falls into the riskiest category as shown in Table 2. The guidelines as per the information calls for the SBC to be removed, redesigned or a detailed analysis conducted. The detailed analysis shows that the most stressed location is again the junction between the mainline and the small bore connection. The stress, however, has intensified significantly and the fatigue life has decreased to 31 years.

The piping is often designed for a maximum of 40 years, the recommendation from the EI Guidelines is correct with respect to the SBC and it should be removed or redesigned. Upon removing the SBC from the mainline the flow of 130 m/s was once again simulated through the piping and the largest stress was found to be at the edge of the flowline where it was fixed to the wellhead (see Figure 9). This critical point gave a fatigue life of 792 years. Therefore, the EI guidelines is conservative in recommending that the mainline be redesigned or resupported.

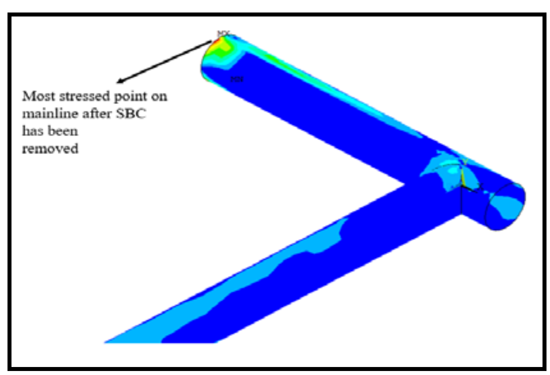

Figure 9. Most Stressed Location on Mainline Piping after Removal of the SBC

At 170 m/s the LOF is 1.1; and falls within the most severe classification in Table 1. The mainline is required to be resupported, redesigned or detailed analysis conducted. The LOF of the SBC, which is required to be calculated, is determined to be 0.7 as well. Hence, as in the previous case the guidelines call for the SBC to be removed, redesigned or a detailed analysis to be conducted.

The detailed analysis shows that the most stressed location at the junction between the mainline and the small bore connection has intensified even more. The fatigue life has now decreased to just 9 years. The recommendation from the EI Guidelines regarding the SBC is once again correct (Energy Institute, 2008). After removing the SBC, the mainline once again had its largest stress located at the edge of the wellhead and a fatigue life of 282 years was calculated. This illustrates that even when the LOF is greater than one, the suggested action for the mainline is too conservative.

One drawback of the EI Guidelines' screening process for FIV is that it fails to take into consideration the orientation of the SBC (Energy Institute, 2008). Consider the case where the SBC is located at the same axial position along the length of the flowline but rotated to lie in the vertical plane as shown in Figure 10. Simulations for the three flow velocities show that although the most stressed location is still at the junction between the SBC and the maninline (see Figure 11), the stress magnitudes have been reduced.

Table 5 shows the fatigue lives for a flowrate of 65 m/s, 130 m/s and 170 m/s are 1951 years, 143 years and 30 years. It is important to note that the LOFs of neither the mainline or SBC have changed because of the rotation of the SBC. It is appropriate for the lowest and highest flow velocities in their recommendation, but is conservative for a flow of 130 m/s (Energy Institute, 2008).

Rotating the SBC is one action that can be taken to reduce the stress levels of the SBC in this particular case. In many situations, however, the physical space may not be available to execute such a change and an alternative modification is required. This challenge is particularly relevant to Brownfield projects where other additional piping routes may already exist in close proximity to the area of interest.

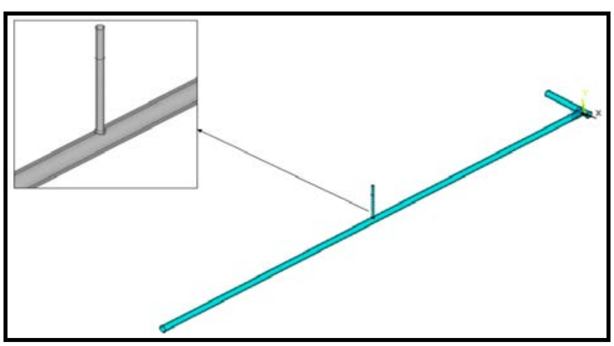

Figure 10. Vertically Oriented SBC on Mainline Piping

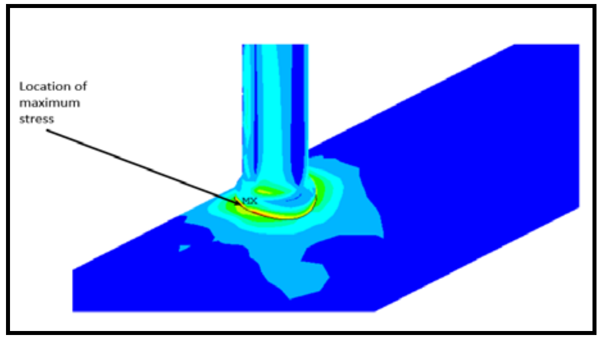

Figure 11. Largest Stress Point on Flowline with a Vertical SBC

Table 5. Results from the Screening Process and Detailed Finite Element Analysis for the Flowline with a Vertical SBC

Velocity (m/s)	Likelihood of failure of mainline as per EI Guidelines	Likelihood of failure of SBC as per EI Guidelines	Fatigue life of most stressed position on the flowline with SBC/ Years to failure
65	0.09		1951
130	0.62	0.70	143
170	1.10	0.70	30

Source: Based on Energy Institute (2008)

The use of an external clamp is a second option that can be used to restrain a SBC from vibrating excessively thereby reducing the stresses at its junction. The clamps are often bolted around the mainline piping and then connected to the end of the SBC, thus providing the constraint. Engineers are advised not to restrain SBCs from any other position other than its mainline, as the effects of thermal expansion may cause the mainline to move independently with respect to the constrained end of the SBC, resulting in large stresses being induced at its junction.

For the horizontal small bore under study a clamp with lengths shown in Figure 12 is used to reduce stress levels at the junction. The clamp is made of a hollow tube steel section with inner radius 0.01 m and thickness 7 mm. The material properties are taken to be the same as the steel piping. The clamp is incorporated in the detailed FE model using BEAM188 elements.

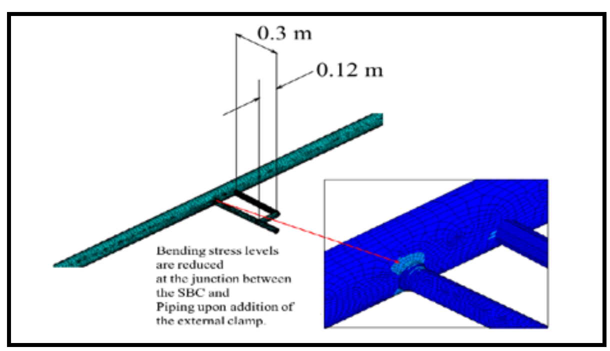

Figure 12. Reducing the Vibration of an SBC by Clamping it to the Mainline

Simulations are then carried out for the flow of 130 m/s and 170m/s, respectively. The largest stress on the piping systems still occurred at the junction of the SBC and mainline, however, the reduced stress PSD resulted in a fatigue life of 142 years for the 130 m/s flow and 44 years for the 170 m/s flow. This represents a 35-year increase in the lifespan for the higher flow rate and a 111-year increase for the lower flowrate. Both SBCs are, therefore, now within acceptable limits.

4. Piping Manifolds

4.1 Wall Pressure Fluctuations in a Piping Manifold

The flow mechanism and pressure fluctuations in a piping manifold are dependent on the piping geometry, flowrate, and intrinsic properties of the fluid. A series of experiments have been carried out to determine the wall pressure fluctuations in a specific piping manifold. A schematic of the test rig is shown in Figure 13. The manifold studied can be deconstructed into three major geometric components: A. The impacting tee, B. The 90º branched tee and C. The 90º radius bend. Each of these geometric configurations have received independent attention from a considerable number of researchers as discussed in the preceding sections. It also known that each of the aforementioned configurations have unique flow patterns and pressure fluctuations which may also change as a flow regime transitions from single phase to multiphase mixtures.

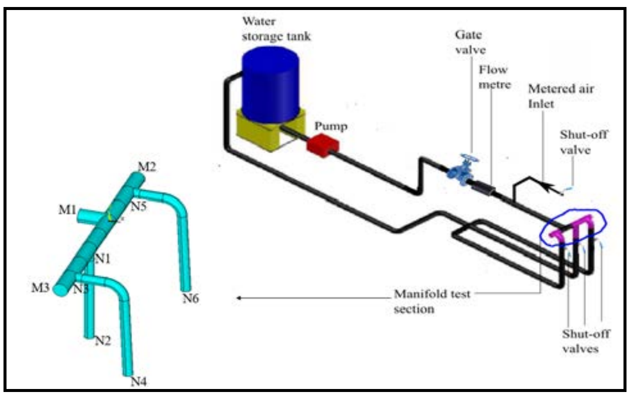

Figure 13. Experimental Test Rig to Investigate the Wall Pressure Fluctuations in Piping Manifolds

The test rig was designed to channel water at ambient temperature from a large storage tank to the manifold test-section. A single impeller Aurora 1070 centrifugal pump pushes water through the piping which has an inner diameter of 77.93 mm and a thickness of 5.49 mm. Water flows through a fully opened gate valve and GPI TM-300F turbine metre before it enters the manifold. A WIKA Type 232.34 pressure gauge was installed to measure the water inlet pressure before entry to the manifold. The internal piping diameter remains the same dimension from the pump outlet to the test manifold inlet, and as a result, there are no upstream disturbances of the fluid prior it entering the manifold.

The test inlet and the distribution channel of the manifold (M1-M2-M3) have a diameter and thickness of 77.93 mm and 5.49 mm, respectively, which is the same as the upstream mainline piping. The ends, M2 and M3, of the distribution channel are closed off using a 3-inch (76.2 mm) nominal diameter hemispherical cap designed according to the standard ASME B16.9 (ASME, 2001). The distribution channel splits the flow into three separate piping channels each having an internal diameter of 52.5 mm and thickness 3.91 mm. The leg N1-N2 is a straight run of pipe directed vertically downwards whilst the legs N3-N4 and N5-N6 both exit on the horizontal plane and are then directed vertically downward. Both the N3-N4 and N5-N6 legs contain a long radius elbow as specified in ASME (2001) with an internal diameter 52.5 mm and thickness 3.91 mm.

Each outlet leg has a ball valve with similar internal radius which can be used to prevent flow through the associated leg. The outlet ball valves are labelled BV1-BV3 for ease of reference. The material for the upstream piping and fittings as well as the test-manifold were all fabricated from carbon steel. All flanges and fittings were welded to the main piping using full penetration butt-welds. The piping downstream the ball valves BV1-BV3 were fabricated from galvanised steel. The downstream piping acts as the return line to the tank and has an internal diameter of 52.5 mm. A range of supports (not shown in the diagram) were placed at several locations to reduce the static stresses on the piping as well mechanical vibrations of the rig. The specific lengthwise dimensions of the manifold and the measurement positions are shown in Figure 14.

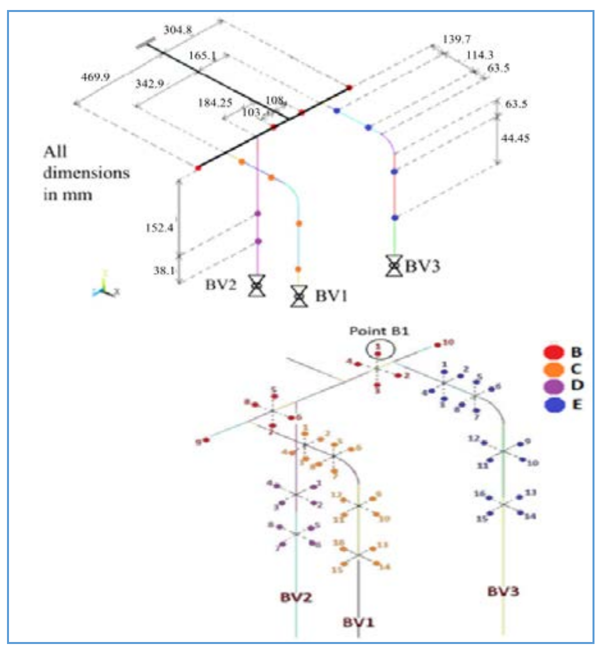

Figure 14. Measurement Locations and Labelling Scheme

In order to measure the underlying wall pressure in the piping manifold, three separate PCB S113B28 pressure sensors were used. At each position along the length of the piping, four measurements were taken at the 0º, 90º, 180º and 360º angles. Two additional points at the centre of each end cap on the manifold were also measured as well a point 15 diameters just downstream the pump to provide a baseline pressure fluctuation for the undisturbed turbulent flow. The undisturbed point is given the notation AX1 from this point on. To accommodate all the measurement points, a total of 51 holes were drilled and tapped such that each sensor can be threaded into place. Owing to the large number of measurement points a colour coded legend is proposed in Figure 14. For instance, the point B1 represents a measurement taken at point 1 on the red dot (circled in diagram).

Specialised bushings were designed for the pressure sensors to be flush mounted with the inside wall of the pipe. The pressure sensors are connected to a multi-channel Kistler Type 5134 power supply. An integrated low-pass filter of 1,000 Hz was used to process the signal prior to sampling. The voltage obtained from the pressure sensors was sampled by a National Instruments NIUSB 6009 analog to digital converter (ADC). An in-house data acquisition program created in National Instruments LabView was used to control the ADC which collected data at a sample rate of 5,000 Hz for two minutes. The two-minute duration was deemed sufficient since the mean square averages were asymptotic after this period.

The test rig (see Figure 13) also incorporated a branch connection that enabled compressed air to be transported through the test manifold. The side branch made of galvanised steel had an internal diameter and thickness of 15.8 mm and 7.11 mm, respectively. Pressurised air from a Kellog 452TV compressor located far upstream of the mainline pipeline was used to investigate the flow of single phase air. A needle valve was added to the line to control the flow of the incoming air into the test manifold. and a check valve and ball valve were located on the branch connection to prevent reverse flow and permit shutting the air on or off respectively. To measure the incoming air-pressure a Wika pressure gauge was used, whilst to measure the air flow a Hedland Flow Meter H771A-150 was included. Since the water storage tank is opened to atmosphere, the air that flows into the tank (unlike the water) never recirculates.

Observing the test rig in its entirety, one can recognise that by closing the air shut-off valve and needle control valve, the air to the manifold is stopped. Upon opening the gate only single phase water passes through the manifold. Similarly, by closing the gate valve and opening the air-line ball valve and needle valve only single phase air passes through the manifold. Evidently, simultaneously opening the gate vale and air valves allows a multiphase mixture to flow through. One can then recognise that by controlling the positions of the gate valve and needle valve along with the outlet manifold ball valves BV1-BV3, the test rig facilitates a wide range of single phase and multiphase flow conditions in several different scenarios.

4.3 Experimental Results and Analysis

Power spectral densities of the wall pressure fluctuations are presented for the following inlet flow conditions:

- Single phase water with an inlet velocity 1.6 m/s and a Reynolds number of 108000.
- Single phase air with an inlet velocity 3 m/s and a Reynolds number of 15844.

Figures 15 and 16 show an example of the variations of the wall pressure fluctuations along the distribution channel and the outlet legs of the manifold for the fully formed turbulent flow of water. On each graph, the PSD of the wall pressure for the undisturbed position (AX1) is also included for comparison.

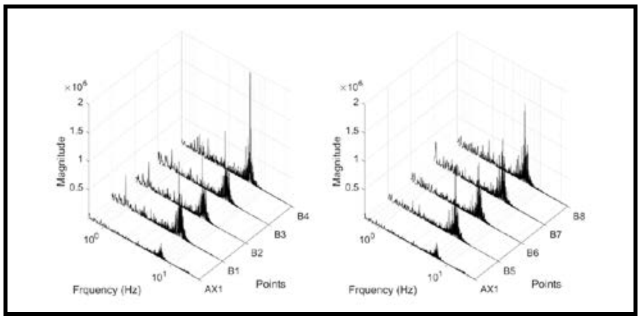

Figure 15. Wall Pressure Fluctuation of Water Flowing at 1.6m/s for Points AX1-B9

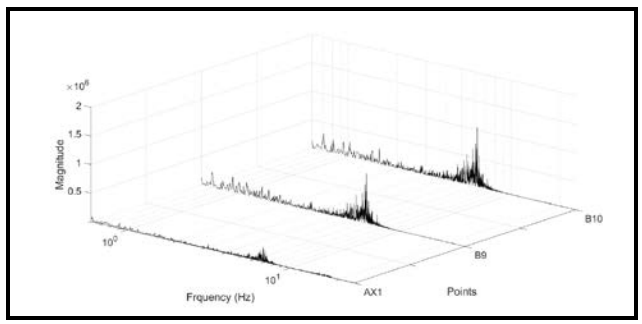

Figure 16. Wall Pressure Fluctuation of Water Flowing at 1.6m/s for Points B9-B10

It is generally observed that the amplitudes in the distribution channel and outlets of the manifold are larger than that of the undisturbed position (AX1). The amplitude of the PSD for all points on the entire manifold are small at the lowest frequencies but show a clear increase between the frequency band of approximately 4-8 Hz with a distinct peak occurring at approximately 6 Hz. Beyond 8 Hz, the amplitudes for all points decrease to negligible levels. The peak within the region of 4-8 Hz is due to the summation of the baseline straight pipe turbulence, a low frequency plane wave and localised flow disturbances. The negligible amplitudes at the higher frequencies indicate that the high frequency acoustic waves were not excited in this piping system. In systems where the velocities and Reynolds numbers are relatively low, similar results have been reported by several authors (Riverin and Pettigrew, 2007; Wang et al., 2002; Tanaka et al., 2016). The position B4 recorded the largest peak and was greater than the undisturbed position by approximately 17 dB. The time averaged mean square pressure levels for each location is calculated and shown in Figure 17.

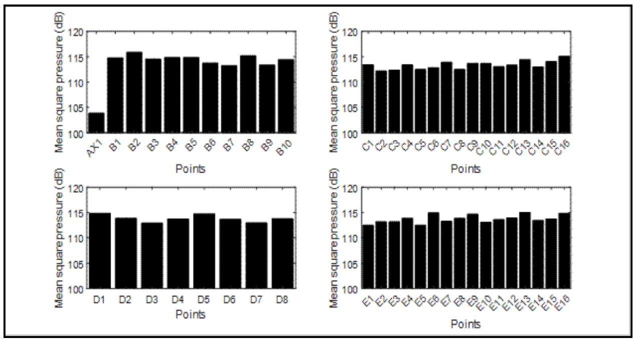

Figure 17. Mean Square Pressure Levels across all Points on the Manifold for Single Phase Water

By analysing the mean square pressure for each point it is observed that all points on the manifold have a mean square value between 113 dB and 116 dB. This is significantly higher than the undisturbed position, which has a mean square pressure of 104 dB. One can therefore conclude that since the baseline wall pressure of the straight pipe is significantly smaller in magnitude than that of the manifold, it must be the case that the contribution of the plane wave propagation and localised turbulent pressure fluctuations contribute significantly more to the wall pressure than the turbulence in the straight piping. It is also clear that these pressure fluctuations are strong enough to propagate through the entire manifold as there is no noticeable attenuation of the mean square pressures along the axial direction of the distribution piping straight through to the outlet piping legs. The variation in pressure fluctuations for the circumferential points at a particular location is also minimal.

Figures 18 and 19 show similar variations of the wall pressure fluctuations along the manifold for single-phase air. The shape of the wall pressure spectrum is similar to that of single phase water. The band of large amplitude pressure has, however, now shifted to be between 0.8 Hz and 2 Hz. Generally, the largest peak occurs at approximately 1.2 Hz. The mechanism which causes these increased pressure levels include non-propagating turbulent disturbances, plane wave propagation and to a much lesser extent; the turbulence associated with the straight piping.

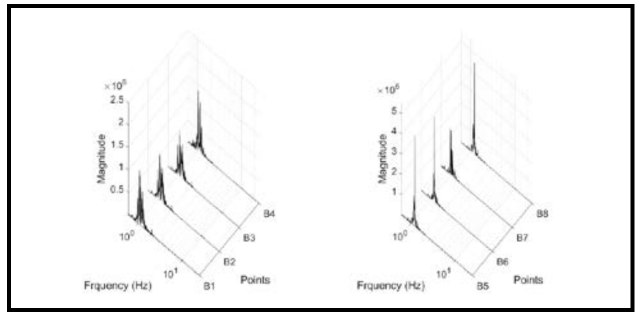

Figure 18. Wall Pressure Fluctuation of Air Flowing at 3m/s for Points B1-B8

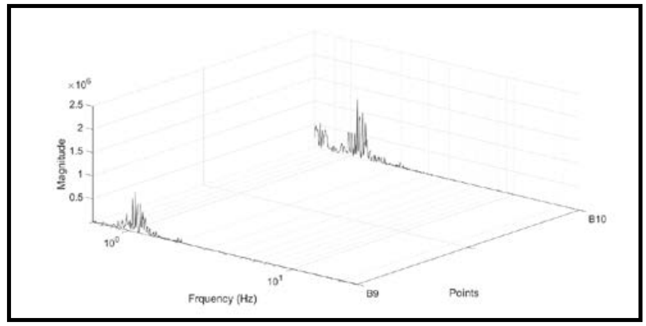

Figure 19. Wall Pressure Fluctuation of Air Flowing at 3m/s for Points B9-B10

A three-dimensional finite element model generated with the commercial finite element software Ansys APDL is used to predict the natural frequencies of the plane waves in the piping system when air is present. The density of air is taken as 1.225 kg/m^3 and the speed of sound in air as 343 m/s. The element type selected is Fluid30. The piping starts at the closed gate valve and ends at the point where the fluid enters the inside of the tank filled with water; both ends are treated as a large impedance mismatch. The branch connection for the inlet air is also included with its entry pressure of 345 kPa. A total of 1,692,975 elements are used for the simulation (see Figure 20). The fundamental natural frequency is calculated to be 2 Hz which is in close proximity to the experimentally observed 1.2 Hz. The mode shape also indicates that the oscillations take the form of propagating plane waves. The model also predicts a number of other plane wave acoustic modes at increasing frequencies, however, similar to the case of water these were not excited due to the relatively low inlet velocity.

The mean square wall pressures are also calculated for the points on the manifold as air passes through the system as shown in Figure 21. Typically, the values lie between 101 dB and 107 dB which shows that there is more variation between measurement points for the case of air as opposed to water. Similar to the case of water, however, the pressure fluctuations do not attenuate with distance along the manifold and remain relatively large. The variation in pressure fluctuations for the circumferential points at a particular location are observed to be more pronounced compared to the case of water for all the output legs. In certain cases, two points on the same circumferential plane may vary from 4 dB to as high as 6 dB.

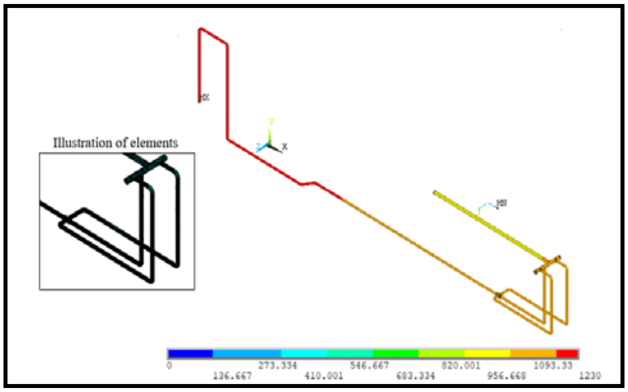

Figure 20. Plane Wave Acoustic Mode at 2 Hz for Air Volume in the Piping System

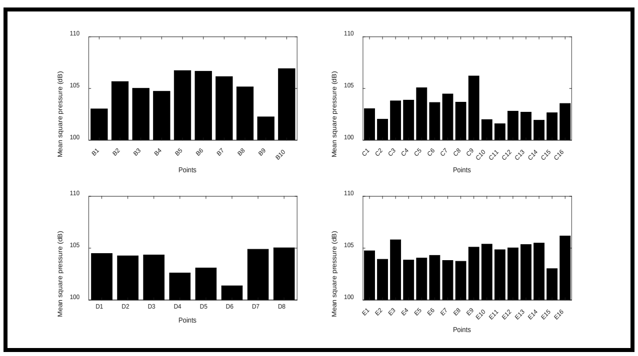

Figure 21. Mean Square Pressure Levels across all Points on the Manifold for Single Phase Air

5. Conclusions

The assessment of piping vibrations in oil and gas processing plants is a compulsory activity required to ensure that the structural integrity of a piping system is not compromised. In the preceding sections, a method to incorporate the random wall pressure excitations within the context of a finite element model to determine the fatigue life at critical locations is described. A specific industrial example of a high velocity gas stream transported through a flowline with a single SBC is used demonstrate the procedure involved. A comparison is made between the results of the detailed finite element model and that of the recommendations by the EI Guidelines for different flowrates.

In general, it is observed that the EI Guidelines is conservative in its recommended actions for the mainline piping. Finite element simulations show that for a range of flowrates the mainline piping stress levels result in fatigue lives that are much greater than the standard design life of 40 years. Conversely, it is also observed that the EI Guidelines generally provided the correct recommended actions for the SBC. Finite element simulations showed that in cases where the fatigue life of the small bore was less than 40 years, the EI Guidelines recommended that it be resupported or removed.

Although, the EI Guidelines recommends taking corrective action for small bore connections prone to failure, it cannot quantitatively evaluate the effectiveness of the change. In this work it is also demonstrated how the finite element model can be used to quantify the increase in fatigue life by taking two corrective actions on the small bore: (1) changing the orientation of the SBC and (2) adding a piping clamp between the mainline and the SBC.

The importance and complexity of the piping manifold in oil and gas industries are discussed. Specifically, the lack of research into the role that wall pressure fluctuations play in generating flow induced turbulence in a piping manifold is highlighted. In this study, the wall pressure fluctuations for a complex piping manifold is investigated for single-phase water flowing at 1.6 m/s and air at 3 m/s separately. Extensive dynamic wall pressure measurements are taken at numerous axial and circumferential points along the manifold. The spectral content of the wall pressures for the case of water indicates that the amplitudes are significantly larger within the manifold compared to an undisturbed upstream position. The increase in wall pressure fluctuations is due to the propagation of a plane wave and localised turbulent action.

Similar observations are made for the case of air flow where finite element simulations are used to validate the presence of a dominating acoustic plane wave. The temporal mean square pressure levels are also calculated and compared across all points on the manifold for both fluids. For the case of water, the pressure levels for each position generally lie within 113 dB - 116 dB whereas for the case of air they lie within 101 dB - 107 dB. Therefore, the pressure pulsations in the manifold are intense enough to propagate throughout the entire manifold, as there is no noticeable attenuation along the axial direction of the distribution piping or the outlet piping legs. In terms of future experimental work on the manifold, it is necessary to investigate the pressure fluctuations at higher flowrates. In this way, the contribution of higher order acoustic modes to flow induced vibration may be obtained.

The results and analysis presented in this study have been limited to single-phase fluid flow. It is often the case, however, that the fluid being transported in industrial pipes are multiphase, consisting of both gas and liquids. Multiphase fluid flow is far more complex than single-phase flow primarily because the flow regime depends on the velocity of the constituent phases. For instance, Mandhane et al. (1974) produced a widely used flow pattern map that distinguishes between the stratified, bubble, annular and slug flow regimes. The EI guidelines suggests that a multiphase fluid can be treated similar to that of a single-phase fluid upon calculating the equivalent density and equivalent velocity of the mixture (Energy Institute, 2008). This is a crude assumption and is yet to receive scrutiny on its range of validity.

A number of recent studies have also indicated that for multiphase flow in piping systems, the underlying power spectral density changes as the gas to liquid volumetric ratio changes (Belfroid et al., 2016; Riverin et al., 2006). This will also lead the dynamic response of the process piping system to behave differently compared to single-phase flow. Therefore, although the inclusion of multiphase fluid flow is beyond the scope of this study, incorporating such effects is the next reasonable step forward.

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Special Paper:

Hydraulic Model Study of Arena Dam Spillway Works, Trinidad

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Abstract: *The work reported in this paper was carried out by the first author - the late Professor Harry Orville Phelps (1929-2018) - in the Fluid Mechanics Laboratory of the Department of Civil and Environmental Engineering at The University of the West Indies at St. Augustine in 1975, when the third author assisted him as his graduate assistant. Unfortunately, this physical model study was not published in the lifetime of Professor Phelps. The third author found a copy of the report prepared in 1975, while preparing a memorial for Professor Phelps, published concurrently in the West Indian Journal of Engineering as well as the Journal of the Association of Professional Engineers of Trinidad and Tobago. Moreover, for the sake of preserving the integrity of original work, it is essentially unaltered for publication. Finally, it is hoped that its publication will add to the history of landmark hydraulic engineering structures built in Trinidad, and indeed in the Commonwealth Caribbean, and equally to Professor Phelps' legacy.*

Keywords: *Dam, Spillway, Scale-Model, Trinidad, Water Supply*

Notation:

- d_0 - *mean depth of flow at head of spillway channel*
- d_1 - *mean depth of flow at tail of spillway channel*
- *n - manning's roughness factor*
- *q - discharge per unit width*
- *u - percentage of air flow*
- *v - mean velocity of flow*
- v_a - *ritical velocity for air entrainment*
- $v*$ - *maximum velocity in spillway channel*
- *F - Froude Number*
- *K - a constant in the equation for air entrainment – eqn. (5)*
- *L - distance of toe of hydraulic jump from upstream end of stilling basin*
- Q_p - *discharge in prototype*
- Q_m - *discharge in model*
- *R - hydraulic radius*

1. Introduction

This report relates to a hydraulic model study of the overflow structure, spillway channel and stilling basin for the Arena Dam of the Caroni-Arena Water Supply Project. Photographs 1 and 2 show the location of the Arena Dam, and its overview, respectively. The essential features of the design are shown in Figures 1 and 2.

The overflow structure, to be built of concrete, was to consist of an entrance section with a base sloping away from the spillway crest at a gradient of 1 in 9.25, and sloping sides, giving a trapezoidal section. Curved vertical walls – quadrants of a circle of radius 25ft. in plan were designed to guide the flow from the reservoir to the spillway channel. At the crest of the spillway, the flow was designed to enter the channel with a direction parallel to the axis of the channel.

The spillway crest was 50 ft. wide with a radius of curvature in the vertical plane of 62.48 ft. In order to accommodate an access road to the dam, the walls of the

Photo 1. Location of the Arena Dam, Trinidad
Source: Water and Sewerage Authority

Photo 2. An Overview of the Arena Dam (Source: Water and Sewerage Authority)

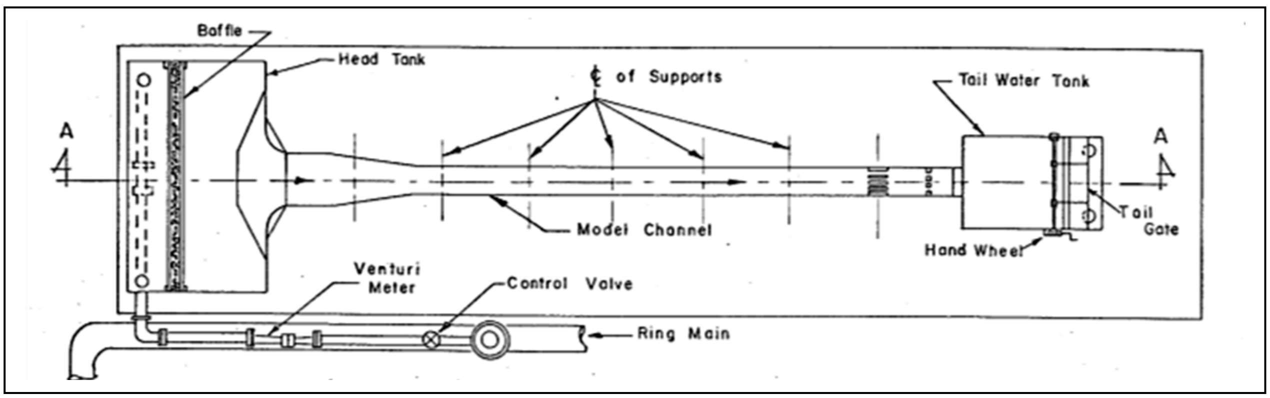

Figure 1. Layout Plan of Spillway – Caroni Arena Dam

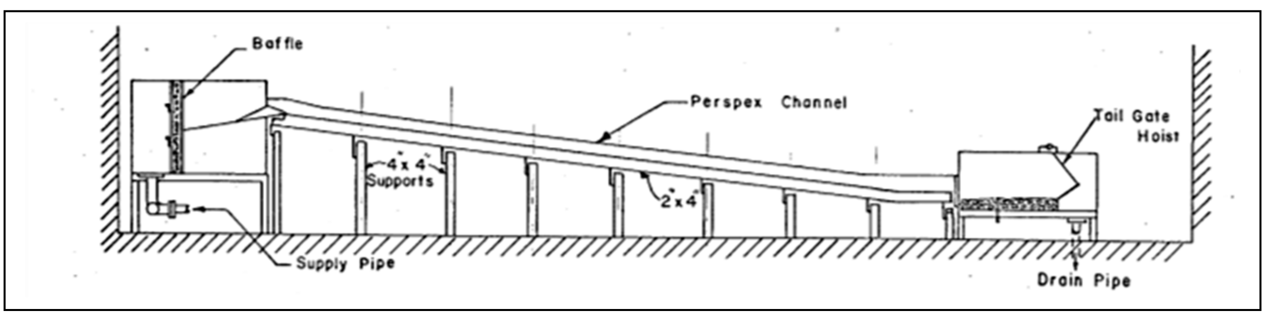

Figure 2. Layout Plan of Spillway – Caroni Arena Dam

first 25 ft. of the spillway channel were designed to act as abutments for a bridge across the channel.

These abutments were vertical and parallel to the channel axis. A converging transition channel of rectangular section joined the end of the 50 ft. wide channel emerging from the spillway crest to the main 20 ft. wide channel which was to lead to the overflow to the stilling basin. The slope of the 670 ft. long spillway channel, including the transition section, was 1 in 9.75 and ended at a horizontal stilling basin.

The high velocities anticipated at the end of the spillway necessitated inclusion of a stilling basin for dissipating energy and inducing the change from super-critical to sub-critical flow through a hydraulic jump. The basin was of conventional design being preceded by a row of 'chute' blocks at the end of the spillway channel and having a row of 'floor' blocks and a terminal sill. The retarded water would then flow down the tailwater channel to the Arena River.

The main objectives of this study are as follows:

1) To design and construct a scale model of the spillway.
2) To test the model under various flow conditions up to a comparable flow of 3,000 ft^3/s for the prototype.
3) To vary the flow conditions and configurations adequately to acquire data for evaluation of hydraulic performance of the entrance, transition, chute and stilling basin.
4) To vary the tailwater level in order to examine its effect on the stilling basin.
5) To adjust the geometric dimensions as may be required to improve performance.

2. The Model

2.1 Design Criterion

The model was constructed to a scale of 1 in 24. The choice of scale was sufficiently large to enable meaningful results to be obtained and at the same time permitted construction to a convenient size for the available space in the Hydraulics Laboratory of the Faculty of Engineering, The University of the West Indies (UWI).

In accordance with the Froude criterion for similarity between prototype and model, the scale ratios for velocity (v), discharge (Q) and Manning's roughness factor (n) were as follows:

$$\frac{v_m}{v_p} = \left(\frac{1}{24}\right)^{\frac{1}{2}} \quad (1)$$

$$\frac{Q_m}{Q_p} = \left(\frac{1}{24}\right)^{\frac{5}{2}} = \frac{1}{2821.3} \quad (2)$$

$$\frac{n_m}{n_p} = \left(\frac{1}{24}\right)^{\frac{1}{6}} = \frac{1}{1.698} \quad (3)$$

where subscripts m and p denote model and prototype respectively. Assuming a roughness factor, n = 0.015 for the concrete surface of the prototype, the required model roughness factor n_m, calculated from Equation (3), was 0.0088. Perspex (lucite) was chosen as the material for the spillway channel because its roughness factor is in the range 0.008 to 0.010 (Chow, 1959), and also because its transparency facilitated observation of the flow.

2.2 Layout and Construction

The general layout of the model is shown in Figures 1 and 2. A galvanised iron (G1) tank 10 ft x 6 ft x 4 ft high, representing the reservoir was fitted with vertical baffle, 4ft from the spillway, made up of ¾ inch gravel between two screens. Water entered the tank from the supply pipe connected to the laboratory ring main through two openings in the base of the tank, located at its corners on the far side of the baffle. The supply of water was conducted to the reservoir tank by 5 inches diameter pipe which was incorporated a control valve and Venturi Meter for flow measurement. The entrance section to the spillway was fabricated of marine plywood and painted to give a smooth impermeable surface which simulated the roughness of concrete in the prototype. Approaches to the entrance section representing the upstream face of the dam were fabricated of GI sheet attached to a frame and extended back to the baffle. The vertical approach walls were also fabricated of GI sheet.

Four perspex sections, each with flanged ends, were bolted together to the entrance section to form the spillway channel and stilling basin. The latter was provided with a base which could be easily withdrawn from the main structure to facilitate changes in the stilling basin elements.

At the downstream end the stilling basin was bolted to the tailwater tank, 6ft x 4ft x 3ft, in which the level could be adjusted by raising or lowering the tailwater gate controlled by a worm gear. Observation of the tailwater level was facilitated by a piezometer well fixed to the side of the tailwater tank and connected to the flow in the tank through a hole at its base.

Provision was made for the drainage of flow from the tailwater tank by two 5-inch diameter openings at the downstream end of the tank. These were connected to a single drain pipe by two branches, and the flow was then led to 12-inch wide flume which discharged over a weir into a weighing tank. Discharge measurements could therefore be made by three independent methods: a Venturi Meter, a sharp-crested weir and a weighing tank.

The perspex spillway channel was rigidly fixed to two 2 inch x 4 inch beams, which in turn were supported at regular intervals by pairs of vertical 4 inch x 4 inch posts. The connections between the 2 inch x 4 inch beams and the twin posts were adjustable. This arrangement provided a simple yet effective method for setting the channel on grade.

3. Measuring Techniques

3.1 Discharge

As stated previously, three independent methods for measuring discharge were employed. However, the calibrated weir and Venturi Meter were used mainly for preliminary tests and to facilitate rapid adjustments of discharge. The weighing method was the most accurate and was used for development of the calibration curve. The experimental error for equivalent prototype discharges lower than 2,000 ft^3/s was less than ± 1%, while that between discharges 2,000 ft^3/s and 3,000 ft^3/s was in the range ±1% to ± 2.5%.

3.2 Water Levels

All water levels, in the reservoir, the channel and the tailwater piezometer well – were measured with depth gauges capable of measurement to the nearest 0.01 inches (0.02 ft. in the prototype). The gauge in the reservoir head-tank was located beyond the zone of drawdown on the spillway crest at the side of the tank. For channel measurements the gauge was supported on rails suspended across the sidewalls, while the tailwater gauge was fixed to the side of the tailwater tank.

3.3 Setting of Channel on Grade

By means of the supporting bolts, the channel could be adjusted both longitudinally and laterally. Adjustments were made with the aid of a precise Engineer's level and a steel scale with a vernier, with which measurements could be made to the nearest 0.001 inches.

4. Calibration of Spillway

The first series of calibration tests was carried out with the boundary geometry in the approaches to the spillway crest as indicated by the original design (see Figure 1).

Subsequently, in order to reduce the height of standing waves in the channel downstream, the curvature in plan of the vertical walls in the entrance section, was altered slightly to conform with an amended alignment of the transition walls (see Figure 3). The second series of tests showed that this change in boundary geometry did not have a significant effect on the calibration curve. Discharge measurement, using the weighing tank and stopwatch, were made for depths of flow over the crest in the range of 0.06 ft. to 0.20 ft. Surface tension effects were therefore negligible, given the flat curvature of the crest.

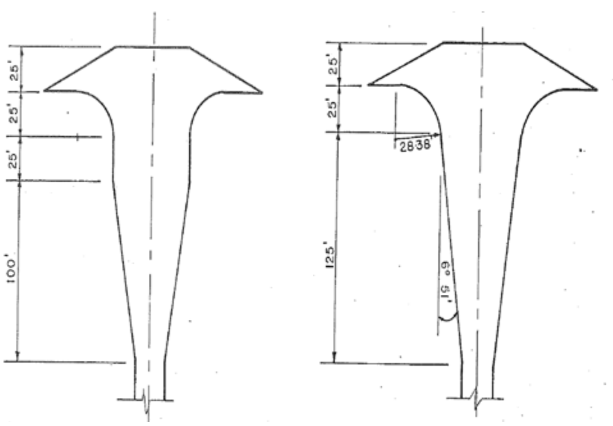

Figure 3. Change in Design of Transition and Entrance Sections – (a) Original Design and (b) Amended Design

The corresponding curve shown in Figure 4, relating prototype discharge to height of reservoir level above the spillway crest was obtained by scaling up the heights and discharges in the model in accordance with the length [(1/24)] and discharge [$(1/24)^5$] scale ratios, respectively. Figure 4 also shows the reservoir water levels related to the same datum as the spillway crest which was 119.

The design discharge was given as 2,540 ft^3/s. Using the calibration curve, the corresponding water level in the reservoir of 125.55 was higher than the anticipated level of 125.4 by 0.15ft. Since the boundary layer in the entrance section of the model was relatively greater than anticipated in the prototype, the latter would have a marginally better performance.

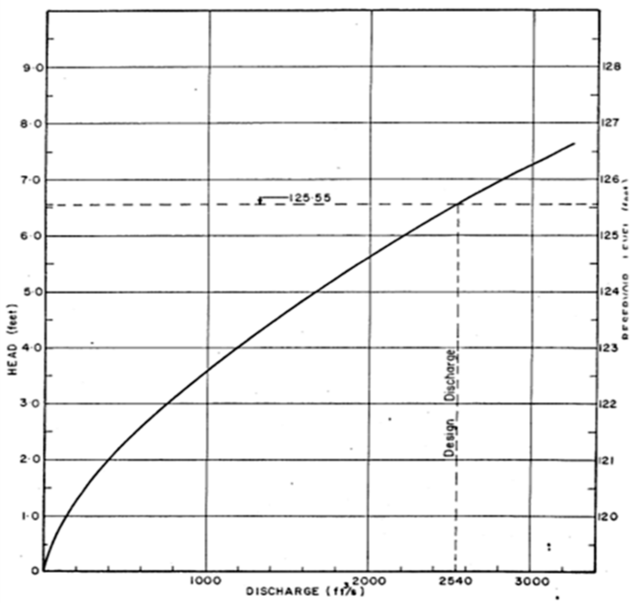

Figure 4. Calibration Curve for Spillway

5. Flow in the Transition and Main Channel

5.1 Scale Effect

Attention must be drawn to the limitations of the results obtained with the model for flow in the transition and main channel, in respect of the prediction of prototype behaviour. Significant differences are expected because of the phenomenon of air entrainment which is dependent on surface tension forces as well as velocity, hydraulic radius, channel roughness and other factors. In the model, surface tension was relatively too great, the Weber Number being greater than that in the prototype by the square of the length scale (576).

5.2 Depths and Velocities of Flow

The most important consideration was the adequacy of the height of side walls of the channel to contain the flow at all discharges. It was known that one of the major influences on maximum depth would be the standing waves generated in the transition and reflected downstream. Another reason for limiting waves is that they contribute to air entrainment which also increases flow depths. Ample provision was made in the design for reasonable freeboard in respect of mean depths of flow at maximum discharge. Particular attention was paid, therefore, to the wave patterns. For convenience, measurements are expressed in terms of the corresponding prototype values.

5.3 Flow Depths due to Standing Waves

5.3.1 Original Design

The geometry of the entrances section *t* the spillway provided a smooth stable flow into the 50 ft. wide channel immediately upstream of the transition, at all discharges. At the highest discharge (3,000 ft^3/s), small negative waves were generated immediately downstream of the spillway crest, converging towards the centre of the channel. The dominant features of the flow were the strong positive waves arising at the abrupt discontinuities in plan of the side walls at the head of the transition. These waves met on the centreline of the transition, 91 ft. downstream of the crest, the first reflection taking place at the end of the transition. Maximum depth (7 ft.) was recorded at the point of convergence of waves on the centre line after the first reflection. Thereafter, the expected attenuation of wave amplitude with successive reflections took place as the flow proceeded downstream. These results are summarised in Table 1.

Table 1. Depths due to Positive Waves at Maximum Discharge (3,000 $ft^{3/s}$)

Distance from Spillway Crest (ft.)	Depth (ft.)	
	Side	Centre Line
91	-	6.4
125	6.6	-
149	-	7.0
175	6.0	-
220	-	6.0
268	5.0	
361	4.2	
454	3.8	

Having regard to the very strong influence on wave heights, and therefore of maximum depths, of the sudden convergence of sidewalls at the beginning of the transition, elimination of this discontinuity was an obvious amendment to the design.

5.3.2 Amended Design

A second series of tests was carried out with the channel geometry altered as shown in Figure 3. The curved walls in the entrance section were made tangential to the transition wall which started at the spillway crest instead of 25 ft further downstream.

A series of small converging positive waves was generated by the sidewalls of the transition, meeting at the centreline and proceeding to the first reflection which took place at the end of the transition where a height of 5.2 ft. was recorded. The convexity of the sidewalls at this point induced a negative wave. The complete picture of the ensuing wave pattern and flow depths in the channel along the sidewalls and the centreline is given in Figure 5. The maximum flow depth, 6.2 ft., occurred 140 ft. downstream of the spillway crest. Thus, significant lowering of maximum depth was achieved. Lowering of depths of flow at wave crests became less marked further downstream.

Attempts to reduce wave heights by baffle walls in the channel, parallel to the direction of flow, were not successful. Further reduction of wave heights may be achieved by lengthening the transition.

5.4 Mean Depth and Velocities at Various Discharges

It was of interest to investigate the mean depths and velocities of flow in the spillway channel for various discharges in order to assess the degree of freeboard. Since the channel slope was greater than critical, the water surface profiles in the main channel were drawdown curves of the 52 type. For discharges less than 100 ft^3/s, however, normal depth was attained very close to the head of the channel. Table 2 shows mean depth d_0 and d_1, at the head and tail respectively, in the spillway channel relative to the discharge, are plotted relative to discharge. Also shown are the maximum velocities of flow, which vary between 54.4 ft/s at 3,000 ft^3/s and 15.6 ft/s at 100 ft^3/s.

Table 2. Flow Data - Main Spillway Channel

Q_p ($ft_{3/s}$)	d_0 (ft)	d_1 (ft)	v_* ft/s
3,000	5.70	2.76	54.4
1,000	1.58	1.44	34.7
250	0.50	0.50	25.0
100	0.32	0.32	15.6

Keys: Q_p = prototype discharge
d_0 = mean depth at level of spillway channel
d_1 = mean depth at tail of spillway channel
v_* = maximum mean velocity in channel

As mentioned previously, the values of depths and velocities obtained by scaling up from the models, and given in Table 2, would not accurately represent prototype behaviour because of the entrainment of air at higher velocities. However, there is no exact theory which can be applied to the data to account for this phenomenon. Estimates of bulking of the flow must therefore be made empirically.

5.5 Effect of Air Entrainment on Depths and Velocities

The entrainment of air in the flow of water associated with high velocities, but is also a function of surface tension, hydraulic radius and channel roughness, and takes place more readily in flows with surface waves. Its most important effects are:

1) the depth of flow is increased, and
2) the velocity of flow and therefore the momentum are reduced.

An expression proposed by Douma (Hall, 1943) may be used to estimate whether air entrainment would occur. The critical velocity v_a at which entrainment begins is given by:

$$v_a = \sqrt{5gR} \quad (4)$$

where R is the hydraulic radius

On this basis entrainment would commence in the transition for all flows.

De Lapp's formula (Hall, 1943) for estimation of the depth d_a of the water-air mixture is:

$$d_a = K^{\frac{2}{3}} \sqrt{\frac{q_w^2}{g}} \quad (5)$$

where q_w = discharge of water per unit width
K is constant

This expression is oversimplified since K is not a constant over a wide range of velocities. Having regard to the range of prototype velocities indicated by the model, a conservative estimate of the depth of the aerated flow was obtained by putting K = 0.5. Douma's Equations (1) and (2) for percentage of air entrained by volume, u, in terms of the actual velocity, v, and hydraulic radius, R:

$$u^2 = 20\frac{v^2}{gR} - 100 \quad (6)$$

The above Equation (6) was used to estimate the velocities of flow after calculation of depths of the air-water mixture by Equation (5). The results of these calculations are summarised in Table 3. Variations of depth with discharge are shown in Figure 5. The values apply to the tail end of the spillway channel and should be compared with the uncorrected values in Table 2.

Table 3. Depths and Velocities of Flow with Air Entrainment

Q_p (ft 3/s)	d_a (ft)	v (ft/s)	%air
3,000	4.44	39.7	15.0
1,000	2.14	26.5	12.0
250	0.85	16.5	11.0
100	0.46	12.2	11.0

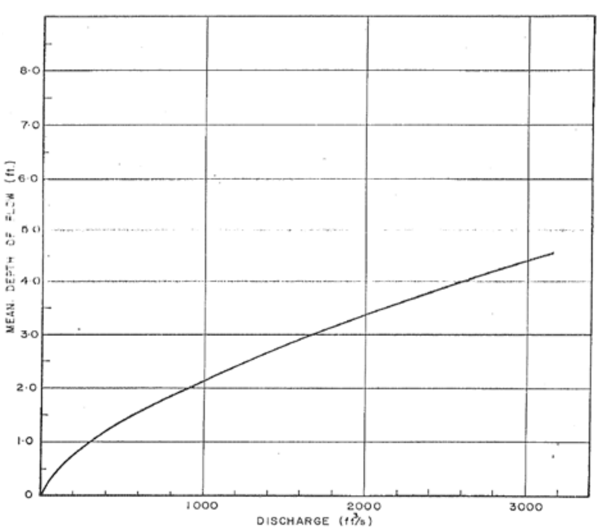

Figure 5. Estimate of Flow Depths with Air Entrainment at Tail End of Spillway Channel

6. Hydraulic Jumps and the Performance of the Stilling Basin

The hydraulic jump at the end of the spillway channel was investigated for the following prototype discharges: 3,000 ft^3/s, 1,500 ft^3/s, 250 ft^3/s, and 100 ft^3/s. Corresponding ranges of tailwater elevations were 65-70, 60-70, and 55-65, respectively.

Here again, model behaviour must be interpreted judiciously because of air entrainment in the prototype. Figure 6 shows standing waves in spillway channel, Q_p. = 3,000 ft3/s. As shown, there is likely to be a considerable reduction of momentum, as a result of the increased resistance to flow. A smaller depth of subcritical flow would therefore be required for the hydraulic jump. The conclusion may readily be drawn that for corresponding flows and tail-water levels, the hydraulic jump would occur further upstream in the prototype than in the model.

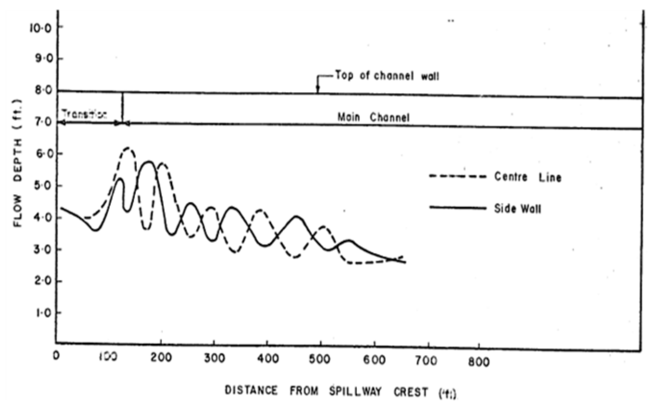

Figure 6. Standing Waves in Spillway Channel, Q_p = 3,000 ft^3/s

6.1 Experimental Results

With the exception of the highest discharge (3,000 ft^3/s) operating against the lower tailwater level, the hydraulic jump took place on the slope of the spillway channel, in some cases far upstream from the stilling basin. The distance L of the toe of the jump from the upstream end of the stilling basin was measured in each case. Results are given in Table 4.

Table 4. Position of Hydraulic Lump

Q_p (ft ^{3}/s)	Tailwater Level (ft)	L (ft)
3000	65	-8.2
3000	70	31.0
1000	65	60.9
1000	70	108.7
250	60	64.1
250	65	113.5
250	70	164.6
100	55	30.0
100	60	80.6

It is evident that in the prototype the jump would take place for all discharges within the stilling basin or further upstream on the slope. The major function of the stilling basin would therefore be fulfilled. It should be noted that the relatively lower velocities in the prototype would reduce significantly the Froude Number, *F*. In the model, *F* exceeded 5 for the three discharges: 3,000, 1,000, and 250 ft^3/s, and was only marginally less (4.87) for $Q_p = 100\ ft^3/s$.

Using the values of velocity and depth estimated for the water-air mixture in the prototype, the Froude Number would all be between 3 and 4. This is the range in which the oscillating jump occurs. An adverse property of this type of jump is the tendency for waves to travel considerable distances downstream with sufficient energy to cause damage to banks. Some mitigation of this effect might occur in the aerated flow but the possibility of such a jump occurring is a factor that should not be ignored in the design.

The design of the stilling basin appears to be deficient in respect of the freeboard allowance for these discharges close to maximum. If the tailwater level for these discharges is between 65 and 70, the surface waves produced in the hydraulic jump would result in overtopping of the sidewalls.

Another factor which should be considered is that the stilling basin is too short to contain the entire length of the jump when it occurs in the basin at high discharges and low tailwater levels. For example, at the discharge 3,000 ft^3/s the Froude Number of the supercritical flow, even allowing for an entrainment, would be close to 4 (it was over 5 in the mode). The ratio of initial to sequent depths is between 5 and 6, giving a length of jump over 60 ft. Structural design of the apron and sidewalls requires knowledge of pressure distribution under all conditions and this is determined by the water surface profiles.

7. Conclusions and Recommendations

Based on the study, several conclusions are drawn and recommendations are made, as follows.

1) Both the original and amended designs give satisfactory flow conditions in the entrance section to the spillway. Modification of the entrance geometry arises from the change in design of the transition.
2) The calibration curve for the prototype spillway obtained by scaling up the results obtained with the model indicates a reservoir level of 125.55, which is higher by 0.15 ft. than the level anticipated in the design. However, due to the thicker boundary layer in the model, a slightly better performance of the prototype is expected.
3) Differences in the relationship between discharge and height of reservoir level above the spillway crest, for the original and amended designs, are negligible.
4) The original design flow in the transition at high discharges produced a strong positive standing wave at the discontinuity in the alignment of the sidewalls, that is, at the end of the 50 feet wide section immediately downstream of the spillway crest - The wave was reflected successively at the sidewalls over the entire length of the channel downstream.
5) At a discharge corresponding to a flow of 3,000 ft^3/s in the prototype, the model indicated that a maximum depth of flow of 7 ft., due to the presence of standing waves, would occur in the main 20 feet wide channel along the centre line after the first reflection.
6) Elimination of the discontinuity by extending the transition section to the spillway crest resu1ted in a reduction of maximum depth from 7 ft. to 6.2 ft.
7) Attempts to further reduce wave heights by introduction of baffles were not successful. Two possibilities for effecting this reduction are:
   (a) lengthening the transition, and
   (b) developing a configuration of the positive wave induced in the transition by a negative wave at its downstream end.
8) Attenuation of the standing waves in the main channel was such that maximum depth at the downstream end was less than 10% greater than the mean depth.
9) Prediction of prototype behaviour from results obtained with the model, especially with respect to depths and velocities of flow and the positions of hydraulic jumps should be made judiciously because of air entrainment.
10) The major effects of entrainment of air are: (a) to increase depth flow, and (b) to reduce momentum. Estimates of the behaviour of the prototype were made by use of empirical equations developed by De Lapp and Douma (Hall, 1943).
11) By use of the empirical equations, it was estimated that the prototype flow would have between 10% and 15% of air entrained between discharges 100 ft^3/s and 3,000 ft^3/s. Taken together with the estimates of depth, the estimates of percentage air enabled calculation of velocities to be made.
12) Reduction of momentum due to the additional resistance caused by air entrainment would reduce the Froude Number at the end of the Spillway channel to valves less than 4. This in turn would cause the hydraulic jump to form further upstream than indicated by the model.
13) Attention should be given in the design to the possibility of an oscillating jump developing as a result of Froude number reduction. This type of jump causes a wave of high energy to be propagated for considerable distances downstream, suitable protective measures should therefore be considered.

14) The height of vertical sidewalls of the stilling basin is insufficient to contain the flow immediately downstream of the jump for the design discharge.
15) The stilling basin design is adequate for the promotion or hydraulic jump for all discharges, but its length is insufficient to contain the entire length of the jump at the designated discharge at tailwater levels below 70.
16) Attention should be given to the effect of water surface profiles on pressure distribution in the structural design of the apron and sidewalls of the stilling basin.

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