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Special Issue on:
"Capstone Projects of Engineering and Associated Disciplines in the Caribbean

Editorial

I. From the Editor

Capstone project is a significant component in Engineering/Technology programme curricula, and provides opportunities to both undergraduate and postgraduate students at universities to develop professional skills like problem solving, analysis, synthesis and evaluation. These projects provide a unique opportunity for students to work on own or with in groups on a chosen topic and to investigate, find, contribute to the engineering society. Even engineering professional accreditation bodies (like, IChemE, JBM, IET, IMechE, ABET, and ENAEE) of the UK, the USA, and in the Europe, scrutinize the student capstone projects with great emphasis on the development or demonstration of professional maturity; mastery of engineering knowledge/tools; and effective presentation and communication skills.

This Volume 40 Number 2 contributes to a Special Issue on "Capstone Projects of Engineering and Associated Disciplines in the Caribbean". The prime objective of this issue is to publish original research, works and empirical results arising from student capstone projects and experiences from the extended areas. In total, eight (8) research/technical articles are edited for this issue.

This issue also includes an announcement and a Call for Papers for the Fourth Industrial Engineering and Management Conference 2018 (IEM4-2018) that is to be hosted at the Faculty of Engineering, The University of the West Indies on 7th-8th December 2018. With the theme on "Striving for business/engineering performance excellence with quality management and IEM practices" the Conference IEM4-2018 invites papers for presentation, and suggested topics of interests fall into two groups of 1) Traditional Industrial Engineering areas and 2) with Quality Management (QM) focus. For Enquiries and Registration, contact Prof. Kit Fai Pun and Dr. Cilla T. Benjamin, c/o Faculty of Engineering, UWI, St Augustine Campus, Trinidad and Tobago, e-mails: KitFai.Pun@sta.uwi.edu; Cilla.Benjamin@sta.uwi.edu

II. About This Issue

The relevance and usefulness of the eight (8) research/technical articles are summarised below.

B.V. Chowdary, M-A. Richards, and T. Gokool, "Virtual Conceptual Design of a Multi-Purpose Fixture for a CNC Milling Machine Using Controlled Convergence Technique", present an integrated approach to designing a multi-purpose, cost-effective fixture to perform several milling operations in the computer numerical control (CNC) environment. Pugh's Controlled Convergence (CC) technique was used to generate alternative designs. The authors claimed that the most feasible alternative was modelled using Virtual Engineering (VE) principles which can allow it to be further analysed for downstream operations. The results indicate that the proposed CC and VE principles were applied effectively to design a multipurpose milling machine fixture.

In their article, "A Controlled Environment Agriculture Greenhouse for the Caribbean Region", **M. Suraj, E.I. Ekwue, and R.A. Birch** examine the effect of temperature and humidity variations on a prototype Controlled Environment Agriculture (CEA) greenhouse that was designed to suit the climatic conditions of Trinidad and Tobago. It was found that the CEA greenhouse had significantly higher growth rates in all plant growth parameters (about two and a half times on the average) than the non-controlled greenhouse. The combination of blue LED light, evaporative cooling, and air circulation fans coupled with natural ventilation resulted in a significant increase in plant growth rates in the CEA greenhouse compared to the greenhouse with only natural ventilation as the weather control measure.

K. Narinesingh, S. Bahadoorsingh, and C. Sharma, "The Development of a Portable Electrical Engineering Educational Outreach Toolkit", explore the use of a portable educational toolkit incorporating electrical engineering theory and principles as required by the primary and secondary school curricula in Trinidad and Tobago. The toolkit contains 1) a Van De Graff Generator, 2) Tesla Coil, 3) Joule Thief and 4) a Combinatorial Logic Designer Board. Results from live demonstrations to selected schools showed that majority of students (90%) indicated that the use of the toolkit could increase their interests in studying science. Some 95% of students indicated that the toolkit made learning science more fun and motivational.

In the fourth article, "The Role of Engineering in the Design of Kings of Carnival Costumes in Trinidad and Tobago", **U. Persad et al.**, share findings from an interview study with costume designers on 1) identifying the design process used, 2) determining the factors that influence the design of the costumes, 3) examining the extent to which Engineering principles be utilised, and 4) recommending strategies for improving the design process. Results indicated that engineering input was not utilised in the costume design process and material selection was based on tradition, availability and cost.

R. Latchmepersad and T. Ragoobar-Prescod, "Performance Measurement of Broadband Connections: An Enhanced Tool", discuss the development of enhanced algorithms and, correspondingly, a software application for the performance measurement of broadband Internet connections. The enhanced tool, TINQA (Totally

Integrated Network Quality Application), is a native Windows® application, developed using the C# programming language and the .NET framework, and measures speed, latency, jitter and packet loss. TINQA produced results similar to those obtained from some of the most popular existent performance testing tools, including speedtest.net, testmy.net and pingtest.net. It was claimed that the algorithms were robust and that the added flexibility in testing did not compromise the accuracy of the tests in the application.

In their article, "Customising a Project Management Framework at a Trinidad-based Paper Manufacturer: A Case Study", **V. Ragbir and K. F. Pun** review a strategic realignment exercise which was done to determine the root causes of project failures, and to tailor-make a project management (PM) framework to govern process improvement projects at Paper Products Limited (PPL). In order to quantify historical project performance and determine the reasons for historical project failure at PPL, a four-phase study was initiated. Phase-1 involved the analysis of projects undertaken from 2012 to 2015 on the cost, schedule and scope variances. Phase-2 determined the root cause of project failures, Phase-3 comprised the development of a PM framework and the final phase involved testing the efficacy of the framework using selected projects at PPL. This case study demonstrated an initiative in fostering PM practices and performance in business.

D. Mohammed et al., "A Lighting Audit of The University of The West Indies St Augustine Campus", document the methodologies and the results of an audit conducted on the St. Augustine campus of The University of The West Indies at night. Inadequate lighting can make the school environment unsafe. The audit was performed to determine the adequacy of the campus lighting. Areas audited were identified via a survey distributed to students of the campus. The illuminance levels were measured at these locations and compared to applicable standards of the Illuminating Engineering Society. The results confirmed that none of the areas evaluated satisfied the lighting levels detailed in the standards. Recommendations and implementation plans accompanied by cost-benefit analyses were developed for each area ensuring the standards are satisfied.

Z. Blackwood and G.S. King, "Vertical Take-off Unmanned Aerial Vehicle with Forward Flight Transition", present the findings from a capstone project that was to design a drone capable of functioning as vertical take-off Unmanned Aerial Vehicle (UAV) with a conversion to horizontal flight. It could serve as a stable controlled flight using a simulator based iterative design process. The vehicle was intended to work in an environment where tedious or boring jobs could be automated. The vehicle design concepts were created through research, benchmarking, design metrics, and virtual flight testing. Both the simulation model and demonstration vehicle adhered to the aim and goals of the project.

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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Virtual Conceptual Design of a Multi-Purpose Fixture for a CNC Milling Machine Using the Controlled Convergence Technique

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Abstract: *Modern computer numerical control (CNC) machines are capable of performing numerous operations on variety of workpieces. An array of parts that are geometrically and physically dissimilar can be machined on a CNC workstation, provided an appropriate fixture is available. It is however quite common in practice to have many dedicated fixtures serving as accessories to a single CNC workstation. The intent of this paper is to present an integrated approach to designing a multipurpose yet cost effective fixture to perform several milling operations. Pugh's Controlled Convergence (CC) technique was used to generate alternative designs. Finally, the most feasible alternative was modelled using Virtual Engineering (VE) principles which can allow it to be further analysed for downstream operations. The results indicate that the proposed CC and VE principles were applied effectively to design a multipurpose milling machine fixture.*

Keywords: *Product development, milling fixture, integration, controlled convergence, virtual engineering*

1. Introduction

Computer numerical control (CNC) machines are widely used for varied material removal processes. Several laboratory-based CNC machines, like milling cutters, lathes and routers, are available in the Department of Mechanical and Manufacturing Engineering, The University of the West Indies, St. Augustine campus. These are used in the manufacturing engineering curriculum, with content on CNC programming. However, among such laboratory based CNC machines there is no on-board means for measuring and recording data relating to cutting forces and moments generated on parts as they are being machined. Additionally, the CNC milling machine, which was shipped with a fixture, is not able to complement its built-in capacity. For instance, the machine is equipped with a 100mm x 150mm vice-type fixture. Whereas the maximum X, Y and Z-axis travel of the machine are 304mm, 157mm and 213mm respectively. This indicates that the machine has a capacity for conducting operations on parts of larger sizes. There is also no facility for locating and holding free-form objects. Furthermore, the inadequate clamping mechanism sometimes leads to deformation on finished work

For the study purposes, a multipurpose fixture will be designed for the aforementioned CNC milling machine that overcomes the identified issues. The proposed fixture would accommodate larger and more geometrically diverse workpieces while minimising deformation as well as permitting greater utilisation of the machine's inherent capabilities, improving its overall effectiveness.

In practice the design and manufacture of a multipurpose machining fixture is a complex task, which involves knowledge of tolerances, geometry, dimensions, procedures and manufacturing processes (Patel and Acharya, 2014). Various aspects of the design of milling machine fixtures have been widely covered by several researchers (Patel and Acharya, 2014). However, there was need to consider an integrated design approach that combined virtual engineering (VE) principles with contemporary product design and development tools for an effective means of generating and selecting alternative designs. In this regard, the current study proposes an integrated approach of Pugh's Controlled Convergence (CC) combined with VE principles for the design of a multipurpose fixture for a CNC milling machine.

2. Background to the Study

Henriksen (1973) defines a fixture as a special tool used for locating and holding a workpiece in the proper position during a manufacturing operation. Hargrove and Kusiak (1994) described the four requirements of a fixture as: accurate location of the workpiece, total restraint of the workpiece during machining, limited deformation of the workpiece, and no machining interference. Hunter et al. (2005) proposed a fixture design methodology comprising of two stages, component geometry and the interference process. Patel and Acharya (2014) integrated the research works of various pioneers (Hunter et al., 2005; Hargrove and Kusiak, 1994; Meyer and Liou, 1997; Li et al., 1999) to develop a methodology for the design of a hydraulic fixture. Hui et al. (2016) developed a flexible fixture to adapt to varying workpieces in terms of size and shape for use in the aircraft industry. However, even though these studies reported on time savings in production, they still require a lot of information on the machining conditions which may not be readily available.

CAD systems have become indispensable in today's product design practices and provide freedom to experiment with function and shape via direct manipulation (Fujita et al., 1999). Research studies targeting the support of integrated approaches combining virtual reality and engineering tools in the early product conceptualisation phase have not been well covered. VE based prototyping is a process of computer-aided product digitisation, whose objective is to speed up the product development process and to reduce the required number of physical prototypes, leading to reduced product development costs (Brunetti and Stork, 2007). Shen et al. (2000) presented an integrated approach to innovative product development using Kano's model and quality function deployment (QFD). Chowdary and Gittens (2008) proposed an integrated approach to the development of a battery-operated passenger cart that focused on recycling and maintenance. Chowdary and Kanchan (2013) presented an integrated product design and development framework that combined DFE guidelines with CAD/CAE principles. Ali et al. (2013) proposed an integrated design approach for rapid product development of a broken product, combining reverse engineering, re-engineering and rapid prototyping. The study concluded that the integrated approach allowed for the development of an enhanced product at a reduced cost and time.

A few studies (e.g., Chowdary and Gittens (2008), Chowdary and Kanchan (2013), and Ali et al. (2013)) have demonstrated the strength of the VE tools in design of products. This study proposes an integrated approach to designing a multipurpose milling fixture that considers simultaneously the traditional product design tools and VE principles.

The machine, which is the subject of this study, is a free standing, computer controlled, 3 axis vertical machining centre designed for training in CNC programming and computer controlled machining. It is a high quality machine that has a touch-sensitive control panel. The machine has variable and programmable spindle speeds and a 1.26kw (1.9HP) DC motor, allowing various materials to be machined. These include steel, brass, wood, aluminum, plastic and wax.

The dynamometer is a device that can be used to measure quasi-static and dynamic forces as well as applied moments during machining cycles. The gathered data can enhance the knowledge of the loads and stresses as well as part distortion introduced at various stages of an operating cycle. In this regard, a multipurpose fixture that can integrate a dynamometer with the selected CNC milling machine can serve as a platform for launching in-depth research into the dynamics of CNC machining. For the purposes of this case, the device selected was the Kistler type 9272 dynamometer.

2. Integrated Approach for the Design of a Multi-purpose CNC Milling Fixture

The integrated approach is depicted in Figure 1. As shown, it begins with conducting literature survey and analysis of trends in the area. Then a case study was selected to identify shortcomings of the original work holding of the machine under consideration. After this step, a review of existing techniques for combating or eliminating such drawbacks was performed. Then the product design specifications (PDS) were formulated which allowed for conceptualisation of viable alternative designs by means of Pugh's CC technique. Modelling the selected alternative designs using VE principles and evaluation of the virtual model completes the design of the proposed multipurpose milling fixture process.

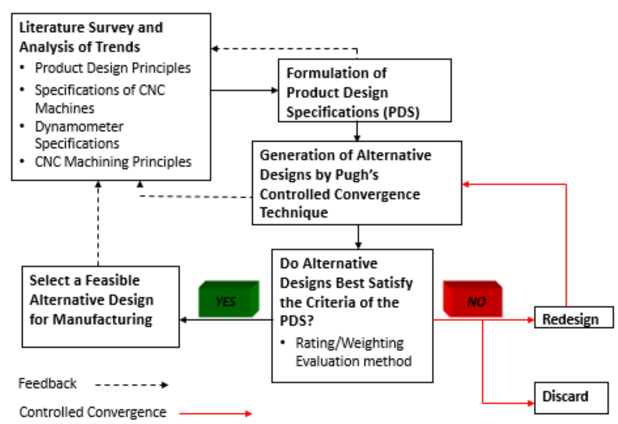
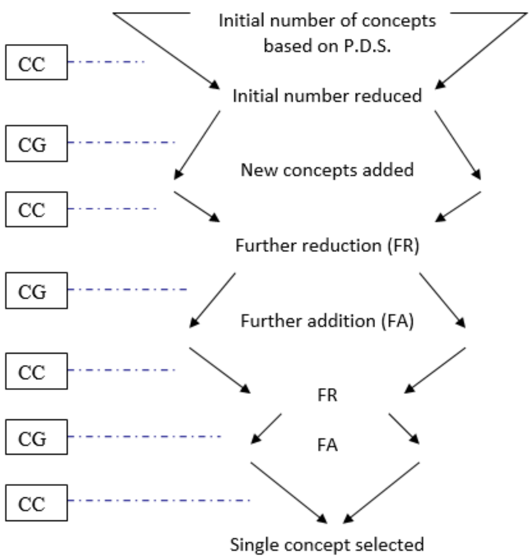


Figure 1. Proposed Integrated Approach for Design and Development of a Multipurpose Milling Fixture

2.1 Applying the method of controlled convergence

Pugh's method of CC, as shown in Figure 2, was applied throughout the proposed multipurpose milling fixture design procedure. Developed in 1980s by Stuart Pugh, CC uses a simple matrix to compare concepts against a set of pre-determined criteria (Frey et al., 2009). An initial set of concepts was first created with the aid of developed PDS. Then design alternatives were reviewed against specified criteria using the Rating/Weighting method. Wherever possible, both the stronger and weaker concepts were strengthened. Weaker concepts that could not be strengthened were discarded, thus effectively reducing the pool of alternatives for possible selection as the final design. In addition, the most beneficial features of several concepts were combined creating more innovative and feasible designs. This method guarantees the continued generation of progressively more robust alternatives with the subsequent emergence of a single final design.



Legend: CC – Controlled Convergence; CG – Concept Generation

Figure 2. Method of Controlled Convergence

2.2 Product Design Specifications

1) Size and weight restrictions:

- The final design should not exceed maximum dimensions of 500mm × 235mm × 130mm, so as to fit comfortably within the selected CNC milling machine as well as facilitate ease of installation.
- The overall weight should not cause significant deflection of the milling machine table or place excessive strain on the individual motors of the machine's X and Y axes.

2) Performance:

- The fixture should be capable of securely locating and holding regularly shaped workpieces as well as the Kistler Type-9272 Dynamometer.
- The capacity of the new design should exceed the maximum capacity of the existing fixture by 40% in at least one axis.
- The device should hold various materials to machine including steel, brass, wood, aluminum, plastic, and wax.
- The fixture should locate and hold work with zero or minimal surface marring and/or deformation of such workpieces during extensive machining operations.
- All features of the design should pose zero threat of interference with the cutting tool and tool changer.

3) Manufacturing Processes:

- Major parts of the assembly were to be fabricated using tooling and equipment available in a typical machine shop.
- Raw material and fasteners available on the local market must be used in the assembly wherever possible.

4) Maintenance:

- Chips and burrs should be easily removed from the fixture at the end of every milling operation.
- Parts requiring lubrication should be easily accessible.
- When not in use, the fixture should be stored in a clean dry environment.
- Before storing, any accumulated coolant is to be removed from the device.
- Any parts made of steel must be regularly oiled to prevent surface corrosion.
- No specially designed or uncommon tools should be required for the maintenance of the fixture.

5) Life in Service:

- The service life of the product should be comparable to that of the milling machine.
- Life in service should be assessed against the criteria outlined in the Performance and Environment categories.

6) Target Costs:

- The total cost of raw material and parts for manufacture should be less than the cost of standard fixture.

7) Environment:

- Exposure to adequate volumes of lubricant.
- The fixture should resist corrosion through the use of special materials and/or surface protection methods such as coating.

8) Safety:

- The fixture should never be manually adjusted during a machining operation.
- Tool paths should be simulated to ensure no threat of collision between the fixture and the cutting tool.

9) Aesthetics:

- The proposed device should be easily operated with its form and function.
- The fixture should look attractive and well finished.

10) Ergonomics:

- Operation of the multipurpose fixture should require only a single person.
- A minimal range of tools should be necessary for assembly and disassembly.

11) Quality and Reliability:

- Aspects of the performance criteria for the design must not significantly deteriorate over its life in service if routine maintenance is performed.

12) Installation:

- The fixture is to be installed according to the instructions for mounting a new work holder as specified in the selected machine user manual.

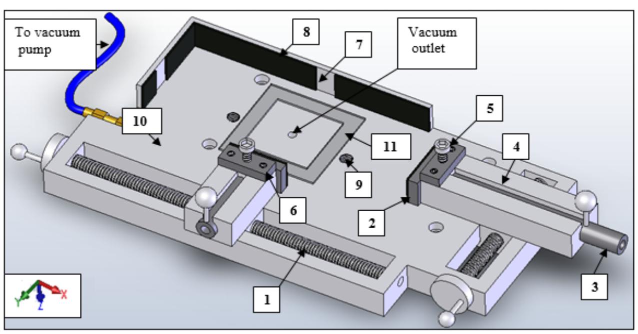
3. Evaluation of Alternative Designs

3.1 Rating/Weighting Matrix

Alternative designs were evaluated against critical elements of the product design specifications as stated earlier and other favourable criteria using a Rating/Weighting method (as shown in Table 1). Each evaluation criterion was allocated a weight factor on a scale of 1-5. The higher the number assigned, the greater the importance of the respective criterion. The alternative designs were then rated against the evaluation criteria on a scale of 1-5. Likewise, the higher the rating the better the alternative satisfied the criterion. Finally, rating and weight factors were multiplied and summed to obtain a total score for each alternative. The highest score was taken to reflect the strongest alternative design. As indicated in Table 1, the highest scoring design is alternative design E, with a total of 128. Consequently, the final design was modelled based on this concept.

3.2 Development of the Selected Design

The design, illustrated in Figure 2, utilises two mutually perpendicular clamp assemblies driven by independent power screws (1). Both clamps (2) are also adjustable perpendicular to the direction of travel along these screws by varying the position of a push rod/clamp shaft (3) within the clamp housing (4). This position can be maintained with ease using a single quick release screw (5) and threaded locking-bracket (6).



Legend: 1. Power screw; 2. Clamps; 3. Push rod/clamp shaft; 4. Clamp housing; 5. Quick release screw; 6. Threaded locking bracket; 7. Fixed locator; 8. Neoprene rubber; 9. Internally threaded holes; 10. Fixture base; and 11. Vacuum gasket tape

Figure 3. The Selected Alternative Design E for Development

The design of this clamping mechanism again allows varied sizes of regularly shaped parts to be easily accommodated (up to 280 mm in X-direction). The fixed locator (7), and the clamps themselves, are padded with a thin layer of Neoprene rubber (8) to minimise surface marring of the workpiece. Two internally threaded holes (9) are also incorporated into the design, allowing the Kistler type 9272 dynamometer to be bolted directly to the fixture base (10). A vacuum work holding system is integrated within the base of the apparatus as well. Utilising zero creep vacuum gasket tape, or an appropriate substitute (11), free form bodies with at least one sizeable flat surface can be held with the aid of a suitable vacuum pump.

4. Discussion

4.1 Effectiveness of Integrated Approach

A multipurpose milling fixture was designed using an integrated Pugh's CC approach combined with virtual prototyping process. Attributes of the new design include:

- An increased work holding capacity of the fixture, with a limit of 280 mm in the X-axis, optimising the available maximum travels of the milling machine.
- Facilitation of the mounting of the Kistler dynamometer, introducing the option for the gathering of data on cutting forces and torques generated throughout milling cycles.
- The possibility for securing work without the application of significant holding force from any clamp. This effectively reduces the likelihood of part deformation and part wastage.
- The added capacity for location of cylindrical workpieces around their circumference with the use of chuck-like jaws, and
- A vacuum system that can allow free-form objects with one substantial flat surface to be located and held.

4.2 Features of Final Design

The final design will be based on alternative design E and will function with the use of two mutually perpendicular clamp assemblies both manually driven by independent power screws. These screws will convert

Table 1. Rating/Weighting Matrix for Selection of Multi-purpose Milling Fixture

Criteria	Weight Factor	Rating					Weight Factor × Rating				
		A	B	C	D	E	A	B	C	D	E
Overall work holding flexibility	5	2	5	3	4	5	10	25	15	20	25
Ability to house dynamometer	5	5	5	5	5	5	25	25	25	25	25
Potential to reduce part deformation	4	3	4	2	3	4	12	16	8	12	16
Ease of manufacture	4	3	3	4	2	3	12	12	16	8	12
Low manufacturing cost	4	4	2	3	3	4	16	8	12	12	16
Ease of part location (ability to reduce setup time)	4	4	3	4	4	4	16	12	16	16	16
Ergonomics	3	3	3	3	3	3	9	9	9	9	9
Maintenance	3	3	4	3	3	3	9	12	9	9	9
		Total					109	119	110	111	128

rotational motion to linear translation. This independent clamping system aims to eliminate part deformation as well as securely locate regular-shaped workpieces of various sizes. Moreover, the multi-purpose fixture base will be made of plain carbon steel. Each power screw incorporates square threads for increased sturdiness. The clamp housings will be constructed of aluminum which has a high strength to weight ratio. The clamps, clamp sliding supports, clamp shafts and locking screw brackets will be fabricated from mild steel stock.

The rear fixed locator will be made of aluminum and can be padded with a 2mm layer of Neoprene rubber to reduce the likelihood of surface marring to any workpiece. In addition to the rear fixed locator, there is also a set of fixed locators. These can be bolted to the fixture base to permit the fixing of tiny work pieces, as the individual travels of the long and short clamp shafts (140mm and 65mm respectively) are limited by space restrictions within the selected CNC milling machine. Each clamp shaft knob will be fabricated of aluminum. All clamps and the removable locators can be padded with a layer of Neoprene. The Kistler dynamometer can be mounted with the use of two 1¼-inch long, 7/16-inch diameter hexagonal bolts.

A vacuum clamping system is also integrated to the fixture base. Using a single ¼-inch brass nipple, the fixture can be coupled to an electric vacuum pump. Zero creep vacuum gasket tape or an appropriate substitute will be applied between the fixture and the work to maintain the vacuum. The essential purpose of this vacuum system is to locate free form bodies with at least one sizeable flat surface.

This integrated approach facilitates effective concept selection by combining the powerful design tools of Pugh's CC method and virtual prototyping. Using this method, concepts with useful features are combined and improved, thus strengthening the concept pool and ensuring that the final chosen concept is of the highest quality. Moreover, the presented approach can be used as an example of the implementation of Pugh's CC method and concept generation and selection. In the future, this approach can be applied to the design of other mechanical devices and components to strengthen and support the effectiveness of the presented approach.

5. Conclusion

An integrated approach for the design of a multipurpose milling machine fixture was presented which featured Pugh's Controlled Convergence and virtual prototyping process. PDS were used to develop alternative designs, the best of which was selected by applying the method of CC. It was shown that the proposed integrated approach was successful in the design of a multipurpose milling machine fixture and in future can be applied to design of other products to further test the efficacy of the approach.

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A Controlled Environment Agriculture Greenhouse for the Caribbean Region

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Abstract: *A prototype Controlled Environment Agriculture (CEA) greenhouse, designed to suit the climatic conditions of Trinidad and Tobago was constructed and tested alongside a non-controlled prototype greenhouse with natural ventilation. In the CEA greenhouse, fan and pad type evaporative cooling were used to reduce temperature; circulating air combined with natural ventilation to reduce the humidity and provide air movement. LED lights were used to extend day length and supplement photons delivered to the plants. The effect of these control measures, in the CEA greenhouse, was evaluated by measuring temperature and humidity variations. Plant growth parameters (plant height, stem diameter, and leaf surface area) were evaluated for the two greenhouses. The mean saturation effectiveness of the coconut fibre cooling pad material used in the evaporative cooler was found to be 25.3%. While, the temperature and relative humidity in the non-controlled greenhouse were higher; those in the CEA greenhouse were lower than the ambient temperature. The CEA greenhouse had significantly higher growth rates in all plant growth parameters (about two and a half times on the average) than the non-controlled greenhouse. The combination of blue LED light, evaporative cooling, and air circulation fans coupled with natural ventilation resulted in a significant increase in plant growth rates in the CEA greenhouse compared to the greenhouse with only natural ventilation as the weather control measure.*

Keywords: *Greenhouse, controlled, environment, Trinidad and Tobago*

1. Introduction

Trinidad and Tobago's food import bill is currently approximately US$ 0.6 billion per annum (Flemming et al., 2015). There is an urgent need to increase food production and reduce this expenditure. Protected agriculture has been proposed as one way to improve agricultural output, by protecting the crops from harsh weather conditions and pests and diseases (DeGannes et al., 2014). If well implemented and followed through intelligently, protected agriculture environment systems will aid in ensuring food security. According to Jensen and Malter (1995), protected agriculture (PA) is "the modification of the natural environment to achieve optimum plant growth." In general, greenhouses are environments which can be controlled to a much higher degree than outdoor fields. Greenhouses involve both passive and active ways of controlling the growing conditions inside the green house. Temperature, light, air humidity, water supply and carbon dioxide in the air can be regulated by the grower. In some modern greenhouses, even infestation by pests and pathogens can be restricted or prevented (EGTOP, 2013).

Martin et al. (2008) reported the rejuvenation in the use of greenhouses in Trinidad and Tobago following a collaborative approach by Agricultural Development Bank (ADB) and others to provide financial, marketing and technical support to persons interested in greenhouse crop production. Sahadeo et al. (2017) investigated the existing greenhouses, locally, regionally and internationally and designed and optimised a new system that could potentially be used in the Caribbean region. They found that while most designs could protect the crops from pests and diseases, temperature and humidity could be reduced only marginally by altering their designs, and changing some materials. They, however, found that to control the environmental parameters adequately, Controlled Environment Agriculture (CEA) greenhouses may be needed in the Caribbean. CEA is a subset of protected agriculture in which case all aspects of the natural environment are modified for maximum plant growth and economic return (Jensen and Malter, 1995; Albright and Langhans, 1996). Control may be imposed on air, temperature, light, water, humidity, carbon dioxide, plant nutrients alongside with complete climatic protection (Jenson and Malter, 1995). Tian et al. (2014) did a comprehensive assessment of a controlled growth environment in which they analysed the effect of environmental factors, like temperature, humidity, light, carbon dioxide and nutrients, on crop development. Their results showed that rapes grew very well; the growth period was short with higher quality yields than rapes grown in natural environment.

The major disadvantage of the CEA greenhouses is that they are very costly and may not be affordable to most local farmers. Before heavy investments are made, it is, therefore, necessary to construct a prototype CEA greenhouse and compare its performance locally (in terms of controlling temperature, humidity and other environmental factors) to a greenhouse with minimal means of weather control. Such an investigation will reveal whether the CEA greenhouses could lead to better crop yields and control of weather conditions. This paper starts the investigation of CEA greenhouses in Trinidad by first designing and constructing a prototype CEA greenhouse and testing its performance against a similarly constructed naturally ventilated greenhouse. This research will predict the feasibility of large-scale use of CEA greenhouses in Trinidad and Tobago and in the Caribbean.

2. Existing Methods for Modifying the Environment in CEA Greenhouses

De Gannes et al. (2014) identified the following problems with CEA greenhouses in the Caribbean: high temperatures, high relative humidity, high carbon dioxide concentration, low oxygen, reduced light especially below minimum threshold level during rainy/cloudy days.

Karlsson (2014) reviewed the various methods of controlling environment in greenhouses (see Figure 1). For instance, temperature is controlled by using natural ventilation, exhaust fans, evaporative cooling, mist cooling and shade curtains. Relative humidity is modified by using circulating fans, exhaust fans, natural ventilation and dehumidifiers. Supplemental lighting is provided using incandescent light bulbs, halogen incandescent bulbs, fluorescent bulbs, high intensity bulbs or light-emitting diodes (LED) lights.

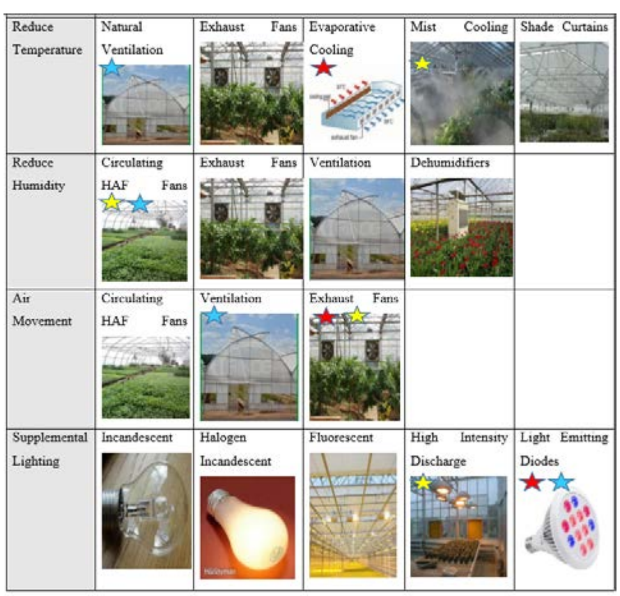

Figure 1. Methods of controlling greenhouse environment

In a CEA greenhouse, an integrated computer system is used to ensure that ventilation, humidity, light intensity, carbon dioxide levels and all other parameters operate in harmony with one another so as to provide the best growing conditions (Albright and Langhans, 1996). While simple on-off switches may be used, a computerised system offers remote monitoring and controls based on specific plant requirements (Karlsson, 2014; Goldammer, 2017). Sensors are placed in greenhouses to acquire data. For sensors to be effective, they must be kept at plant canopy height with limited direct influence from vents, fans or drafts (Karlsson, 2014).

In computerised systems, sensors send data through a data acquisition (DAQ) device for signal conditioning or through an analogue-to-digital converter (ADC) to computer software to analyse and process this data, to activate some type of control. Information from the computer software is used to activate the actuators using digital-to-analogue convertors. Thermostats or controllers are also utilised in CEA greenhouses. While thermostats control temperature, controllers continuously monitor the greenhouse environment (Karlsson, 2014). Cheap and non-complex on/off systems (Goldammer, 2017) allow sensors to be directly connected to environmental controllers that use relay controls to switch on and off of pumps and fans. This is one way of reducing the cost of CIA greenhouses and was adopted in this study.

3. Design and Construction of Prototype Greenhouses

Two prototype greenhouses were constructed and placed alongside each other (see Figure 2). Both greenhouses utilise the Quonset structure which has been altered to improve natural ventilation, by means of a butterfly vent. De Gannes et al. (2014) recommended the Quonset model of greenhouse with a split-roof as the best for the Caribbean region. Sahadeo et al. (2017) modelled and tested this model and verified this recommendation. Greenhouse A is a CEA greenhouse, while Greenhouse B is also a protected agriculture structure but with natural ventilation as the only means for controlling environment. The latter greenhouse was constructed so that both greenhouses could be tested side to side to see if there are advantages of the CEA greenhouse. Each greenhouse is 2 m length, 1.5 m width and 2 m depth.

The framework of the greenhouses was constructed with 12.5 mm and 25 mm-diameter polyvinyl chloride (PVC) pipes. PVC cement was used to stick all the pipes into their fittings. The greenhouse frame was covered with a 0.15 mm thick, ultra violet (UV) resistant, low density, clear polyethylene glazing material with a light transmittance of 80% to 90%. The main structure and glazing of protected greenhouses have been fully described by Sahadeo et al. (2017). Figure 3 shows the diagram of the CEA greenhouse (Greenhouse A).

(a) Greenhouse A: With controlled environment

(b) Greenhouse B: With no controlled environment

Figure 2. The two constructed prototype green houses

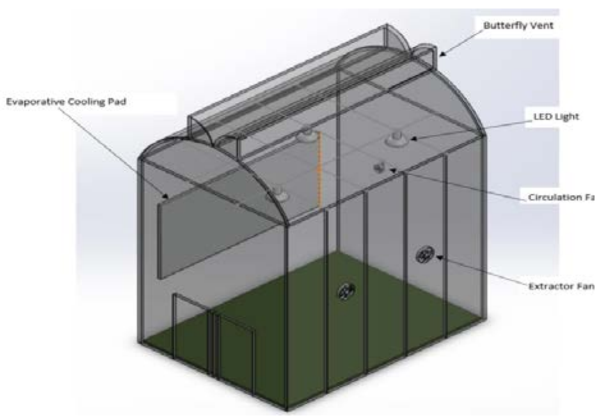

Figure 3. Controlled Environment Agriculture greenhouse (Greenhouse A)

Temperature control was achieved using two extractor fans (each 30.5 cm diameter) and a pad evaporative cooling system. The pad frame (1.6 m width, 0.8 m height and 0.762 m thickness) was constructed using pitch pine pieces. The pad material was shredded coconut fibres. Deoraj et al. (2015) found that coconut fibres are efficient for local use as pad material in evaporative coolers. For maximum efficiency and effectiveness, the greenhouse was designed to be air-tight, so that there was no disruption in or alternative path to airflow. Extractor fans drew the air from outside through the pad, since nature does not allow for a vacuum. The pad was continuously being wetted by a 0.01 hp pump (not shown in Figure 3) which supplies water to it from a tank.

As the air passed through the wet pad, it was cooled by evaporation. Evaporative cooling, however, works best in less humid conditions, since the cool, moist air being drawn through the pad adds humidity to the environment. The efficiency of evaporative coolers was tested in Trinidad by Deoraj et al. (2015) with some limited success. The CEA greenhouse therefore utilised in addition, natural ventilation so as to ensure that even without any of the automated systems being engaged, air was constantly exchanged between the external and internal environment, so that the crops got a fresh intake of air regularly.

As the hot air expands and rises, it escapes the greenhouse through the butterfly vent. When the internal temperature of the greenhouses exceeds maximum threshold of about 35^{o}C (monitored by a temperature controller), the evaporative cooling system will be activated, the exhaust fans and pump will switch on and the evaporative cooling process will start. When the temperature drops to the optimum level, the system will disengage. When the humidity inside the greenhouse exceeds 70% (monitored by a humidity controller), the two circulating fans (each 100 mm diameter), will switch on. When the humidity drops below 70%, the circulating fans will switch off. However, if the exhaust fans of the evaporative cooling system are on, the circulating fans will not switch on and vice versa. This is to avoid turbulence and vortices from developing due to the simultaneous circulation of air and the air being pulled through the greenhouse by the extractor fans.

Supplementary lighting was achieved using three light emitting diode (LED) fixtures. LED grow lights (Figure 3) have several advantages over traditional light sources: They are energy efficient, cheap to maintain and are long-lasting (Karlsson, 2014). The LED lights encourage photosynthesis and crop growth (Tian et al., 2014; Suraj, 2017).

4. Testing of the Constructed Prototype Greenhouses

Two tests were carried out. The first test examined the efficacy of the coconut fibre as an evaporative pad on two operating parameters of evaporative cooler (saturation efficiency of the evaporative pad and the temperature difference between the ambient conditions and the inside of the CEA greenhouse). The procedure used by Deoraj et al. (2015) was used in this study. A tank was filled with pipe-borne water (T_{avg} = 28.6^{o}C) and the pump was switched on. The airflow rate of the extraction fans was measured with an anemometer. Wet and dry bulb thermometers were used to measure the wet and dry bulb air temperatures entering the evaporative pad and another dry bulb thermometer was used to measure the temperature of the air entering the greenhouse. Temperatures were measured every 15 mins for 3 hours. The test was performed in the morning (9.00 a.m. to 12 noon) and it was repeated in the evening from 1 p.m. to 4 p.m. The saturation effectiveness of the evaporative cooling pad was calculated using the Equation 1 (ASHRAE, 2007).

$$\varepsilon = \frac{t_1 - t_2}{t_1 - t'} \times 100 \quad (1)$$

Where ε is saturation efficiency (%), t_1 is dry bulb temperature of entering air (K), t_2 is dry bulb temperature of leaving air (K) and t' is the wet bulb temperature of entering air (K).

The second test involved the planting of some vegetable crops in both greenhouses to test the efficiency of the CEA greenhouse. Two plant troughs, each 120 cm length and 60 cm width were filled with peat moss mix to a depth of 20 cm, and placed in the two greenhouses (see Figure 2). The troughs had openings at the bottom which allowed for drainage. Seedlings of the same maturity (two weeks old) collected from a nursery were transplanted to the two troughs. The crops in each trough included 3 plants of 535 variety roma tomatoes (Solanum lycopersicum 'Roma'); 3 plants of bronze lettuce (Lactuca sativa Mignonette Bronze); and 3 plants of pak choi (Brassica rapa spp. Chinensis).

The troughs were manually watered every day at 9.00 a.m. at the rate of 9 Litres day^{-1} for the three weeks of testing. A fungicide (Carbendazim, 50SC) was sprayed onto the leaves of each plant weekly. Plant heights, and stem diameters were measured three times a week with a ruler and Vernier caliper respectively. Leaf areas of each plant were measured using a grid paper. The ambient temperature and humidity as well as those for the greenhouse with natural ventilation were measured with a digital thermo-hygrometer, while those for the CEA greenhouse were recorded by temperature and humidity controllers. Readings of temperature and humidity were taken from 9.00 a.m. to 12 noon, as well as from 1.00 p.m. to 4.00 p.m. every two days.

5. Results and Discussion

5.1 Saturation Effectiveness and Temperature Difference

Table 1 shows the saturation effectiveness of the evaporative cooling pad and the temperature difference between the ambient air and inside of CEA greenhouse (Greenhouse A). The average saturation effectiveness attained for the coconut fibre pad was 25.3% (morning: 19% and 31.5% in the evening). The saturation effectiveness corresponds to temperature difference

Table 1. The temperature difference between the ambient air and inside of CEA greenhouse

Period of testing (mins)	Morning period (9.00 a.m. to 12 noon) Temperature difference (°C)	Saturation effectiveness (%)	Evening period (1 p.m. to 4 p.m.) Temperature difference (°C)	Saturation effectiveness (%)
0	1.5	20.0	3.0	46.2
30	2.3	30.7	2.0	36.4
60	2.0	26.7	1.0	18.2
90	1.5	21.4	1.5	27.3
120	1.0	15.4	2.5	40.0
150	0.5	9.1	1.5	27.3
180	0.5	10.0	1.5	25.0

Saturation effectiveness and temperature difference, as expected, were higher in the evening than in the morning and this agrees with results by Dagtekin et al. (2009) as the weather conditions throughout the day affected the system.

These values were much lower than the corresponding average values of 53.5% and 3.6 °C found by Deoraj et al. (2015) for coconut fibres similar to the ones used in this test. They operated their fans at 4 m/s, 6 m/s and 8 m/s compared to average of 2.4 m/s speed of the extraction fan in the present tests. Several other factors which affect pad performance including surface area of the pad, pad thickness, size of perforation of the pads, relative humidity of air passing the pad, volume of water used and number of layers may also have contributed to the lower values obtained (Sreeram, 2014).

5.2 Temperature and Humidity in the Ambient Air and in Greenhouses A and B

Figures 4 and 5 show the average daily temperature and humidity of the ambient air as well as those in Greenhouses A and B during the crop growth test period, respectively.

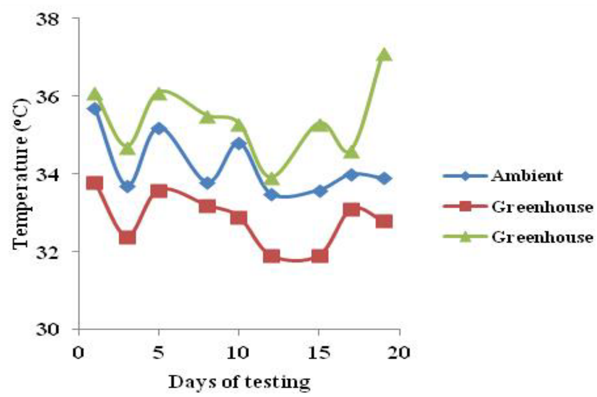

Figure 4. Temperature of the ambient air and inside the two greenhouses

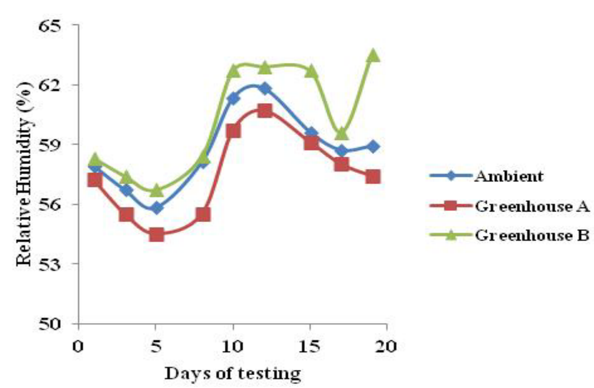

Figure 5. Relative humidity of the ambient air and inside the two greenhouses

Results show that the temperature and relative humidity inside the CEA greenhouse (Greenhouse A) were lower than those for the ambient air.

This is not surprising since the temperature and relative humidity of the CEA greenhouse were controlled via evaporative cooling and air circulation, respectively. The reverse was obtained for Greenhouse B where the lack of control meant that the two parameters were higher than the values for the ambient air. It was shown in Section 5.1 that the evaporative system was able to effectively reduce the temperature from ambient conditions by 1.6°C. Greenhouse B on the other hand had no accommodation for control of air movement other than natural ventilation, making the humidity higher than that in the CEA greenhouse.

5.3 Plant Growth Parameters in the Two Greenhouses

The plant parameters used to compare the performance of the two greenhouses were plant height, plant diameter and leaf area. Obtaining the three parameters required non-destructive tests. Table 2 shows the values of the plant height and plant diameters of the three vegetable crops. Average growth rates for the height and diameter were calculated by subtracting the initial value of the parameter from the final value and dividing by the test period (19 days). The heights and diameters of all the three crops were much higher in the Greenhouse A (CEA greenhouse) than in Greenhouse B with natural ventilation.

On the average, the average growth rates in the Greenhouse A, in terms of height, were at least 1.77, 2.67 and 3.88 of the values in the Greenhouse B for tomatoes, lettuce and pak choi, respectively. For the crops, the respective values for plant diameter were 1.12, 2.4 and 55. This suggests that the CEA greenhouse was most effective for the pak choi and least for tomatoes. Thus, it is evident that a combination of all the control variables (temperature, humidity, light intensity and air movement) was responsible for the improvement in plant growth in the CEA greenhouse.

Wheeler et al. (1991) were the first to propose that plant developmental response to blue light (400 – 500 nm) was dependent on absolute blue light for stem elongation in soybean. Blue wave lights affect phototropism, the opening of stomata (which regulates a plant's retention of water) and chlorophyll production (Reece and Campbell, 2011). Crops in CEA greenhouse were grown under LED blue light. Plant stem diameter changes due to both cambial growth (microstructural layer responsible for secondary growth of stems and roots) and water content (Sevanto, 2003). With higher temperature, the plant transpires at a faster rate, causes exhaustion and lack of water retention in the stem of the plant.

Figure 6 shows the growth of the leaves in the three crops during the testing period. The results followed the same trend as for plant height and stem diameter discussed above, with the CEA greenhouse having much larger areas for the three crops than Greenhouse B (about two and half times on the average). The best results for the CEA greenhouse were obtained for pak choi followed by lettuce and then tomatoes. The values widened as time of testing increased showing that the differences in plant development between the two greenhouses are expected to increase as the growth period extends.

Shin et al. (2001) found that leaf area, stem length and stem diameter generally increased with decreasing temperature. Wang et al. (2014) demonstrated that LED blue light optimised photosynthetic performance by improving the photosynthetic rate, increasing leaf area and prolonging active photosynthesis duration under low irradiance. Chlorophyll absorbs light within the range of 400-500 nm most effectively (red and blue light).

Table 2. Growth parameters for the three crops during the test period

Days after planting	Tomatoes		Lettuce		Pak choi	
	Height	Stem diameter	Height	Stem diameter	Height	Stem diameter
	(cm)	(x 10^{-1} cm)	(cm)	(x 10^{-1} cm)	(cm)	(x 10^{-1} cm)
1	11.0*/11.0	0.154/0.155	7.6/7.0	0.297/0.294	5.7/5.7	0.197/0.196
3	12.4/12.3	0.161/0.159	8.9/7.1	0.313/0.310	8.6/6.0	0.207/0.199
5	14.9/14.4	0.171/0.165	9.9/7.7	0.321/0.314	9.9/6.9	0.234/0.214
8	20.5/16.9	0.195/0.179	11.2/8.1	0.331/0.318	11.2/7.6	0.303/0.215
10	23.5/18.5	0.219/0.193	11.9/8.6	0.335/0.320	13.0/8.3	0.326/0.223
12	26.6/19.6	0.225/0.213	13.0/9.1	0.346/0.326	14.6/8.9	0.367/0.243
15	29.6/21.6	0.247/0.245	14.0/9.5	0.368/0.338	15.9/10.2	0.387/0.257
17	30.0/21.7	0.257/0.246	14.6/9.7	0.383/0.339	16.1/10.4	0.416/0.264
19	30.2/21.9	0.259/0.248	15.2/9.9	0.405/0.340	16.4/10.5	0.435/0.278
Average growth rate (cm or mm day^{-1})	1.01/0.57	0.0055/0.0049	0.40/0.15	0.0057/0.0024	0.97/0.25	0.238/0.0043

*- Values of the growth parameters are average for the three plants in the Greenhouse A/Greenhouse B.

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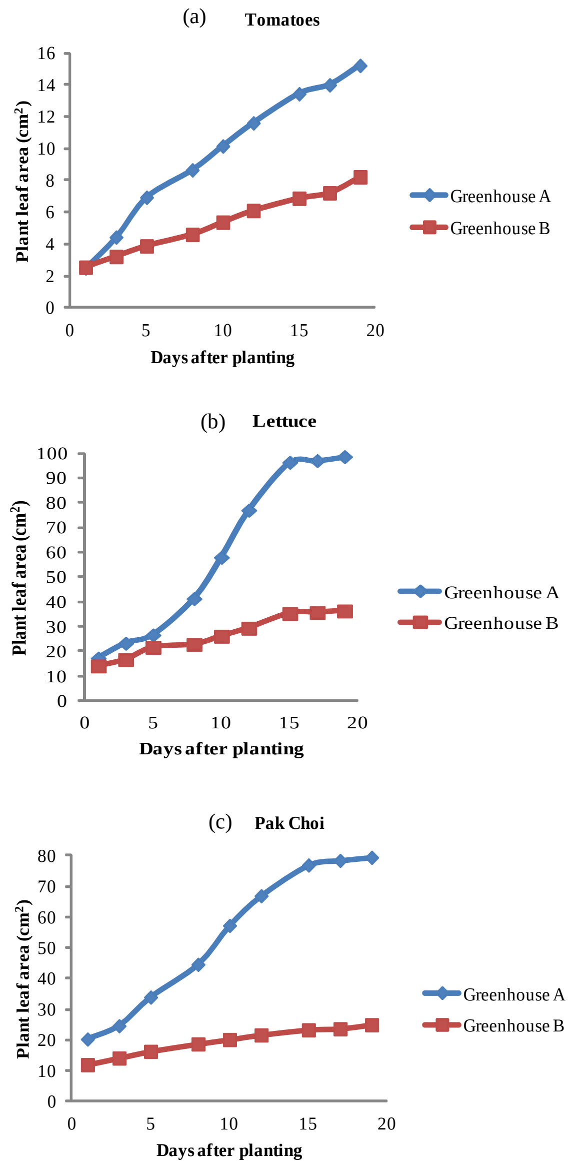

Figure 6. Values of mean leaf area for the three types of crops in the two greenhouse during the testing period

6. Conclusion

A CEA greenhouse was designed, built and tested by examining the effects of different control parameters on system performance and plant growth. The saturation effectiveness of the pad and temperature difference between the ambient and the inside of the CEA greenhouse were found to be 25.3% and 1.6^{o}C respectively. The impact of controlling temperature and humidity on the CEA greenhouse was assessed, by comparing the results to those of the non-controlled environment and ambient conditions. The results indicated that the controlled environment provided effective cooling and humidity reduction, whereas the non-controlled environment elevated ambient temperature and humidity conditions. Plant growth parameters (height, stem diameter and leaf surface area) within the CEA greenhouse were much greater than those for the naturally ventilated greenhouse.

The combination of using blue LED light, evaporative cooling, and air circulation fans coupled with natural ventilation gave a significant improvement in plant growth rates in the CEA greenhouse. The total cost for two greenhouses was about US$ 600. Further work will evaluate the efficiency and cost of fully functional CEA greenhouses so as to further validate these findings. Instead of the simple on/off switches method utilised to control the CEA greenhouse environment, an integrated computer control system will be investigated in future research.

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The Development of a Portable Electrical Engineering Educational Outreach Toolkit

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Abstract: *A strong STEM (science, technology, engineering and mathematics) workforce is central to economic growth and development. To build such a workforce, there is need to promote STEM disciplines. This paper describes the use of a portable electrical engineering outreach toolkit that targets primary and secondary students. The Outreach Toolkit contains 1) a Van De Graff Generator, 2) Tesla Coil, 3) Joule Thief and 4) a Combinatorial Logic Designer Board. Based on the electrical engineering theory and principles as required by the primary and secondary school curricula, live demonstrations are to be conducted using these devices. Complemented with the Toolkit, there are user manuals and a suite of videos that describe various experiments, safety precautions and maintenance requirements. For evaluating the efficacy of the toolkit, a group of 1 primary and 1 secondary schools from the South Eastern Education District of Trinidad and Tobago was based, and their students and teachers were invited to participate a demonstration of the toolkit. Results showed that majority of the secondary school students (90%) indicated that the use of the toolkit could increase their interests in studying science. Some 95% of students indicated that the toolkit made learning science more fun and motivational, and would like to have the device equipped at their school.*

Keywords: *STEM, Combinatorial Logic Designer Board, Educational Outreach Toolkit, Trinidad and Tobago*

1. Introduction

There is a pressing need for the Caribbean to embrace STEM (science, technology, engineering and mathematics) education to boost interest in sciences, encourage the pursuit of jobs in science and engineering and promote awareness of the link between science/engineering and regional economic development (Foundation, 2015). Encouraging young people to pursue a career in engineering is paramount to developing a strong STEM workforce. Such a workforce would address regional challenges such as energy sustainability, food security and economic decline. Educational outreach refers to activities that support formal and/or classroom-based education, as well as informal education that occurs outside the classroom (Education, 2002).

It has been widely argued that informal forms of education could boost interest in learning, in conjunction with formal education. Educational outreach is beneficial for a number of reasons. For instance,

- Students who struggle in a formal school setting may blossom in an informal setting.
- Informal education could boost students' confidence in a classroom setting.
- Teachers tend to adhere to a fixed curriculum in the classroom (formal setting) whilst out of the classroom programmes (informal setting) allow more flexibility with content.

In order to engage primary and secondary school students in science, live demonstrations are effective (Differently, 2013). This paper describes the development of a portable electrical engineering educational outreach toolkit that can be used encourage primary and secondary school students in science, particularly electrical engineering. The outreach toolkit comprises four devices, these are: 1) the Joule Thief, 2) a Van De Graff Generator, 3) a Combinatorial Logic Designer Board, and 4) a Tesla Coil. Based on the electrical engineering theory and principles as required by the primary and secondary school curricula, live demonstrations are to be conducted using these devices. For example, a school teacher could use the Van De Graff Generator to demonstrate the principles of electrostatics (see Table 1).

Each device in the outreach toolkit is accompanied with a set of user-friendly manuals and videos, which describe various experiments that can be performed. For facilitating these experiments, a set of Teachers' notes for each experiment is also provided. In addition, the user manual outlines safety precautions and maintenance tips for each device. This paper describes the design of the toolkit, presents test results and assesses the cost of producing the toolkit.

Table 1. Topics addressed by each device of the outreach toolkit

Device	**Topics addressed**.
Van De Graff Generator	Electrostatics, charging by induction and conduction, triboelectric series, Faraday's ice pail effect, types of charges and force on charge in electric field.
Joule Thief	Transistor operation as a switch, charging and discharging of inductors, LED electrical characteristics, introduction to boost converter, voltage clamping using diodes, and capacitive smoothing.
Tesla Coil	Electric fields, florescent lamp operation, flux linkage, transformer operation.
Combinatorial Logic Designer Board	Operation of the fundamental logic gates, operation of flip flops, half adder, full adder and three bit binary counter, counting in binary, converting between binary and decimal, switch bouncing, conductivity of the human body, conductors and insulators.

2. Devices in the Outreach Toolkit

2.1 Van De Graff Generator

Description

A Van De Graff (VDG) generator is a machine used to generate a high DC voltage by moving charge from a source to an isolated dome via a rotating belt (see Figure 1). This device is to conduct various electrostatic experiments (see Table 1).

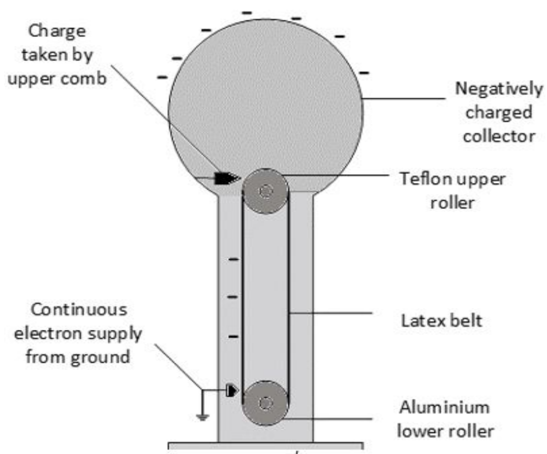

Figure 1. Generic Van De Graff generator

Operation

The Triboelectric series lists the materials that would become most positive or negative when in contact with another material (EESemi, 2001). This series is used decide on which materials for the upper and lower rollers. Roller materials are chosen as far apart on the Triboelectric series to achieve maximum static charging. The operation of the Van De Graff generator is explained as follows:

1) Charging the lower roller:
The AC motor is powered from a 110 V supply. As the belt revolves around the upper and lower rollers, the surface of the lower roller becomes charged by the frictional charging between the roller and the belt. The quantum of charge developed by the roller and the belt depends on where the materials are on the triboelectric series. In this explanation it is assumed that the lower roller has a greater tendency to become positive. As the belt continues to rotate and charge the lower roller there is a resulting charge imbalance. This occurs since the electrons from the roller moves onto the belt. Therefore, the roller becomes positive and the belt becomes negatively charged. The positively charged roller now attracts the electrons from the grounded lower comb and the process of charge movement repeats.

2) Charges move across the air:
This attraction causes electrons to concentrate at the tip of the lower comb. As the belt continues to rotate and charge the lower roller, the electric field between the belt and comb tips becomes strong enough to separate the electrons and the nuclei of the surrounding air molecules. This results in a conductive path known as corona discharge or plasma. Electrons from the plasma stick to neutral air molecules giving them a net negative charge. The negative comb repels the negative air molecules. This results in a negatively charged wind (ion wind) emanating from the comb.

3) Charges are caught by the belt:
The conductive path caused by the corona discharge allows for the ion wind to move in the direction of the positively charged lower roller. The belt intercepts the ion wind thereby increasing the negative charge of the belt. As the belt rotates, negative charges are constantly sprayed on the rubber belt. The lower comb is grounded. Therefore, there is a continuous supply of negative charge.

4) The belt carries charge to the upper roller:
The negatively charged belt rotates to the top roller near the upper comb. The electrons in the tip of the upper comb are repelled by the strong negative charge of the belt and positive charge accumulates at the tips of the comb. This creates a strong electric field between the belt and the upper comb, which causes corona discharge. The free electrons resulting from the discharge is attracted to the positive comb tips. The positive air molecules are attracted to the negatively charged belt, thus neutralising the belt.

5) Charges exit at the top comb to the dome
The upper comb is electrically connected to the collector. As the belt repels more electrons into the upper comb the charges distribute evenly on the outer surface of the

collector. In this way, the collector continues to accumulate negative charge as the belt rotates.

2.2 The Tesla Coil

Description

A tesla coil was a device invented by Nikola Tesla in 1831. The device utilises a resonant air-core transformer circuit to produce a high voltage, low current and high frequency AC current. Voltages over one million volts could be generated, and are discharged from the toroid (top load) of the tesla coil in the form of sparks. For this project, the Tesla Coil is a solid-state device and does not require capacitor banks or a spark gap to produce oscillations. This low-power and compact device utilises a transistor to control the resonance of the primary and secondary coils. Figure 2 shows the circuit design of the Tesla coil, named as the Slayer Exciter (Sadaghdar, 2015). Both J. Stiffler and G. Bluer of the United States were the inventor of this version of the Tesla Coil. This device can be used to demonstrate Faraday's Law and the existence of electric fields (see Table 1).

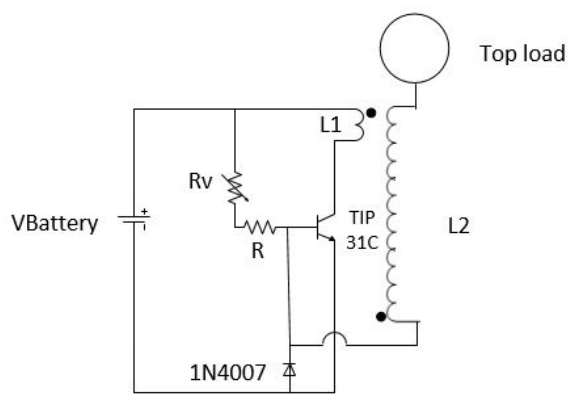

Figure 2. Slayer Exciter circuit diagram
Source: Adopted from Sadaghdar (2015)

Operation

Operation of this circuit starts when the switch is closed (switch not shown in the diagram). At this instance, the transistor's state is 'off'. Therefore, the current through the primary coil L_1 is zero and the voltage induced across the secondary coil L_2 is zero.

As the transistor turns on, the current of the collector increases and it flows through the primary coil, creating an increasing magnetic field. The magnetic field of the primary induces a voltage across the secondary such that the top-load is positive. Due to the voltage of the top-load, there exists an associated electric field. The negative voltage induced at the bottom of the secondary forces the base of the transistor low, turning off the transistor. Since there is no current flow through the primary coil, its magnetic field collapses. Hence, the secondary magnetic field also collapses.

At this stage, current starts flowing into the base of the transistor again and the process repeats. This process repeats at a frequency in the order of kilohertz. The system is always in resonance, since the transistor will only turn back on when the secondary coil magnetic field has collapsed.

2.3 Joule Thief

Description

A Joule thief is a circuit that uses an AA battery with a voltage ranging between 0.75 V and 1.5 V and is able to power multiple LEDs. The circuit was invented by Z. Kaparnik of the United Kingdom (Kaparnik, 1998), and it first iteration was named as 'One Volt LED-A Bright Light'. Kaparnik presented three variations of his circuit for operating LEDs from a supply below 1.5 V. In 2002, Clive Mitchell named his variation of Kaparnik's design 'The Joule Thief'. His variation was different only in terms of component values. This device can be used to demonstrate series/parallel connections and charging/ discharging of inductors.

Operation

Figure 3 shows the circuit design for the Joule Thief that was adapted from Kaparnik (1998). With the power switch on (not shown), current flows through the primary winding, L_1, through resistor, R, and into the base of the transistor. The transistor begins to turn on. Therefore, current starts to flow through the secondary windings, L_2. The cathode of the diode is more negative than the anode, but the diode will not light since the battery voltage is a maximum of 1.5 V, while the led typically requires 2.0 V to light. Therefore, no current flows through the LED.

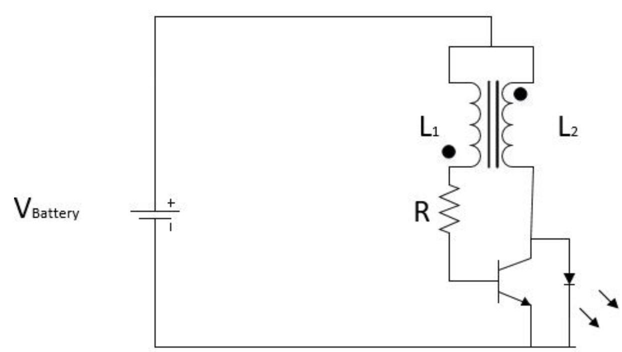

Figure 3. Joule Thief circuit diagram
Source: Adapted from Kaparnik (1998)

The current through the secondary coil (L_2) is larger than that through the primary (L_1). The interaction between the magnetic fields of L_1 and L_2 creates a positive feedback system between the coils. This increases the current through $L_{2,}$ creating a stronger magnetic field which induces an emf across L_1, resulting in an increased base current to the transistor. This increase in base current causes the current through L_2 to increase, continuing the positive feedback process.

This process continues until the inductor core or transistor reaches saturation, if either saturates there cannot be any further increase in magnetic field strength. Since there is no changing magnetic field, there will not be an induced voltage across L_1. This causes a voltage to be generated across L_1 in a direction to oppose the source. The base current drops and the transistor enters the cut off region.

Since the transistor is now off, the L_2 magnetic field collapses. This would generate a voltage spike that appears across the LED, forward biasing it and the LED lights. Once the magnetic field of L_2 collapses, current starts flowing through L_1 again into the base of the transistor, and the positive feedback process restarts. It shows that the LED is not always on, but instead flashes at a fast rate so that the brain perceives it as always being on.

2.4 Combinatorial Logic Designer Board

Description

The Combinatorial Logic Designer Board is a hands-on device that allows the user to build various digital circuits. The board features logic circuits required by the CXC and CAPE syllabi. These circuits include, *T* flip-flop, *SR* flip-flop, 3-bit binary adder using *T* flip-flop, half adder and full adder. The board also allows for custom-built circuits. Input is via push button switches, slide switches and a light sensor. Output devices are LEDs, seven segment displays and a buzzer. One use of the Logic Board is to demonstrate conductivity of the human body, counting in binary and the conversion between binary and decimal.

Operation

The Combinatorial Logic Designer board consists of four main sections that can be interconnected using banana plugs. These sections are as follows:

1) User input section: The user is able to choose between push buttons, slide switches or a light sensor as the input stimulus.

2) Logic gates: The user is able to verify the logic gate truth table (NOT, OR, NOR, AND, NAND, and XOR) by observing its input/output characteristics.

3) Circuit selection field: The user selects a circuit to be explored, for example, the 3-bit binary counter or the half adder. The user can choose any form of input for the selected circuit. Inputs are fed to the selected circuit using banana plugs.

4) Output: This section contains the devices that will respond to the signals received from the selected circuit. The signaling section consists of a seven-segment display, LEDs and a buzzer.

3. Design of the Toolkit

3.1 The Van De Graff Generator

The Van De Graff generator was designed in part using design recommendations made by Beaty (1996), Graff (2008) and Ritchey (2010). The design utilised a 12-inch sphere which could generate a maximum voltage of 360 000 V. Figure 4 presents a demonstration of operating the Van De Graff Generator.

Figure 4. Operating Van De Graff Generator

The following is a summary of the design specifications for the VDG:

- Largest collector is used to maintain portability of the outreach toolkit (i.e., 12-inch aluminum gazing ball).
- 6.35 cm wide latex rubber used for belt.
- Adjustable speed motor (1,000 rpm max)
- Distance between the collector and base is at least twice the radius of the collector.
- Collector is highly polished
- Aluminum lower roller
- Teflon upper roller
- PVC column (26 inch)
- VDG mounted on Plywood base

3.2 Joule Thief

Figure 5 shows the Joule thief circuit design that is adapted from Kaparnik (1998). A 1.5 V AA battery would be needed to turn on a LED of the device. Figure 5 shows a completed Joule Thief. The design specifications for the Joule Thief are determined. These are summarised as follows:

- Center tap transformer is to be created with twenty turns of 32 AWG enamel wire on both the primary and secondary coils.
- Ferrite core is to be obtained from a compact fluorescent lamp.
- 2N3904 Transistor is used for high current gain and low cost.
- Designed to turn on a LED with a supply battery voltage of at least 1 V.

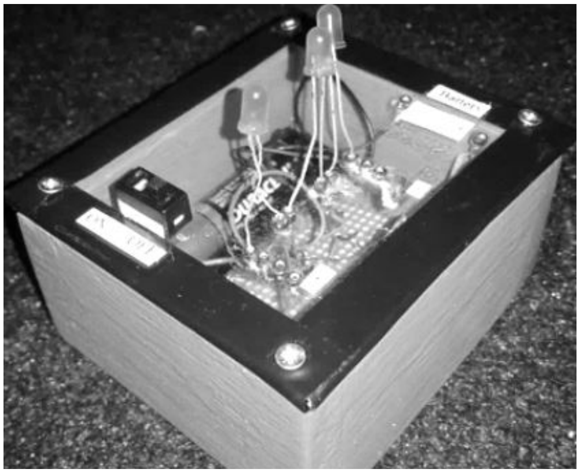

Figure 5. Completed Joule Thief

3.3 Tesla Coil

Figure 6 depicts the Tesla Coil circuit design that is adapted from Sadaghdar (2015). The Tesla coil was designed to light a fluorescent lamp wirelessly from as far as possible, while maintaining portability. The fluorescent lamp lights wirelessly because of the changing electric field produced by the secondary coil. Therefore, a larger secondary voltage would increase the range of the Tesla Coil. Since the current through the primary coil, L_1, and the turns ratio directly affect the voltage across the secondary coil, these variables were set to maximum, while maintaining safety and portability requirements.

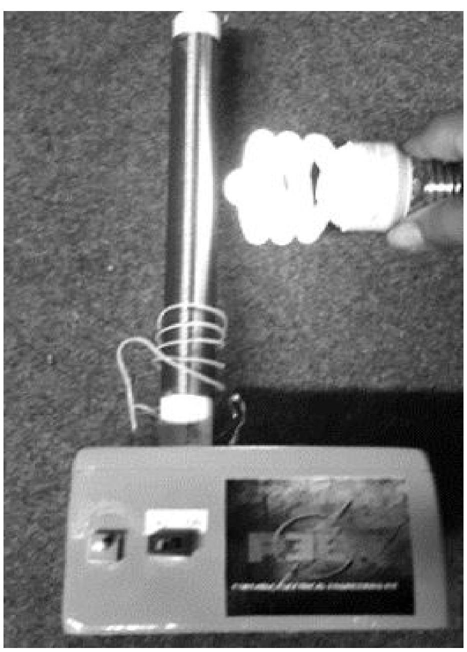

Figure 6. Operating Tesla Coil

The design specifications are determined for the Tesla Coil. These are summarised as follows:

- TIP31C transistor is to be used for high power and switching frequency capability.
- For safety, the current through the primary coil is to be set to the maximum value (400 mA).
- The turns ratio is to be set to a maximum value while maintain portability (Max secondary coil length = 18 cm).
- Variable resistor is to be added to the base of the transistor to allow power level adjustments of the Tesla Coil.
- 18 V source supply voltage.

3.4 Combinatorial Logic Designer Board

The Logic Board is powered with a 9-V battery, and all ICs used have identical electrical characteristics (i.e., V_{OL}, V_{OH}, V_{IL}, $V_{IH,}$ and V_{DD}). This allows for direct integration of the ICs. The Logic Board consists of the following sections: Inputs, 3-bit counter, Adders, Logic Gates, Flip-flops and outputs. Figures 7 and 8 show a completed Logic Board, and the Block diagram of the Logic Board circuitry, respectively.

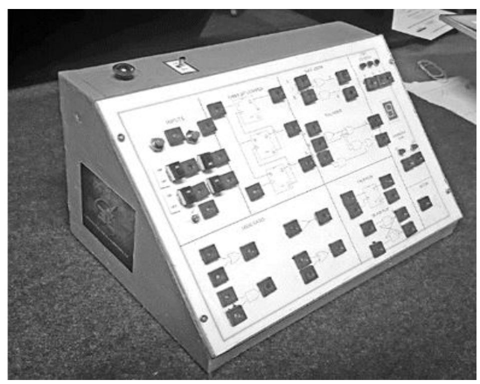

Figure 7. Completed Logic Board

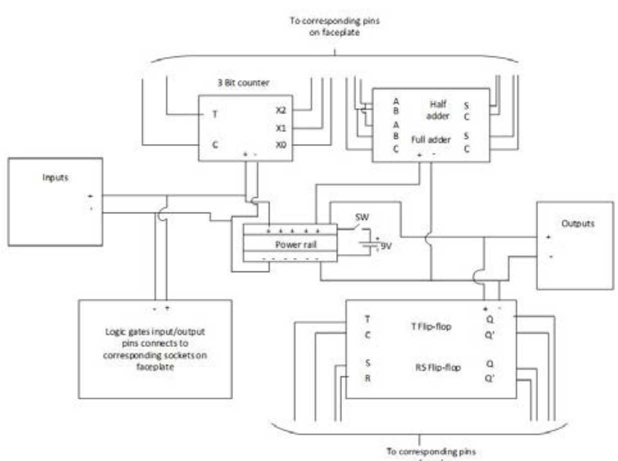

Figure 8: Block diagram of the Logic Board circuitry

4. Results and Functionality of the Devices

The Logic Board passed various unit and integration tests. The user manual provides a brief description of the Logic Board's origins precautions for using the board and the procedure for conducting seven unique experiments. From the results obtained, the Joule Thief was able to turn on a 1.80 V LED using a minimum supply voltage of 0.87 V. Using a 1.50 V battery and loaded with one LED and a 1Ω current sensing resistor (R1), results are recorded. Figure 9(a) and 9(b) show the actual output waveform obtained, and give the corresponding designed output current expected, respectively.

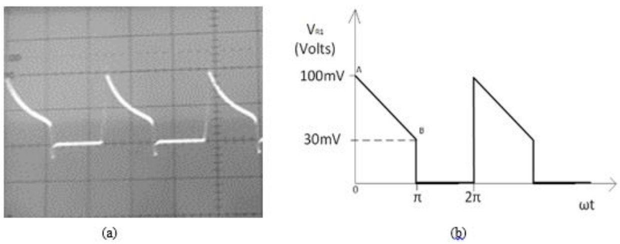

Figure 9. Output current waveform

Equation of line

$$AB = \frac{70\times10^{-3}}{-\pi}\ \omega t\ + 0.1 \qquad (1)$$

Average voltage across R_1,

$$V_{R1}\ =\ \frac{1}{2\pi}\int_0^{\pi}\frac{70\times10^{-3}}{-\pi}\,\omega t\ +\ 0.1\quad \omega t \qquad (2)$$

$$= 32.50mV$$

Average output current, $I_{avg} = \frac{V_{R1}}{R_1}$ $= 32.50mA$

The average output current is 32.50 mA and average output power is 21.678 mW.

There are three experiments provided in the user manual. The Tesla coil Slayer Circuit is able to light a fluorescent lamp held approximately 7 cm away from the secondary coil. This range is satisfactory.

The VDG is able to achieve an average collector voltage of 153 kV. The arc length is measured by slowly moving a discharge wand towards the collector and measuring the distance between the collector and wand at the point of arcing (collector is allowed to charge for 30 seconds between discharges). The estimated voltage developed, $V_{D,}$ is calculated using equation 3, where the arc length is in centimetres:

$$V_D = Arc\ length \times 30\ kV \qquad (3)$$

Moreover, it is recommended that the VDG be operated in a low humidity environment for best results. The average arc length is 5.1 cm, and hence, the average developed voltage, V_D, is 153 kV. Table 2 provides a summary of number of experiments and the performance of respective devices.

Table 2. Performance summary of the devices

Device	Performance	Number of experiments
VDG	Average developed voltage = 153 kV.	5
Tesla Coil	Range of at least 7 cm	3
Joule Thief	Average output current 32.50 mA.	4
Logic Board	All circuits are functional.	7

5. Outreach Toolkit Demonstration

For evaluating the efficacy of the Portable Electrical Engineering Educational Outreach toolkit, it was taken to one primary and one secondary school in the, South Eastern Education District of Trinidad and Tobago. Feedback from students and teachers from both schools is collated and analysed.

5.1 Primary School Feedback

1) From Students

A demonstration session of the toolkit was made to students of the Standard four and five at the school. Students were eager to investigate the devices. For instance, they asked questions about the Van De Graff Generator, such as: "*Would current flow through your body if three persons were holding hands and only one was touching the collector*?" A student was able to suggest that an electromagnetic wave from the Tesla Coil caused the fluorescent lamp to light.

At the end of the session, students showed keen interests and would like to have the device equipped at their school. Figure 10 shows a photo taken of the primary school students investigating the VDG.

Figure 10. Primary school students investigating the VDG

2) From Teachers:

The Session received positive feedback from teachers who attended the session. Most teachers expressed that the outreach toolkit would be a valuable tool for engaging students in science, and requested periodic demonstrations at their school, at all levels.

5.2 Secondary School Feedback

1) From Students:

A group of 45 students (from both Form 3 and Form 6) were present for the demonstration session of the toolkit. Before the start of the session, a set of standard questionnaires about the toolkit were provided. The questionnaire had two parts, requiring students to answer pre-demonstration and then post-demonstration questions.

From the pre-demonstration data and results, 55% of the students indicated they were interested in pursuing science, while 30% and 15% were interested in Business and General Studies, respectively. Students thought that performing science experiments would be fun. From the post-demonstration data and results, all students shared their views that the presentation was very interesting (75%) and was interesting (25%). Moreover, a majority (some 90%) of the students indicated that the use of the toolkit could increase their interests in studying science. Some 95% of students indicated that the toolkit made learning science more fun and motivation, and would like to have the device equipped at their school.

2) From Teachers:

Physics teachers expressed a great need for the outreach toolkit at their school after seeing how engaged the students were during the demonstration. Comments received include:

- "*The outreach toolkit is ideal for prompting students to think outside the box and become engaged in scientific discussions.*"
- *"It makes the students want to learn more, since they are fascinated by the devices."*
- "*The smiles I saw on your faces, I do not know what I am going to do without this equipment.*"

6. Financial Assessment

Figure 11 shows a sample set of the Outreach Toolkit housed in the carrying case. An attempt was made to address the financial implications in making/equipping such a Toolkit. One experienced person had already gone through the learning curve, and taken up the task to make/construct the sample toolkit. The expected time for construction of the Toolkit was calculated neglecting delays (time for paint/glue to dry and breaks). Within the limits of the assumptions made, the estimated time for construction of the Toolkit is 47.50 hours.

Figure 11: Devices housed in the carrying case

The material cost for the toolkit (excluding labour costs) to produce the Toolkit is amounted approximately TT$2,000.00 per unit (i.e., TT$1,866.60 + 136.04 = TT$2,002.64 or US$318.90; Exchange Rate: US$1.00 ≈ TT$6.30). Table 3 shows a summary of a preliminary financial assessment for the Toolkit.

An equivalent Outreach Toolkit is not commercially available. Only similar Van De Graff Generators and Tesla coils are commercially available but cost 105% and 137% more than the devices in this paper respectively. The carrying case is custom built to house the items in the Toolkit, therefore the carrying case is not commercially available. It is expected that if the Toolkit is accepted in schools, the manufacturing costs would drop significantly using economies of scale.

7. Conclusion

The Toolkit is an educational tool used to conduct live demonstrations electrical engineering theory and principles as required by the primary and secondary school curricula. It consists of four devices, with accompanying user manuals and accessories. The material cost of the toolkit is approximately $2,002.64, and the estimated time for construction is 47.50 hours. The Joule Thief, Tesla Coil and the Combinatorial Logic Designer Board performed satisfactorily. These devices are equipped to conduct a list of experiments described in the user manual.

Table 3. Summary of financial assessment for the Outreach Toolkit

Device	Cost to construct (TT$)	Cost for manual and accessories (TT$)	Labour hours required
Van De Graff generator	998.80	34.00	16.00
Tesla Coil	54.05	55.00	4.00
Logic Board	245.75	25.00	12.00
Joule Thief	42.04	22.04	3.50
Carrying case	568.00	0.00	12.00
Totals	**$1,866.60**	**$136.04**	**47.50 hours**

Based on the feedback from the school visits and demonstration session, both Primary and Secondary school teachers indicated that the outreach toolkit would be an asset to their school as it provides a mechanism to engage students in scientific experiments that are both fun and educational. Majority of the secondary school students indicated that the outreach kit made learning science more fun, and enhanced their interests in learning. Some 95% of students who attended the session would like to have the device equipped at their school. Primary school students were equally excited and engaged in the demonstration sessions. The Toolkit would thus be an essential item in the laboratories at schools. It would be suggested the Ministry of Education to consider the Toolkit as one of the essential tools for engaging students in science learning through experimentation.

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Chandrabhan Sharma *is Professor of Energy Systems with the Faculty of Engineering, The University of the West Indies. He is the Head of the Centre for Energy Studies and the Leader of the Energy Systems Group. Professor Sharma has served as a member of the Board of Directors of the local Electric Utility for over 10 years, and is a member of the Board of Directors of the largest bank in the country. Prior to joining the academic staff at the university, he was attached to the petrochemical industry in Trinidad. His interests are in the area of power system operations and control.*

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The Role of Engineering in the Design of Kings of Carnival Costumes in Trinidad and Tobago

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Abstract: *Information is lacking on the design process and key design issues faced by Kings of Carnival costume designers in Trinidad and Tobago. Unlike parade floats, Kings of Carnival costumes consist of large decorative pieces mounted on a three-wheeled frame that is moved around by a single masquerader who enacts a stage performance with the costume. To address this problem, a qualitative study was conducted through semi-structured interviews involving fifteen Kings of Carnival costume designers within the last three years. The study was sought to identify the design process used, extract the factors that influence the design of the costumes, examine the extent to which Engineering principles are utilised, and recommend strategies for improving the design process. Results indicated that engineering input was not utilised in the costume design process and material selection was based on tradition, availability and cost. Designers did not take into consideration the mechanical properties of materials during the construction of costumes. This resulted in a lot of trial and error during the construction and extremely heavy and uncomfortable costumes. External factors such as wind and rain were not being adequately addressed in the design process resulting in sub-optimal and unreliable designs. Recommendations to improve the design process include the implementation of a more rigorous design process, workshops to train designers in specific engineering tools that could be used, a modular costume design platform, revision of material selection and analysis of costume reliability to withstand unpredictable external loads. In addition, it is necessary to provide simple and accessible engineering support to local designers while easing their fears about keeping the art form intact and maintaining their creative edge.*

Keywords: *Carnival, costume design, design process improvement, Trinidad and Tobago*

1. Introduction

In Trinidad and Tobago (T&T), there are three key Carnival art forms, of which masquerade is the oldest. It can be traced to the French planter class who came to the island accompanied by their slaves following the Cedula de Population edict of 1783 (Van Koningsbruggen, 1997). Carnival has always been about social expression and the voice of society which is displayed on the streets. Since its birth, it has evolved into bands led by a King and Queen. These King and Queen carnival costumes are used to portray a specific theme. Unlike parade floats, Kings of Carnival costumes consist of large decorative pieces mounted on a three-wheeled frame that is moved around by a single masquerader who enacts a stage performance with the costume. Despite the creativity on display, the masqueraders carrying these large costumes have been known to fall or have general difficulty in moving with them on. In addition, parts of costumes have fallen off or become damaged while performing on stage. Given these issues, the aim of this research paper is to determine the design process and key design issues faced by Kings of Carnival costume designers in Trinidad and Tobago.

There is limited published information on how Kings of Carnival costume designers execute the design process and how methods and tools from engineering design could improve the quality of designs. Therefore, there is a need for research and documentation of the extant design processes employed and key design issues faced by Kings of Carnival costume designers in Trinidad and Tobago. Specifically, this paper aims (1) to identify the design process used and factors that influence the Kings of Carnival costume design, (2) to examine the existing role of engineering in Kings of Carnival costume design and (3) to recommend strategies for improvements in the design process to improve the quality and creativity of Kings of Carnival costume design.

2. Background to the Carnival in T&T

Carnival in Trinidad and Tobago originated in the year 1785 after the Cedula of Population for Trinidad in which was a decree proclaimed by King Carlos of Spain in 1783 (Anthony, 2011). This celebration has always been a day of freedom for the population of Trinidad and Tobago, and the Kings and Queens competition reflects this freedom of expression by showcasing thematic portrayals. The King of the Band costume is an exhibition of the Mas Band's skills, craftsmanship, and ingenuity in design. The display of the costume is accompanied by narratives, dance sequences, flashing lights, and fireworks compiled to create an artistic piece to tell a visual story. These costumes often require extensions, wheels, and expert production to assist the masquerader who carries it on stage. An example of a winning Kings of Carnival costume is shown in Figure 1.

Figure 1. Winning Kings of Carnival Costume 2017: Ted Eustace portraying "Crypto - Lord of The Galaxy"

The costume should exude the essence and energy of the idea it is trying to project (Geus, 2006). The role of the costume is identified as essentially performing the following functions: (1) visually defining and enhancing the charter, (2) supporting the overall theme, (3) supporting the dramatic actions, (4) expressing its spirit and (5) providing interest. In the Kings of Carnival competition, the name sets the theme and visual outlook of the character, and it is up to the designer to use the structural and dynamic features of the costume to convey an idea to the judges and audience. The stage performance is carried out by an individual masquerader in a costume that can weigh more than 200 lbs supported with a maximum of 3 wheels for mobility.

The judges' expectations for the Kings of Carnival costumes are exceptional craftsmanship, some level of creative authenticity, a visual impact with the various uses of colours, the portability of the costume and the presentation. Based on these judging criteria, Engineering has played an insignificant role in the design of Kings of Carnival costumes. The costume designer must be able to translate the visual concept of the creative crew into the costume design for the stage. The designer must understand the physical space in which the piece will be performed, the people for whom they design and the characters they will play.

Legendary designer Wayne Berkeley outlined the secret of his success with the Kings and Queens costumes which involves taking into account the ability and the temperament of the person who will wear it (Berkeley and Nanton, 1999). When asked about his ability to portray a design he replied, *"Very often I choose my individual masqueraders. If they are new to me but have played Kings and Queen many times previously, I try to get to know them - to understand the way they feel about the costume and what their capabilities are, in terms of showing the costume to full advantage"* (Berkeley and Nanton, 1999).

Costume designers must also be able to (Geus, 2006; Noel, 2016):

1) Supply the design as required, with colour and detailed information.
2) Design a costume that will fit the budget and meet the needs of the presentation.
3) Supply all information on the assemble and disassembly of the costume, and any extra information required such as details on trims and accessories, and
4) Advise on post-production duties regarding maintenance and alterations.

The design process usually begins with the main idea to be portrayed originated by the band leader or a selective sectional leader. Sketches are then created and artistically drawn. After the final imagery is chosen, the craft team moulds and constructs the design through trial and error. The final costume is then tested by the performer and the designer. The designer would not want the performer to be uncomfortable and damage the costume (Berkeley and Nanton, 1999).

Historically, Geraldo Vieira was responsible for some of the more technically involved costumes in the Kings of Carnival competition. He utilised wire bending techniques in designing birds, fish and human-like structures. He also introduced the use of plastic mouldings in costume design to make lighter, stronger costumes. In addition, Vieira introduced special effects such as fireworks, pyrotechnics, and robotic structures to create novel Kings of Carnival costume designs (NIHERST, 2009). Though hailed as a legendary technical and innovative designer, few designers to date have demonstrated the willingness to step outside the traditional boundaries of traditional craft methods.

Though the aforementioned examples of legendary, designers demonstrate innovative design approaches, the state of current Kings of Carnival costume design practice across the sector is not clear. Studies into current Kings of Carnival costume design are practically non-existent, especially studies investigating the role of engineering in the design process. An exception to this is the work of Noel (2013) where the author investigated the practice of wire bending in carnival costume design with an eye toward implementing computational design approaches based on shape grammars. She also investigated the use of a shape grammar computational approach to encourage a new generation of costume designers. Noel (2016) found that there is a large gap in knowledge of how costume designers design and what support tools are needed to aid in the design process. Designers work with "prototypists" who select materials and construction techniques to bring the design idea to life. Mostly manual tools and process are employed in construction. There is a clear need for further investigation into how Kings of Carnival costumes are designed with an eye to supporting the process with engineering tools and techniques.

3. Methodology

In order to determine the current design process and key design issues faced by Kings of Carnival costume designers in Trinidad and Tobago, a qualitative methodology was employed (Yin, 2003, Robson, 2016). Semi-structured interviews were used as the primary source of data collection as this method provides for deep exploration of the research questions while leaving room for further probing. A list of the Kings of Carnival participants from 2014, 2015, and 2016 (three years) was obtained from the National Carnival Commission and National Carnival Bands Association. From this list, a sample of six Kings of Carnival costume masqueraders were selected for each year – the first two places, middle two places, and last two places in the competition. This resulted in 18 potential interviewees. From the sample of 18 potential interviewees, 13 were willing to take part in the study. To increase the sample size, the research team opted to approach interviewees from other designers in the list (including Queens of Carnival). Thus, two additional interviewees were recruited resulting in a total of 15 participants for the study.

The questionnaire used for this paper was divided into five categories (participant data, design, materials, performer, and external factors) as shown in Appendix 1. Although the questionnaire was focused on specific topics, participants were also free to discuss issues of interest to them. All participants were contacted via telephone to explain the aims of the study, issues to be covered and to schedule the interview. Once the participant agreed to meet, a mutually suitable date and time were set. Interviewers engaged study participants as much as possible to explore and understand their design experiences and views. Eight (8) participants opted to keep personal data private, and the interview team acceded by omitting personal data.

The responses from the participants were recorded and documented and then given to the participants to verify. This approach allowed for the verification of the data being collected. A content analysis methodology was used to organise and simplify the data from the interviews into meaningful and manageable categories for analysis to be performed (Yin, 2003, Robson, 2016). Data was stored in an Excel worksheet in the form of tables, and the documented interviews were categorised, quantified where appropriate and ordered for analysis.

4. Results

4.1 Participant Data

The majority of participants were unwilling to give their personal data or allow such data to be published, and therefore this information will not be divulged.

4.2 Design

All the interviewees stated that their design philosophy is heavily influenced by an ideology or story that they want to portray. Diverse subject areas such as politics and other current affairs play an integral part in influencing the design philosophy. One designer even went as far to say that *"Mas is their own Calypso Review tent"* implying that it is their forum for expression similar to Calypso song composition and performance.

When asked about their design process in creating their final product, the participants described a generic process with three phases: (1) The conceptualisation phase, (2) the sketching phase, and (3) the construction phase. This is a year-round process and is often launched as soon as the previous carnival season ends. Participants also ranked what was most important to them based on the judging criteria of the competition (this is shown in Table 1 and Figure 2). Participants ranked creativity and authenticity as being the most important factors.

With respect to Engineering involved in the design process, there was generally a wall of defence built by the interviewees. All participants reported that they had never once before sought engineering consultation when producing a costume design. Four (4) out of the fifteen (15) interviewees (27%) expressed their fear that bringing engineering into the long-found tradition of the competition would dull the entire culture of it as engineers would not be able to "*feel the mas*".

Table 1. Participant ranking of judging criteria

	Creativity	Authenticity	Visual Impact	Presentation	Craftsmanship	Portability
First	7	3	-	4	1	-
Second	8	4	1	2	-	-
Third	-	1	4	7	2	1
Fourth	-	-	2	8	1	4
Fifth	-	-	1	2	3	9
Sixth	-	-	-	-	5	10

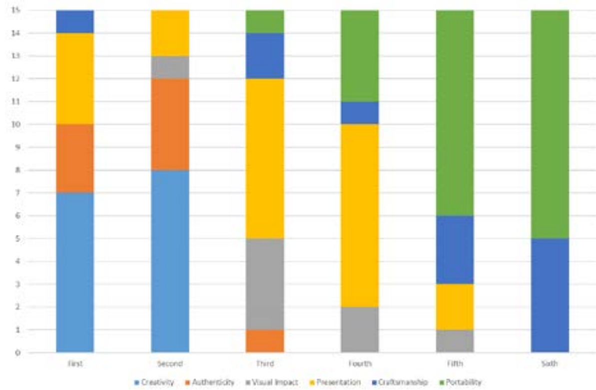

Figure 2. Participant ranking of judging criteria

Participants believed that there is a tension between engineering and the creative arts. There was a continual reference by participants to the costume design process as an art and they seemed resistive to the notion that engineering analysis and application could provide any benefit to their craft. Participants also felt that engineering would rob the costume design process of the "soul" that designers put into it.

As interviews progressed, this antagonistic attitude to engineering was mitigated by informing participants that the aim of the study is not for engineers to take over their craft, but instead the aim is to find out how best engineers could help them optimise their current process and help them be more innovative. However, when asked to discuss the role of Engineering in the future of the costume design process, participants were generally doubtful that the discipline had anything significant to contribute.

4.3 Materials

Participants indicated that rarely would a costume designer outsource materials for a costume. This is due to the cost of making the costume being a limiting factor - most of the designers bore costume costs out of their own pockets. Therefore, materials are locally sourced predominantly at hardware stores, and should a desired material not be found, another substitute material would be used. The materials generally used are hollow section steel (rectangular, circular or square section), mild steel tubing, PVC, cane, wire, stainless steel sheets, fabric, glue, tape, fiberglass.

With respect to the selection of these materials, little consideration is given to understanding the material's properties. Eight (8) of the fifteen (15) interviewees (53%) mentioned their basis for choosing materials to be one of 'trial and error'. This method is widely used amongst the designers as they only rely on their experience and hands on experiments to select construction materials. There was no weight limit set by designers as the weight of the finished costume would be decided based on how much weight the performer would be able to handle. The average height of a costume is 12-18 ft while the average width is 8-15 ft.

Costume durability continues to be a main challenge for designers. There have been many instances in the past where pieces of the costumes are broken off during the preliminaries or semi-finals. One interviewee said that *"… make the costume and pray to God that it can make it through till the end in one piece."*

4.4 Performer

Participants described the complaints that performers make when wearing and portraying the costumes. The frequency of these complaints is shown in Figure 3. The difficulty in dealing with the wind and moving around with the costume were the most frequent complaints mentioned by eight participants. Seven participants also mentioned the weight of the costume as being an issue. Two participants mentioned the heated conditions while wearing the costume and one participant mentioned skin irritation. The wind, movement and weight factors all point to a larger issue with physical discomfort, because if the performer cannot comfortably move with the costume, then failure at the competition would be likely.

Interestingly, the choice of performer is commonly made after the costume is complete and the process reaches the testing and competing phases. Therefore, it precludes the customised design of a costume to suit a particular performer. This clearly leads to design requirements for a lighter, more comfortable and more manoeuvrable costume that would be minimally impacted by wind loading. Therefore, the structural design of the costume and the dynamics of its movement need to be improved. No engineering analysis is currently conducted on the costume as a means of validation, and this area is ripe for collaboration with engineers to model, simulate, analyse and optimise the structural and dynamic behaviour of the costume.

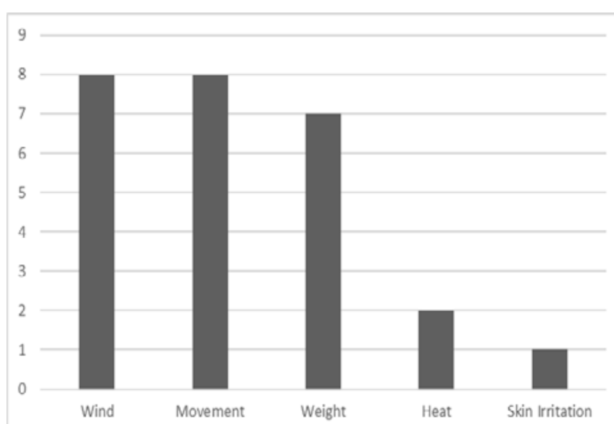

Figure 3. Frequency of Performer Complaints

4.5 External Factors

Participants indicated the range of external factors that impacts the costume design (shown in Figure 4). The size of the stage is used to determine the size of the costume and the ramp of the stage plays an integral role. The length of the ramp determines if one or more costumes can be on standby while one costume is being used on the stage. While on the stage, unpredictable external environmental factors including wind, rain, light, noise and humidity affect the costume design and performer. These factors could lead to failure of the costume and sub-optimal performances.

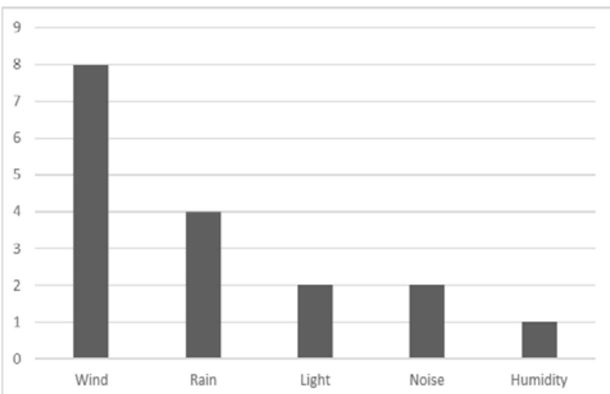

Figure 4. Frequency of mention of external factors

Wind is the most challenging aspect for the masquerading of the costume mentioned by eight participants. It poses a threat to not only the costume but to the person that is parading it. A moderate wind can cause a costume to be knocked down which could result in injury to the performer. An example of this occurred when a performer was toppled over in the 2010 competition and tore ligaments in his knee due to the strain of the 300lb costume. Secondly, rain can cause a slippery surface on the stage causing slips, trips, and falls mentioned by four participants. But it doesn't only have to be a downpour of rain to cause difficulty - dew, spilled liquid, the tracking of moisture onto the stage and sweat droplets can cause a major slip accident. In addition, rain can ruin a costume if it gets wet. A costume that is made of materials such as feathers or kite paper would be destroyed should rain fall during a performance.

Ambient light and noise also affects the performer and performance (mentioned by two participants). The costume is designed to reflect light which forms part of the presentation while the costume is moving on stage. Materials are utilised that are reflective and generate patters of reflection as the costume moves. Noise can contribute to the disruption of the performance by distracting the performer or masking the response of the audience and instructions to the performer. Though humidity was mentioned by one participant as a factor, performers understand and train for this condition. One designer went on to say *"The performer has to know what they getting into, literally, because I need them to execute it exactly as I envisioned or else it is a failure."*

5. Discussion

Based on the results presented in the previous section, it is evident that designers employ a rudimentary costume design process with significant trial and error. Compared to design process models (Otto and Wood, 2000, Clarkson and Ekert, 2005, Eppinger and Ulrich, 2007), there is room for more conceptual design exploration in the areas of materials selection and structural design. In addition, design analysis and optimisation can contribute to improved costume reliability to mitigate the effects of wind and rain. Designers used a set of steps that they referred to as their own "creative process". However, when asked if they conducted own analysis of their process, most replied in the negative. This showed a lack of awareness in their respective process and how it could be improved.

The design of Kings of Carnival costumes has not changed much over the years due to a combination of cost constraints (the belief that new methods and materials are expensive) and the desire to preserve the traditional nature of the art form. Designers also see a long and involved design process as part of being creative. Participants felt that if it was too "easy" they would lose some of the "essence" of the experience. This issue of cost seemed dominant in the design community and was the major factor behind most design decisions. On the contrary, designers did not see how design process improvement and engineering approaches could help reduce costs.

Designers demonstrated resistance to change and a need to preserve the traditional way of operation. This contradicts the sentiment that many carnival stakeholders have regarding the need for carnival to change and adapt to survive. However, a few designers have seen the need for evolution and are more open to the addition of steps that will help them remain relevant and modernise the art-form of costume design. To remain relevant, designers need to improve and adapt to tools and techniques that can improve their designs while keeping costs low.

Engineering approaches are ideally suited to this task. However, the challenge remains in how to convince designers to use Engineering tools or work with engineers when designing costumes. If the current costume design process is to be improved, designers must first be convinced to partner with engineers and experience the benefit of engineering input. In addition, accessible tools and educational materials need to be produced for designers so that they could be educated in design process improvement. The following section lists some recommendations to achieve these goals.

6. Recommendations

Five (5) recommendations are provided which can be useful in improving the design process for Kings of Carnival costumes.

6.1 Produce Educational Materials for Design Process Improvement

Given that the current costume design process lacks structure and is sub-optimal, there is a need to educate practicing designers on the principles of good design and methods for the different phases of the design process. The main argument should be that an improved design process would lead to cost effectiveness and more innovative costume designs. To combat the resistance to change, engineers should reach out and work with leading costume designers to partner with them in the development of training materials. This would improve the probability of adoption in practice.

6.2 Design and Engineering Workshops for Costume Designers

There are currently no workshops focused on introducing simple engineering methods to costume designers. Recommendation 1 would feed into this recommendation where targeted short workshops should be carried out by engineers for costume designers. The workshops could target areas such as design process improvement, low-fidelity prototyping, materials selection, structural design, design for reliability, design optimisation, and cost reduction. Workshops can provide a forum for designers and engineers to work together and allow them to build relationships.

6.3 Develop Modular Structural Costume Design Platforms

Current costumes are mostly built up from scratch every year making assembly, disassembly and transportation unpredictable and difficult. Most current designs already utilise a core upon which additional pieces are attached. This concept could be extended to form a general design approach for modularity. The introduction of a modular design structure would allow for quick assembly and disassembly of costumes and save on costs in the long term.

6.4 Investigate New Materials and Construction Methods

New materials and construction methods need to be presented to designers with ideas on how they can be utilised to serve the creative process. This may be controversial as the materials used are considered part of the art-form itself e.g. wire bending. However, the aim should not be to replace all traditional materials, but demonstrate new ways of working with these materials in addition to selecting new materials, and also how to utilise processes such as three dimensional (3D) Printing and prototyping.

6.5 Analyse Costume Designs for Functional Performance

This recommendation seeks to address the issue of environmental factors particularly wind and rain which have been highlighted as factors which cause the most problems. Many costumes are designed with large plumes and moving parts, resulting in a large surface area for wind forces to act. Through design simulation (fluid dynamics) or the testing of small prototypes, the effects of wind loads could be reduced. Methods from the discipline of Architecture, especially computational design, could easily be applied to costume design and analysis. Designers would need engineering support in developing CAD models of the costume structure and in running simulations.

There is also scope for the development of simple and usable CAD and Engineering analysis software for the carnival costume design sector. For rain effects, non-slip materials could be used for coating both costumes and also stage surfacing materials. There are many water-proofing products that could be used directly on fabrics without tarnishing the material. The use of such products can resolve issues such as the increase and change in weight distribution of the costume due to the water logging of fabrics.

7. Conclusions

The design and creation of carnival costumes represents a significant part of the culture of Trinidad and Tobago. This study showed that the acceptance of engineering support and new ways of making in this traditional practice has been met with resistance. In addition, there are areas in the costume design process where engineering approaches could reduce costs and improve costume quality. To rectify this issue, five (5) linked recommendations were provided for educating designers and bringing engineers and costume designers together. Further work will involve the implementation of these recommendations and the development and evaluation of new costume design methods and tools with costume designers.

Appendix 1. Costume Designer Interview Questions

A. Participant Data

1. Name:
2. Age:
3. Educational Background:
4. Work experience:
5. How many years have you been designing Carnival costumes:
6. Current position/role:

B. Design

1. Describe your design philosophy i.e. how do you approach the costume design problem?

2. Describe the design process when creating a costume i.e. list all the steps you take from start to finish in producing a costume (be as detailed as possible).
3. Out of the weighted judging criteria, rank the criteria from most important to least important when designing.
4. Have you ever consulted with engineers when producing a costume design? (Depending on the answer, ask why?)
5. Do you see a role for engineering design support the costume design process? (If NO, ask why? If YES, ask in what ways engineers can support).

C. Materials

1. What are the types of materials used in costume design? Which are locally sourced and which are sourced from outside the country?
2. What considerations do you take into account with regard to material properties and selection when designing?
3. How does cost factor in to your design considerations?
4. What is your costume design weight limit?
5. What is the range of costume heights that you design within?

D. Performer

1. What are the most common performer complaints/feedback that you receive?
2. Where does physical comfort of the costume rank when designing?
3. What is the most difficult performer design requirement to accommodate in the design?
4. Do you design a costume with a performer in mind or choose a performer to fit the costume? Why?

E. External Factors

1. How does the performance environment affect the costume design?
2. Do you take external factors e.g. wind, ambient light, noise, humidity etc. into account when designing?
3. Which external factor plays the biggest role/has the largest effect on the costume design performance?
4. How do the costume designs fail? How often do these failures occur? (Get a ranked list)

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Performance Measurement of Broadband Connections: An Enhanced Tool

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Abstract: *The performance of broadband Internet connections is an important qualifier in discussions about user experience, Internet Service Provider (ISP) assessments and national economic status. Performance can be quantified in a number of ways, including speed, latency, jitter and packet loss. While several tools have been developed to measure these parameters, many of these tools measure only one metric and offer limited flexibility for user configurations, such as single broadband connections and fixed test times. This paper discusses the development of enhanced algorithms and, correspondingly, a software application for the performance measurement of broadband Internet connections. The enhanced tool, TINQA (Totally Integrated Network Quality Application), is a native Windows® application, developed using the C# programming language and the .NET framework, and measures speed, latency, jitter and packet loss. The algorithms used to measure latency, jitter and packet loss were based on the employment of Windows® Raw Sockets and the Internet Control Message Protocol (ICMP), while the algorithm used to measure speed was based on downloading and uploading relatively large files (>250 MB) from and to several public File Transfer Protocol (FTP) and Hypertext Transfer Protocol (HTTP) speed test servers. TINQA produced results similar to those obtained from some of the most popular existent performance testing tools, including speedtest.net, testmy.net and pingtest.net. Additionally, the results were consistent across multiple tests, indicating that the algorithms were robust and that the added flexibility in testing did not compromise the accuracy of the tests in the application.*

Keywords: *Broadband Performance, Network Quality, Speed, Latency, Jitter, Packet Loss*

1. Introduction

The quality of broadband Internet connections can not only significantly affect individual users' experiences with web-based applications, but also, on a larger scale, influence a country's economic status. Ericsson (2013) found that increases in broadband speeds could drive increases in Gross Domestic Product (GDP), allow for better access to social services (such as improved healthcare) and promote improvements in energy efficiency within a country. At the other end of the spectrum, Claypool and Claypool (2010) investigated the impact of broadband quality on individual users, and found specifically that delays in the arrival of data packets could severely degrade the performance of online games, thereby ruining the experience for players. Additionally, Apteligent (2015) found that 48% of their surveyed users would uninstall or stop using an application if it regularly ran slowly (suffered from high latencies).

These findings demonstrate that various parameters can influence and can be used to measure the performance of web-based applications, and consequently show that a definite need exists to quantitatively characterise the quality of broadband connections according to key performance indicators.

Beuran et al. (2003) showed that speed, latency, jitter and packet loss all correlated directly to user-perceived quality (UPQ) for web-based services such as file transfers and Voice over Internet Protocol (VoIP) calls, while Sugeng et al. (2015) stated that these same four parameters can have a significant effect on applications such as video streaming. Ookla (2010) agreed with both these authors, stating that speed, latency, jitter and packet loss are widely accepted as the fundamental attributes necessary for a quality Internet experience.

At the present time, several tools exist to measure these four metrics. However, the current tools individually focus on a subset of the metrics, thereby resulting in the need to orchestrate multiple tests in order to attain an overall quality characterisation for a given broadband connection. For example, Ookla allows users to measure download and upload speeds at their speedtest.net website, while latency, jitter and packet loss tests are facilitated at their pingtest.net website (Ookla, 2010). Additionally, most of these tools lack functionality for automatic, long-term testing. Such testing allows for higher-level analyses of broadband connections, such as performance with respect to time, network architecture, and Internet Service Provider

(ISP), as illustrated by the Federal Communications Commission (FCC, 2016) in their annual report on fixed-broadband performance.

With this in mind, this paper describes the development of an application that was created to fill the aforementioned gap by providing an improved testing platform. This platform not only facilitates measurement of some of the most critical metrics of a broadband connection from a single application, but also allows for much greater flexibility in the test configurations as well as in the presentation of results.

More specifically, TINQA draws from the best measurement techniques that are implemented in the existing tools. The remainder of this paper is structured as follows: the following section defines the four key broadband performance metrics as they are used in this paper. Subsequently, the paper examines the most ubiquitous tools and methods that currently exist, feeding into the discussion that follows on the development of TINQA. A comparative, empirical analysis of the existing tools and TINQA is then rendered before the conclusion, which summarises the key features of TINQA and potential improvements, is presented.

2. Defining broadband performance metrics

The significance of establishing definitions for the broadband performance metrics lies with the need to ensure that comparisons are made on a like-for-like basis and that the user is aware of what is being measured. This section presents the background to the development of the definitions for each of the measurement metrics, in turn, under study. It begins by outlining the standard IETF definitions and then describing how definitions were developed for use in this research, for each parameter.

2.1 Speed

In their discussion on broadband speed measurements, Beur et al. (2010) stated that capacity, available bandwidth and bulk transfer capacity were three of the most popular references for speed in the context of broadband connections. Chimento and Ishac (2008) discussed capacity and available bandwidth in depth in the IETF's RFC 5136. In their discussions, they defined Internet Protocol (IP) layer link capacity, *C*, as the maximum number of IP-layer bits that can be transmitted from the source *S* and correctly received by the destination *D* over the link *L*, during the interval [*t*, *t+i*], divided by *i*, where i refers to the interval over which the transmission occurs. Building upon this definition, they provided the following mathematical description of available bandwidth, *AvailB*.

$$AvailB = C * (1 - Util)$$

where *Util* refers the link utilisation, which is in turn defined as the fraction of the capacity that is being used and is a value between 0 (that is, nothing is used) and 1 (that is, the link is fully saturated). This relationship between capacity and available bandwidth/capacity is illustrated in Figure 1.

Mathis and Allman (2001) discussed bulk transfer capacity in the IEFT's RFC 3148, where the term was defined as a measure of a network's ability to transfer significant quantities of data with a single congestion-aware transport connection (e.g. TCP). Of these definitions for capacity, available bandwidth and bulk transfer capacity, Beur et al. (2010) state that bulk transfer capacity, as described above, is the parameter that is most often reported by research in this area and most often the focus of broadband quality tests. Strauss and Kaashoek (n.d.) also discuss these terms and similarly conclude that bulk transfer capacity is the most relevant, as it allows for accurate estimates of TCP application performance over a network.

Although Mathis and Allman (2001) in RFC 3148 state that bulk transfer capacity must be defined in terms of a single connection, Beur et al. (2010) show that multiple connections are required for the most accurate speed measurements. The latter also show that many of the most popular performance measurement tools utilise multiple connections. With these considerations in mind, in this research, speed is defined using a modified form of the IETF's standard definition of bulk transfer capacity in RFC 3148. Namely, speed is defined as a measure of the amount of data which can be transferred along a network path in a particular interval of time, using multiple connections and a congestion-aware protocol such as TCP.

Figure 1. Illustration of the relationship between (total) capacity, utilised capacity and available bandwidth (capacity)
Source: Abstracted from AppNeta (2012)

2.2 Latency

Kwon (2015) explains that packets experience delays at each node in their movement from one node to another. Four types of delays are identified: processing delay, queuing delay, transmission delay and propagation delay. Kwon (2015) considers end-to-end latency to be the sum of these four delays. However, as discussed by Luckie et al. (2001), the Ping tool - the most widely used tool to investigate network delay - calculates round-trip-time (RTT), rather than the end-to-end latency. RTT or round-trip-delay (RTD) refers to the delay between the transmission of a packet and the reception of an acknowledgement or reply for that packet (adapted from Almes et al., 1999). In order to establish a common baseline with the Ping tool, therefore, latency is defined as the total time taken for a packet to be transmitted from one host to another, and for a response to be received from that host. This definition therefore includes the total processing delay, queuing delay, transmission delay and propagation delay for both directions of packet transfer.

2.3 Jitter

Demichelis et al. (2002) define jitter (in the context of IP packet delay variation) in the IETF's RFC 3393 as the difference between the one-way-delay of a selected packet pair in a stream of packets going from measurement point 1 to measurement point 2. Zhang et al. (2002) further clarify the term by providing the following diagram which illustrates the delay variation in consecutive packets.

However, this definition of jitter by Demichelis et al. (2002) assumes that both measurement points are under the control of the tester, as it requires timestamps to be collected at both points for the measurement of one-way-delay. However, it was desired that the jitter test developed could be conducted when only a single measurement point was controllable. Therefore, the definition of jitter was modified slightly from the IETF's to utilise RTT instead of one-way-delay. Jitter is therefore defined in the context of this research as the difference between the RTT of a selected packet pair in a stream of packets going from measurement point 1 to measurement point 2, then returning to point 1.

Figure 2. Diagram illustrating jitter in transmitted packets
Source: Adapted from Zhang, et al. (2002)

2.4 Packet Loss

DVEO (2016) defines packet loss as the phenomenon where one or more packets, transmitted over an IP network, fail to arrive at a destination. The rate of occurrence of this phenomenon is the packet loss rate, typically measured as a percentage. Freire (2007) provides a similar definition, stating that the packet loss rate refers to the fraction of the total transmitted packets that did not arrive at the intended receiver.

Based on this description, packet loss will be defined simply as the phenomenon where a transmitted packet is never received by its intended recipient, with the packet loss rate defined mathematically as:

$$\textit{Packet loss (\%)} = [(P_T - P_R) / P_T] * P_T$$

where: P_T = Total number of packets transmitted, and
P_R = Total number of packets received successfully.

3. Analysis of existing tools- and metric measurement techniques

This section examines some of the most popular tools associated with broadband connection quality measurement, with particular attention paid to the techniques utilised to gather the required data. The outcome of this analysis is the identification of the best approaches for performance measurement of the metrics under study, which will subsequently drive the development of TINQA.

3.1 speedtest.net

Ookla's speedtest.net testing platform is arguably one of the most popular broadband performance testing tools (Gavaletz et al., 2012). The platform is affiliated with over 80% of the world's ISPs and has facilitated over 9 billion tests (Ookla, n.d.). It is unsurprising, therefore, that many investigations have been performed on their testing methodologies. Beur et al. (2010) performed one such analysis, in which they presented detailed descriptions of the techniques employed by Ookla. The following steps summarise their description of the download speed test:

1. A series of small files are downloaded to roughly gauge the user's download speed, after which a suitable file size is chosen for the test.
2. The test downloads several copies of the file size chosen, through (up to) eight parallel hypertext transfer protocol (HTTP) connections.
3. Samples of the download speed are taken at a rate of (up to) 30 Hz.
4. The samples are sorted, and the highest 10% and lowest 30% are removed. The average of the remainder is then computed as the average measured download speed.

The upload speed test follows the same methodology, with the direction of data transfer reversed, up to step 4. At step 4, only the upper 50% of the samples are used to compute the average measured upload speed.

Beur et al. (2010) praised the use of multiple connections, stating that it effectively saturated connections and moved the bottleneck in the test to the access link rather than to the buffers on the end devices. Additionally, they investigated the use of sampling and the discarding of the highest 10% and lowest 30% of samples for the download test, stating that this method of skimming was found to improve the average speed computed by considering only the most representative samples of network capacity and also by compensating for TCP's deliberately conservative congestion control algorithms by discarding a larger fraction of the lowest sample values. However, they also noted that the skimming percentages chosen were not systematically determined, and as such they could possibly be further optimised. Additionally, the only explanation given for the discarding of the lowest 50% of samples in the upload test was that this eliminated anomalies in the test. It was therefore decided that for the improved tool to be developed, skimming percentages of 10% and 30% would be used for both the upload and download tests initially, and the percentages would then be further optimised through systematic testing.

Beur et al. (2010) highlighted two further observations: that the test examines a number of servers to determine which would allow for the lowest latency during the test and that the default test length is 10 seconds. The use of a low-latency test server is crucial as high latencies severely degrade throughput on TCP-based connections, such as the HTTP connections by Ookla (Rogier, 2016). The default test length of 10 seconds is also used by other tools and was confirmed by Beur et al. (2010) to be an acceptable testing time for many cases.

Moreover, Abolfazli et al. (2015) conducted tests involving speedtest.net and concluded that the methodology produced accurate results with a standard deviation of ≤0.44 Mbps. Therefore, the testing process described above was taken as an important baseline for the development of the improved tool in this research.

3.2 Network Diagnostic Tool (NDT)

M-Lab's Network Diagnostic Tool (NDT) was also analysed by Beur et al. (2010). They discussed how the tool differed from many others by transferring as much data as possible in a specified window of time (10 seconds) for their speed test, rather than utilising a fixed file size for download while testing the network connection.

This unique approach was found to be advantageous for several reasons. Firstly, it eliminated the setup time incurred by other tests due to the need to estimate an appropriate file size for the connection. Secondly, this technique ensured that the connection under test remained saturated throughout the predefined test period. With smaller file sizes, tests may have completed prematurely due to completed file transfers.

Feamster (2016), however, who investigated the link between connection count and achievable throughput over TCP, stated that NDT's speeds results were inaccurate due to its use of only one connection for testing. It was therefore concluded that if our improved tool was to utilise the novel approach presented by M-Labs, this methodology had to be strengthened using other techniques such as the utilisation of multiple connections for the test.

3.3 testmy.net

Although no third-party analyses of the testmy.net tool were evident in the literature, the unique flexibility and functionality offered by this tool provided several ideas for the development of the improved tool. The site offers users the choice of using single-threaded or multi-threaded tests to measure speed, rather than letting the number of connections be determined algorithmically during the testing process. This added flexibility would be extremely useful for users such as application designers, who wish to investigate the performance that their application would achieve with particular numbers of parallel connections. Additionally, the site offers graphing capabilities that allow users to observe how their speeds varied for the duration of the test. Figure 3 illustrates a sample of this graphing functionality.

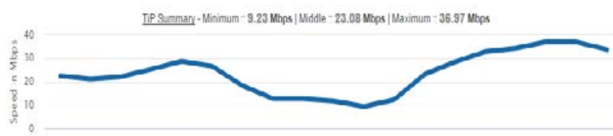

Figure 3. Example of a speed test graph
Source: Obtained from http://testmy.net

Additionally, for registered users, the tool logs measurements to a database. This allows deeper analyses, such as being able to compare results across several tests or across several users of the same ISP. These features of testmy.net provided guidance for additional functionality in the improved tool, in all of the metric modules.

3.4 Ping

Ping is a widely used latency measurement utility (Shamsi and Brocmeyer, 2009). It utilises ICMP to transmit a series of echo request packets and waits for the echo reply packets usually sent in response. The sequence numbers of the echo requests and replies are compared to attempt to tag each request-reply pair with a timestamp or RTT value. This process is illustrated in Figure 3.

The RTT values are then processed and minimum, average and maximum values are computed. Huston (2003) mentioned further measurement techniques using the Ping utility, stating that the data returned by the tool could be used to infer variance (jitter) and dropped packets (packet loss) as well.

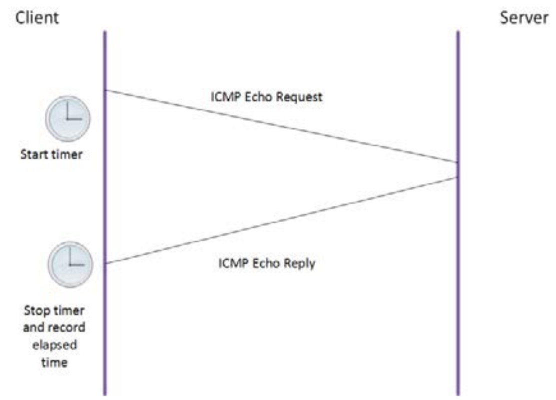

Figure 3. The process of RTT measurement using Ping

Anuskiewicz (2008) investigated jitter measurement in detail and describes the following methodology for determining jitter:

1. The RTT for the first packet successfully received by a host is calculated and stored as a reference RTT.
2. When the second packet is received, the RTT is also calculated and stored as the current RTT, and the difference between this current RTT and the reference RTT is calculated and stored as one value of jitter. The reference RTT is now updated to the last RTT measured.
3. Step 2 is repeated until the desired numbers of jitter measurements are obtained.
4. Minimum, maximum and average jitter values are then computed.

Based on this methodology, it was concluded that the Ping tool could be adapted for the determination of jitter. Moreover, Shamsi and Brocmeyer (2009) describe packet loss measurement strategies and, based on their descriptions, Figure 5 illustrates how the Ping tool could be used to infer packet loss that was created for this research.

Based on these discussions, the techniques employed by the Ping tool were deemed valuable for use in the latency, jitter and packet loss test modules of the enhanced tool.

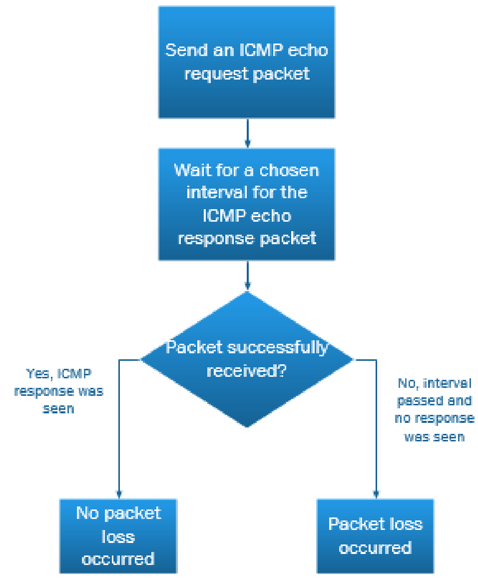

Figure 5. The technique to measure two-way packet loss
Source: Adopted from Shamsi and Brocmeyer (2009)

4. Summary of considerations for design of enhanced tool

This section presents the development of TINQA. It focuses on the algorithms used in the development of the four performance tests – speed, latency, jitter and packet loss tests – which ultimately make up the four main modules of the application. The approaches will be utilised in the development of TINQA, based on the analyses of existing tools. For each of the developed modules, the incorporation of the techniques as summarised in Table 1 is referenced.

Table 1. Summary of the techniques adopted for TINQA Development

Tool	Metric	Techniques adopted for TINQA	Justification of adopted techniques
speedtest.net	Speed	Multiple TCP connections	Creates saturated connections; bottleneck in access link rather than end device buffers
		Discarding of highest 10% and lowest 30% of samples	Accounts for throughput losses due to TCPs congestion management mechanisms
		Low latency test servers	Reduction of throughput degradation on TCP-based connections
		Default test length of 10 sec	Widely used and proven adequate
NDT	Speed	Transfer of as much data as possible in a fixed time period	Elimination of setup time; test connection remains saturated throughout test period
testmy.net	Speed	Choice of single-threaded or multi-threaded tests	Can examine performance using parallel connections
		Graphing capabilities	Visual analyses can be performed
		Logging of metric measurements	Greater flexibility in performance analysis/reporting
Ping	Jitter, Packet loss, Latency	Use of ICMP echo request and echo response packets	Allows for accurate measurement using a popular technique, which allows for easy comparison of results.

4.1 Speed test module

The speed test module was designed to determine both download and upload speeds of a user's connection. The following steps describe the algorithm utilised for the test:

1) The user is prompted for several configuration parameters including their preferred test server, number of download and upload connections to be run in parallel, and time over which the tests should be run.
   The servers available for the tests consist of several FTP and HTTP servers around the world, specifically configured for running speed tests. All the chosen servers have large files (>512MB) available for downloading, which ensured that the tests would be suitable for high speed connections. The number of parallel connections was set to 6 by default, as this was shown by Altman et al. (2006) to achieve almost 95% link utilisation (independent of the link capacity). The time for which the tests were run was set to 10s by default, based on the findings of Beur et al. (2010).
2) Once the user initiates the test, TINQA begins the download test and immediately opens a number of parallel TCP connections (depending on user preference). A copy of the largest speed test file available on the selected server is then downloaded through each of the open connections, and the cumulative download speed over all the connections is sampled at a rate of 5Hz. The results are graphed to the user.
   This step combines the advantages of M-Lab's NDT tool and Ookla's speedtest.net tool, allowing TINQA to produce speed test results almost instantaneously, while utilising multiple parallel TCP connections to ensure that the network link is fully saturated during the test.
3) The download speed is continuously sampled for the time configured by the user, after which the downloads are cancelled and the partially downloaded files are deleted.
4) TINQA then processes all the download speed samples, removing the top 10% and bottom 25%. These numbers were adjusted from the findings of Beur et al. (2010), as they were found, through testing, to produce more accurate results. The remaining 65% of the samples are used to determine the average download speed.
5) TINQA then prepares several large (250 MB) files consisting solely of 0s, and opens a number of parallel TCP connections (determined by the user) to the chosen FTP upload server.
6) The files are uploaded to the server, the upload speed is sampled at a rate of 5Hz and graphed for the user.
7) Once the chosen test time has elapsed, the uploads are cancelled. The files created for uploading are deleted from the user's machine, and the server similarly deletes the received files.
8) TINQA repeats step 4 for the upload speed samples to determine the average upload speed of the link. Although Beur et al. (2010) showed that Ookla skimmed the entire lower 50% of values, it was found that using the same percentages of the download speed test produced accurate results for the upload test as well.
9) The user is given the option of storing the recorded speed results in a database, which allows them to fetch the results at a later time and observe how their connection's download and upload speeds vary over time.

4.2 Latency test module

This module was designed to allow users to perform easily configurable tests to measure the latency of their connection. The following steps describe the algorithm used by this module:

1) The user is prompted for several parameters governing the test. These parameters include the remote server to test to, the packet data size, the time-to-live (TTL) value, the timeout value, the interval between sending ICMP echo requests, and the option to set the don't-fragment flag. The defaults for all these parameters are set to the defaults of the Windows Ping tool, to leverage users' expected familiarity with that tool. The user is also given the choice of running the test for a specific time period or until a specific number of ICMP echo requests are transmitted.
2) The test is initiated, and ICMP echo request packets are formed according to RFC 792 by Postel (1981). The packets are transmitted out of a socket and a timer is started. When a corresponding ICMP echo reply message is received, the timer is stopped and the RTT for the packet pair is recorded as one sample of latency.
3) Step 2 is repeated for either the time or the number of packets set by the user. Each sample of latency is added to a graph as it is obtained.
4) Once the test has completed, the samples are processed and the minimum, maximum and average latency are computed.
5) The user is given the option of storing the results in a database, which allows them to later view how their connection's latency varies over time.

4.3 Jitter test module

This module was designed to allow users to perform easily configurable tests to measure the jitter of their connection. The following steps describe the algorithm used by this module:

1) The user is prompted for several parameters governing the test. These parameters include all parameters mentioned for the latency test module.

2) The test is then initiated, and ICMP echo request packets are again created. However, for this test, the first RTT value recorded is not sampled, but is simply stored as the reference RTT.
3) Step 2 is repeated and another value of RTT is obtained. The modulus of the difference between this new RTT value and the reference RTT value is then calculated, and the result of this calculation is stored as the first sample of jitter.
4) Steps 2 and 3 are repeated for either the time or the number of packets set by the user. Each sample of jitter is added to a graph as it is obtained.
5) Once the test has completed, the samples are processed and the minimum, maximum and average jitter are computed.
6) The user is given the option of storing the results in a database, which allows them to later view how their connection's jitter varies over time.

4.4 Packet loss test module

This module was designed to allow users to perform easily configurable tests to measure the packet loss of their connection. The following steps describe the algorithm used by the module:

1) The user is prompted for several parameters governing the test. These parameters include all parameters mentioned for the latency test module.
2) The test is initiated, and ICMP echo request packets are again created. However, for this test, TINQA does not measure RTT values, but rather simply listens for ICMP echo replies. Once the echo request is transmitted, a timer is started. If the corresponding ICMP echo reply is received within the timeout period specified by the user, then no packet loss has occurred. However, if the timeout period passes and no reply is received, packet loss is said to have occurred. In both cases, one sample of packet loss has been obtained.
3) Step 2 is repeated for either the time or the number of packets set by the user. Each sample of packet loss is added to a graph as it is obtained.
4) Once the test has completed, the samples are processed and the packet loss percentage is computed.
5) The user is given the option of storing the results in a database, which allows them to later view how their connection's packet loss varies over time as a simple average. This test sends packets at a fixed rate (with respect to time), and as such no weightings are considered for the results to be presented as a moving average.

4.5 Integration of Modules

The four modules were then coded using C#, using the .NET framework to combine the functional code with the GUI. A MySQL database was used to store the results of the tests and subsequently fetch them for viewing, and a fifth module was added to control the flow of the gathered results to and from the database, ensuring that users were able to easily view their results on demand.

5. Comparative analysis of TINQA and other broadband performance measurement tools

In this section, the performance of TINQA is compared to those of existing tools in order to verify its functionality, accuracy and robustness. Tests of each of the modules are presented. All tests were conducted on an ADSL2+ Internet connection with advertised speeds of 2Mbps/512Kbps at approximately the same time of day, with no other hosts or applications utilising the network and with the same host machine used for all tests.

5.1 Comparison of speed test tools

Since Beur et al. (2010) showed that tools which utilise multiple parallel connections produce the most accurate speed test results, two popular multithreaded tools - speedtest.net and testmy.net - were chosen for comparison.

All tools were configured to utilise servers in northern Europe in order to reduce the influence of latency on the tests. testmy.net was additionally configured to use 6 servers for the test, to match the default number of connections of TINQA. speedtest.net did not allow for such configuration. Additionally, speedtest.net was found to be the only other popular speed test tool which offered multithreaded upload tests. Therefore, the upload speed test results from testmy.net were measured using a single connection. Tables 2 and 3 show the results of the download and upload testing, respectively.

Table 2. Results of comparison of download tests

Test number	TINQA result	Tool used	Tool result	Percentage difference
1	1.88 Mbps	speedtest.net	1.95 Mbps	-3.72%
2	1.88 Mbps	speedtest.net	1.99 Mbps	-5.85%
3	1.89 Mbps	speedtest.net	1.98 Mbps	-4.76%
4	1.88 Mbps	testmy.net	1.60 Mbps	14.89%
5	1.88 Mbps	testmy.net	1.30 Mbps	30.85%
6	1.88 Mbps	testmy.net	1.50 Mbps	20.21%

Table 3. Results of comparison of upload tests

Test number	TINQA result	Tool used	Tool result	Percentage difference
1	0.66 Mbps	speedtest.net	0.56 Mbps	15.15%
2	0.66 Mbps	speedtest.net	0.57 Mbps	13.64%
3	0.66 Mbps	speedtest.net	0.59 Mbps	10.61%
4	0.62 Mbps	testmy.net	0.54 Mbps	12.90%
5	0.69 Mbps	testmy.net	0.62 Mbps	10.14%
6	0.70 Mbps	testmy.net	0.61 Mbps	12.86%

The results obtained in Table 2 illustrate that the download speeds recorded by both TINQA and speedtest.net were very consistent, with all speeds within a ±0.1 Mbps range. Conversely, the results obtained by testmy.net varied significantly, with a maximum deviation of 0.3 Mbps. This variance was attributed to testmy.net's method of selecting an appropriate file size for the download test. The tool measured the minimum file size, which took longer than 7 seconds to download to the host machine, and used this file size for the test. However, it was found that this tool utilised file sizes smaller than 3 MB for all tests in this comparison, which resulted in tests completing very quickly. Larger file sizes may have produced more stable results.

The results in Table 3 illustrate that the upload speeds recorded by TINQA were consistently higher than those recorded by both speedtest.net and testmy.net, with a maximum deviation of +0.1 Mbps. This was attributed to the difference in processing of the samples for the upload speed and it was decided that further testing would be required to tune the skimming percentages for the upload test, to ensure that the results were more in line with other tools.

5.2 Comparison of latency test tools

For the latency test comparison, TINQA's results were compared to the results produced by the Windows® Ping tool, since this allowed for comparison using the same protocol (ICMP) and for similar configurations for both tools. Ookla's pingtest.net tool was also chosen to compare the latency measured using ICMP in TINQA to the latency measured using TCP in pingtest.net. For all tests, the Bright House Networks server located in Orlando, Florida, was used, since this server was available for testing in all the tools.

Table 4 shows the result of the testing. It was observed that there were no significant differences in latency results between the three tools. Although a high difference of 23.2% was recorded in one test, this result was likely an outlier caused by varying traffic demands in the link between the tool and the test server, since this result was much lower than the others and since all other tests produced much lower differences. Increasing the number of packets used for the test may reduce such fluctuations and therefore decrease the occurrences of these significant outliers.

Table 4. Results of comparison of average latency using selected latency test tools

Test number	TINQA result	Tool used	Tool result	Percentage difference
1	200 ms	pingtest.net	217 ms	-8.5 %
2	271 ms	pingtest.net	236 ms	12.9 %
3	228 ms	pingtest.net	203 ms	11.0 %
4	206 ms	Windows Ping	199 ms	3.4 %
5	206 ms	Windows Ping	232 ms	-12.6 %
6	155 ms	Windows Ping	119 ms	23.2 %

It was also observed that the latency measured by TINQA using ICMP and the latency measured by Ookla's pingtest.net using TCP were similar, indicating that neither protocol was being prioritised over the other along this route. However, details about Ookla's configuration for this test, such as default packet size and TTL, could not be located, so deeper analyses into these tests could not be performed.

5.3 Comparison of Jitter Test Tools

For the jitter test comparison, the line quality test by freeola (n.d.) and Ookla's pingtest.net were chosen since they allowed for specification of the server to be used for testing, allowing for servers in close proximity to be used for all of the tests. The servers chosen were all located in the southern part of the UK.

The results of the comparison are presented in Table 5. It was observed that the differences in jitter values varied more significantly than the other tests, but were still relatively close. The variation in the results were attributed to variations in traffic patterns between the client and server in the tests, since these tests were all performed from a client machine located in Trinidad and Tobago to a server located in the UK, which meant that there were a large number of nodes and links in the path being tested, and each of these nodes and links would exhibit their own traffic and device load fluctuation. However, similarly to the latency test, increasing the number of packets used for the test may decrease these outliers.

Table 5. Results of comparison of average jitter using selected jitter test tools

Test number	TINQA result	Tool used	Tool result	Percentage difference
1	171.8 ms	pingtest.net	145 ms	26.8 %
2	109.9 ms	pingtest.net	129 ms	-19.1 %
3	234 ms	pingtest.net	277 ms	-18.4 %
4	121 ms	freeola	149 ms	-23.1 %
5	252 ms	freeola	265 ms	-5.2 %
6	254 ms	freeola	225 ms	11.4 %

5.4 Comparison of packet loss test tools

The packet loss test comparison was performed using the same tools as the jitter test comparison, since these tools also provided results for packet loss. The results of the comparison are presented in Table 6. All results were observed to be similar, with only one outlier of 2% observed. This outlier was likely due to a transient traffic spike along the path being tested, which resulted in a node along the path discarding some of the test packets.

Table 6. Results of comparison of packet loss percentage using selected packet loss test tools

Test number	TINQA result	Tool used	Tool result	Percentage difference
1	0 %	pingtest.net	2 %	2 %
2	0 %	pingtest.net	0 %	0 %
3	0 %	pingtest.net	0 %	0 %
4	0 %	freeola	0 %	0 %
5	0 %	freeola	0 %	0 %
6	0 %	freeola	0 %	0 %

6. Conclusion

In this paper, some of the most popular tools and techniques used for the measurement of broadband Internet connection quality were examined and the findings used to develop a new tool - TINQA. TINQA provides a unified testing platform, allowing for measurement of four of the most important key performance indicators (speed, latency, jitter and packet loss) from a single application. Additionally, TINQA offers greater flexibility than existing tools in how tests are configured, allowing additional user configurations for parameters such as test time and number of parallel connections. Moreover, TINQA offers better processing and presentation of results, allowing for storage of results in a database and graphing capabilities. Based on the initial testing of TINQA, it is evident that the tool provides results similar to those provided by the most popular tools on the market. This aids to validate its performance and demonstrates that the increased flexibility of the tool does not compromise its functionality and reliability.

Despite its enhanced capabilities over existing performance measurement tools, TINQA can be further improved. More extensive testing can be undertaken in order to perform additional tuning of TINQA's tests, by utilising tools such as NetEM (described by The Linux Foundation (2016)) to manipulate parameters such as RTT and packet loss. Another possible avenue for optimisation is in the percentage of samples skimmed from the speed tests, with the actual percentage being determined by conducting a large number of tests over connections of different speeds and architectures. Additionally, support can be provided for a greater number of testing servers and for tests, using protocols such as User Datagram Protocol (UDP) and HTTP-based speed tests, and TCP-based latency, jitter and packet loss tests.

In addition, TINQA can be ported to other platforms so that it can be used on Linux and Macintosh-based systems. This final improvement would pave the way for the tool to be used in specialised hardware-based testing platforms, such as the platform developed by SamKnows for the Federal Communications Commission (FCC, 2016).

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Customising a Project Management Framework at a Trinidad-based Paper Manufacturer: A Case Study

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Abstract: *There has been a huge excess of low-cost paper on the market and a global price erosion of manufactured product. Paper Products Limited (PPL) – a Trinidad-based tissue paper manufacturer, was ruthlessly exposed to this changing environment. This paper reviews a strategic realignment exercise which was done to determine the root causes of project failures, and to tailor-make a project management (PM) framework to govern process improvement projects at PPL. In order to quantify historical project performance and determine the reasons for historical project failure at PPL, a four (4) phase study was initiated. Phase-1 involved the analysis of projects undertaken from 2012 to 2015 on the cost, schedule and scope variances. Phase-2 determined the root cause of project failures, Phase-3 comprised the development of a PM framework, incorporating the common processes advocated in literature and the final phase involved testing the efficacy of the framework using selected projects at PPL. Trial implementation of the customised PM framework achieved a reduction in budget, schedule and scope variation by 20%, 18% and 1%, respectively. These performance improvements were attributable to enhancements in the framework's approach to developing the risk management plan, the work breakdown structure and the stakeholder management. As validated by an executive review of the PM framework, the adoption of the framework could enhance PM practices and sustain PM performance improvements at PPL. This case study demonstrates an initiative in fostering PM practices and performance in business. The results and implications of the analyses discussed are of potential value to the field of studies. Evaluations are suggested to examine critical processes and individual steps, and future studies could validate the key elements identified for the customised PM framework.*

Keywords: *Project management, framework, project success, paper products*

1. Introduction

"Operations keep the lights on, strategy provides a light at the end of the tunnel, but project management is the train engine that moves the organisation forward" (Gumz, 2012). Adopting effective project management (PM) practices is a key to unlocking performance improvement and to providing the foundation for continuous improvement. This has gained popularity in recent times as organisations strive to succeed in the highly competitive and dynamic market which globalisation and e-commerce has created.

China's meteoric rise as the world's largest paper producer has had a ripple effect on the industry. The influx of low cost paper in the second decade of the 21st century has forced global manufacturers to operate optimally in order to defend their market shares (Ragbir, 2015). In 2012, Paper Products Limited (PPL) – a Trinidad-based tissue paper manufacturer, attempted to insulate itself from the searing competition by focusing on optimisation and cost reduction. As such, in 2012, the Process Improvement Team (PIT) was formed to design and manage optimisation projects in order to reduce production costs at PPL (Ragbir, 2015). However, these projects often incurred significant budget, schedule and scope variances. Despite initial promising results, the PIT began to experience project delays, cost overruns and unfavourable business results as the complexity and quantity of projects assigned to them increased. Underpinning these problems was the absence of a framework or strategy for governing PM practices at PPL.

This paper reviews the core features and components of three (3) common PM frameworks in relation to the determination of project success. The benefits and challenges of instituting PM practices are also explored and finally, the ability of the implementation of a customised PM framework to counteract historical failures and reduce the scope, schedule and budget variances of projects undertaken by the PIT at PPL is examined.

2. Project Success and the Project Management Framework

Customarily, project success has been defined as compliance with project plans (i.e. budget, schedule and scope compliance) as this usually signals proper use of design, timeliness of delivery and optimum value creation. Conversely, Baker et al. (1997) proposed that project success should instead be measured by the level of satisfaction from the end user, as compliance to plan will not matter if the outcome or end-product is substandard. Building on these ideas, Baccarini (1999) identified six (6) critical criteria for project success: time, cost, quality, strategic goal attainment, end user satisfaction and overall stakeholder acceptance.

Moreover, studies completed by the Economist Intellegence Unit (EIU 2009, 2010) suggest that proper PM practises were critical to the ability to remain successful and/or competitive during difficult economic times, providing evidence of the importance of PM principles to organisational success. Executives and experts were confident in organisations to deliver better results if they utilised a structured methodology for PM. This methodology (hereafter referred to as the PM framework) is defined by McConnell (2010) as a sub-section of tasks, processes, tools and templates which are used in amalgamation by the management team to provide foresight to the major structural elements of the project, in order to initiate, plan, execute, control, monitor, and terminate the project activities throughout the project life-cycle. Experts have proposed varying approaches to developing PM framework that facilitate sustainable project success. As such, the methodologies advocated by Naybour (2010, 2014), Project Management Institute (PMI 2013) and PRINCE2 (Adler, 2008) were studied. Table 1 depicts a comparison of the three approaches.

3. Challenges of Instituting PM Practices

Recently, high performing organisations have invested more resources into developing their PM maturity in order to ensure greater efficiencies, improved customer satisfaction, improved quality, lower costs, increased stakeholder satisfaction and greater competitive advantage (Ragbir, 2015). However, these organisations vary significantly with respect to their organisational structures, objectives, strategic drivers, constraints and business models. Therefore, a blanket solution for PM cannot be applied across the industry. Instead, the PM framework should be tailored to reflect the size, duration and complexity of projects undertaken and be adaptable to the level of organisational PM maturity, the nature of the industry and the organisational culture of the industry. Whitaker (2014) defines this tailoring as "the process of referencing framework documents, standards and other relevant sources and utilising those elements that provide processes, tools and techniques that are suitable for that particular organisation."

In addition, according to PMI (2013), a customised approach can lead to improved project performance through the utilisation of existing organisational process assets (e.g. lessons learnt from past failures and organisational policies and procedures). This cause-and-effect relationship was further validated by Whitaker (2014) via surveys issued to PM practitioners to determine the frequency of tailoring in the industry; the level of success and the level of PM maturity. Implementing a customised PM framework however presents some unique challenges. In order for the framework to be adopted, there must be top-level support and buy-in. Furthermore, to ensure this buy-in, the project team must ensure alignment between the framework and the organisation's strategy (PMI, 2014). Additionally, the project team must ensure that the implementation is aligned with the organisational culture and that the project team is comprised of competent individulas with the right behaviours for the type of project. This ensures acceptance from various levels of the organisation.

Table 1. Comparison amongst Three PM Approaches

Core Features and Components	Naybour (2014)	PMI (2013)	Adler (2008)
1. Establishing ownership of framework	√	√	√
2. Clarification of roles and responsibilities to establish chains of command and ensure accountability	√	√	√
3. Identification of inputs and constraints to the PM methodology	--	√	--
4. Identification of available resources	--	√	--
5. Definition of levels of governance for different projects	√	--	--
6. Establishment of effective communication	√	√	√
7. Design of project lifecycle with stages and gates	√	--	√
8. Development of key documents and associated templates	√	√	--
9. Establishment of effective reporting process	√	√	--
10. Product delivery	√	√	√
11. Monitoring and review	√	√	--
12. Project close-off	--	--	√

Moreover, the project team must carefully balance stakeholder's expectations to ensure that they are realistic while still providing significant value to generate management support. Finally, the team must be able to successfully manage risks in order to drive the implementation to completion and help effect a performance improvement.

4. Exploring PM Practices at PPL

4.1 Diagnosis of PM Performance and Challenges

PPL has recently been encountering challenges associated with declining project performance and the resultant negative effects on the total cost of goods sold of semi-finished products. The management team realised a need to ensure that its operations could be sustained and that its products would remain competitive in the market. While PPL lacked a documented or structured approach to PM practices, there existed an informal procedure for managing projects based on their relative complexity. A complex project was defined as one which required process engineering design and/or a lifecycle of more than three (3) months, whereas simple projects were regarded as small in scale and routine in nature. Table 2 depicts the approaches in managing complex versus simple projects at PPL.

An analysis of the existing PM approach was undertaken and deficient or sub-standard practices were identified. From the analysis, it was found that at inception, there was no guideline or standard in place for preparing a problem description, aim, scope of works and the initial (approximate) project cost. Additionally, project roles and responsibilities were not developed nor was the project team established at this stage. Most worrying was that a high level risk assessment was not completed, nor was approval from the project sponsor sought at inception.

Many obvious deficiencies existed at the planning phase. Firstly, there was limited stakeholder involvement during this phase. Secondly, the approach to budget and schedule preparation was rudimentary, being based commonly on historical experiences and therefore lacking consideration for task effort, resource requirements or management reserves. Thirdly, the planning phase completely omitted a quality management plan, a stakeholder management plan and a communication management plan, thereby permitting non-conformances to go unnoticed and adding additional complexity in the form of resistance to project acceptance and support.

For the execution phase, it was found that no procedure existed to evaluate, manage and communicate changes to the project plan. The absence of this process could amplify the effect of project delays and budget variances, and also reduce the likelihood of stakeholder and project sponsor satisfaction upon handover. Similarly, it was found that the close-out phase did not include the preparation of a 'lessons learned' document nor was a post-completion audit done. Therefore, the system facilitated the occurrence of repeat errors. Moreover, the analysis identified roadblocks to project success outside of the existing PM strategy. Notably, the organisational structure itself – hierarchical in nature – served to limit staff involvement (outside of their department) and also weakened the Project Manager's authority. Evidence also showed that there had been a lack of upper management support in providing the right resources and infrastructure to support the PM function.

4.2 Execution of a PM Study: Procedures

A PM study was initiated to quantify historical project performance and to determine the reasons for historical project failure at PPL (Ragbir, 2015). This involved four (4) main phases as elaborated below.

Table 2. PPL's approaches in managing complex projects versus simple projects

Phase	Processes	Deliverable	Complex Projects	Simple Projects
Initiation	Prospect proposal to address operational issue/performance gap		√	√
	Management approval to develop prospect		√	--
	Needs Analysis for project	Project Requirement List	√	√
Planning	Engineering Analysis and Planning	Technical Design Document	√	--
		Engineering Drawings	√	--
	Project Planning (WBS, Project Schedule, Responsibility Chart, Risk Management and Budget)	Project Definition Report	√	√
	Management approval to pursue project	Signed project approval document	√	√
	Selection of project team		√	√
	Review of project plans		√	√
Execution	Kick-off meeting		√	√
	Initialisation and implementation of work based on the project schedule and report progress at weekly meetings	Completion of works	√	√
	Implementation Review	Project Report	√	√
	Handover to final user/department		√	√
Close Out	Technical and Commercial Closure	Signed project closure document	√	√

Phase one involved the analysis of projects undertaken from November 2012 to January 2015, with the purpose of determining the following:

a) Cost variance – Budget for the project versus actual cost of the project.
b) Schedule variance – planned days for the project (to completion) versus actual amount of days taken for the project to be completed.
c) Scope variance – Number of work packages planned to complete the project versus actual number of work packages completed for the project.
d) Average variance – the average of the cost, schedule and scope variances.

Additionally, within this phase, a survey was used to gather information on stakeholder's opinion of the existing PM process. This was designed to determine the effectiveness of the existing strategy, the level of involvement, the level of confidence in and among the teams and the perceived level of support by upper management.

The Second Phase focused on determining the root cause of project failure for projects having an average variance of -5% or worse. To simplify the process and ensure maximum participation from project members, the A3 thinking process was used to determine the root causes of problems. This is a systematic problem solving tool utilising a structured problem description (such as where, when, what, who and how), an Ishikawa diagram for potential causes, a five-why analysis to determine the root cause(s) of project failure and the formulation of appropriate corrective actions (Toolshero, 2017). These corrective actions along with those derived from the analysis of the stakeholder survey were incorporated into the development of a customised PM framework.

The Third Phase comprised the actual development of the PM framework. The framework's structure was designed by adopting common processes advocated by PMI (2013), Naybour (2014) and PRINCE2 (Adler 2008). The content was developed by using corrective actions from the A3 problem solving analyses and the stakeholder survey to specifically address the deficient areas of current PM practices at PPL.

At Phase Four, the efficacy of the framework was tested. This was done by comparing current project performance to the performance of projects governed by the customised framework on a trial basis. Additionally, the responses of an executive survey were used to determine the comprehensiveness of the framework for its intended use and its ability for organisation-wide utilisation.

4.3. Results of the PM Study

Table 3 depicts a summary of the performance analysis on historical projects with respect to budget, schedule and scope variance. It was found that 57% of the projects had an average variance of -5% or worse and were thus considered failed projects. More importantly, these failed projects accounted for 71% of total project expenditure by the PIT, thereby suggesting that project failures tended to occur in the higher budgeted projects. Furthermore, these failed projects (by virtue of their actual durations)

Table 3. Historical Project Performance

Project Type	Code	Budget Variation	Schedule Variation	Scope Variation	Average Variance
Chemical Trial	CT-1	0%	-28%	12%	-5%
	CT-2	8%	0%	0%	3%
	CT-3	-26%	-33%	4%	-18%
	CT-4	12%	17%	0%	10%
	CT-5	-9%	-15%	0%	-8%
HSE	HS-1	8%	0%	-4%	1%
	HS-2	62%	50%	0%	37%
	HS-3	0%	-175%	0%	-58%
	HS-4	11%	1%	0%	4%
	HS-5	2%	22%	0%	8%
Optimisation	OP-1	-23%	-17%	0%	-13%
	OP-2	0%	-23%	14%	-3%
	OP-3	-72%	-34%	-26%	-44%
	OP-4	-23%	19%	0%	-1%
	OP-5	9%	0%	0%	3%
	OP-6	-38%	-59%	-6%	-34%
	OP-7	20%	76%	8%	35%
Contaminant Removal	CR-1	16%	0%	0%	5%
	CR-2	-23%	-25%	-3%	-17%
	CR-3	-40%	-72%	48%	-21%
Relocation	RE-1	0%	0%	0%	0%
Totals		-18%	-18%	-3%	

accounted for 63% of the PIT's project time and 53% of the tasks completed by the team. This indicated that the planning and execution strategies for projects needed to be reviewed as more time was being spent on failed projects.

The A3 thinking process was applied to these 'failed projects' to determine root causes of failure and to develop potential corrective actions. Table 4 summarises the results of this analysis. It was found that 76% of the corrective actions devised addressed core PM practices. From these, risk management was found to be particularly deficient with it being identified as a cause of failure in forty four percent (44%) of the failed projects analysed. Similarly, the strategy for communications management and contract management presented significant areas of opportunity with both being identified as a root cause of failure in 33% of the projects analysed.

Table 4. Results of A3 Thinking/Problem Solving Process for Failed Projects

Project	Identified Root Cause	Corrective Action Plans
CT-1	Poor communication between project team and core operations team	Establish proper communications management plan
	Failure to form contingency plan for operational problems	Establish proper risk management plan
	Inadequate technical support	Ensure proper technical support is provided
	Lack of PM checks on electrical system prior to project implementation	Review PM schedules with maintenance to help identify possible risks
CT-3	Insufficient planning - contract agreement insufficient	Establish proper contract management plan
	Frequency of communication between project team and vendor was insufficient	Establish proper communications management plan
	Process Description provided was not comprehensive (did not cover full range of possibilities)	Establish proper procedure for compiling comprehensive project definition reports
	Failure to identify lost time (due to polymer failure) as a project risk	Establish proper risk management plan
	Sampling frequency (to establish baseline) was inadequate	Implement continuous sampling for all process stream analyses
CT-5	Failure to procure required technical expertise	Establish proper resource planning protocol
	Contract agreement does not include compensation from vendor for equipment delays	Establish proper contract management plan
	Lack of testing for incoming raw materials - quality assurance plan	Implement stringent raw material analysis
HS-3	Contract agreement does not include penalising vendor for delays	Establish proper contract management plan
	Insufficient resources (expertise)	Establish comprehensive resource planning methods
	Absence of resource allocation agreement	Create inter-departmental staff usage application form
	Poor description of environment in project definition	Establish guidelines for the preparation of project definition report
OP-1	Poor communication between E&I team and project team	Revise SOP and Toolbox procedures
	Poor communication between E&I team and project team	Establish proper project execution plan
	Critical spare parts list was incomplete	Revise critical spare parts list
OP-3	Failure to evaluate English proficiency of foreign staff prior to site visit	Establish proper communications management plan
	Failure to evaluate English proficiency of foreign staff prior to site visit	Issue English competency evaluation prior to bringing foreign technicians
	Absence of resource allocation agreement	Create inter-departmental staff usage application form
	Failure to complete a time study to determine employee's idle time	Establish proper resource planning methodology
	Failure to involve stakeholders in planning phase of projects	Establish proper stakeholder identification and management plans
	Failure to correlate potential translations errors as delays (risk identification)	Establish proper risk management plan
	Poor Budgeting procedure	Establish proper cost management plan
	Inaccurate classification of risk	Establish proper risk management plan
OP-6	Failure to identify risk	Establish proper risk management plan
	Absence of a data verification step in trial plan	Establish a 'plan-do-check' system
	Lack of training	Re-evaluate technical training programmes
	Poor PM planning for lab equipment	Develop laboratory equipment PM schedule
CR-2	Poor procurement strategy	Establish proper procurement strategy for projects
	Absence of a change management plan	Establish proper change management plan
	Absence of a materials management plan	Establish proper materials management plan
	Failure to use up to date geo-technical information	Ensure that up-to-date data is used for analysis
	Frequency of stakeholder meetings was insufficient	Establish proper stakeholder management plan
	Failure to identify risk	Establish proper risk management plan
CR-3	Poor procurement strategy	Establish proper procurement strategy for projects
	Lack of available expertise	Ensure project team is equipped with required expertise
	Lack of available expertise	Ensure that employees capabilities are adequate before beginning project
	No change management plan	Establish proper change management plan
	Poor Resource planning	Establish proper resource planning procedures

Table 5. Stakeholder Survey Responses

	Survey Question	Responses				
		Strongly Disagree	**Disagree**	**Neutral**	**Agree**	**Strongly Agree**
Planning	From Project Definition, I have a comprehensive understanding of the projects aims and objectives	5%	27%	14%	50%	5%
	The quantity of work assigned to me is sufficient (not too much or too little)	0%	32%	23%	45%	0%
	The time allocated to me to complete each task is sufficiently planned (i.e. the duration is neither too long nor too short)	0%	59%	14%	27%	0%
	The risk identification process is thorough. A full anlaysis of threats are done to determine all plausible risks for the duration of the project	18%	45%	14%	23%	0%
	I feel fully involved in project planning	9%	32%	36%	23%	0%
Execution	Throughout the duration of the project, the assigned manpower (from external departments) is allowed and supported in the fulfillment of their project duties	0%	45%	14%	41%	0%
	Throughout the duration of the project, resources allocated for project use are readily issued by the controlling manager/department	9%	45%	18%	27%	0%
	In execution, variations from the plan are well documented and communicated to the project team and necessary stakeholders	14%	50%	18%	14%	5%
	These changes are properly and effectively managed with little to no adverse effects resulting unexpectedly	14%	55%	23%	9%	0%
Close Out	Upon completion, the end user is satisfied with the performance and deliverables of the project	0%	23%	27%	45%	5%
	Upon completion it is clear to all stakeholders that the project's aims and objectives were achieved	0%	32%	27%	36%	5%
Overall	Communications throughout the project lifecycle (among all relevant parties) is effective and occurs at the required frequency	23%	50%	5%	23%	0%
	I feel confident in the abilities of each team member to complete the task(s) assigned to them	14%	14%	23%	45%	5%
	There is a strong belief within the team that we can successfully complete the project being undertaken	0%	9%	36%	45%	9%
	Management provides the necessary support throughout the project's lifecycle	9%	41%	27%	14%	9%
	Project documentation is adequate and effective	5%	68%	9%	18%	0%
	There are an adequate number of effective control systems in place to prevent project failure	18%	55%	14%	14%	0%

Additionally, inadequacies were identified in the project definition, stakeholder management and change management strategies with each of these being found as a root cause of failure in 22% of the projects analysed. As evidenced in the results of the stakeholder survey, this was a key to the analyses of the failed projects at PPL. This survey provided insights into how effective the PM strategy was perceived to be, its adequacy, the team morale and the perception of the team's ability to deliver good results.

Table 5 shows the responses of the Stakeholder Survey. The results suggested that the majority of respondents possessed a clear understanding of the deliverables expected from each project and were satisfied with the quantity of work assigned to them. However, most felt constrained with the time allocated to complete these tasks. Further evidence of the inadequacy of the risk management system was provided by the fact that 63% of respondents perceived the risk identification process to be incomprehensive leading to the inference that there would also be an absence of a risk mitigation strategy. Overall, respondents felt that their involvement in the planning phase was below expectations – providing the researcher with a major area of improvement to be considered for the framework.

The analysis of the execution phase unearthed a core issue impeding progress whereby respondents believed that resources (e.g. manpower) were not readily available by supporting departments, thereby limiting the team's ability to perform job tasks optimally. Further evidence of the need to work on a communication management plan was provided by the fact that 64% of respondents shared that changes/variations were not documented and communicated in an efficient manner. In addition to the issues identified in the project phases, the survey highlighted the inadequacy of the overall project communications strategy. Moreover, while respondents felt confident in the ability of their team members, half of the respondents believed that management had failed to provide the necessary support throughout the project lifecycle. Most notably, the survey highlighted stakeholders' concern that there were not sufficient controls in place within the existing PM strategy to support consistent performance.

5. Focusing Improvement of the PM Framework

Incorporated with the major findings of the PM Study, the components and process attributes were derived for the development of customised PM framework. Table 6 depicts a list of components and attributes of the project initiation, planning, execution, and close-out phases.

One pertinent area in need of refinement was found to be risk management at PPL. The historical shortcomings were addressed in the framework by developing a process involving the entire project team for risk identification. Part of this process involves the review by an expert and/or the project manager to ensure that no risks are omitted. Following this, the risks are then classified according to both their impact and likelihood of occurrence. Impact and likelihood are ranked on a scale of one to five and the product of these two values is used to prioritise the risks. These risks are then managed by using three approaches – (1) avoiding the risk by eliminating it or protecting the project from its impact, (2) mitigating the risk by reducing the impact or probability of the risk occurring or (3) transferring the risk consequence to another party. Depending on the approach taken, appropriate plans are devised and reviewed with the project champion and project sponsor. Moreover, the risk register is kept as a live document and reviewed periodically to ensure that risks are consistently managed in an efficient manner.

Significant gaps in the stakeholder management plan were also found and as such, a more structured and inclusive approach was designed. This involves using the project team to list all possible stakeholders for the project and placing them into the appropriate quadrants of a power interest grid as shown in Figure 1.

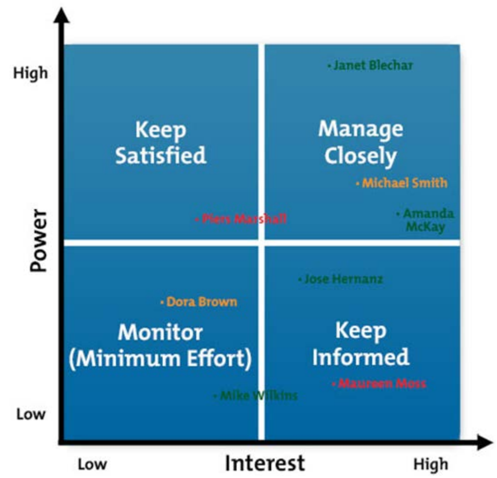

Figure 1. Power-Interest Matrix
Source: Abstracted from Thompson (2014)

Table 6. Components of the Customised PM Framework

Phase	Component and Guidelines
Initiation	Guideline for Developing Background to Project
	Guideline for Developing Purpose Statement, Scope and Objectives
	Guideline for Defining Project Roles and Responsibilities
	Guideline for Setting up the Project Team
	Guideline for Developing a High Level Work Breakdown Structure (WBS)
	Guideline for Developing a High Level Risk Assessment
	Guideline for Developing Cost Estimates
	Guideline for Developing a High Level Project Charter
	Guideline for Review and Approval
Planning	Conducting a Planning Kick-Off Meeting
	Creating a Detailed Work Breakdown Structure (WBS)
	Guideline for Developing a Milestone Plan
	Guideline for Developing a Responsibility Matrix
	Guideline for Conducting Stakeholder Analysis
	Guideline for Stakeholder Management
	Guideline for Developing a Communications Management Plan
	Guideline for Developing a Risk Management Plan
	Guidelines for Developing a Cost Management Plan
	Guidelines for Developing a Quality Management Plan
	Project Procurement Management
	Guideline for Closing the Planning Phase
Execution	Tracking Process
	Change Management
	Maintaining Quality
	Conducting Executive Review
	Schedule Updating and Reporting Process
	Guidelines on Completing Phase Sign Off and Review
Close-Out	Guidelines to Project Close Out

This model suggests that the greatest efforts must be made to satisfy high power - interested persons, while significant work should be assigned to high power - less interested people to keep them satisfied, but not too much that they become disinterested. Low power - interested people however are to be kept adequately informed and communicated with in order to minimise disruptions and issues and low power - less interested people are to be monitored, but not overwhelmed with excessive communication. Henceforth, the plan requires analysing the stakeholders to obtain key information on the most appropriate means of communication and engagement. This information thus becomes a key input to the communications management plan.

To ensure that projects undertaken by the PIT could progress in a timely manner and that the expectations of the end user could be met, a new strategy and improved communications management plan had to be devised. For each project, the project team would be required to define the overall objectives of project communication plan (i.e. what, when and why there is a need to communicate to each stakeholder or stakeholder group). The frequency and duration of communication (via e-mail, phone call, and meetings) could then be defined along with emergency procedures. Finally, the communications strategy is reviewed with the project team, followed by key stakeholders to ensure alignment and to resolve concerns prior to implementation.

It is imperative that the proposed framework includes a guideline on how changes should be managed in order to ensure improved and sustainable project performance, as the analysis found that no such procedure existed for the PIT. For changes which affect the project's scope or schedule, the following management plan was designed.

The change request must first be evaluated and assessed. Only if the change provides a significant benefit or avoids a major risk, should it then be accepted. The change request must be documented and approval must be obtained from the project sponsor and team. Once this approval is granted, any necessary corrective actions arising from the change should be executed and if possible the project should be crashed to keep it on schedule and within cost. From this point onwards, the project plans must be updated to reflect the change and any consequence of the change must be communicated to key stakeholders.

Notable additions to the proposed PM framework ensure that the strategy facilitates proper project execution. It encompasses various guidelines for 1) defining project roles and responsibilities, 2) conducting a planning kick-off meeting, 3) developing a quality management plan and project procurement management plan, 4) progress reporting during execution, and 5) closing out a project. The proposed framework therefore provides the team with a standard for developing each component in each phase of a project in order to maximise the chances of success. Moreover, the strategy is more structured and aligned with current best practices. Project documentation, controls and accountability were improved and an inclusion was made for lessons learned in order to ensure continuous improvement within the organisation.

6. Evaluation of the PM Framework

6.1 Trial Implementation of the Framework

The framework was applied to the management of two (2) short-term projects (including project code OP-8 and CT-6). The performance of both projects was compared to that of the historical projects to determine if there were any benefits from its use. The findings of this trial revealed the following:

1) The average variance for OP-8 was -1% while the average variance for historical optimisation projects (OP-1 to OP-7) was -8%;
2) The average variance for CT-6 was 4% while the average variance for historical chemical trials (CT-1 to CT-5) was -4%;
3) The total average budget variance for framework governed projects was 2% compared to -18% for historical projects;
4) The total average schedule variance for framework governed projects was 0% compared to -18% for historical projects;
5) The total average scope variance for framework governed projects was -2% compared to -3% for historical projects.

From the trial implementation, the use of the framework led to a 20% improvement in budget variance, 18% improvement in schedule variance and a 1% improvement in scope variance. Such significant improvements were undoubtedly not attributed to luck but were largely attributed to key framework components by project experts and executives at PPL.

The improvements in budget variance were attributed to the application of the cost management plan and the guidelines for developing the work breakdown structure (WBS). Suitably developing this WBS increased accountability and improved engagement as the project team became the owner of the work packages. In addition, the final task list provided the input to the cost management plan as each work package was then assigned a delivered cost based on the sum of their component costs. This structured breakdown of costs ensured that budgets were more accurate and reduced variations.

The framework's improved risk management approach facilitated a more thorough evaluation of threats and associated mitigation strategies. This was particularly evident in the case of CT-6, where the contingency plan for the risk of delivery delays by the supplier was triggered once the communication of a delay on the port was sent from the supplier to PPL. The execution of this contingency plan ensured that start-up was not delayed.

Proper stakeholder management and communications management played a vital role in reducing delays. This was particularly evident in OP-8 where the warehouse team (which was involved in project planning) was able to communicate a potential threat arising out of the timeliness of raw material requests and as such, the team was able to factor this into their materials management thereby avoiding any delays. Additionally, the new communication procedure used for OP-8 allowed the maintenance team to alert the project team of specific maintenance work that was required prior to start up. These jobs could then be executed in advance, thus allowing the project timeline to be unaffected.

During project execution, the framework also proved to be a game changer as the proposed procedures for reporting, handling requests for changes and maintaining quality also aided in keeping control of the project and so achieving project performance targets. Most notably, the procedure for change management ensured that the change to the production target for OP-8, was only accepted after approval by the sponsor and team and from this point the project plan was revisited to ensure that schedule resources and budget usage were optimised. OP-8's project plan was updated and the change was communicated to the project team and key stakeholders, thereby minimising the impact on the project's deliverable.

Moreover, the team was particularly pleased by the benefits of the quality review system which enabled the early detection of a breach in the permit to work system for CT-6. This early warning allowed the necessary adjustments to be made by the contractor and the project was so allowed to progress without any delays. Overall, the PM framework served to provide a structured, comprehensive and functionally applicable methodology for the management of process improvement projects at PPL. It allowed for thorough planning, successful execution and effective close out thereby adding greater control and accountability in order to effect improved project performance.

6.2 Executive Review of the Implementation

The development of PM framework, the results of the trial implementation, a description of the methods employed during data collection and analysis and an executive review were shared with the executive team at PPL in order to facilitate a discussion on the validity of the methods employed for data analysis, the applicability/adequacy of the framework to PPL and the potential of the framework to improve project performance and foster PM within the organisation. Table 7 shows a summary of responses from the Executive Survey. It was found that the management team considered the applicability of the PM framework and supported the adoption as a strategy to improve project executions and performance and as a key tool in achieving PPL's organisational goals. The executive committee also expressed the satisfaction with the methodical approach to quantifying project performance and unearthing the

Table 7. Responses from Executive Review

Survey Questions	Responses				
	Strongly Disagree	**Disagree**	**Neutral**	**Agree**	**Strongly Agree**
1. The analysis of historical projects was accurate and unbiased	0%	0%	0%	100%	0%
2. The methods used to determine the root causes of project failure were applicable to PPL's operation and was conducted using industry standard best practices	0%	0%	0%	75%	25%
3. The proposed PM framework has addressed the majority of failures of the historical project management system	0%	0%	25%	75%	0%
4. The guideline for implementation and development of each section of the framework is comprehensive	0%	25%	25%	50%	0%
5. The proposed PM framework is applicable to PPL	0%	0%	0%	50%	50%
6. The improvements in budget, scope and schedule compliance which were obtained from the trial application of the framework warrant a prolonged trial application to process improvement projects at PPL	0%	0%	0%	75%	25%
7. I would support the application of this proposed framework to process improvement projects undertaken by the Production department at GBPP	0%	0%	0%	75%	25%
8. In my professional opinion, the PM framework will help to foster proper project management practices within the Production department with respect to their improvement projects	0%	0%	0%	75%	25%
9. The PM framework can be used as a model for developing proper PM strategies throughout the organisation	0%	0%	0%	50%	50%
10.The PM framework can aid in improving project performance, thereby helping PPL to achieve its long-term organisational goals	0%	0%	50%	50%	0%

reasons for poor project performance, thereby further validating the methodology used for the study.

7. Conclusion

The study had four (4) objectives – 1) to quantify project failure by the PIT at PPL from November 2012 to January 2015, 2) to determine the root causes of these failures, 3) to custom design a PM framework to counteract these failures, and 4) to test the efficacy of the framework. From the analysis of project documents it was found that 43% of process improvement projects ended in failure. These failed projects represented 71% of the PIT's project expenditure, 63% of their time and 53% of the work completed by the team.

The A3 thinking process and the results of the stakeholder surveys found that 76% of project failures could be linked to sub-standard PM practices. Of these, risk management, communications management and change management required the greatest focus. As such, a comprehensive PM framework was suitably designed to improve project performance by structuring the framework according to best in class recommendations specifically focused on strengthening the deficient areas identified from the root cause analyses.

The trial application of the framework to two projects at PPL was coupled with an executive review of the framework. The study found that the initial application to short-term projects led to a reduction in budget, schedule and scope variation by 20%, 18% and 1% respectively. Additionally, the executive review validated the research methods, provided support for a prolonged trial and supported the institutionalisation of the framework as a departmental standard. Evaluations are suggested to examine critical processes and individual steps, and future studies could validate the key elements identified for the proposed PM framework.

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A Lighting Audit of The University of The West Indies St Augustine Campus

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Abstract: *Many students and staff utilize the facilities of The University of The West Indies St. Augustine campus at night. Inadequate lighting can make the school environment unsafe. This paper documents methodologies and the results of an audit conducted on the campus. The audit was performed to determine the adequacy of the campus lighting. Areas audited were identified via a survey distributed to students of the campus. The illuminance levels were measured at these locations and compared to applicable standards of the Illuminating Engineering Society. The results confirmed that none of the areas evaluated satisfied the lighting levels detailed in the standards. Recommendations and implementation plans accompanied by cost-benefit analyses were developed for each area ensuring the standards are satisfied.*

Keywords: *Lighting audit, illuminance measurements, lighting designs, financial assessment, design simulation, implementation plans*

1. Introduction

Over 22,000 students and staff use the facilities of The University of The West Indies St. Augustine campus (UWI, 2016). Many of these facilities have existing lighting systems, and some have been recently implemented, while some of the lighting systems may not be suitable. To identify the areas that have insufficient lighting, the lighting systems on campus were reviewed based on standards that recommend lighting levels. Methodologies were reproduced in order to conduct a lighting audit. A project was initiated to audit existing lighting systems to determine the adequacy of the campus lighting. Based on the findings of the audit, recommendations and future implementation plans were identified.

A lighting audit is a process by which lighting systems can be evaluated by comparing these systems to existing standards. The purpose of an audit is to determine the effectiveness of the existing system and determine where improvements can be made. To ensure the existing systems satisfy the specific standard(s) with financial consideration. The recommended changes would improve the safety and comfort of individuals using the campus. Adequate lighting throughout the campus will also improve the sense of security of the university community.

In order to determine areas that may have insufficient lighting, a survey was distributed to the students of the university. The students were broadly asked to identify areas with insufficient lighting. Responses from the students along with university guidance were used to identify areas to be audited. The illuminance levels of these areas were then evaluated. Table 1 shows the types of premises and total area evaluated per different types and the percentage covered for the audit.

Table 1. Different Types of Premises and Total Areas Evaluated for the Lighting Audit

1. Car Parks	Area (m^2)
Heart Ease Car Park	3,516.4 m^2
Trinidad Government Railway (TGR) South Car Park	2,688.6 m^2
Sports and Physical Education Centre (SPEC) Car Park	606 m^2
Dudley Huggins Car Park	826.8 m^2
Sub-total:	7,637.8 m^2
Percentage of car parks evaluated:	17.7 %
2. Roadways	Area
North Entrance Roadways	2,815.3 m^2
SPEC Entrance Roadway	1,799.6 m^2
South Entrance Roadways	1,739.1 m^2
Entrance Roadway Adjacent to Heart Ease Car Park	1,162.8 m^2
Sub-total:	7,516.8 m^2
Percentage of Roadways evaluated:	24.57 %
3. Walkways	Area
Walkway Adjacent to Block 13	1,325.2 m^2
North Entrance Walkway	56.7 m^2
South Gate Entrance Walkway	116.4 m^2
Sub-total:	1,498.3 m^2
4. Field	Area
SPEC Cricket Field	49,577.1 m^2
Percentage of fields evaluated:	29.67 %

This paper reviews available methods used to perform the lighting audit, and provides a comparison of recommended lighting level standards and the chosen methods for carrying out the audit. It reports the main results of the audit, and presents the analysis and recommendations for improving the lighting on campus.

2. Methodology

The method for performing the lighting audit was sub-divided into three (3) main parts, namely 1) determining areas to be audited, 2) data acquisition, and analysis of data.

2.1 Determining areas to be audited

In order to determine areas that may have insufficient lighting, a survey was distributed to the students of the university. The students were broadly asked to identify areas with insufficient lighting. Responses from the students along with university guidance were used to identify areas to be audited.

2.2 Data Acquisition

Data acquisition included performing illuminance measurements on the different areas outlined in the scope. In addition to the illuminance measurements, data was gathered based on the type, wattage, and position of fixtures in the areas being audited. Information such as the fixture wattage was provided by the Division of Facilities Management (DFM). The following describes methods of performing these illuminance measurements. These methods describe how the sample points were determined, as well as the height and orientation of the sensor while taking the measurements.

2.2.1 Measuring Parking Lot Lighting

Richman (2012) suggested a method for measuring parking lot lighting. This method was used to evaluate the illuminance levels of the parking lots on campus, and is described below:

1. The dimensions of the area being evaluated were identified via the ArcGIS web application and by physical measurements.
2. The area was divided into a horizontal grid and measurement points on the surface area were identified.
3. It was ensured that the measurement points were evenly spaced in both directions and the distance between two points was at a maximum of fifteen (15) feet.
4. It was ensured that there existed at least three measurement points between poles in both directions.
5. Vertical planes which represented the vertical lighting in the area were identified. These vertical planes were typically the vertical grids situated directly between two poles.
6. Vertical measurements were taken five (5) feet above the surface of the area being evaluated. These measurements were taken in the two main directions of vehicular travel.
7. Horizontal measurements were taken one meter above the ground at each measurement point.
8. Precautions were taken to ensure that there were no obstacles that may have blocked light from the sensor.
9. Precautions were taken to ensure measurements were not taken during fluctuations in the lighting levels due to obstructive light from passing vehicles.
10. Measurements were recorded.

The method used for non-uniformly illuminated areas or non-illuminated areas are described, as follows:

1. For areas where the poles were not uniformly spaced, an existing row of luminaires that were parallel to the site boundary was identified. The average spacing of these luminaires was used as the basis for setting the measurement grid.
2. In the case where there were no luminaires or none of the luminaires were operational, the grid was developed such that the distance between two points was at a maximum of fifteen (15) feet.
3. The procedure for taking vertical and horizontal measurements remains unchanged.
4. Precautions were taken to ensure that there were no obstacles that may have blocked light from the sensor.
5. Precautions were taken to ensure measurements were not taken during fluctuations in the lighting levels due to obstructive light from passing vehicles.
6. The measured values were recorded.

2.2.2 Measuring Roadway Lighting

For evaluating street lighting a 9-step method advocated by Grieneisen et al. (2006), Bhubaneswar Municipal Corporation (2013) and Parmar (2014) is adopted. These steps are listed below;

1. The area between two light poles was divided into a grid with nine sample points.
2. At the location of the first pole three sample points were equally spaced along the width of the road and sidewalk.
3. Similarly, at the location of the second pole three sample points were equally spaced along the width of the road and sidewalk.
4. The last three sample points were located at the centre of the two poles. These three sample points were equally spaced along the width of the road and sidewalk.
5. If the fixtures on the roadway were not operational or there were an absence of fixtures, a grid layout was still used in order to determine the illuminance values.
6. Measurements were taken horizontally one meter above the ground at each sample point.

7. Precautions were taken to ensure that there were no obstacles that may have blocked light from the sensor.
8. Precautions were taken to ensure measurements were not taken during fluctuations in the lighting levels due to obstructive light from passing vehicles.
9. The measurements were recorded.

2.2.3 Measuring Walkway Lighting

This method was used to evaluate walkways on campus. The steps are as follows:

1. The area was divided into a grid.
2. The size of the grid depended on the dimensions of the walkway and spacing of the poles. The distance between two points was at a maximum of fifteen (15) feet.
3. Horizontal readings were taken one meter above the ground.
4. Vertical readings were taken five feet above the ground in the direction of pedestrian traffic on the walkway.
5. Precautions were taken to ensure that there were no obstacles that may have blocked light from the sensor.
6. The average illuminance was found by taking the sum of the measured values and dividing it by the number of measurements taken.

2.2.4 Measuring Field Lighting

The method used for evaluating the illuminance levels of the cricket field is elaborated as follows:.

1. The dimensions of the field were analysed via the ArcGIS application and by physical measurements.
2. The infield was divided into a grid, such that each subsection had a dimension of 37.16 m^2 (400 ft^2).
3. Based on the analysis of the data gathered for the infield, the outfield was divided into a grid with each subsection having a dimension of 148.645 m2 (1600 ft2).
4. Measurements were taken at the centre of each subsection with the sensor placed one meter above the surface of the field.
5. Precautions were taken to ensure that there were no obstacles that may have blocked light from the sensor.
6. The measured values were recorded.

2.3 Analysis of Data Acquired

The data gathered was used to calculate parameters such as the average illuminance and uniformity ratio. These parameters were then compared to the recommended values outlined in the chosen standards. Based on the comparison, conclusions were made as to whether the area being evaluated met the recommended standard or not.

Standards from multiple organizations were considered for evaluating the lighting levels around campus, however, standards from the Illuminating Engineering Society (IES) were chosen. These standards were chosen since they were more detailed and provided guidelines for design procedures. Table 2 shows the standard chosen for each area.

Table 2. Chosen Standards for Respective Areas

Area	Chosen IES Standard
1) Parking Lots	Lighting for Parking Facilities
2) Roadways	Roadway Lighting
3) Walkways	Roadway Lighting
4) Field	Sports and Recreational Area Lighting

The standard chosen for parking lots was IES RP-20-14 Lighting for Parking Facilities (IES, 2014a). Table 3 shows the reference data of the Parking Lot Standard. The following describes how the data was analysed for different areas.

Table 3. Parking Lot Standard

Parking Lots – All Ages (Asphalt) surfaces		
E_{avg} (lux)	E_{vmin} (lux)	(E_{max}/E_{min})
5	2.5	1.5

where: E_{max} = Maximum Horizontal Illuminance
E_{min} = Minimum Horizontal Illuminance
E_{avg} = Average horizontal illuminance
E_{vmin} = Minimum Vertical Illuminance

$$E_{avg} = \frac{\sum_{i=1}^{n} E_i}{n} \qquad (1)$$

where, E_{avg} = Average horizontal illuminance
E_i = Individual measured illuminance at point (i)
n = Number of samples taken

The uniformity ratio of the Parking Lot was calculated as follows:

$$Uniformity\ Ratio_{\ (Parking\ Lot)} = E_{max} / E_{min} \qquad (2)$$

The standard chosen for evaluation of walkway lighting was Roadway Lighting IES RP-8-14 (IES, 2014b). The average illuminance was calculated using Equation (1) and the uniformity ratio of walkway was calculated as follows (see Table 4):

$$Uniformity\ Ratio_{\ (Walkway)} = E_{avg} / E_{min} \qquad (3)$$

Table 4. Maintained Illuminance Values for Walkways

	E_{avg} (lux)	E_{vmin} (lux)	E_{avg}/E_{min}
Pedestrian Areas	5.0	2.0	4.0

The standard chosen for the evaluation of street lighting was Roadway Lighting IES RP-8-14 (IES, 2014b). The roadways internal to the university were classified as collector roadways. A collector roadway supports the traffic between the major and local streets. The surface of the roadways was classed as R3 which is defined as an asphalt road with dark aggregates and a rough texture after months of usage. The pedestrian conflict was considered high due to the large number of pedestrians in the area at night (see Table 5).

Table 5. Maintained Illuminance Values for Pedestrian Conflict Areas

Road	Pedestrian conflict area	E_{avg} (lux)	E_{avg}/E_{min}
Collector	High	12	3

In order to attain the average illuminance E_{avg} a weighted sum of the measured values was taken. The weightings are based on an area factor for which the illuminance at that point is considered constant. This method was advocated by Grieneisen et al. (2006) Bhubaneswar Municipal Corporation (2013) and Parmar (2014). The average illuminance of the nine point grid used to measure roadway lighting was determined as follows:

$$E_{avg} = \frac{P1+P3+P7+P9}{16} + \frac{P8+P2+P6+P4}{8} + \frac{P5}{4} \quad (4)$$

Where, P1, P2, P3, P4 P5, P6, P7, P8 and P9 are illustrated in Figure 1.

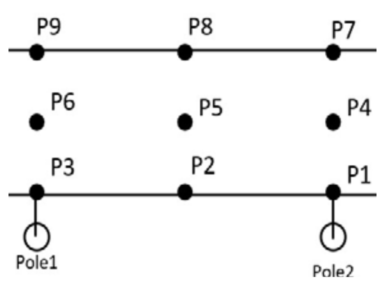

Figure 1. Nine Point Method

If there were an absence of fixtures on the roadway or the fixtures were not operational, the average illuminance can be calculated using Equation (1). The uniformity ratio was calculated using Equation (3).

The standard chosen for evaluating the field lighting was Sports and Recreational Area Lighting IES RP-6-15 (IES, 2015c). The Cricket field was classed as a class II field based on the IES RP-6-15 classification for college facilities. The coefficient of variation (CV) is the ratio of the standard deviation to the mean or average. The equations used to calculate the standard deviation (σ) and CV are:

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n}\left(E_i - E_{avg}\right)^2}{n}} \quad (5)$$

$$CV = \sigma / E_{avg} \quad (6)$$

The average illuminance and uniformity ratio are determined using Equations (1) and (2), respectively. Table 6 shows a summary of the recommended lighting levels of the field.

Table 6. Recommended Illuminance Levels for Class II Cricket Field

	E_{avg} (lux)	E_{max}/E_{min}	CV
Infield	750	1.5:1	0.1
Outfield	500	2:1	0.17

Where, CV = Coefficient of Variation

3. Development of Recommendations

If the lighting in an area did not meet the recommended standard, this confirms the existing lighting design for that area requires upgrading. These upgrades may be in the form of modifications to existing design or implementation plans for a new design. Modifications may include the implementation of new fixtures on existing poles. Implementation plans for a new design included a new layout of poles with new lighting fixtures.

Since the lighting systems audited could not be modified due to a lack of specifications of the existing fixtures and unevenly spaced poles, new designs were required. Several steps were involved in creating a new lighting design. These are:

1. The area was assessed based on the overall shape and dimensions. Based on the type of area an IES standard was chosen that gave recommended lighting levels for the area. For example, the IES standard entitled Roadway Lighting was chosen for evaluating the roadway lighting.
2. Multiple lighting fixtures applicable to the area were compared. Some of the parameters that were compared are as follows:
    - Defining Technology (e.g. filament, solid state device, low pressure discharge, etc.)
    - Output power (units = W)
    - Efficacy (units Lm/W)
    - Colour Rendering Index (CRI)
    - Correlated Colour Temperature (CCT) (units = K)
    - Cost of fixture
3. Design principles outlined in the standard applicable to the area being evaluated were reviewed.
4. Calculations of assessments were performed with the aid of a simulation software in order to determine the number of fixtures required. The simulation was also used to aid in the design and to verify that the design met the recommended standard. The simulation software used was DIALux, this software allows the user to design, calculate and visualize light professionally (DIAL GmbH, 2017). DIALux is used as a planning tool by over 680,000 lighting designers worldwide (DIAL GmbH, 2017).
5. A financial assessment was performed in order to determine which design would be the most cost effective solution. The financial assessment took into consideration all cost in the implementation and running of the design. The financial assessment gave an indication of the savings attained by choosing one design over another.

4. Financial Assessment

The power demand (KW) for each design considered was calculated using the following equation:

Power Demand (KW)
= (Number of lamps ×Power per lamp)/1000 (7)

The energy consumption and energy cost for each design was calculated as follows:

Energy consumption per year
= Power Demand × operating hours per year (8)

Energy cost per year
= Energy consumption per year × Energy cost per kWh (9)

The power demand, energy consumption and maintenance cost of each design was compared and the differences were found. These differences were used to calculate the yearly savings attained by choosing the design with the lowest energy consumption. The yearly savings attained by choosing one project (project one) over another (project two) was calculated as follows:

Total Yearly Maintenance Cost
= average maintenance cost per fixture × number of fixtures (10)

Total yearly running cost
= Energy Cost Per Year + Total Yearly Maintenance Cost (11)

Yearly savings
= running cost of project two-running cost of project one (12)

The total cost of implementing a design was calculated as follows:

Total installation cost
= (number of fixtures ×installation cost for fixture)
+ (number of poles × installation cost per pole (13)

Total purchase cost
= (number of fixtures × Cost of fixture)
+ (number of poles × Cost of pole) (14)

Capital Cost = Total installation cost + Total purchase (15)

The decision of choosing one project over another can result in savings. A cash flow analysis is performed to determine the savings after a period of years. The initial and yearly savings would be considered as the cash inflows. Such an analysis is shown below:

Initial Savings
= Capital Cost of project two - Capital Cost of project one (16)

Total Savings
= Initial Savings + (yearly savings × amount of years) (17)

The simple cash flow analysis above does not take into consideration the discount rate. A discounted cash flow analysis utilises the discount rate in order to determine the present value of future cash flows. The sum of the present values of future cash inflows, plus the initial savings would give the total discounted cash inflow. This analysis was performed with the assumption that the energy cost remains constant. The total discounted savings can be found as follows:

$$\text{Total Savings}_{\text{(discounted)}} = C_0 + \sum_{t=1}^{T} \frac{C_t}{(1+r)^t} \quad (18)$$

where, C_t = cash inflow during period t (yearly savings)
C_0 = total initial cash inflow (initial savings)
r = Discount rate
t = Time period (year after initial investment)
T = Total time period (amount of years)

5. Results

The illuminance measurements taken at parking lots were used to calculate the average illuminance and uniformity ratio. Similar measurements were taken for walkways, roadways and cricket fields, respectively. Tables 7-10 compare the audit results obtained to the recommended standard.

Table 7. Results for Parking Lots

Parking Lot	E_{avg} (Lux)	E_{vmin} (Lux)	E_{vmin} (Lux)	E_{max}/E_{min}
IES RP-20-14 (Lighting for Parking Facilities)	*5*	*2.5*	*2.5*	*15*
Heart Ease	6.9	1.8 Facing (north)	1.3 Facing (south)	38.7
SPEC	6.8	0.4 Facing (east)	0.04 Facing (west)	32.8
Dudley Huggins Car Park	3.7	0.1 Facing (east)	0.5 Facing (west)	50.5
TGR South Car Park	4.2	0.5	0.4 Facing (south)	201

Table 8. Results for Walkways

Walkway	E_{avg} (lux/fc)	E_{vmin} (facing North) (lux)	E_{vmin} (facing South) (lux)	E_{avg}/E_{min}
IES RP-8-14(Roadway Lighting)	*5*	*2*	*2*	*4*
Walkway adjacent to block 13	1.8	0.3	0.3	15.3
North Entrance	6.7	1.3	2.2	3.9
South Entrance walkway	14.8	1.3	1.5	4.1

Table 9. Results for Roadways

Road	E_{avg} = Average Illuminance (lux)	Uniformity ratio = E_{avg}/E_{min}
IES RP-8-14 (Roadway Lighting)	*12*	*4*
North Roadways	23.2	11
South Entrance Roadway	9.7	16.2
Entrance from Heart Ease Car park to SAC	12.6	15.8
SPEC Entrance Roadway	6.1	10.2

Table 10. Results for Cricket Field

	E_{avg}	E_{max}/E_{min}	CV
IES (2015) RP-6-15 Recommended lighting levels for Infield (Sports and Recreational Area Lighting)	*750*	*1.5*	*0.1*
Measured levels for Infield	352.5	1.3	0.067
IES (2015) RP-6-15 Recommended lighting levels for Outfield (Sports and Recreational Area Lighting)	*500*	*2*	*0.170*
Measured levels for Outfield	314.4	4.4	0.233

6. Discussion

6.1 Parking Lots

1) At *Heart Ease Car Park*, six 250 W HPS fixtures are presently used to illuminate the car park. The fixtures were installed with a large boom angle (angle to horizontal) in an attempt to compensate for the absence of fixtures at the centre of the car park. Installing these fixtures in such a manner (large boom angle) would not only be ineffective at illuminating the car park, it can also aid in light pollution such as sky glow, light trespass and glare (McColgan, 2007). The measured illuminance at the car park met the recommended average horizontal illuminance, however, the recommended uniformity ratio and the minimum vertical illuminance were not met. The uniformity was significantly higher than the recommended value. This suggests that there were large differences in illuminance levels throughout the car park.
2) At *SPEC Car Park*, one 400 W metal halide lamp is used to illuminate the car park. This single fixture cannot properly distribute light evenly throughout the entire carpark, hence the uniformity ratio and the minimum vertical illuminance did not meet the recommended standard. The average horizontal illuminance was the only parameter that met the recommended level.
3) At *Dudley Huggins Car Park*, three 250 W mercury vapour fixtures and a 250 W high pressure sodium fixture were used to illuminate the car park. None of the fixtures at the car park were operational at the time. The entire area was divided into a grid and illuminance measurements were taken. Due to the absence of working luminaires at the car park, none of the recommended lighting levels were met.
4) At *TGR South Car Park* two 250 W high pressure sodium fixtures were used to illuminate the car park. One of the fixtures was not working at the time of the evaluation. The area was divided into a grid and illuminance measurements were taken. None of the recommended standards were met since this one fixture is unable to illuminate the entire car park.

6.2 Walkways

There were no fixtures installed on the walkway adjacent to block thirteen. High pressure sodium lamps from the neighbouring car park and savanna would aid in partially illuminating the walkway. The lighting levels on this walkway did not meet any of the recommended standards.

Ten pole top compact florescent lamp fixtures were used to illuminate the north entrance walkway. These fixtures were mounted at an average height of one point two meters (1.2m). The illuminance levels of this walkway met with respective standards except for the minimum vertical illuminance in the northerly direction. The mounting height of the luminaires on this walkway was insufficient to provide proper vertical lighting.

A 250 W mercury vapour lamp and two 250 W high pressure sodium lamps were used to illuminate the south entrance walkway, however, only one of the high pressure sodium fixtures was working at the time of the evaluation. The lighting levels of this walkway met with the recommended average horizontal illuminance. However, it did not meet the recommended minimum vertical illuminance and the uniformity ratio.

6.3 Roadways

Six 400 W Metal Halide fixtures along with four 250 W HPS fixtures were used to illuminate the SPEC entrance roadway. None of the HPS lamps were working at the time of the evaluation. The average horizontal illuminance and uniformity ratio of the roadway did not meet the recommended standard. The roadway can be divided into two sections. Section one would be the segment of the roadway that has HPS lamps and section two would be the segment that has metal halide lamps. While analysing the data gathered from these sections separately, it showed that the average illuminance of both sections did not meet with respective standards. The recommended uniformity ratio was met for section one, however, the illuminance levels on this section was very low. Table 11 shows a summary of results of the analysis.

Table 11. Results for SPEC Entrance Roadway

Section	Average Illuminance (lux)	Uniformity ratio E_{avg}/E_{min}
Section one (HPS)	1.4	2.227
Section two (Metal Halide)	9.69	16.145

The entrance roadway adjacent to Heart Ease Car Park was illuminated via 250 W high pressure sodium lamps. The average horizontal illuminance of the roadway met with the recommended standard. However, the uniformity ratio of the roadway was significantly higher than the recommended value. The uniformity of the light on the roadway was poor due to the spacing of the poles. The poles were not uniformly spaced along the roadway, large spaces between poles caused some areas to be poorly lit. The distance of the poles from the roadway and the overhang of the fixtures also varied. These factors would also have a significant influence on the uniformity ratio of the roadway.

The south entrance roadway was illuminated via one 250 W mercury vapour lamp and five 250 W high pressure sodium lamps. The mercury vapour fixture and two of the five high pressure sodium fixtures were not working at the time of the evaluation. There was an absence of luminaires on a large segment of the roadway. Both the average horizontal illuminance and uniformity ratio of the lighting on the roadway did not meet the recommended standard.

6.4 Cricket Field

The diameter of the cricket field was measured at 400 feet. This diameter extended beyond the boundary lines of the playing area to ensure the boundary was well illuminated. The field is being illuminated via a ten pole arrangement. Sixteen 1000 W metal halide lamps are mounted on each pole, which gives a total of 160 lamps. Twelve of these lamps were not working at the time of the evaluation. The initial evaluation was performed on the main playing area of the field, and this area is called the infield. The infield is the 756.25 m^2 area located at the centre of the field. The infield encompasses the pitch where the main activities of the game occur.

The initial evaluation of the infield showed that the uniformity ratio and the coefficient of variation met the recommended standard, however, the average horizontal illuminance did not meet the recommended standard for a class two cricket field. The outfield was then evaluated using a reduced number of sample points since it was already established that the field did not meet all the recommended standards. A grid with each subsection having an area of forty square feet was used to evaluate the outfield. Analysis of the data gathered from measurements of the outfield showed that the lighting of the outfield did not meet any of the recommended standards.

7. Recommendations and Implementation Plans

The audit highlighted areas that did not meet the recommended lighting level standards. Modifications to the existing design or a complete re-design of the lighting in these areas would be required in order for the recommended IES standards to be met. The recommended luminaire layouts were different for each area due to the shape, total area and required lighting levels. The luminaire distribution types were specific to the areas in which they were placed and the layout of these luminaires were arranged in order to meet the recommended standards. These luminaires are energy efficient, have good colour rendering and provide proper lighting.

For cost effectiveness and ease of implementation, the Division of Facilities Management suggested that the fixtures used in the designs be easily accessible in the local market. The capital costs include an estimation of the installation costs along with the total purchase cost for the designs. Table 12 provides a summary of design data and references for parking lot, walkway, roadway and the cricket field. These designs recommended would meet with the lighting level standards. For illustration purposes, Figures 2 and 3 show examples of simulated design for the SPEC Car Park and the Walkway Adjacent to Block 13, respectively. Besides, Figures 4 and 5 illustrate a 3D rendering and a sample layout of luminaires at the SPEC Cricket Field, respectively.

Table 12. Summary of Design Data and References for Parking Lot, Walkway, Roadway and Cricket Field

1. Parking Lot Design			
	Fixtures	Number of Fixture	Capital Cost (TTD)
Heart Ease	ATG AL07	14	$119,558
SPEC		5	$46,985
TGR South		9	$84,573
Dudley Huggins		5	$46,985
2. Walkway Designs			
	Fixtures	Number of Fixture	Capital Cost (TTD)
Walkway adjacent to block 13	ATG AL07	7	$65,779
North Entrance	QSSI KH25	3	$30,132
South Entrance walkway	QSSI KH25	3	$30,132
3.Roadway Designs			
	Fixtures	Number of Fixture	Capital Cost (TTD)
Roadways (1000 feet)	M2RR25C M-250R2 GE Lighting	21	$204,225
4.Field Designs			
	Fixture	Number of Fixture	Capital Cost (TTD)
SPEC Cricket Field	COOPER - MHXL-T5-1500-MT	120	$543,000

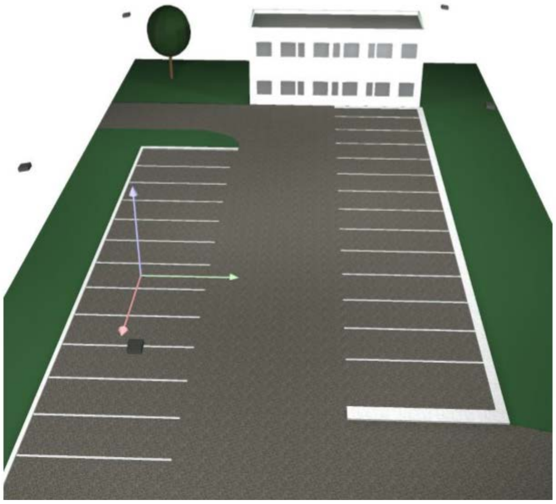

Figure 2. 3D Rendering for the SPEC Car Park

Figure 3. 3D Rendering of the Walkway Adjacent to Block 13

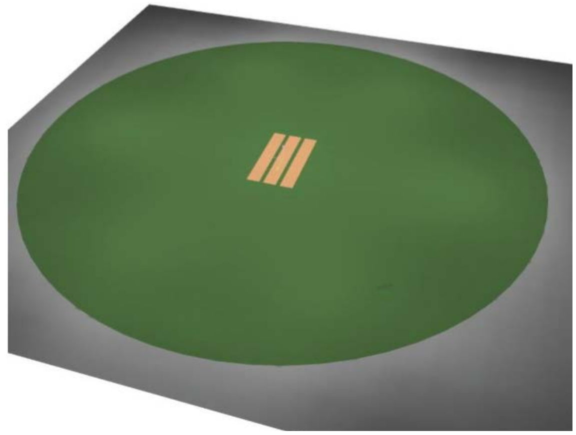

Figure 4. 3D Rendering of the SPEC Cricket Field

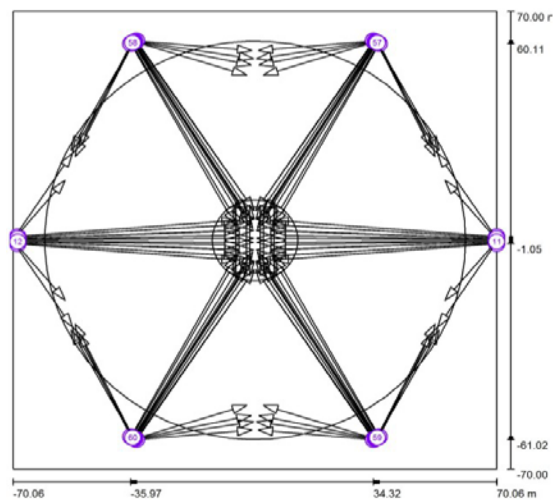

Figure 5. SPEC Cricket Field Luminaires (Coordinates List)

The simulation results of the recommended designs are summarised in Table 13 for Parking Lots and Walkways, Table 14 for Roadways and Intersections and Table 15 for the SPEC Cricket Field, respectively.

Table 13. Lighting levels of Recommended Designs for Parking Lots and Walkways

	E_{avg} (Lux)	E_{vmin} (Lux)	E_{vmin} (Lux)	E_{max}/E_{min}
1. Parking Lot				
IES) RP-20-14	*5*	*2.5*	*2.5*	*15*
Heart Ease	16	2.98 Facing (north)	2.6 Facing (south)	3.125
SPEC	21	2.8 Facing (east)	2.68 Facing (west)	1.9
Dudley Huggins	15	3.35 Facing (east)	3.08 Facing (west)	3.85
TGR South	15	2.54 Facing (north)	2.86 Facing (south)	2.273
2. Walkways				
IES RP-8-14	*5*	*2*	*2*	*4*
Walkway adjacent to block 13	14	2.29	2.29	2.31
North Entrance	19	2.34	2.31	2.7
South Entrance walkway	21	3.05	3.03	2.25

Table 14. Lighting Levels of Recommended Designs for Roadways and Intersections

	E_{avg} (Lux)	E_{max}/E_{min}
1. Roadways		
IES RP-8-14	*5*	*4*
Roadway	14	2.31
2. Intersections		
IES RP-8-14	*24*	*4*
Three Way Intersection	32	2.46
Four Way Intersection	72	2.77

Table 15. Lighting Levels of Recommended Designs for the SPEC Cricket Field

	E_{avg}	E_{max}/E_{min}	CV
IES (2015) RP-6-15 Recommended lighting levels for Infield	*750*	*1.5*	*0.1*
Design Infield Lighting levels	765	1.087	0.0242
IES-RP-6-15 Recommended lighting levels for Outfield	*500*	*2*	*0.17*
Design Outfield Lighting levels	603	1.8	0.142

8. Conclusion

The areas that were audited were identified by a survey. Results of the evaluated areas confirmed that 50% of the car parks, 66.67% of the walkways and 50% of the roadways met the recommended average horizontal illuminance defined by the IES standards. The maximum uniformity ratios of these areas were significantly higher than the recommended values and the minimum vertical illuminances were lower than the recommended values defined by the IES standards. Therefore, none of these areas met all the recommended lighting levels.

Some of the fixtures at the areas being audited were not working at the time of the evaluation, hence the lighting levels in these areas could not have met the standards. Maintenance of these fixtures should have been performed prior to the audit in order to accurately determine if the installed lighting could have met the recommended standards.

One of the major limitations in performing the audit was time. Constant rescheduling of measurements were required due to rainy weather which delayed the completion of the audit. Access to the standards reviewed was also limited. These standards were only accessible through the TTBS (Trinidad and Tobago Bureau of standards) library, therefore multiple visits had to be made in order to acquire the required information.

After the audit was conducted recommendations were made in order to improve the lighting in the areas evaluated. Recommendations for retrofit designs that would reuse the installed fixtures were not possible since specifications of the installed fixtures were not available. Recommendations were made for the installation of new fixtures that can be purchased locally. Since there were no available specifications of the existing fixtures new designs were required for 100% of the areas audited.

Acquiring quotes on fixtures that can be purchased locally proved to be a difficult task. Therefore, the designs were done using fixtures that quotes were provided for. This limited the choices of fixtures for the recommended designs. The estimated yearly maintenance cost of a fixture was $200. This cost had a significant impact on the designs recommended. The estimated capital cost was $543,000 for the recommended design for the cricket field, $298,101 for the car parks and $126,043 for the walkways. The total cost for implementing all the proposed designs was $967,144. The simulated results showed that all the recommended designs met the recommended lighting levels detailed in the applicable standards.

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Vertical Take-off Unmanned Aerial Vehicle with Forward Flight Transition

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Abstract: *This paper presents the findings from a capstone project that was to design a drone capable of functioning as vertical take-off Unmanned Aerial Vehicle (UAV) with a conversion to horizontal flight. It could serve as stable controlled flight using a simulator based iterative design process. The vehicle was intended to work in an environment where tedious or boring jobs could be automated. The vehicle design concepts were created through research, benchmarking, design metrics, and virtual flight testing. Both the simulation model and demonstration vehicle adhered to the aim and goals of the project. This project demonstrates the acceleration in design timelines that can be achieved, even by an undergraduate engineering student, who becomes skilled in using an advanced knowledge-based simulation tool.*

Keywords: *Aerospace, Unmanned Aerial Vehicle (UAV), Vertical Take-off and Landing (VTOL), Simulation*

1. Introduction

Consider the case of pilots performing repetitive and simplistic tasks such as coastal and maritime surveillance, aerial law enforcement activities, and aerial cinematography. These tasks are often tedious and time consuming, and these pilots could be transferred to more engaging and rewarding roles, and they can be replaced with cost efficient autonomous vehicles. Commonly these take the form of “drones” or quadcopters (D'Andrea, 2014). However, there are no commercially available vehicles on the market at the time of writing which can satisfy the criteria of high speed, long range conventional flight, and vertical take-off, both of which are needed in a variety of aerial activities (Ozdemir, et al., 2014).

When one thinks of civilian drones, typically one thinks of a quadcopter. Quadcopters, also called a quad rotor helicopters, use two pairs of identical fixed pitched propellers, and use independent variation of the speed of each rotor to achieve control. Quadcopters are cheaper and more durable than conventional helicopters due to their mechanical simplicity. However, quadcopter designs possess too limited a range, and too slow a speed. For maritime operations, it may be essential for a vehicle to be able to take off from a small coastal base and subsequently travel long distances of coastline, or to be able to operate entirely from an ocean-going vessel (Stone & Clarke, 2001).

A commercially available, unmanned vehicle which is capable of high speed, long range flight as well as vertical take-off would be able to satisfy a wide range of needs and capabilities. This paper presentsc an optimal overall design, and explores the capability of knowledge-based tools to form an iterative, software based design process.

2. Background

The type of vehicles of interest for this research was those capable of Vertical Take-off and Landing (VTOL) operations and transitioning to a more efficient conventional flight mode (Sinha, et al., 2012). VTOL is a type of aircraft which can hover, take off, and land, vertically. Both fixed wing aircraft and rotary wing aircraft (such as helicopters) can be classified as VTOL’s. During the development of the XV-15, an experimental tiltrotor designed by NASA (2015) and built by Bell Helicopters, both NASA and the US Army Aeronautical Research Laboratory (AARL) developed an in-depth chart of possible VTOL configurations (see Figure 1).

The traditional way of determining vertical flight and hovering efficiency is to consider the power loading of the vehicle. This is a simple ratio between the weight of the vehicle and the power of installed engines. A more efficient vehicle requires less powerful engine to hover at a given weight. Another method of measuring hover efficiency is disc loading, i.e., (Weight of vehicle) / (Area of thrust producing structure). The thrust producing structure may be rotor area, propeller area, or jet exhaust area. A VTOL aircraft with high power loading and low disc loading is the most efficient at hovering (Markman and Holder, 2000; Warwick, 1992).

Helicopters and Gyrodynes are both rotary winged vehicles, so from a power loading and disc loading analysis perspective, they are very similar in performance. Tiltrotor, tiltwing, and gyrodyne vehicles utilise either propellers or rotors (Groenaeronautics, 2014). However, ducted fans are a potential third power plant alternative. A ducted fan is a propulsion device in which a propeller is mounted within a cylindrical shroud or duct, and they may have several advantages over standard propellers (Bensen, 2003). These are:

- Ducted fans are more efficient than a conventional propeller.
- The duct can be designed to take advantage of the Bernoulli effect to give greater high speed efficiency.
- For the same static thrust or lifting capability, a ducted fan has a smaller diameter than a standard propeller.

Figure 1. Overview of VTOL Vehicle Concept Designs
Source: Abstracted from Maisel, Giulianetti and Dugan (2000)

Vehicle categories can be analysed in terms of their hovering efficiencies. Tiltrotor and tiltwing vehicles have the highest hovering efficiencies amongst fixed-wing vehicles, with lift fan and direct lift propulsion vehicles falling behind (see Figure 2).

2. Methodology: Concepts Development and Selection

2.1 Concepts Development

The main objectives for the design of this UAV were that it be easy to control and stable through all flight phases, and that it meets the requirements of surveillance described in the Introduction.

A simple morphological table was created (see Table 1). Six aircraft design concepts were generated below.

Concept 1: Quad Tiltrotor - This aircraft design used four swivelling engines mounted on the wingtips in a quad tiltrotor configuration. The vehicle would theoretically have greater hovering performance but sacrifice horizontal flight performance.

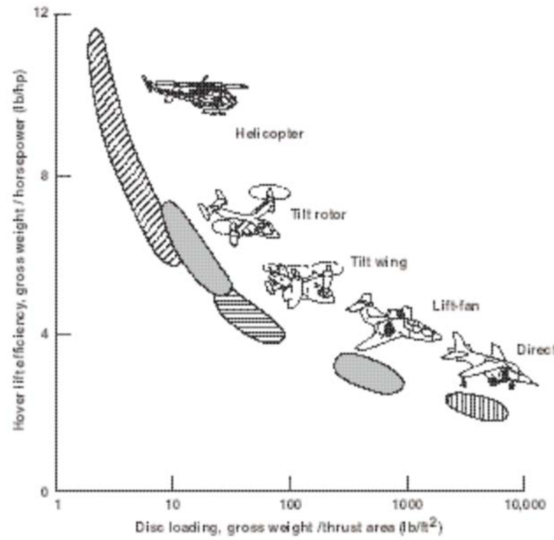


Figure 2. Comparison of Configuration Hover Efficiency

Concept 2: Dual Tiltrotor - This concept used two engines mounted on the wingtips in a dual tiltrotor configuration. To improve stability along the lateral axis, it featured a small pitch rotor mounted in the empennage. Compared to concept one this vehicle would have greater horizontal flight efficiency but have slightly lower vertical flight stability.

Concept 3: Quad Tiltwing - This design featured four engines in a tiltwing configuration. Tiltwing vehicles have superior horizontal flight efficiency compared to tiltrotors, but have slightly lower vertical flight capability. Winglets have been added to improve cruise efficiency. *Concept 4: Dual Tiltwing* - This concept vehicle uses two engines in a dual tiltwing configuration. The design had the highest theoretical horizontal flight efficiency, but the lowest vertical flight stability.

Concept 5: Quad Ducted Fan - This concept used four engines in a tiltrotor configuration. Ducted fans are more efficient than open propellers, and can lead to lower noise and higher efficiency.

Concept 6: Gydroyne - The design is a rotary wing vehicle. It would have the greatest hovering capability, and possess respectable horizontal capability.

2.2. Concept Selection and Pairwise Comparison

First, a list of required metrics was produced for concept comparison. These included: Mechanical Complexity, Software Complexity, Flight Stability, Hover Efficiency (Disc Loading), Hover Stability, Cruise Efficiency, Cruise Speed, Wing Area (Wing Loading), Durability, Reliability, Range, Portability, Agility, Ease of Maintenance, and Ease of Use. The metrics were then weighted per their relative importance using a pairwise comparison.

The six concepts were subsequently compared using a concept comparison table (see Table 2). The concept

Table 1. Morphological Table

Solutions	VTOL Type	Thrust producer	Number of Thrust Points	Tail Thruster	Structural Support Material
↓	Tiltrotor	Propeller	Four	Yes	Wood
	Tiltwing	Ducted Fan	Two	No	Carbon Fibre
	Gyrodyne	Rotor	One	-	Aluminium

Table 2. Concept Comparison Table

	Concept 1		Concept 2		Concept 3		Concept 4		Concept 5		Concept 6	
Metrics	**Values**	**%**	**Values**	**%**	**Values**	**%**	**Values**	**%**	**Values**	**%**	**Values**	**%**
Mechanical Complexity	2	0.01	1	0.00	3	0.01	2	0.01	2	0.01	1	0.00
Software Complexity	3	0.12	2	0.08	3	0.12	2	0.08	2	0.08	2	0.08
Cruise Speed	3	0.21	2	0.14	3	0.21	3	0.21	3	0.21	2	0.14
Range	1	0.09	2	0.18	2	0.18	3	0.26	2	0.18	2	0.18
Portability	2	0.03	2	0.03	2	0.03	2	0.03	2	0.03	3	0.04
Ease of Maintenance	3	0.15	3	0.15	3	0.15	3	0.15	3	0.15	3	0.15
Agility	3	0.24	3	0.24	3	0.24	3	0.24	3	0.24	3	0.24
Safety	2	0.23	3	0.35	2	0.23	3	0.35	3	0.35	2	0.23
Reliability	3	0.18	3	0.18	3	0.18	3	0.18	3	0.18	3	0.18
Wing Area (Wing loading)	3	0.12	2	0.08	3	0.12	2	0.08	2	0.08	3	0.12
Hover Efficiency (disc loading)	3	0.24	2	0.16	3	0.24	2	0.16	1	0.08	3	0.24
Hover stability	3	0.32	3	0.32	2	0.21	2	0.21	3	0.32	3	0.32
Cruise Efficiency	1	0.06	2	0.12	3	0.18	3	0.18	2	0.12	3	0.18
Durability	3	0.18	3	0.18	3	0.18	3	0.18	3	0.18	3	0.18
Ease of Use	3	0.40	3	0.40	3	0.40	3	0.40	3	0.40	3	0.40
Total:	38	2.57	36	2.60	41	2.68	39	2.71	37	2.59	39	2.68

with the highest final value of 2.71 was Concept 4, the single tiltwing. The concepts tied for 2nd and 3rd place were Concept 3 the double tiltwing, and Concept 6 the Gyrodyne. Due to the closeness of the highest scores (2.71 and 2.68), as well as the highly theoretical nature of the metrics and pairwise comparison, the three losing designs were eliminated from the selection process, and the top three concepts advanced to the next phase of concept selection.

2.3. Concept Flight Testing Comparison

Preliminary 3D models of the three concepts that performed best in initial Concept Selection were built and simulated in the Laminar Research X-Plane 10 simulation package. X-Plane uses Blade Element Theory to calculate flight dynamics, breaking the geometric shape of the aircraft down into several small components, running calculations on each section several times per second. As such, X-Plane is highly suitable for design work.

The X-Plane models were scaled so they would be capable of performing the tasks outlined in the Introduction, though the data from the planform can be scaled up or down in the software to simulate vehicles of different scales as long as Reynold's numbers, Froude numbers, and Mach numbers (in the case of compressible flow) are maintained. Tests do not completely cover all ranges of detail and similarity that full scale testing might accomplish. For example, a scale rigid model operating in a wind tunnel at full flight Mach numbers tested through a range of angles of attack will not totally portray the performance of the real full-size vehicle as this test model would not take inaccuracies such as elastic deformation into consideration. (Wolowicz and Bowman, 1979). If the scale model and full-scale model have sufficient similarity, accurate flight dynamics can be determined for one using the other.

The flight characteristics of the concepts were compared in the following phases of flight:

1) Stability and controllability during a hover
2) Ease of transition from vertical to horizontal flight
3) Stability and controllability during forward flight
4) Ease of transition from horizontal to vertical flight

The vehicles were tested in ideal atmospheric conditions. This was to obtain the raw characteristics of the vehicle without any atmospheric interference. Wind speed, precipitation, turbulence, and any other disruptive atmospheric effects were all disabled for this testing. The following parameters were consistent throughout all testing phases:

Table 3. Standard Testing Conditions

Ambient Temperature	Atmospheric Pressure	Starting Altitude	Hovering Altitude	Transitioning Altitude
31.99ºC	1.01bar (1 atm)	2.71m ASL	7-8.5m AGL	16-20m AGL

Wing and propulsion test parameters for each Concept are shown in Tables 4 and 5, respectively. Parameters were obtained through benchmarking and component data research. In some cases, engineering judgement was used to select suitable values.

Table 4. Wing Parameters Used

Parameter	Concept 3	Concept 4	Concept 6
Wing Semi length	1.29m (fore) 1.71m (aft)	1.71m (wings) 0.97m (V-Tail)	0.71m (stub wings)
RootChord	0.57m	0.57m (wings) 0.74m (V-Tail)	0.57m (stub wings)
Tip Chord	0.38m	0.38m (wings) 0.35m (V-Tail)	0.38m (stub wings)
Sweep	-9.0º (fore) 7.0º (aft)	7.0º (wings) 25º (V-Tail)	0º
Dihedral	0º	0º (wings) 45º (V-Tail)	0º
Long. Arm	0.92m (fore) 2.85m (aft)	1.80m (wings) 3.67m (V-Tail)	1.81m (stub wings)
Control Surface Deflection	20º		20º (vertical tail)
Control Surface Chord Ratio	0.3		0.3 (vertical tail)

Table 5. Performance Parameters Used

Parameter	Concept 3	Concept 4	Concept 6
Engine Power (each engine)	7.46KW (10hp)		
Engine RPM (Top of Green Arc)	1180rpm		510rpm
Engine RPM (Redline)	1950rpm		550rpm
Prop Mass Ratio to Solid Aluminium	0.3		
Prop Radius	0.5m	0.5m (engines) 0.21m (pitch rotor)	2.35m (rotor) 0.41m (other)
Prop Chord (Root/Tip)	0.11m/0.06m		0.21m/0.21m (rotor) 0.11m/0.06m (other)
Engine/Prop Gear Ratio	1.00	1.00 (engines) 0.25 (pitch rotor)	1.00 (rotor) 0.27 (other)

Each Concept UAV was tested thoroughly in hover (vertical) flight, horizontal flight and in transition between vertical and horizontal flight. For each of these phases, a detailed description of vehicle performance was recorded, and a score from 0 to 10 was assigned (with 10 being the best performance). Each UAV was tested three times in all phases and were re-analysed and re-scored each time. Analysis was repeated to ensure that the scores assigned were accurate and reasonable due to the subjective nature of this testing. The results of this testing are shown in Tables 6 and 7.

Despite having the highest score after pairwise comparison, Concept 4 has the weakest flight performance. Concept 3 emerged from the flight testing with the highest score and was selected for further development and analysis.

Table 6. Results of Subjective Flight Testing

	Hover Stability	Hover Controllability	Transition Stability	SLS	Average Score
Concept 3	9	8	8	9	8.5
Concept 4	6	6	5	10	6.75
Concept 6	5	9	9	7	7.5

SLS = Straight and Level Stability

3. Detailed Design

The strongest performer in the flight test, Concept 3, consists of four wings and engines in a tiltwing configuration. Winglets improve cruise efficiency. Transition from vertical flight to horizontal flight mode involves rotation of the entire wing with the engines mounted on them.

The design was refined with a variety of minor design improvements using the X-Plane simulator to achieve the optimal aerodynamic characteristics before detailed testing. Improvements were:

1) Selecting the most effective yaw control system. During hovering flight, the yaw stability and control of the vehicle could be achieved via two main methods: (a) Differential speeds of like-turning engines. These functions via increased thrust on clockwise engines paired with decreased anticlockwise thrust, using the resulting turning moment for yaw control; and (b) Control surfaces mounted in the airstream of the rear propellers. Extensive simulation testing of both configurations in X-Plane showed that using the flaps on the rear wing for yaw provided much faster and more accurate control response than relying on opposite engine torque.
2) The size and sweep angle of both the forward and rear wings were altered to balance mechanical feasibility (construction and internal supports) and aerodynamic characteristics. Initially the forward wing was swept forwards, but this sweep was

Table 7. Summary of Concept flight performance

Flight Characteristic	Concept 3	Concept 4	Concept 6
Hovering Performance	• Very stable, requires few control inputs, fairly quick response.	• Mixed performance, sluggish controls outside ground effect, very stable within.	• Very solid roll and pitch performance, but yaw stability is lacking nuance and response.
Vertical to Horizontal Stability	• Requires very apt inputs from pilot, but transition can be done easily.	• Slightly better than Concept 3, trimming is required for stability.	• Excellent transition performance with dead simple procedure.
Horizontal Flight Performance	• Very stable and easy to fly, minimal trim is needed to maintain stability.	• Incredibly stable, terrifically agile, banking produces minimal slip.	• Stable and responsive, but roll and pitch rates are fairly sluggish.

removed to reduce effects such as yaw instability and aero-elastic twisting of the wing. Reducing the sweep angle of the wings made them straighter and easier to manufacture.

3) The forewing was made 5% larger to adjust the centre of lift. This eliminated the requirement for slight up-pitch trimming for the UAV to remain in perfectly level flight without pilot input. Since the centre of mass cannot be moved in order without compromising hover stability, the centre of lift was instead shifted forwards. The selection of a 5% increase in wing area resulted from simulation-based experimentation with a range of areas (1%, 3%, 5% and 7%).

Throughout the design phase, the X-Plane simulator allowed for virtual experimental development that was akin to building several prototypes. Thus, the final initial design before testing was already been refined enough that most of the issues such as instability were resolved before a physical prototype was built. This is a big benefit of using a software prototyping approach.

The final specifications for the UAV are shown in Figure 3 and Figure 4. The model was to be accompanied by a physical demonstrator vehicle that was constructed using balsa wood. This concept was constructed in Blender 3D, a general 3D graphics software, then transferred to Solidworks to produce CAD drawings.

In order to determine the properties of these components, the aerodynamic forces experienced in flight had to be considered for accurate part selection. The following were calculated:

a) The estimated structural mass (using Mass = Density x Volume) was found to be 107g.
b) Vehicle performance characteristics using the eCalc RC calculator for Multicopters. From it, the estimated overall vehicle mass was 850g.
c) Vehicle performance characteristics using the eCalc RC calculator for Multicopters. From it, the estimated overall vehicle mass was 850g.

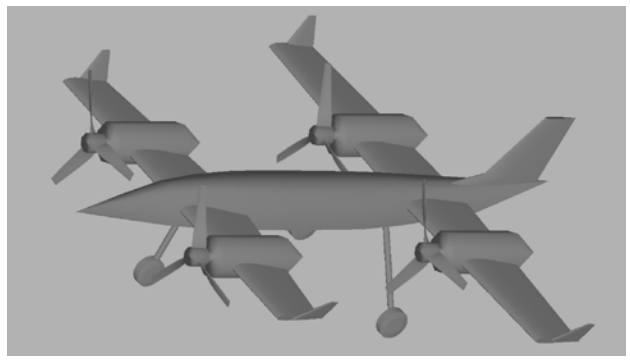
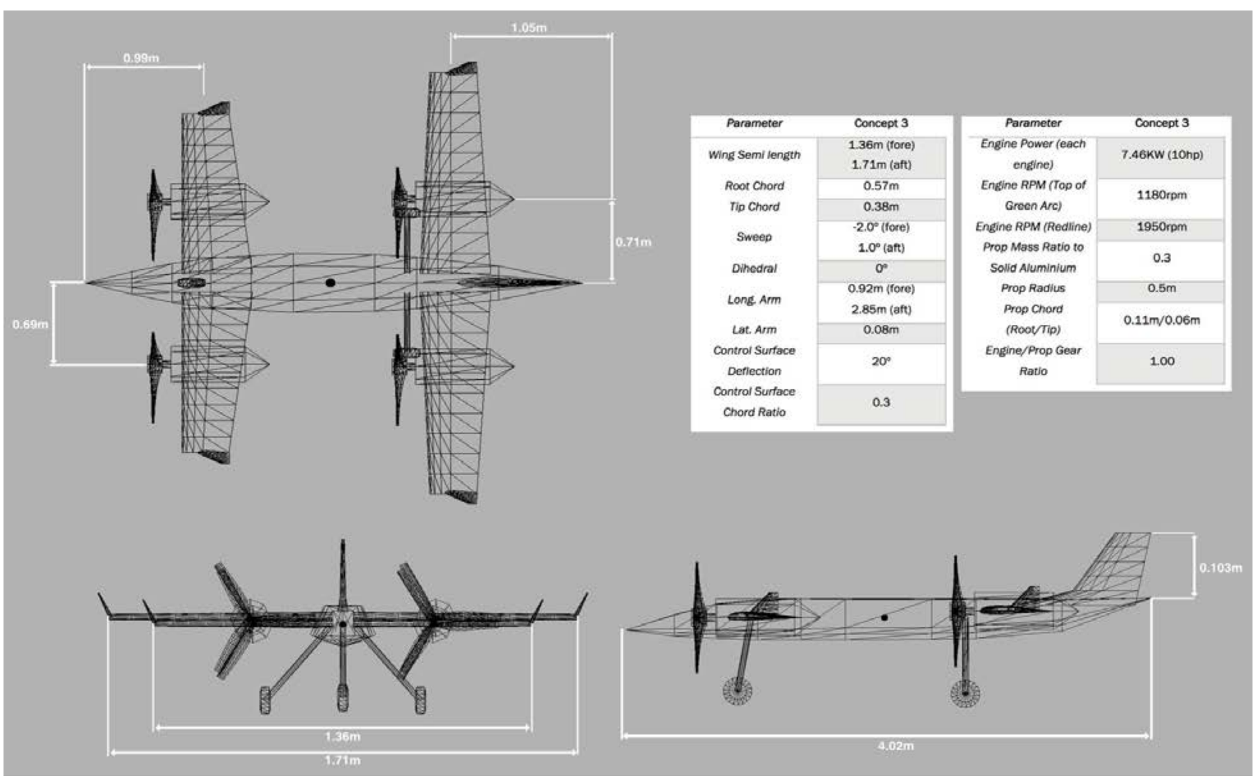


Figure 3. Overview of Final Design



Parameter	Concept 3
Wing Semi length	1.36m (fore) 1.71m (aft)
Root Chord	0.57m
Tip Chord	0.38m
Sweep	-2.0° (fore) 1.0° (aft)
Dihedral	0°
Long. Arm	0.92m (fore) 2.85m (aft)
Lat. Arm	0.08m
Control Surface Deflection	20°
Control Surface Chord Ratio	0.3

Parameter	Concept 3
Engine Power (each engine)	7.46KW (10hp)
Engine RPM (Top of Green Arc)	1180rpm
Engine RPM (Redline)	1950rpm
Prop Mass Ratio to Solid Aluminium	0.3
Prop Radius	0.5m
Prop Chord (Root/Tip)	0.11m/0.06m
Engine/Prop Gear Ratio	1.00

Figure 4. Final Design Specifications

d) Vehicle performance characteristics using the eCalc RC calculator for Multicopters. From it, the estimated overall vehicle mass was 850g.

e) The torqueing force experienced by the wings as they rotate through the airflow. This will allow appropriate servo sizing. Considering:

The force exerted on a flat plate (dynamic head) by moving air is given by:

$$P_D = ½ \rho V^2$$

where ρ is air density

The stall speed of an aircraft wing is determined by:

$$V_{stall} = \sqrt{\frac{2Wg}{2\rho S C_{Lmax}}}$$

Where S is wing area (m^2), C_{Lmax} is the coefficient of lift at stall (dimensionless), W is aircraft weight (kg), g is gravity, and ρ is air density (NASA, 2014).

The NACA 2412 airfoil was used for the vehicle. At 5º alpha, C_{Lmax} is 1.59 (obtained from X-Plane Simulator). Thus,

$$V_{stall} = \sqrt{\frac{2 \times 0.533 \times 9.81}{2 \times 1.205 \times 0.06171 \times 1.59}} = 8.40\ m/s$$

Flying just above the stall speed at 9m/s,

$$P_D = ½ \times 1.205 \times 9^2 = 48.80\ Pa$$

Thus:

$$F = 48.8 \times 0.06171 = 3.011\ N = 0.307\ kg$$

The wing when transitioning between flight phases can be approximated as a flat surface hinged at the point of the wing spar, with the motor mounted to the leading edge. Hence,

$$\sum CW = \text{UDL across 3.5cm}$$
$$= (0.307 \times 3.5) \times 3.5/2 = 1.88\ kgcm$$

and

$$\sum ACW = (0.307 \times 6.9) \times 6.9/2 + 0.05 \times 4.5 = 6.31\ kgcm$$

$\therefore$ net moment = 5.6 *kgcm* at 9 *m/s*

This then is the torque requirement of the servo motor required to drive the rotation of the tilt wings.

5. Presentation and Analysis of Simulation Results

Despite the existence of a physical prototype, all analysis was conducted using Laminar Research X-Plane. Simulation results were an excellent indication of the performance of the real vehicle, if it was correctly built. Given that the main objective of the UAV design is that it be easy to control and stable through all flight phases, including transitions, to fulfil surveillance requirements, these characteristics are tested throughout the analysis. Throughout all of these tests, environmental parameters from the initial concept selection phases were held constant (see Table 3). For all vertical flight tests, the vehicle was maintained in a stable hover at 8m AGL.

5.1 Vertical Take-Off and Hovering Flight Phase

In Vertical Flight, yaw control is achieved by control surfaces aligned in the vertical airflow, which generated differential wing lift that rotates the UAV about its Centre of Lift. The vehicle's yawing response was observed and measured.

When full yaw control inputs were applied, the vehicle's yawing response was observed and measured. Figure 5 compares the rudder control input to the yaw rotation rate, or yaw response. Yaw response with the benefit of the control surfaces is deemed to be acceptable. The UAV's angular velocity changed immediately when given an input, though acceleration was slow, taking 2.05s to reach peak velocity. This relatively slow response did not hinder flight performance during the leisurely stage of hovering.

Full pitch control inputs were applied. Figure 6 compares the pitch control input to the pitch rotation rate, or pitch response, which was much faster than the yaw response. It took approximately 1.3s to reach maximum pitch rate, or approximately 63% faster. This faster response was due to the greater torque produced by the differential engine thrust compared to the control surfaces, where the delta in power was significantly greater than the difference in torqueing force in yaw control. Figure 7 shows the Engine RPM response versus pitch response.

The roll response (Figure 8) was even faster than the pitch response, as it took approximately 0.8s to reach maximum roll rate, or approximately 62% faster than pitch. Roll response was faster than pitch response due to the roll axis having a much lower mass moment of rotational inertia than the pitch axis. Figure 9 compares the asymmetrical engine thrust produced by the left and right engine pairs (engine speed as the proxy) in order to generate the roll response. In vertical flight mode, roll is generated by differential thrust between the engines on the two sides. The control algorithm must ensure that the roll response is rapid, stable and predictable in this flight mode.

During lift force analysis, the vehicle did not leave the ground until thrust reached a sufficient level. Then, it accelerated exponentially as it gained altitude. The wing lift generated increased nearly linearly as thrust increased. Based on the data from these tests, the vehicle concept demonstrates acceptable controllability and precision in a hover.

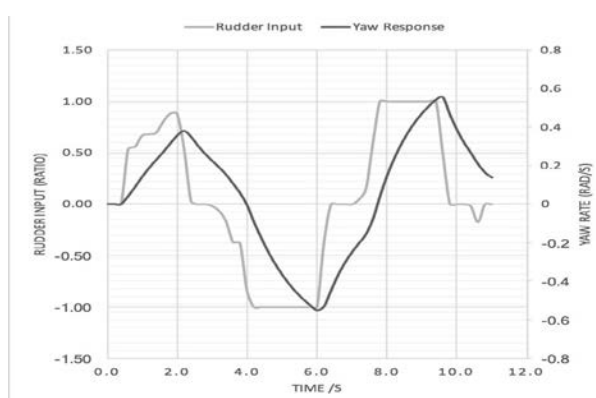


Figure 5. Yaw Response Graph

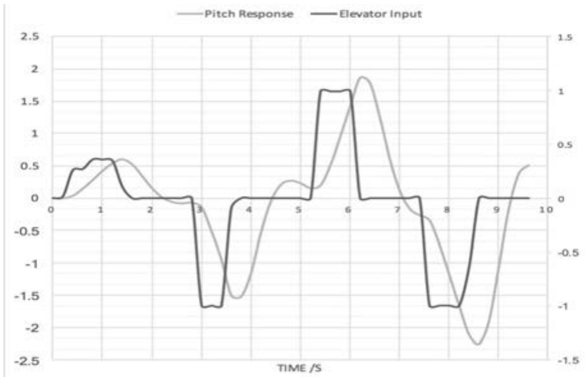


Figure 6. Hovering Pitch Response Graph

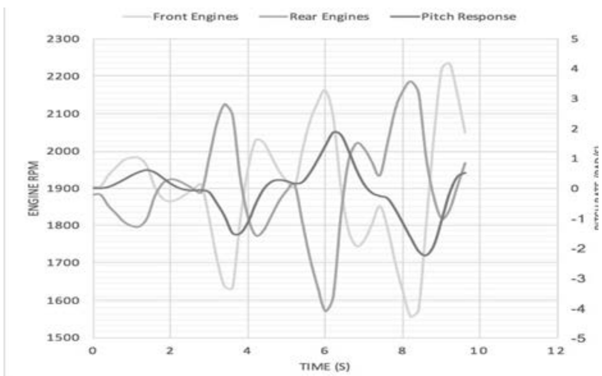


Figure 7. Engine RPM versus Pitch Response Graph

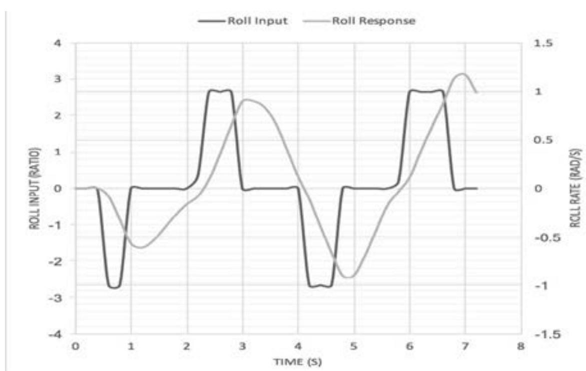


Figure 8. Hovering Roll Response Graph

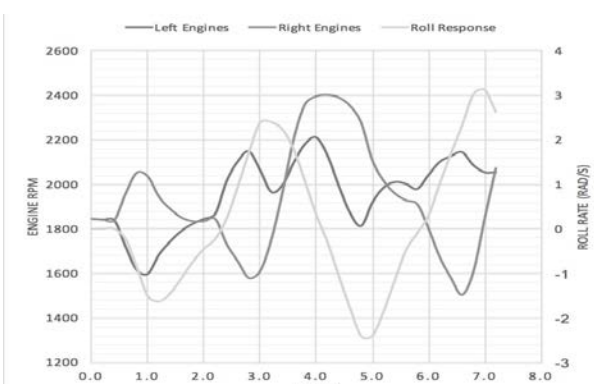


Figure 9. Engine RPM versus Roll Response Graph

5.2 Transition from Vertical to Horizontal Flight

This transition phase involves the vehicle's wings rotating from a vertical position to a horizontal position to move from vertical/hovering flight, to horizontal/ wing-borne flight. Both wings rotate simultaneously, and move at 15 degrees per second, completing the rotation in 6 seconds. These rates were derived from the X-Plane knowledge base for VTOL rotations.

It is important that the vehicle was not unstable, and that the pilot does not lose control during the transition phase. For this test, the simulation vehicle was placed in a hover, and the transition phase was initiated. As the vehicle's wings rotated, the vehicle accelerated, and the wings gradually began to generate lift. However, the vehicle may have pitched upwards or downwards as its various surfaces accelerated in the airflow. Pilot elevator input was required to keep the aircraft straight and level.

This test observed the natural stability of the vehicle during this transition phase, meaning it assessed the degree of pilot input needed to maintain straight and level flight. It can be seen from all the graphs (which were obtained from the same test) that a moderate elevator input was required to compensate for varying aircraft pitch and wing lift during the transition. Very little corrective input was needed until the wings reached a 60 degree change from the vertical, where large downward pitch is needed to correct the vehicle's tendency to pitch upwards. However, this pitching effect was not significant enough that vehicle control became difficult or challenging.

5.3 Straight and Level Flight

From straight and level flight at 30 m above ground level and 180 km/h airspeed, the vehicle was rolled, pitched, and yawed with maximum control inputs in each direction. The control responses in the three axes were observed and recorded.

Roll response is extremely fast and accurate, with minimal overshoot. The vehicle is very agile in this axis. The pitch response is slightly more sluggish, and the response gradually tapers as opposed to rapidly changing (see Figure 10). The reason for this is differing mass moments of inertia between the axes. The yaw response, however, was very interesting (see Figure 11). Once a control input is given, the vehicle responded almost immediately but it snapped back in the other direction in an oscillatory manner. This situation was a case of positive dynamic stability. This occurred because the vertical tail entered the airflow at an angle relative to the airflow, which caused it to generate a lifting force that torqued the aircraft in the direction opposite to the yaw, producing a damped oscillation. This characteristic requires further tuning to ensure it becomes sufficiently stable.

Aerodynamic stability of the UAV was explored using two methods. Firstly, it was banked up to 30º left and right, and the sideslip characteristics were observed and recorded. Secondly, from straight and level flight, the UAV was pitched upwards and downwards with full elevator control input.

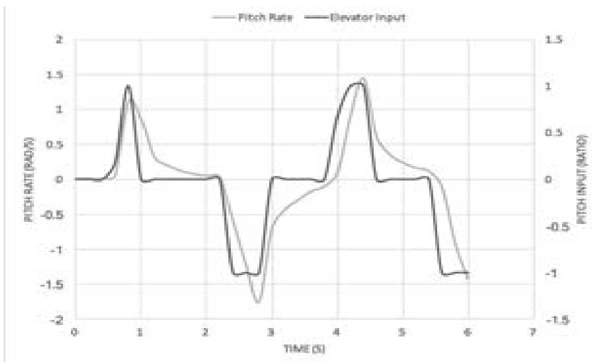


Figure 10. Horizontal Pitch Response

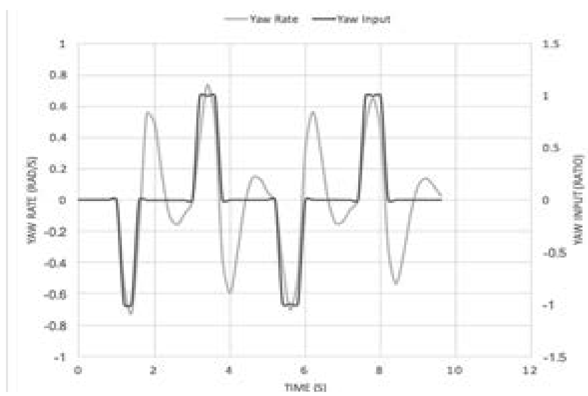


Figure 11. Horizontal Yaw Response

Slip is a phenomenon whereby the axis of an aircraft is misaligned with its trajectory. High slip during indicates aerodynamically inefficiency and reduces lift-to-drag ratio, adding drag without increasing lift. An aircraft flying with a slip is in uncoordinated flight. The vehicle was tested in banking turns: as the vehicle banks up to ±30º, the slip reaches a maximum of 3º (see Figure 12). Slip above 10º is considered excessive, but this slip angle is acceptable.

Angle of Attack (AOA) refers to the angle between the aircraft's pitch and its actual flight path. A low AOA during manoeuvring indicates efficient flight, as the lift-to-drag ratio remains low, and good manoeuvrability as the aircraft is capable of changing trajectory at the desired rate, as opposed to drifting and lagging behind. As vehicle pitch rate increased, AOA also increased in an almost 1:1 fashion (see Figure 13).

The UAV did drift initially, but rapidly recovered. When the vehicle was initially pitched upwards, AOA spiked, but it rapidly settled to near zero within 2-3 seconds. This response shows minimal amounts of drifting and thus very efficient pitch manoeuvrability. This pitch efficiency is due to the vehicle's tandem wing arrangement. As the vehicle pitched and AOA changes, both wings experienced a change in lift. This is a characteristic of all airfoils, where higher AOA generates greater lift up to an angle of about 10º. The rear wing thus either increases or decreases in lift asymmetrically to the fore wing due to its larger size and produces a torqueing effect to point the vehicle into the airflow.

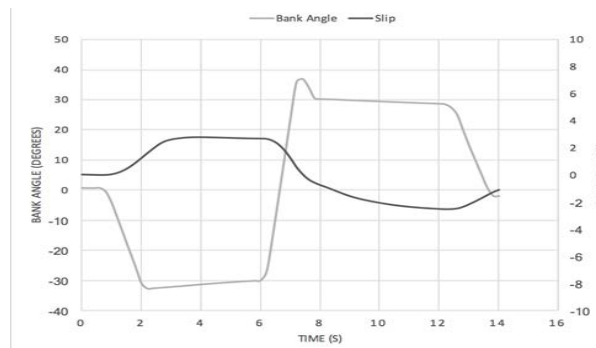


Figure 12. Slip During Banking Turn

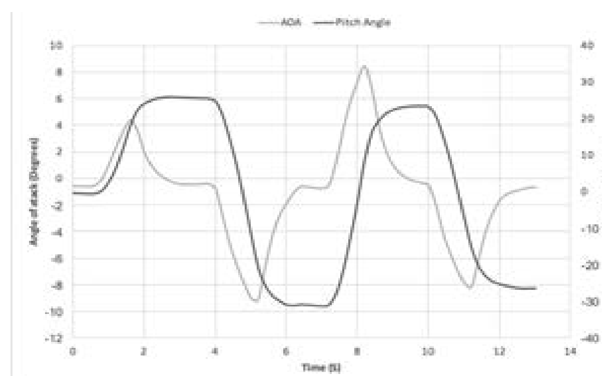


Figure 13. AOA vs Pitch Angle

5.4 From Horizontal to Vertical Flight

This transition was the inverse of the previous transition analysed and involved the vehicle's wings rotating from a horizontal position to a vertical position to shift from horizontal flight, to hovering flight. As before, both wings rotated simultaneously at 15º per second.

As before, to assess stability, the simulation vehicle started from stable horizontal flight, and the transition was initiated. As the vehicle's wings rotated, it began to decelerate, and the wing lift decreased as the engines took over. It is immediately noticeable that this transition (in Figure 14 through Figure 17) is less stable than the Vertical to Horizontal transition. The UAV oscillates and adept pilot input was needed to keep it level. This instability was due to the wing interacting with the bulk airflow.

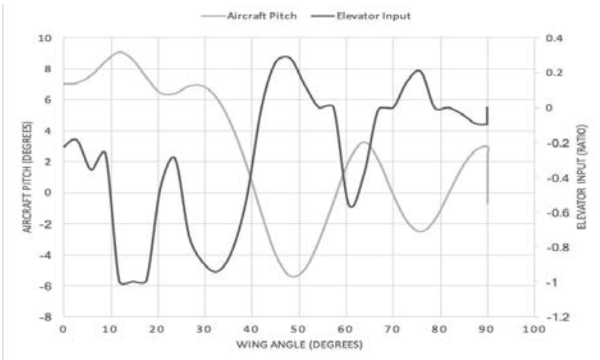


Figure 14. 2nd Transition Natural Stability wrt Wing Angle

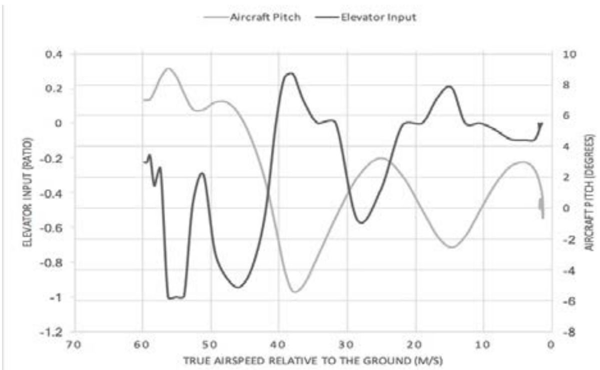


Figure 15. 2nd Transition Natural Stability wrt Airspeed

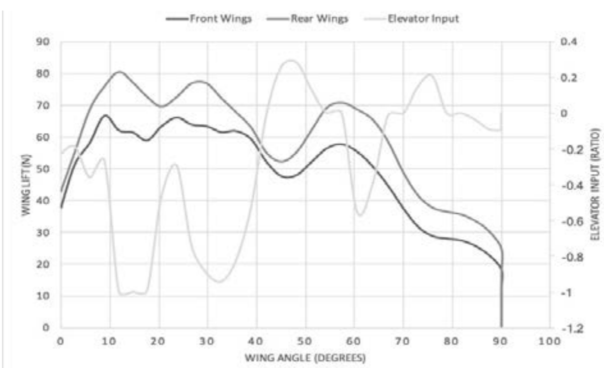


Figure 16. 2nd Transition Lift Forces wrt Wing Angle

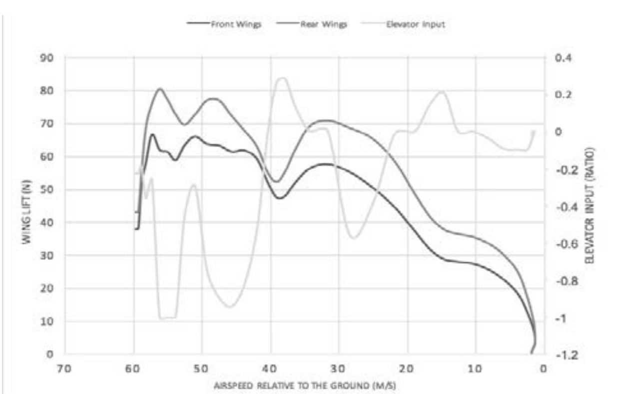


Figure 17. 2nd Transition Lift Forces wrt Airspeed

As the wing rotated vertically and began to stall, it essentially became a flat plate moving perpendicularly through air. This caused the vehicle to slow down rapidly to a hover, but it generated turbulent vortices which cause pitch instability. Analysing the wing in a virtual wind tunnel, the below images help to illustrate these phenomenon (see Figure 18).

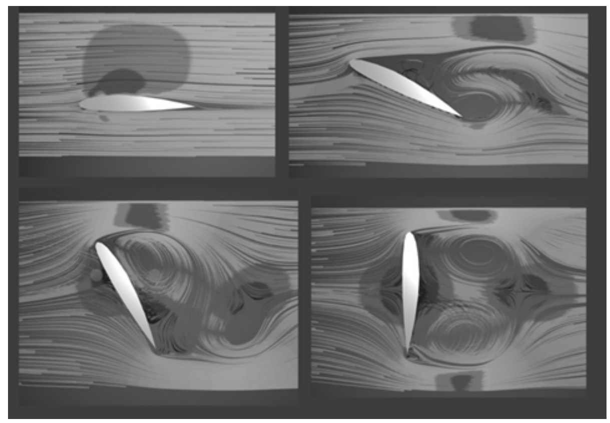


Figure 18. Turbulence Generated During 2nd Transition Phase

The Horizontal to Vertical Flight transition phase could be improved by modifying the wing design so that only a segment of it rotates, or reducing the overall wing area, thereby reducing the area forming turbulent air; rotating the wing more slowly, or in steps to dilute the effects of instability; or rotating the wings at different rates to modify the effects of the vortices along the vehicle. With more time, these options could be investigated in the simulation environment.

5.4 Summary of Analysis

With all four phases of flight being analysed, we can come to the following conclusions:

For Hovering Flight, the UAV control responses are slightly delayed, but acceptable. The asymmetrical mass moment of inertias between the pitch and roll axis result in both having differing responses, different to a typical quadcopter.

For the Vertical to Horizontal Flight Transition, the UAV requires some control input, but it is not so much that the transition becomes difficult or challenging. Low required control input means less work for a pilot or an automated transitioning system.

For Straight and Level Flight, the UAV demonstrates excellent pitch and roll response characteristics. When yawed sharply the UAV enters a damped dynamic oscillation. Slip and AOA are within acceptable rates for aircraft, and the vehicle is aerodynamically efficient in flight.

For the Horizontal to Vertical Flight Transition, the UAV requires some complex control inputs to counteract the tendency to naturally pitch around on its own. This pitching is due to the wing rotating vertically in the airflow and producing an unstable mass of vortices which cause unstable wing airflow. Design modifications could be explored to correct this.

6. Conclusion

This paper has reported on the use of simulation tools to accelerate the design and virtual testing of a novel UAV concept as an undergraduate student project. It demonstrates the usefulness of knowledge-based tools to accelerate the concept design process, and to produce a much more optimised final product. Further detailed design and developments are required, including validation of simulation results, but a relatively robust and well-tested design of a complex system has already been developed with minimal financial cost and without physical testing. That this was done by an undergraduate engineer as his final year project is a showcase for the potential democratisation of design processes by using software-based tools to greatly speed up the prototyping and design process.

The UAV developed and analysed in this paper performs satisfactorily in all phases of flight in still air, and the overall performance accomplishes the goals set out initially. The vehicle is stable and easy to control in three of the four flight phases, with the fourth phase being of a more moderate stability. Future work includes testing in non-stable air; validation of the simulation results using a physical prototype in a wind tunnel; and further refinement of the design solution, particularly the Horizontal to Vertical flight transition.

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■

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