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The Industrial Engineering and Management Journal, IEMJ (ISSN 3006-810X) is an international journal published twice yearly by The Society of Caribbean Industrial Engineers (SCIE). The journal aims at contributing to the development of viable engineering skills, techniques, management practices and strategies relating to improving the performance of enterprises, community, and the quality of life of human beings at large. Built upon the industrial engineering and management domain, IEMJ positions itself to the Caribbean development by identifying and supporting emerging research areas and promoting engineering profession and practices and associated disciplines of 1) mechanical and manufacturing, 2) chemical, 3) electrical and computer, 4) civil and environmental, and 5) geomatics engineering and land management, as well as their applications in the region.

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Editorial

On behalf of the Editorial Board, we are writing this message to present Volume 2, Number 2 of *The Industrial Engineering and Management Journal* (IEMJ). This issue features four (4) scientific/technical papers. The relevance and usefulness of respective articles are summarised below.

A sustainable social development project was defined as a temporary endeavour that is designed and undertaken to improve the well-being and quality of life of individuals and communities by addressing social and economic inequalities and promoting social inclusion. In the first article, **G. Ambrose**, "Exploring the Use of Agile Project Management Methodologies in Sustainable Development Social Projects", reviewed themes related to project management methodology, agile project management and project success. From literature, there is a positive relationship between project management (PM) methodology and project success. Projects undertaken with an agile approach tend to show higher rates of success. This paves a need for more research into the use of agile methodologies and measuring their impact on success of sustainable development social projects. Future work would expand the investigations on how to strengthen the relationship between PM methodologies (particularly agile) and project success. It would focus on the agile applicability in sustainable development social projects and explore how they would align with the national development projects to the Sustainable Development Goals (SDGs) in Trinidad and Tobago (T&T) and the wider Caribbean region.

S. Jaggernath-Furlonge and **K.F. Pun,** "A Review of Organisational Resilience Models for Revitalising Manufacturing Resilience and Adaptability", investigated into the dimensions of Organisational Resilience (OR) dominating the field of study, and used a multi-dimensional Resilient Organisations (RO) paradigm to facilitate the analysis. Three dimensions of Organisational Resilience (OR) have been identified dominating the field of study. One dimension being phases of organisational resilience, namely, anticipation (before the adversity), adaptive (during the adversity), and adaptation (after the adversity) and their respective factors. The other two dimensions refer to the resilient levels and the social perspectives. Twelve emerging OR frameworks/models advocated in literature were chosen with their strengths and weaknesses addressed. Results showed that these frameworks/models could be grouped under (3) categories of 'not multidimensional', 'multi-dimension to some extent', and 'conceptual and applied to organisations'. The analysis points to a quest for a cohesive RO model that could borrow the strengths of the existing models. Future work would determine the key components of the cohesive model and validate the applicability of the model empirically for guiding manufacturers towards revitalising resilience and adaptability.

K.N. Hassanali and **K.F. Pun**, "A Lean Productivity Framework for Guiding Capital Project Executions in Industrial Firms", explored lean principles that could improve project productivity towards the effective management of delays. Recent studies suggested that many lean productivity (LP) factors contribute toward this agenda. Amongst these factors are 1) a standardised workforce, 2) an optimised site, 3) reliable supply chains, 4) standard work schedules, and 5) people motivation. A recent 2021 study on LP was undertaken across various industrial sectors in Trinidad and Tobago (T&T). Empirical data showed a significant relationship between each LP factor and project delay. A generic lean productivity framework was proposed incorporating LP factors into the planning and execution phases of capital investment projects. The framework sheds light on the LP issues and its adoption would help industrial firms with PM practices and facilitate the attainment of benefits (human, social, economic, and environmental) from the delivery of their capital projects.

In their article, "The Use of Cloud Optical Depth in the Assessment of Solar Resource Potential in the Lower Caribbean Region", **N. Ramsamooj, J. Davis** and **G. Latchman**, proposed a computational method to assess the solar resource potential in the lower Caribbean region. This method uses a novel combination of remotely sensed high-resolution cloud optical depth data and terrain shadowing effects. Clear-sky and all-sky irradiance components are determined from air pressure, precipitable water, aerosol optical depth, Angstrom exponent, and cloud optical depth data. The method was used to determine solar maps for Trinidad and Tobago, which has few ground irradiance measurements. Solar maps for the year 2021 were produced using weekly averaged data to reduce computation time. Case studies of photovoltaic energy potential were conducted at seven locations within T&T. The predicted photovoltaic energy potentials had percentage differences between 2.5% and 15.5% when compared to corresponding values from the Global Solar Atlas. The solar forecasts presented have wide applicability because they can be utilised across different locations owing to the wide-spread availability and open-source nature of the required datasets.

On behalf of the Editorial Office, we gratefully acknowledge all authors who have made this issue possible with their research work. 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. Moreover, 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 practicing engineers and professionals from industry and other organisations as

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We hope you will enjoy reading this issue, and that you find the articles useful to stimulate your research into the vibrant areas of Industrial Engineering and Management (IEM). We invite you to submit your research work and papers for publication in our coming issues.

KIT FAI PUN, *Editor-in-Chief*
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Exploring the Use of Agile Project Management Methodologies in Sustainable Development Social Projects

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Abstract: *A sustainable social development project was defined as a temporary endeavour that is designed and undertaken to improve the well-being and quality of life of individuals and communities by addressing social and economic inequalities and promoting social inclusion. "Can an Agile project management methodology be used in a sustainable development social project and what would be the impact of doing this in a SIDS?" This paper reviews literature pertaining to the use of agile project management methodologies in sustainable development social projects. It explores themes related to project management methodology, agile project management and project success. From literature, there is a positive relationship between project management methodology and project success. Projects undertaken with an agile approach tend to show higher rates of success. This paves a need for more research into the use of agile methodologies and measuring their impact on success of sustainable development social projects.*

Keywords: *Project Success; Project Management Methodologies; Sustainable Development; Agile Project Management; SIDS*

1. Introduction

Sustainable development social projects are defined as social projects whose goals can be aligned with the Sustainable Development Goals (SDGs) of the United Nations within the context of a Small Island Developing State (SIDS) such as Trinidad and Tobago.

In 2000, the member countries of the United Nations (UN) committed to the implementation of Millennium Development Goals (MDGs) which involved a global effort to eradicate poverty. In 2012, at the UN Conference on Sustainable Development in Rio De Janeiro, the SDGs were developed to replace the MDGs. This move was done to continue the excellent work resulting from the MDGs which included "reducing income poverty, providing much needed access to water and sanitation, driving down child mortality, drastically improving maternal health, and making huge strides in combatting HIV/AIDS and other treatable diseases such as malaria and tuberculosis" (UNDP, 2015). These SDGs are accomplished through several projects often facilitated by UN funding or from other multinational financing organisations. Attaining these goals can be tied to the success of the projects used to implement the changes these goals seek to realise.

Over the years, project management (PM) has been marred by the high percentage of failed projects costing billions of dollars (PMI, 2018). Traditionally, PM approaches use a more predictive (or plan based) approach to project work where bulk of the project planning is done upfront and then the work executed sequentially (Serrador and Pinto, 2015). However, project work can range from very definable work which can be easily planned upfront to high-uncertainty work which constantly changes and requires frequent adaptations (PMI, 2017a).

Agile project management is a broad term for PM approaches using the principles of the Agile Manifesto that is organised around four (4) key values and twelve (12) principles which focus on the value that projects create for stakeholders (Agile Alliance, 2001). Agile approach emphasises self-organising teams, continuous planning, rapid releases, customer collaboration, responding to change and value driven delivery (Crowe, 2016).

Agile PM methodologies can be adopted in projects where the work is highly unpredictable, and constraints are rapidly changing. Limited empirical work has been conducted into agile suitability in various areas (Serrador and Pinto, 2015). This paper reviews literature on PM methodologies in the context of agility and sustainable development social projects.

2. PM Methodologies and Project Success

The Great Pyramids of Giza, the Panama Canal, Apollo 11, the iPhone, and the latest mobile game may all seem different however one commonality is that they can all be classified as projects. Though PM as a discipline has only in recent times gained a surge in popularity, projects have been used in some form or the other since ancient times. In modern times many organisations utilise projects to achieve strategic objectives (Meredith et al., 2009) which has further strengthened the need for PM as the success (or lack thereof) of projects frequently draws a lot of stakeholder attention.

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ISO 10006: 2003 defines a project as a "unique process, consisting of a set of coordinated and controlled activities with start and finish dates, undertaken to achieve an objective conforming to specific requirements, including the constraints of time, cost and resources." (ISO, 2003). According to Project Management Institute (PMI, 2017a), a project is "a temporary endeavour undertaken to create a unique product, service, or result." The PMI uses the term "endeavour" to describe a project alludes to a process or processes which are intentionally done to achieve a goal. Projects therefore do not just "happen" but are planned, decided upon, and then executed preferably using some form of management. By defining projects as temporary the PMI's definition correlates to that of ISO 10006: 2003, as temporary indicates that projects have a defined beginning (start date) and end (date). Table 1 depicts the description characteristics used to define a project.

Table 1. Project Description Characteristics between PMI's PMBOK Guide and ISO 10006: 2003

PMI's PMBOK Guide	ISO 10006: 2003
Endeavour	Unique process
Temporary	Start and finish dates
Undertaken to create unique product, service or result	Undertaken to achieve an objective

Both the PMI and ISO 10006: 2003 highlight the importance of projects producing a deliverable or achieving an objective which should satisfy certain requirements or criteria. The achievement or failure to achieve this deliverable or objective would affect the project's success within certain constraints. The key benefit projects provide to organisations is that they enable organisations to move from their present state to a future desired state which provides greater business value to the organisation over time. Projects provide many benefits to organisations including satisfying statutory requirements; creating/improving/fixing products, processes, and services; implementing business improvements; and satisfying stakeholder/shareholder requests and requirements. Figure 1 illustrates the organisational transitions via projects.

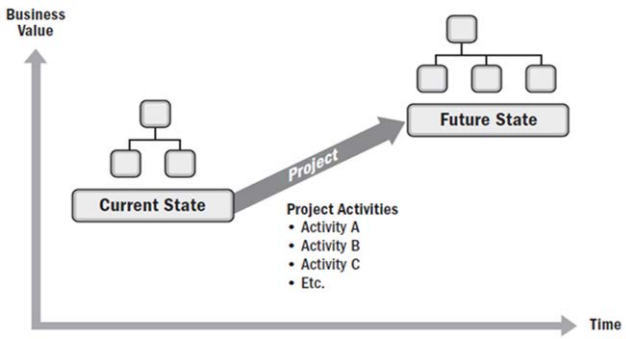

Figure 1. Organisational Transitions via Projects
Source: PMI (2017a)

Projects would go through some form of selection process. To achieve the desired results, there must be some form of management of the many activities and processes. This is where the science of PM comes into focus. As the global environment becomes more integrated and competitive in the 21st century, organisations will utilise projects more to not only remain relevant but to gain competitive advantages (KPMG, 2013).

3. PM Processes and Lifecycle

According to the Project Management Institute (PMI), PM is defined as "the application of knowledge, skills, tools, and techniques to project activities to meet the project requirements." (PMI, 2017a). Whereas ISO 21500: 2012 defines PM as "the application of methods, tools, techniques, and competencies to a project (ISO, 2012).

PM provides many benefits to individuals and organisations when effectively applied. PMI identifies some of these including "meeting business objectives; ensuring the project benefits are realised to stakeholders; managing the project constraints (scope, quality, schedule, costs, and resources); and managing project risks". Kerzner (2013) also advocates the PM benefits as "Identification of functional responsibilities to ensure that all activities are accounted for, regardless of personnel turnover; measurement of accomplishment against plans; improved estimating capability for future planning; and knowing when objectives cannot be met or will be exceeded".

To achieve the PM goals and specific project objectives, there are several processes which can be grouped. According to PMI (2017b), there are five main process groups, namely:

1. *Initiating* – Project or phase definition.
2. *Planning* – Establishing scope and objectives.
3. *Executing* – Performing the actual work to achieve the objectives.
4. *Monitoring and Controlling* – Tracking, reviewing and regulation of project performance.
5. *Closing* – Finalisation of the project or phase.

The primary focus to achieve the desired PM objectives via managing these processes and associated activities, but not necessarily the project itself. Munns and Bjeirmi (1996) identified the difference between the project and PM in terms of the life span of their deliverables where they identify the project's deliverable(s) as being of a long-term nature than the deliverable of the PM itself. For instance, a new bridge or computer software typically has a long lifespan. Whereas the deliverable(s) of PM have a short lifespan and are focused primarily on-time delivery, within budget expenditure and appropriate performance standards of the project.

The PM lifecycle can be viewed as a subset of the project's lifecycle, such that even project success and

PM success can also differ (Cooke-Davies, 2002). Figure 2 depicts the scope of project success. PM success can be different from project success. Research has shown that the application of PM has improved project success.

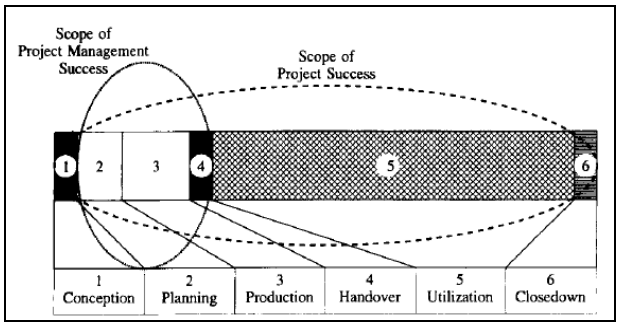

Figure 2. The Scope of Project Success
Source: Munns and Bjeirmi (1996)

The Standish Group published the "CHAOS Report" that describes the state of project success by identifying where a high rate or project failure or a low percentage of successful projects. Attarzadeh and Ow (2008) reviewed information from the report showing a reduction trend in project failure rates in Table 2.

Table 2. CHAOS Report - Project Success, Challenge, Failure Rate Comparisons

	1994	**1996**	**1998**	**2000**	**2002**
Succeeded	16%	27%	26%	28%	34%
Challenged	53%	33%	46%	49%	51%
Failed	31%	40%	28%	23%	15%

Source: Attarzadeh and Ow (2008)

According to a survey undertaken by KPMG along with Australian Institute of Project Management (AIPM) and International Project Management Association (IPMA) in 2019, it was reported that "19 percent of organisations deliver successful projects, at least most of the time and 44 percent of organisations are likely to deliver projects that meet original goal and business intent." (KPMG, 2019). The has been an increasing use of PM methodologies within organisations which have contributed towards increased project success rates. The report shows an increase in the use of agile PM delivery approaches from 24% in 2018 to 47% in 2019. It is to note that as project success can be defined from many different perspectives, clarification of the definition of project success is therefore vital for an accurate conclusion to be made about the effect of PM on project success.

4. PM Approaches and Agile methodologies

Project success can be measured against the overall project objectives whereas PM success can be measured against cost, time, and quality (de Wit 1988). Baccarini (1999) asserts that success encapsulates both project success and PM success. Project success is focused on goals and purpose whereas PM success is focused on inputs and outputs. Success criteria (as related to the project success measures) vary with the success factors (as related to the inputs to the PM system or approach used during the project lifecycle). Cooke-Davies (2002) asserts that the distinction between project success and PM success is thus important as this helps to distinguish between success criteria and the success factors.

Given the unique nature of projects, most projects will have different success criteria as each project is initiated to meet some specific purpose. However, the management of the project using various PM approaches are not as unique as the projects themselves which would identify how the differences in approaches affect various types of projects.

Moreover, the PM lifecycle is a subset of the project lifecycle which covers the entire scope of the project's success. According to PMI (2017b), there are four (4) types of project lifecycles, namely:

1. Predictive
2. Iterative
3. Incremental
4. Agile

The differences hinge upon the way in which the project requirements are developed, the activities are performed, the deliverables are produced, and the project's goals are managed. Different project lifecycles would require different PM approaches. For instance, predictive lifecycles use a traditional approach where the deliverables occur at the end of the PM process. This is thus applicable when the project has stable requirements.

Iterative lifecycles, incremental and agile lifecycles, however, are more applicable when the project has fewer stable requirements as they allow for more changes to be incorporated into the PM process. This approach to embracing change enables the PM process to have a higher probability of success in terms of achieving the PM objectives especially in changing environments.

By accommodating changes throughout the project lifecycle iterative, incremental, and agile approaches help to better manage scope creep, ensuring that the project scope is delivered to stakeholder requirements within constraints of time, cost, and quality (Goodpasture, 2015). Figure 3 shows a comparison between the predictive, iterative, and incremental lifecycles according to PMI's Agile Practice Guide.

Agile approaches incorporate elements of both the iterative and incremental approaches. This flexibility along with the ever-increasing adoption (PMI, 2017b) of hybrid agile approaches presents an opportunity for research into the applicability of using agile approaches in various PM environments even those where agile is not traditionally applied. Agile PM methodologies would suit projects where the work is unpredictable or where constraints are changing. This, however, does not mean that agile or a hybrid-agile PM approach cannot be used

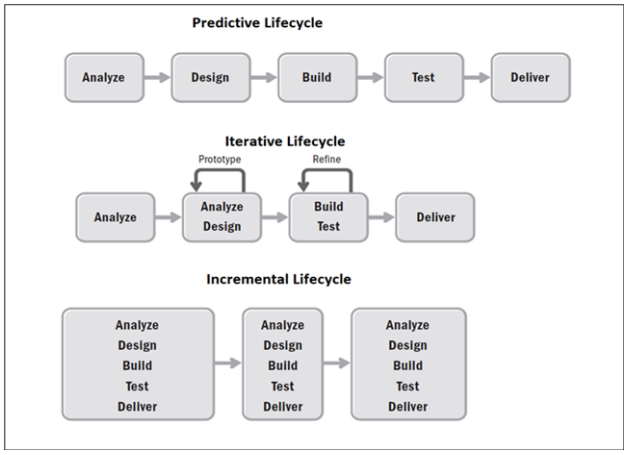

Figure 3. Comparison of Project Lifecycles
Source: PMI (2017b)

for traditional projects.

In their 2019 project management survey, KPMG, IPMA and AIPM have identified that use of agile approaches is becoming more widespread (KPMG, 2019). As more organisations are adopting an agile approach, there appears to be a correlation with the increasing rate of PM success, and particularly in many IT-driven and sustainable development social projects.

5. Social Development and SDGs

Social development is a multifaceted topic which can be difficult to define in simple terms. Aspalter (2006) proposes that social development covers areas such as health, education, hygienic standards, and access to safe sources of water, among others. Midgley (1995, 25) defines social development as “a process of social change designed to promote the well-being of the population as a whole in conjunction with a dynamic process of economic development”.

According to the United Nations (UN), sustainable social development refers to "the process of creating an environment that promotes the well-being of people, by enabling them to exercise their civil, political, economic, social, and cultural rights, and to access essential goods and services, such as food, shelter, health care, education, and clean water and sanitation, while ensuring that the natural resource base is managed in a way that meets the needs of present and future generations" (United Nations, 2023a, 2023b).

Sustainable social development is closely linked to the concept of sustainable development, which involves balancing economic, social, and environmental considerations to ensure that development is equitable and meets the needs of the present without compromising the ability of future generations to meet their own needs. In this regard, key pillars of social development have been identified. These include:

1. Promoting social inclusion and reducing social and economic inequalities,
2. Strengthening social protection systems,
3. Enhancing social cohesion and reducing conflict,
4. Promoting gender equality and women's empowerment, and
5. Strengthening the role of civil society and community-based organisations.

These pillars are reflected in the UN's SDGs which are adopted in 2015 as part of the 2030 Agenda for Sustainable Development (UNDP, 2015). A total of 17 SDGs is listed below:

1. No Poverty
2. Zero Hunger
3. Good Health and Well-being
4. Quality Education
5. Gender Equality
6. Clean Water and Sanitation
7. Affordable and Clean Energy
8. Decent Work and Economic Growth
9. Industry, Innovation, and Infrastructure
10. Reduced Inequalities
11. Sustainable Cities and Communities
12. Responsible Consumption and Production
13. Climate Action
14. Life below Water
15. Life on Land
16. Peace, Justice, and Strong Institutions
17. Partnerships for the Goals

These SDGs are interconnected and progress in one area can have positive impacts on other areas. They are meant to be integrated, indivisible and transformative and they are intended to bring about fundamental changes in the way that societies operate to create a more sustainable and equitable future (UNDP, 2015). There are a total of 232 indicators for the 17 SDGs, which are organised into three categories: core, additional, and supplementary. The core indicators are used to measure progress towards achieving individual goals at the global, regional, and national levels, and are used to measure progress in different sectors, such as education, health, and the environment. They are also used to track progress in different population groups, such as women, children, and vulnerable or disadvantaged groups. The additional indicators would provide more detailed information and measure progress in specific areas or sectors, while the supplementary indicators provide additional context and information that could help to understand progress.

Countries which have pledged to completing the SDGs including Small Island Developing States (SIDS) also measure their implementation progress through the monitoring and evaluation of projects related to the SDGs or sustainable development social projects. To measure progress towards SDGs, data is collected from a variety of sources, including national statistics, household surveys, and other data sources. The data is analysed and used to calculate the values for the indicators, which are then used to track progress towards

achieving individual goals. The results of the analysis are reported in the form of progress reports, which are published periodically to provide updates on the status of the SDGs.

6. Social Development Projects and Agility

Many social development projects are often implemented by governments, non-governmental organisations (NGOs), or community-based organisations, and they can be funded by a variety of sources, including government agencies, international organisations, and philanthropic foundations. The goal of social development projects is to create positive, lasting change in the lives of individuals and communities by addressing the root causes of social and economic inequalities and promoting social inclusion and cohesion.

Agile PM can be used for the design and delivery of social development projects. Adopting agility can help these projects with more responsive to changing needs and to deliver value to the communities that could achieve lasting, sustainable results. The use of agile PM emphasises flexibility, collaboration, and adaptability, which are important considerations in complex, dynamic social systems. These are elaborated below:

1. *Flexibility*: Agile approaches allow teams to respond quickly to changing needs and priorities by adapting the project plan as needed. This is important in social development projects, which often operate in complex and rapidly changing environments.
2. *Collaboration:* Agile approaches prioritise frequent, face-to-face communication and collaboration among team members, as well as collaboration with stakeholders. This can be particularly useful in social development projects, where multiple stakeholders may be involved and where community engagement is often an important factor in success.
3. *Adaptability*: Agile approaches allow teams to experiment and learn from their experiences to continuously improve their approach. This can be especially valuable in social development projects, where the goal is to achieve lasting, sustainable change.

7. Conclusion and Future Work

This paper presents an exploratory look on both PM methodology and project success. From the literature reviewed, there exists a relationship between the PM methodology used and project success (Munns. 1996; Baccarini, 1999). It was found that adopting agile PM approaches could help with higher success rates of projects (PMI, 2018). Despite the literature on agile PM approaches in non-IT environments is limited, there is room and great potential for agile to be extended to other areas than IT projects (Serrador and Pinto, 2015).

Can an agile PM methodology be used in the delivery of a sustainable development social project? and what would be the impact of doing this in a SIDS such as in Trinidad and Tobago (T&T)? Future work would expand the investigations on how to strengthen the relationship between PM methodologies (particularly agile) and project success. It would focus on the agile applicability in sustainable development social projects and explore how they would align with the national development projects to the SDGs in T&T and the wider Caribbean region (GORTT, 2016). Moreover, comparison of agile PM success would be made against others where predictive PM methodologies are used in the delivery of these projects. Data can be collected from project practitioners involved in these projects to provide qualitative measures of success.

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A Review of Organisational Resilience Models for Revitalising Manufacturing Resilience and Adaptability

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Abstract: *In responding to the COVID-19 pandemic, many manufacturers have recognised the pressing need to adopt change to sudden disruptions. Resilience is a means of overcoming adversities like the pandemic in organisations. This paper reviews the literature on identifying the enablers and factors affecting Resilient Organisation (RO) development in the manufacturing sector, using the search engine of ProQuest Central and Emerald Insight for the period 2011 to 2022. By consolidating the relevant literature, three dimensions of Organisational Resilience (OR) have been identified dominating the field of study. One dimension being phases of organisational resilience, namely, anticipation (before the adversity), adaptive (during the adversity), and adaptation (after the adversity) and their respective factors. The other two dimensions refer to the resilient levels and the social perspectives. Among many emerging OR frameworks/models advocated in literature, twelve of them were chosen with their strengths and weaknesses addressed. A multi-dimensional RO paradigm was proposed to facilitate the analysis. Results showed that these frameworks/ models could be grouped under (3) categories of 'not multidimensional', 'multi-dimension to some extent', and 'conceptual and applied to organisations'. By identifying shortcomings of the existing RO models and frameworks, the analysis points to a quest for a cohesive RO model that could borrow the strengths of the existing models. Future work would determine the key components of the cohesive model and validate the applicability of the model empirically for guiding manufacturers towards revitalising resilience and adaptability.*

Keywords: *Organisational Resilience Factors, Resilience Framework/Models, Resilient Organisations, Vulnerability*

1. Introduction

The COVID-19 pandemic has exposed the vulnerability of manufacturers to adversities and disturbances and has impacted the global economy significantly. Vulnerability is a "lack of ability to endure or withstand the effects of adverse environmental conditions (Teng-Calleja, Sabile and Villasanta. 2020). Adversities and disturbances refer to events that prevent organisations from delivering their products or services properly (Rahi, 2019). These events include natural disasters, extreme disasters such as pandemics, economic recession (Ma, Xiao, and Yin, 2018), and even evolving global marketplace (Ishak and Williams, 2018). They would typically have a negative impact on the operational environment and cause an interruption in the normal workflow in organisations. Madani and Parast (2023) advocate that adversity is divided into three stages, i.e., before, during and after the disturbance. To survive and thrive on adversity, having and building proper organisational resilience is anticipated (Rodríguez-Sánchez, 2021). Resilient organisations (RO) are those entities that rebound and prosper after business disruption, because they are resistant to the impacts of disruption.

Response, recovery, and contingency are the basis for resilience. Recent literature has identified various principles, criteria, and attributes in connection with guiding organisations to anticipate, prepare for, respond, and adapt to incremental change and sudden disruptions (Denyer, 2017). Many practitioners and researchers have postulated different organisational resilient (OR) and associated models, frameworks and approaches e.g., the Integrated Value Framework (Visser, 2021), the Capability-based Model (Duchek, 2020), the Strategic Management of Organisational Resilience (SMOR) Framework (de Moura and Tomei, 2021), and the Integrated Model of Organisational Resilience (Madani and Parast, 2023), among others. This paper reviews the advocates and features of these models. There are six sections. Following the introduction, Section 2 explains the methodology used. Section 3 describes the characteristics of twelve emerging OR frameworks/models in literature, whereas Section 4 presents a comparison of their strengths and weaknesses and identifies any gaps. Section 5 discusses the need for a multi-dimensional paradigm and Section 6 concludes an agenda for OR development.

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2. Methodology and Search Results

Based on the methodology advocated by Kitchenham (2004), this paper is intended to identify the parameters and variables that could constitute an integrated framework for organisational resilience. Three study questions (SQ) are set as follows:

- *SQ-1*: What is an integrated framework for resilient organisations from literature?
- *SQ-2*: What are the RO models proposed in the literature?
- *SQ-3*: How do these proposed RO models compare to the integrated RO framework?

The literature search was conducted using ProQuest Central and Emerald Insight. These databases were selected as they comprise of abstracts, full text, and referencing details for articles identified under the respective searches, from around the world. ProQuest Central has almost 33,000 publications, almost 18,000 are scholarly journals. "ProQuest Central is the largest single periodical resource available, bringing together complete databases across major subject areas". These databases facilitate screening, filtering, and allowing the review procedure to be manageable. Scholarly Journals, conference proceedings and books written in English during the period 2011 to 2022 which were peer reviewed, and full text were accepted for review.

The following search strings were used.

- ***S1:*** (*T1*= ((organisational resilience factors) OR (organisational resilience enablers)) OR (*AB1* = ((organisational resilience factors) OR (organisational resilience enablers))
- ***S2:*** (*T2* = ((resilient organisation models)) OR (*AB2* = ((resilient organisation models))

Query 1 searches for documents with key terms in the title (*T1*) and/or the abstract field *AB* related to *SQ-1*. Query 2 searches for documents with key terms in the title (*T2*) and/or the abstract field *AB* in relation to *SQ-2*. The selection process was made. First, the search uses *S1* and *S2* and applies the filters as specified by the criteria. It then screens the titles and abstracts followed by the full text documents. Table 1 shows the distribution of publication types of OR for the period 2011-2022.

Table 1. Distribution of Publications 2011-2022

Year	Number of Papers
2011	5
2012	1
2013	4
2014	3
2015	4
2016	6
2017	4
2018	10
2019	12
2020	12
2021	21
2022	30

In terms of research papers, viewpoints, literature reviews, books, case studies and conceptual papers. Most of the papers reviewed were research-oriented, case studies and conceptual studies. Statistics show that there appears to be a drastic increase in the number of publications on OR after 2019. The search for RO models in Title (*T2*) and Abstract (*AB2*) indicated zero results. However, RO models were identified from reviewing some journals using *S1*. The models selected have a surviving and thriving aspect in the manufacturing and related domain.

3. Findings and Analysis

3.1 Levels of Resilience

Organisational resilience is "the ability of an organisation to anticipate, prepare for, respond and adapt to incremental change and sudden disruptions in order to survive and prosper" (Denyer, 2017). Resilience of organisations have been identified at different levels (Wall and Bellamy, 2019; Rodríguez-Sánchez, 2021). These are:

1) *Individual/Employee Resilience* – A resilient organisation requires resilient employees (Zaato and Ohemeng 2015; Ur Rehman et al., 2021). According to Lengnick-Hall, Beck and Lengnick-Hall, (2011), employee resilience is "the ability to recover from adversity" and is viewed as a "developable quality" (Malik and Garg, 2020; Naswall et al., 2019). Resilience can be developed with strategic human resources management (SHRM), training and development, empowerment and employee engagement and well-being. Some inherent factors are social competence, personal competence, and family coherence.
2) *Team/Group Resilience* - Rodríguez-Sánchez and Perea (2015) define team resilience as a "capacity that teams have in order to overcome crisis and difficulties". The factors that build team resilience are collective efficacy, transformational leadership, and teamwork.
3) *Supply Chain (SC) Resilience* - External disturbance would affect supply chains which in turn affect organisations in an interconnected world (Burnard and Bhurma, 2019). Kaviani et al. (2020) added that there is a need for resilience of the supply chain, and a company is as resilient as its supply chain. Flexibility, redundancy, collaboration, visibility, and velocity are amongst the elements supporting supply chain resilience (Tukamuhabwa et al., 2015). Redundancy is maintaining an idle response capacity, to access e.g., investments in safety stocks and backup suppliers or storage (Rice and Caniato, 2003; Kamalahmadi and Parast, 2016). It is keeping some resources in reserve in case of disruption such as safety stock.

Being able to recover from a disruption quickly is improved by increasing redundancy (Sheffi and Rice, 2005; Kaviani et al, 2020). However, over-redundancy (exhausting resources to have reserves) could put a financial burden on the organization, and an optimum redundancy level should be determined.

3.2 The Social Perspective

Recent studies identified the social perspective of OR. These are cognitive capabilities, behavioural resilience, and contextual abilities, as elaborated below.

1) *Cognitive capabilities* – These refer to the shared purpose and values or a collective mind for adversity (Ma, Xiao, and Yin, 2018). Such capabilities are the knowledge and expertise used to respond well when adversity strikes (Teng-Calleja, Sabile and Villasanta. 2020). According to Lengnick-Hall, Beck and Lengnick-Hall, (2011), staff continuous development, cross-function assignments and group incentives facilitate cognitive resilience.
2) *Behavioural resilience* - It is concerned with the behaviours that enable an organisation to devise new habits during disruptive conditions, such as information sharing, cooperation, and coordination (Ma, Xiao and Yin, 2018; Teng Calleja et al., 2020).
3) *Contextual abilities* - The relationships between employees and customers, evaluations and empowerment are contextual aspects (Lengnick-Hall, Beck and Lengnick-Hall, 2011). This refers to the organisation's ability to use social capital for quick action when disruption occurs.

3.3 Phases of Organisational Resilience

There are three phases of OR, moving from the anticipation via adaptive to adaptation, as advocated in the literature (Väkilzadeh and Haase, 2020; Mokline and Abdallah, 2021). The core OR characteristics across these phases are described below.

3.3.1 The Anticipation Phase

Before adversity or disruption occurs, organisations attempt to make predictions or anticipations of potential disturbances and prepare mitigation plans (Väkilzadeh and Haase, 2020; Mousa et al., 2020). Anticipation capabilities involve preparations to ensure the organisation is equipped to handle adversities (Crichton, Ramsay, and Kelly, 2009). Väkilzadeh and Haase (2020) outlined two building blocks of the anticipation phase as:

1) *Environmental scanning and Risk Management* - Scanning the environment for possible adversities is advocated by Burnard, Bhamra and Tsinopoulos (2018), Väkilzadeh and Haase (2020) and Burnard and Bharma (2019). Mitigation planning can then begin (Carmeli and Markman, 2011; Väkilzadeh and Haase, 2020), risk management identifies risk and opportunities in organisations (Mokline and Abdallah, 2021).
2) *Resilience Planning* – Recent studies recognised the need for, and importance of resilience plans to prepare for adversity (Păunescu and Argatu, 2020; Väkilzadeh and Haase, 2020). These plans would be incorporated into disaster management planning (Väkilzadeh and Haase, 2020; Hartel and Latremore, 2011), crisis management plan (Fleming, 2012) and strategic management planning (Demmer, Vickery and Calantone, 2011).

3.3.2 The Adaptive Phase

During the occurrence of a disturbance, the mitigation plans from the anticipation phase are put into effect as the organisation makes system adjustments to stay afloat (Conz and Magnani, 2020). Karman (2020) regards this phase as absorptive and adaptive phase. Väkilzadeh and Haase (2020) outlined innovation as one building block. Other factors include system robustness and redundancy (Madani and Parast, 2023) and adaptive capacity (Zaato and Ohemeng, 2015; Ahn, Mortaza and Minshall, 2018; Rahi, 2019; Yang and Cheng, 2020).

In this phase, robustness is the ability to keep on functioning with little effort (Madani and Parast, 2023), whereas redundancy is maintaining an idle response capacity such as safety stocks and backup suppliers or storage (Kamalahmadi and Parast, 2016; Kaviani et al., 2020). Conversely, Doerfel, Chewning and Lai. (2013) argued that too much redundancy could exhaust the organisation's resources. Adaptive capacity is thus a measure of the culture of the organisation that allows it to make decisions in a timely and appropriate manner (Zaato and Ohemeng, 2015). Madani and Parast (2023) argued that this could be achieved through flexibility, agility, and collaboration.

3.3.3 The Adaptation Phase

This Adaptation phase occurs after the disruption has taken effect (Burnard, Bhamra and Tsinopoulos, 2018; Madani and Parast, 2023). Learning and organisation change management are the building blocks of the phase (Väkilzadeh and Haase, 2020). Reflection and learning include 'lessons learnt', whereby information is exchanged with those outside the organisation so that they can benefit from each other's experiences (Väkilzadeh and Haase, 2020; Linnenlueke and Griffits, 2013). Moreover, change management requires that organisation members be committed to the change (Weiner, 2009 and Rafferty, Jimmieson, and Armenakis, 2013). The idea of constantly changing by developing new capabilities to keep pace with disruptions and thereby turning the disruption into an opportunity is supported by Zhou et al. (2022) in what they refer to as bounce-forward resilience.

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3.4 Identification of Enablers/Factors of Resilient Organisation Development

The multidimensional criteria are used to assess the OR models proposed. Table 2 depicts a list of the OR enablers contributing to the RO development in manufacturers, and their sources in the literature. Several common enablers across three phases of OR include leadership (Bell, 2019; Wilkinson et al., 2016 and Naswall et al., 2019), organisational culture (Andersson et al., 2019; Väkilzadeh and Haase, 2020), knowledge management (Tamanna, 2019; Mafabi and Kabagambe, 2021), information sharing (Wieland and Wallenburg, 2013; Naghshineh and Lofti, 2019), financial resources (Väkilzadeh and Haase, 2020), technological resources (Andersson et al., 2019; Labaka, Hernantes and Sarriegi, 2016), inter-organisational relationships and collaboration. Specific OR enablers per individual RO phases include:

1) In the *Anticipation* Phase - Environmental scanning and planning, and risk management.
2) In the *Adaptive* Phase - Innovation/creativity, redundancy, robustness, agility, flexibility, and adaptive capacity.
3) In the *Adaptation* Phase - Organisation learning, and organisation change.

3.5 Twelve Emerging OR Models/Frameworks

There are twelve (12) emerging OR models and frameworks advocated in the literature under study. These models would have a surviving and thriving aspect in the manufacturing and related domain, and are listed and elaborated, as follows:

3.5.1 The Resilient Management Process Model

Lichte, Torres, and Engler (2022) advocates the Resilient Management Process that focusses on risk assessments and the importance of knowledge to facilitate this by construction of a living data and information base (DIB) and details operational measures for gathering, maintaining, and extending the available knowledge (see Figure 1). This DIB enables the description of the current situation and historical events in relation to Critical Infrastructure Systems and Organisations (CISO), environment, and evolving scenarios. At the onset, the Organisational Resilience Management (ORM) assesses whether the available knowledge is sufficient to perform the intended resilience management. Any deficiencies are thereafter addressed by collating additional data and environmental models, or expanding methodological capabilities, improving awareness regarding both known and unknown risks. Risk developments due to the current

Table 2. RO Factors/Enablers and Sources

FACTORS/ENABLERS	SOURCES
ANTICIPATION PHASE	
Environmental Scanning	Väkilzadeh and Haase (2020); Burnard, Bhamra and Tsinopoulos (2018); Hales and Chakravorty (2016); Paraskevas and Quek (2019); Carmeli and Markman (2011); Burnard and Bharma (2019).
Resilience Planning	Ghufran et al. (2022), Hartel and Latremore (2011); Sahebjamnia, Torabi and Mansouri (2015); Väkilzadeh and Haase (2020); Păunescu and Argatu (2020); Fleming (2012); Demmer, Vickery and Calantone (2011); Yang and Cheng (2020).
Risk Management	Bonilla (2015); Hopkins (2014); Jivaasha (2020).
ADAPTIVE PHASE	
Adaptive Capacity	Rahi (2019); Demmer, Vickery and Calantone (2011); Boin and van Eeten (2013); Zaato and Ohemeng (2015); Yang and Cheng (2020); Bharma, Dani and Bernard (2011).
Agility	Ghufran et al. (2022), Kantur and Iseri-Say (2012); Braunscheidel and Suresh (2009); Christopher and Peck (2004).
Flexibility	Denhardt and Denhardt (2010); Zaato and Ohemeng (2015); Burnard, Bhama and Tsinopoulos (2018); Haase and Eberl (2019); Yang and Cheng (2020); Holbeche (2018).
Innovation and Creativity	Kendra and Wachtendorf (2003); Yang and Cheng (2020); Senbeto and Hon (2020); Väkilzadeh and Haase (2020); Ahmed, Kilika and Gakenia (2021); Ahn, Mortaza and Minshall (2018); Mafabi, Munene and Ntayi (2012).
Redundancy/Robustness	Kavanagh (2011); Denhardt and Denhardt (2010); Zaato and Ohemeng (2015).
ADAPTATION PHASE	
Organisation Learning (and Lessons Learnt)	Acar et al. (2022), Väkilzadeh and Haase (2020); Ishak and Williams (2018); Yang and Cheng (2020); Kim and Miner (2007); Holbeche (2018).
Organisation Change	de Moura and Tomei (2021), Duchek (2020), Väkilzadeh and Haase (2020).
ALL PHASES	
Technological Resources	Andersson et al. (2019); Ignatiadis and Nandhakumar (2007); Labaka, Hernantes and Sarriegi (2016); Linnenluecke and Griffith (2013); Väkilzadeh and Haase (2020).
Trust and Information Sharing	Ghufran et al. (2022), Acar et al. (2022), Wieland and Wallenburg (2013); Naghshineh and Lofti (2019); Barrat and Oke (2017); Stern and Baird (2015); Adobor, Darbi and Damoah (2022).
Inter-organisation relationships	Herbane (2019); Linnenluecke and Griffiths (2013); Martinelli, Tagliazucchi and Marchi (2013); Rahi (2019); Karman (2020); R-Toubes, Araujo-Vila and Fraiz-Brea (2020); Yang and Cheng (2020); Kim, Jung and Chilton (2016), Ates (2022), Zhou et al. (2022).
Knowledge Management	Mafabi and Kabagambe (2021); Barasa Mbau and Gilson, (2018); Williams et al. (2017); Gakhar and Phukon (2018); Scholten, Scott and Fynes (2014).
Leadership	Bell (2019); Rahi (2019); Gover and Duxbury (2018); Wilkinson et al. (2016); Naswall et al. (2019), Ngoc et al. (2021).
Organisation Culture	Wamalwa and Ochola (2022), Andersson et al. (2019); Spee (2020); Sawalha (2015); Păunescu and Argatu (2020); Väkilzadeh and Haase (2020), Ates (2022), Ngoc et al. (2021).
Collaboration	Ponis and Koronis (2012); Hohenstein et al. (2015) and Tukamuhabwa et al. (2015).

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situation where the *Actual* situation is compared with the *Target* situation identifies irregularities in the risk indicators. Analysis and simulation are performed to identify, evaluate, and select risk mitigation measures.

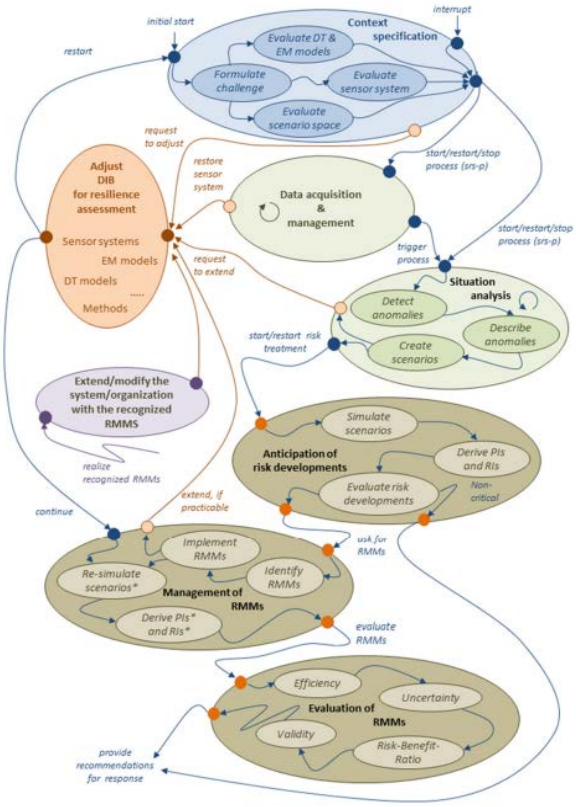

Figure 1. The Resilience Management Process
Source: Lichte, Torres, and Engler (2022)

3.5.2 The ResilFRAM Model

Figure 2 depicts the ResilFRAM model that stresses the maintenance of the design and construction work teams, the encouragement of collaboration between teams, the development of innovative design and construction solutions and the continuous monitoring of market trends. Saldanha et al. (2022) contended that the development of routes ultimately enhances the interconnection of the four resilience abilities (such as anticipating, learning, monitoring, and responding), with one enhancing the other, making the organisation able to display potential for resilient performance in diverse situations.

3.5.3 The System Dynamics (SD) Model

Figure 3 shows the System Dynamics (SD) Model. Malik et al. (2022) identified the important resilience capabilities for risk mitigation and continual improvement. These comprise four stocks: 1) people, products, and assets visibility, 2) collaborative information exchange, 3) process improvements and 4) learning from experience.

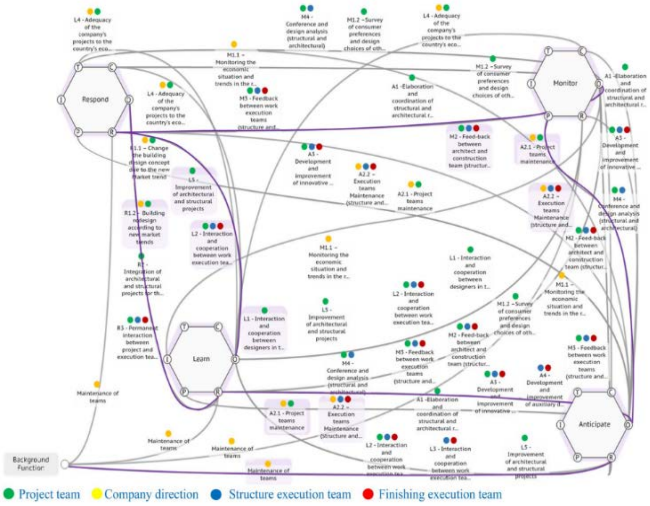

Figure 2. The ResilFRAM Model
Source: Saldanha et al. (2022)

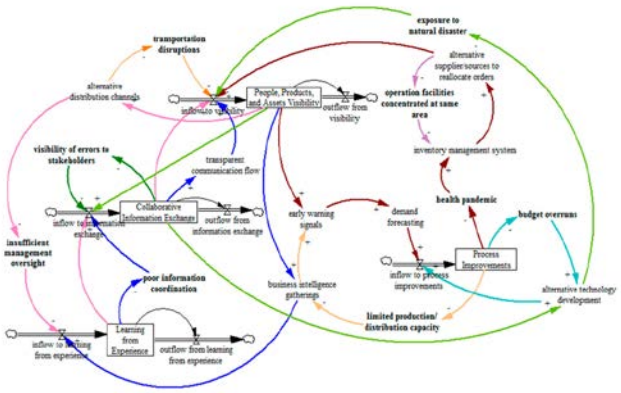

Figure 3. System Dynamics Model
Source: Malik et al. (2022)

The SD model highlighted the critical risks, their effects on the entire system and key capabilities and mitigation of risks to enhance systems resilience. Visibility of people, products, and assets, collaborative information exchange, business intelligence gatherings, alternative suppliers, and inventory management systems are the most important resilience capabilities.

3.5.4 The Roadmap Model of Organisational Resiliency

According to Aung and Fernando (2022), a roadmap model consists of resilience stages of 'Anticipation', 'Coping', and 'Adaptation', in parallel with employee engagement and organisational commitment. Figure 4 shows the roadmap that provides guides for enhancing organisational resilience and sustainability along with appreciative resilience practices and aspirations of post-crises. Appreciative resilience includes hope, despair, and forgiveness. Aspirations for the postcrises include the future of organisation, employees' contributions to achievement, success of organisation and difference between now and after crisis.

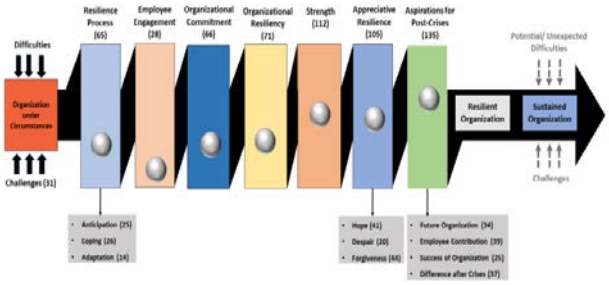

Figure 4. A Roadmap of Organisational Resiliency
Source: Aung and Fernando (2022)

3.5.5 The Conceptual Integrative Model of Organisational Resilience

Hillmann and Guenther (2022) advocated a conceptual integrative model of OR. As depicted in Figure 5, the cause indicators are resilient behaviours, resilience resources or resilience capabilities that govern a response that is resilient. Besides, how the organisations respond can result in growth and learning.

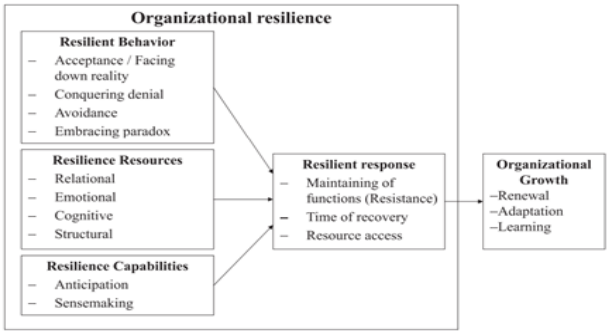

Figure 5. The Conceptual Integrative Model of Organisational Resilience
Source: Hillmann and Guenther (2022)

3.5.6 The Integrated Model of Organisational Resilience

Madani and Parast (2023) advocated an Integrated Model of Organisational Resilience (see Figure 6). This model originates from the Plan-Do-Check-Act (PDCA) cycle (Dahlgaard, Khanj and Kristensen, 2008) and is integrated into organisational capabilities, resilience capabilities, resilience measures and disruptions.

The model proposes four resilience capacities. These are:

a) *Predictive Capacity* (Before the disruption) – This is to predict disruptions, recognise vulnerabilities and prepare human resources via education and training programmes.

b) *Absorptive and Adaptive Capacity* (During the disruption) – Such capacity is being able to absorb the initial shock by monitoring, warning and control systems and redundant resources. For instance, it can be flexible contracts, multiple sources, and expansion of collaborations, after the direct impact of the disturbance.

c) *Restorative Capacities* (After the disruption) – These are concerned with restoration in terms of recovery level, recovery time and recovery cost.

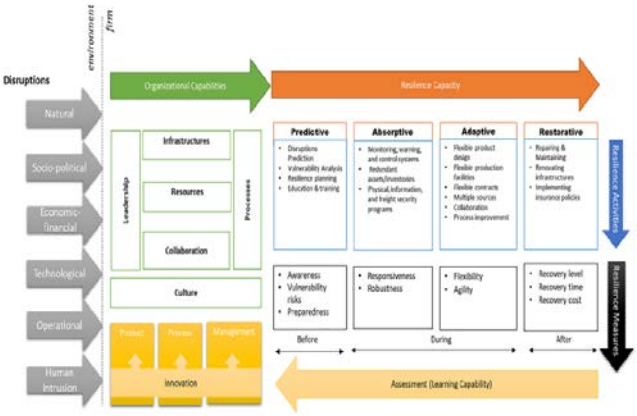

Figure 6. The Integrated Model of Organisational Resilience
Source: Madani and Parast (2023)

3.5.7 The Strategic Management of Organisational Resilience (SMOR) Framework

The Strategic Management of Organisational Resilience (SMOR) Framework has three levels. According to de Moura and Tomei (2021), these are: 1) *the Environmental level* – i.e., Sharing experiences with companies from the same sector, 2) *the Organisational behavioural level* – i.e., Linked to anticipation, response, and learning capacities, and 3) *the Individual behavioural level* – i.e., the behaviours that employees should develop. As shown in Figure 7, these dimensions are supported by organisation practices. The model is temporal in nature suggesting actions before, during, and after an adverse event.

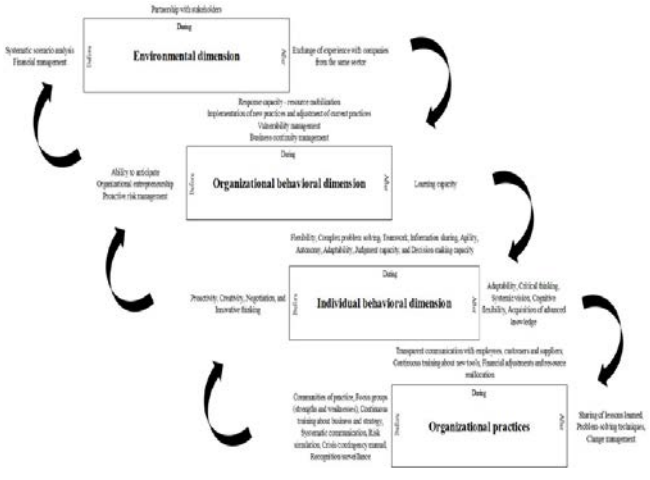

Figure 7. The Strategic Management of Organisational Resilience (SMOR) Framework
Source: de Moura and Tomei (2021)

3.5.8 The Capability-Based Conceptualisation Model of OR

As advocated by Duchek (2020), the Capability-Based Model has three successive phases of resilience. These are 1) Anticipation (before the unexpected event), 2) Coping (during the unexpected event), and 3) Adaptation (after the unexpected event). Figure 8 depicts a capability-based conceptualisation model of OR. It shows the need for resource availability in three phases, the importance of social resources in the coping phase and power and responsibility in the adaptation phase. Cognitive actions and behavioural actions are an important aspect of the model.

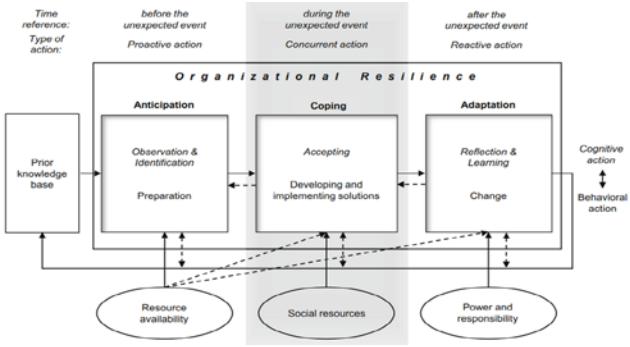

Figure 8. A Capability-based Conceptualisation of Organisational Resilience
Source: Duchek (2020)

3.5.9 The Integrated Value Framework

Visser (2021) applied systems thinking to develop an Integrated Value Framework (see Figure 9). The framework derives five (5) "triggers" for change, namely, disruption, disconnection, disparity, destruction, discontent (Laszlo, 2010; Capra and Luisi, 2016) and thereafter, five counter-forces of breakthrough for innovation.

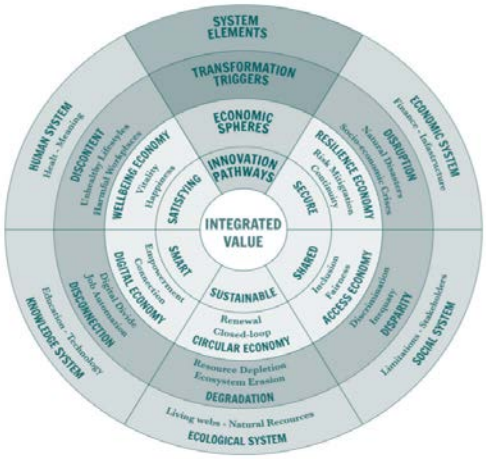

Figure 9. The Integrated Value Framework
Source: Visser (2021)

3.5.10 The Integrated (Cognitive-Behavioural-Contextual) Model on Organisational Resilience

Organisational resilience is an organisational capability to survive in, adapt to, bounce back from, and often thrive in unexpected, sometimes disastrous events and, in a broader sense, turbulent environments". Ma, Xiao and Yin (2018) advocated that OR progresses across different levels from individual to group and organisational levels (see Figure 10). Cognitive, behavioural and contextual residencies are incorporated into the model.

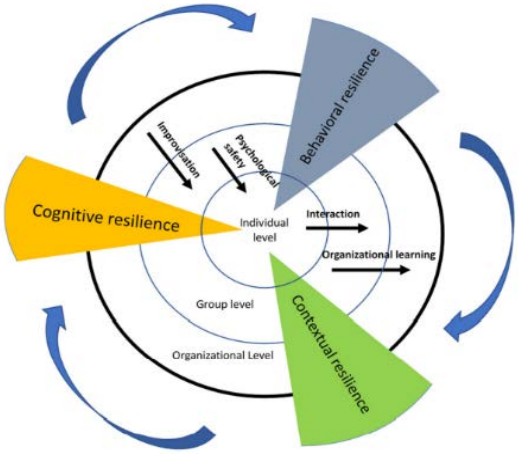

Figure 10. The Cognitive-Behavioural-Contextual Model of Organisational Resilience
Source: Ma, Xiao and Yin (2018)

3.5.11 The Leading Indicators Framework of Organisational Resilience

Figure 11 shows the leading indicators framework of organisational resilience. According to Seville (2018), the framework has three OR pillars, namely 1) leadership and culture, 2) networks and relationships and 3) whether the organisation is ready to change. Besides, there are thirteen (13) leading indicators identified in facilitating organisational resilience (Lee Vargo and Seville, 2013).



Figure 11. The Leading Indicators Framework of Organisational Resilience
Source: Seville (2018)

3.5.12 The Overall Framework of Organisational Resilience

Yang and Cheng (2020) developed the overall framework of organisational resilience. As shown in Figure 12, this model has three resilience phases of preparation, response, and evolution. The key aspects are the corporate social responsibility and inter-organisational relationships. "After the crisis, reflection and turning the crisis into an opportunity can promote a virtuous cycle of organisational development and sustainable resilience".

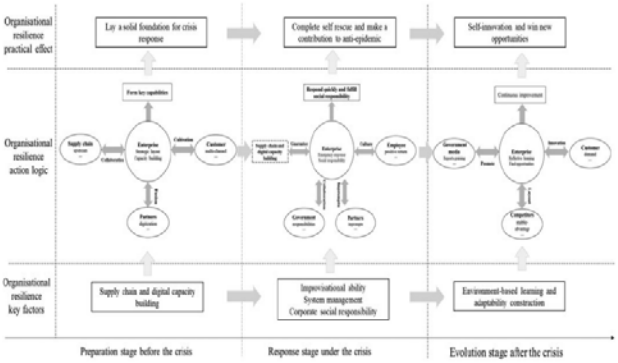

Figure 12. The Overall Framework of Organisational Resilience
Source: Yang et al. (2021)

4. Comparison Among OR Models/Frameworks

Table 3 shows the strengths and weaknesses of 12 OR models/frameworks, whereas a comparison of their features are summarised in Table 4. The multi-dimensional nature of the paradigm is used to compare the features among the twelve RO models/frameworks emerged (see Figure 13). Highlights of the comparisons and observations are made. as follows:

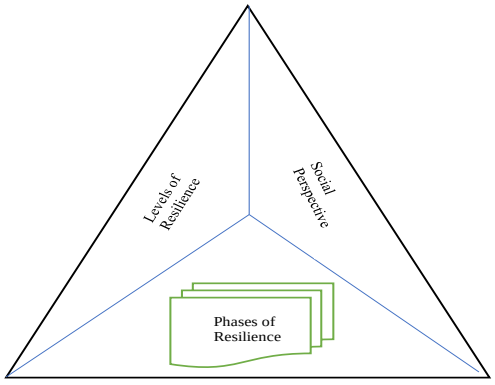

Figure 13. The Multi-dimensional Nature of Integrated OR Paradigm

1) The Conceptual Integrative Model of OR (Hillmann and Guenther, 2022), the SMOR Model (de Moura and Tomei, 2021), the Integrated Model of OR (Madani and Parast, 2023), the ResilFRAM Model (Saldanha et al., 2022), the Resilient Management Process Model (Lichte, Torres, Engler, 2022), the System Dynamics Model (Malik et al., 2022), the Roadmap Model of Organisation Resiliency (Aung, 2022), the Overall Framework of OR (Yang et al., 2021) and Capability-Based Conceptualisation Model (Duchek, 2020) utilise the phased approach.
2) Interorganisation relationship where experiences and information are shared between organisations, is a common enabler among most OR models.
3) Cognitive, behavioural and context resilience were key enablers of the Capability-Based Conceptualisation Model (Duchek, 2020), the Integrated Model on RO (Ma, Xiao and Yin, 2018), the SMOR Model (de Moura and Tomei, 2021) and the Conceptual Integrative Model of OR (Hillmann and Guenther, 2022).
4) The Integrated (Cognitive-Behavioural-Contextual Model) on RO (Ma, Xiao, and Yin, 2018), the SMOR Model (de Moura and Tomei, 2021) and the Conceptual Integrative Model (Hillmann and Guenther, 2022) utilised organisational levels of resilience.

Three (3) categories of OR models were identified, including:

1) *Non-Multidimensional Models* – The Leading Indicators Framework (Seville, 2018), and the Integrated Value Framework (Visser, 2021) are not multi-dimensional. They identify key indicators. Whilst the ResilFRAM Model (Saldanha et al., 2022), the Resilient Management Process Model (Lichte, Torres, Engler, 2022), the System Dynamics Model (Malik et al., 2022), the Roadmap Model of Organisation Resiliency (Aung and Fernando, 2022), the Integrated Model of OR (Madani and Parast, 2023) and the Overall Framework of OR (Yang and Cheng, 2020) addressed some or all resilience phases aspects i.e., one dimension was captured.
2) *Multi-dimensional to Some Extent* – The Capability-based Conceptualisation Model of OR (Duchek, 2020) installs the enablers in the resilience phases with cognitive and behavioural actions. Besides, the SMOR Model (de Moura and Tomei, 2021) and the Conceptual Integrative Model (Hillmann and Guenther, 2022) address various resilience phases, the individual and organisational levels of resilience, as well as the cognitive and behavioural capabilities. Moreover, the Integrated (Cognitive-Behavioural-Contextual) Model on OR (Ma, Xiao and Yin, 2018) addresses the organisational levels and the cognitive, behavioural and contextual aspects of resiliencies.
3) *Conceptual and Applied to Organisations* – Only three models including the ResilFRAM Model (Saldanha et al., 2022), the Integrated Value Framework (Visser, 2021) and the Overall Framework of Organisational Resilience (Yang et al., 2021) fall into this category.

Table 3. Strengths and Weaknesses among Selected RO Models and Frameworks

Models/Frameworks	Strengths	Weaknesses
1. The Resilient Management Process Model (Lichte, Torres, Engler, 2022)	Frequent risk Assessments are the basis for this model. Additionally, constant knowledge acquisition for the identification of risk and mitigation plans are significant. It contains living data and an information database.	The frequent risk assessments and knowledge acquisition could be a financial concern, but an optimum level would be beneficial. This is not a multi-dimensional model. Only the anticipation phase is covered.
2. The ResilFRAM Model (Saldanha et al., 2022)	Collaborations amongst teams are a key aspect of this model. Anticipating, monitoring, and responding to disturbances are covered. A case study is included	It is not a multi-dimensional model. Only resilience phases are addressed.
3. The System Dynamics Model (Malik et al., 2022)	Looks at risk mitigation and learning from an experience perspective like "lessons learnt" situations. This is practical and a strong benefit of this model.	It is not a multi-dimensional model.
4. The Roadmap Model of Organisational Resiliency (Aung and Fernando, 2022)	A focus on employees' aspirations and their contribution to future organisation success is commendable. Anticipation, coping and adaptation. OR phases are addressed.	It is not a multi-dimensional model.
5. The Conceptual Integrative Model (Hilmann and Guenther, 2022)	Considers the multi-dimensional nature of resilience to some extent.	The Model is conceptual. There is no report of its industrial applications.
6. The Integrated Model of Organisational Resilience (Madani and Parast, 2023)	A Vulnerability analysis is conducted which is a key benefit of this model. It addresses resilience phases of anticipation/absorption and adaptive/adaptability.	This is a conceptual model. It does not consider the multi-dimensional nature of resilience. There is no report on its industrial applications.
7. The Strategic Management of Organisation Resilience Framework (de Moura and Tomei, 2021)	Vulnerability management is conducted during the disruption. It considers the multi-dimensional nature of resilience, in terms of resilience phases capabilities, cognitive/behavioral actions and individual/group dimensions.	The model was developed with dimensions of organisational resilience. Supply chain resilience is not considered.
8. The Capability-Based Conceptualisation Model of OR (Duchek, 2020)	Considering the multi-dimensional nature of resilience, in terms of resilience phases capabilities of anticipation /coping /adaptability and cognitive/behavioural actions.	This is a conceptual model. Individual, group, and supply chain are not considered. There is no report of industrial applications.
9. The Integrated Value Framework (Visser, 2020)	It is multi-dimensional to some extent. It identifies vulnerabilities / forces of breakdown, and five counter forces of breakthrough for innovation. Pilot study is incorporated.	All dimensions of resilience are not considered. A pilot study had been undertaken and recoded.
10. The Integrated (Cognitive-Behavioural-Contextual) Model on Organisational Resilience (Ma, Xiao and Yin, 2018)	It considers the multi-dimensional nature of resilience, in terms of individual/ group/ organisational levels resilience and cognitive/ contextual/behavioural resilience.	This is a conceptual model. The authors recommend future exploration of this model. There is no report on its industrial applications.
11. The Leading Indicators Framework of Organisational Resilience (Seville, 2018)	It identifies three OR pillars with a list of leading indicators of resilience.	It does not consider the multi-dimensional nature of resilience. There is no report on its industrial applications.
12. The Overall Framework of Organisational Resilience, Yang et al., 2020)	It stresses corporate social responsibility, inter-organisational relationships, and sustainability. A case study is provided.	It is not multi-dimensional.

5. Discussion

As the rate of change accelerates and competition intensifies globally, a company's survival is dependent on how well it can position itself and how it optimises its efforts to anticipate, prepare for, respond, and adapt to incremental change and sudden disruptions. The success and continuity of the organisation depends on its performance. Cost, quality, flexibility, delivery, and innovation are well-established competitive performance priorities. Fostering OR adaptation and performance sustainability is a relatively new concept in manufacturing, particularly in developing countries, like Trinidad and Tobago (T&T).

In T&T, there have been a few statistics in relation to dealing with adversities and disturbances in the manufacturing sector. According to the Central Bank of Trinidad and Tobago, the gross domestic product (GDP) contribution of the manufacturing sector of the country was 18.1% in 2019 and 16.5% in 2020 (CBTT, 2021). For the accommodation and food services GDP remained at 1.9% for 2019 and 2020; financial and insurance services 7.9% and 7.8% for 2019 and 2020, respectively, water supply increased from 1.2% to 1.3%, electricity also increased from 1.9% to 2.0%.

Moreover, "most of the job losses were in the construction (including water and electricity service) and manufacturing (including mining and quarrying) sectors, where there were 13.3 thousand and 8.9 thousand fewer persons employed, respectively". The manufacturing sector of T&T was producing at only 61.9 % of its full capacity in 2020 (CBTT, 2020). In the first quarter of 2021, eleven (11) industries experienced year-on-year declines in real economic activity (GORTT, 2021). Manufacturing showed a decline in economic activity of 10.5 percent. These statistics alert the need to reduce the vulnerability of manufacturers and re-establish them to

Table 4. Comparison among 12 Organisational Resilience Models and Frameworks

Models and Frameworks / RO Dimensions	**1. The Resilient Management Process Model** (Lichte, Torres, Engler, 2022)	**2. The ResilFRAM Model** (Saldanha et al., 2022)	**3. The System Dynamics Model** (Malik et al., 2022)	**4. The Roadmap Process Model of Organisational Resiliency** (Aung and Fernando, 2022)	**5. The Conceptual Integrative Model of OR** (Hilmann and Guenther, 2022)	**6. The Integrated Model of Organisational Resilience** (Madani and Parast, 2021)
Organisational Levels	---	---	---	---	Individual	---
Resilience Phases	Risk assessment are the basis and constant knowledge acquisition to improve risk and mitigation plans.	Anticipating and monitoring.	Risk mitigation	Anticipating	Anticipating, and sensemaking.	Predictive (Before disruption) - Predicting disruptions, recognising vulnerabilities, resilience activities and preparing human resources via education and training programmes.
	---	Responding	---	Coping	Resistance, recovery, and time.	Absorptive and Adaptive (during disruption) Absorptive - Responsiveness and robustness. Adaptive - Flexibility and agility.
	---	Learning	Learning from experience	Adaption and aspiration.	Renewal, adaptation, and learning.	Restorative (after the disruption) - Recovery level, time, and cost.
Inter-organisational Relationships	---	Yes	Collaborative and information sharing	---	Relational	Organisation capabilities - Collaboration, culture, resources, processes, infrastructure, and leadership.
Cognitive/ Behavioural/ Contextual	---	---	---	---	Behavioural and cognitive.	---

Table 4. Comparison among Models and Frameworks *(Continued)*

Models and Frameworks / RO Dimensions	**7. The Strategic Management Framework of Organisational Resilience** (de Moura and Tomei, 2021)	**8. The Capability-Based Conceptualisation Model of OR** (Duchek, 2020)	**9. The Integrated Value Framework** (Visser, 2020)	**10.The Integrated (Cognitive-Behavioural-Contextual) Model on OR** (Ma, Xiao and Yin, 2018)	**11 The Leading Indicators Framework of Organisational Resilience** (Seville, 2018)	**12. Overall Framework of Organisational Resilience** (Yang et al., 2020)
Organisational Levels	Individual and organisational	---	---	Individual, group and organisational.	---	---
Resilience Phases	Before disruption - Scenario analysis, financial management, risk management, negotiation, innovation, focus groups, continuous training, communication, risk simulation and crisis recognition. Unpredictable events not considered.	Anticipation (before disruption) - Based on prior events. Observation and identification and making preparation. Resources availability required.	---	---	Leadership and culture change.	Preparation stage before the crisis.
	During disruption - participation with stakeholders, vulnerability management, response and resource mobilisation, teamwork, information sharing. Agility; continuous training and communication with stakeholders. Resource reallocation.	Coping (during the disruption) - Accepting and developing and implementing solutions. Resources availability and social resources needed.	---	---	---	Response stage under the crisis.
	After disruption - Exchange of experiences, learning capacity, adaptability, critical thinking; lessons learnt, problem solving and change management.	Adaptation (after disruption) – Reflection, change, learning. Resources availability, power, and responsibilities required.	---	---	---	Evolution stage after the crisis.
Inter-organisational Relationships	Interorganisation relationships to share experiences.		Connect people and things using AI, big data.	---	Networks and relationships	Collaborations, and corporate social responsibility.
Cognitive/ Behavioural/ Contextual	Cognitive and behavioural.	Cognitive and behavioural.	---	Cognitive, contextual and behaviourial.	---	---

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be resilient.

Recent studies have explored various enablers and factors affecting RO. Different OR dimensions have been identified. One dimension being phases of organisational resilience, namely, anticipation (before the adversity), adaptive (during the adversity), and adaptation (after the adversity) and their respective factors. Other dimensions refer to resilient levels and social perspectives. The need for and importance of the multi-dimensional OR concept has been recognised. Furthermore, this paper reviewed the twelve emerging OR models and frameworks advocated against the multi-dimensional RO paradigm.

A diagnosis of these models and frameworks showed that the multi-dimensional nature of OR has not been fully encapsulated. Some of them had merits which could be included in the multi-dimensional RO paradigm. The idea of avoiding over-investing in capabilities which are not necessary is appealing, especially in disruptive times. These are merits of the SMOR model on vulnerability management (de Moura and Tomei (2021) and the Integrated Model of OR on vulnerability analysis (Madani and Parast, 2023). Vulnerabilities are first assessed and only capabilities to address these weaknesses are invested. Moreover, the Resilient Management Process Model (Lichte, Torres, Engler, 2022) advocates the conduct of risk assessments regularly based on constant knowledge acquisition to improve on identification of risk and mitigation plans. This can be borrowed for the RO model developments. Furthermore, over-redundancy in the coping phase is another common issue, which can exhaust resources (Jaggernath-Furlonge, 2022) and should also be addressed.

6. Conclusion

By incorporating different resilience phases (such as anticipation, adaptive and adaptation), social perspectives (such as cognitive, behavioural and contextual) and the resilience levels (such as individual, team and supply chain resilience), the multidimensional paradigm could be developed encompassing the strengths of the existing OR models. This paradigm could integrate vulnerability analyses and consistent knowledge acquisition for risk assessments.

This study identifies a growing cognizance for industrial organisations and particularly manufacturers to revitalise exposure to adversities and disturbances. Over-redundancy and overinvesting in capabilities should be avoided. Although there are merits of various OR models advocated in literature, there are gaps and a truly multi-dimensional OR model is needed. This necessitates investments in knowledge acquisition and environmental scanning with regular risk assessments and mitigation planning.

Future work would pilot-test the paradigm in selected organisations and/or manufacturers, for instance those that have been operating below capacity and been seriously affected under the Covid-2019 pandemic, for instance, in T&T. The pilot test would incorporate various OR dimensions and factors (such as resilience phases, social perspective, and resilience levels). It is anticipated that the multidimensional paradigm could guide manufacturers responding and adapting to incremental change and sudden disruptions and gain sustainable performance.

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A Lean Productivity Framework for Guiding Capital Project Executions in Industrial Firms

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Abstract: *Industrial firms invest in capital projects to attain their long-term corporate goals and to foster sustainable development. However, inadequate planning and execution practices have resulted in a plethora of delays in delivery. This paper explores lean principles that could improve project productivity towards the effective management of delays. Recent studies suggested that many lean productivity (LP) factors contribute toward this agenda. Amongst these factors are 1) a standardised workforce, 2) an optimised site, 3) reliable supply chains, 4) standard work schedules, and 5) people's motivation. A recent 2021 study on LP was undertaken across various industrial sectors in Trinidad and Tobago (T&T). Empirical data showed a significant relationship between each LP factor and project delay. A generic lean productivity framework was proposed incorporating LP factors into the planning and execution phases of capital investment projects. The framework sheds light on the LP issues and its adoption would help industrial firms with project management practices and facilitate the attainment of benefits (human, social, economic, and environmental) from the delivery of their capital projects.*

Keywords: *Lean, productivity, delay, capital projects, framework*

1. Introduction

The Republic of Trinidad and Tobago (T&T) has the third highest gross domestic product per capita based on purchasing power parity in the Americas (IMF, 2017). In recent times, the leadership councils of industrial firms in T&T have placed special focus on the global movement towards a clean energy future. Industrial firms are those enterprises engaged in the production of capital goods and/or services within the manufacturing, construction, and oil and gas sectors in T&T. Many of these capital projects are internal development projects intended to assemble the facilities that allow these enterprises to economically function at both the firm and the national levels (Hassanali and Pun, 2022a). To attain sustainability within industrial firms, planning and execution of capital projects would incorporate the economic, social, and environmental governance principles that foster sustainable operations, social change, and biodiversity (Deloitte, 2022). As such, there has been a need for the on-time delivery of capital projects, making delay prevention a top priority.

The problem of delays is ubiquitous globally, with no exception to the project environment in T&T. Common delay factors in industry include: 1) poor workforce estimation (Adebowale and Smallwood, 2018), 2) inefficient site layouts (Almamlook et al., 2020), 3) capricious supply chain channels (Karia et al., 2021), 4) absence of standard work schedules (Sarmento and Ferreira, 2021), and 5) low worker motivation (Momade and Hainin, 2019). To combat these types of delays, the concepts and practices of both lean and productivity are considered.

Lean is a way of thinking about creating needed value with fewer resources and less waste that would lead to greater productivity and less delays in a project environment (Hassanali and Pun, 2021). Traditionally, productivity is the ratio of output to input (Dabirian et al., 2017). Many productivity studies (like, Durdyev and Hosseini (2019) and Ismaila et al. (2022)) identified a surfeit of factors that improve productivity. Moreover, studies exploring the relationship between lean and productivity in a project management (PM) context are rare. Studies (like, Fliedner, (2022), Fliedner and DeHondt (2015), and Tangl and Vajna (2018)) were primarily conducted in an operations management setting with limited studies in the PM field. By integrating the lean principles posited by Bertelsen (2002), productivity could be improved via: 1) establishing a standard workforce (Durdyev et al., 2012), 2) optimising the site layout (Schwabe et al., 2019), 3) establishing reliable supply chains (Luo et al., 2020), 4) establishing standard work schedules (Sobieraj and Metelski, 2022), and 5) employing motivation strategies (Azize, 2021).

Research efforts have not yet been able to provide a synthesised conceptual view on the potential synergies of the 'lean' and 'productivity' integration. This paper

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identifies critical LP factors in a project setting and determines the capability of individual LP factors in managing delays during project execution. It aims to develop a lean productivity framework (LPF) for facilitating capital projects deliveries in industrial firms by adopting the theory of planning as described by Koskela and Howell (2002a) and the theory of execution as interpreted by Koskela and Howell (2002b).

Following the introduction, Section 2 reviews the concepts constituting the building blocks of the LPF. Section 3 outlines the study methodology and Section 4 presents the empirical results of the LP study in T&T. In Section 5, the main components of the proposed framework are described, while Section 6 discusses its applications and concludes the study with recommendations for future work in sustaining PM practices in capital projects deliveries in T&T.

2. Literature Review

2.1 The Delay Factors

Delay is defined as the time overrun either beyond the completion date specified in a contract, or beyond the date that the parties agreed upon for delivery of a project (Awari et al., 2016). Delays often occur when the time required to complete projects is more than that which was specified in the contract (Al Hammadi and Nawab, 2016). It is critical to specify the actual causes of delay (Rashid, 2020). Manpower shortage and a lack of the requisite skills required to perform the job were critical contributors to project delay as posited by Oshungade and Kruger (2017). Poor site management and inefficient site coordination restricted the free-flow of project activities, thereby resulting in delays (Aziz and Abdel-Hakam, 2016). Besides, the late delivery of materials, equipment, and machinery on site led to interruptions in the workflow (Durdyev et al., 2017). Other delay factors include poor planning and scheduling (Adeyemi and Masalila, 2016), and the lack of commitment, motivation, and morale of the project workforce (Zaki et al., 2018).

2.2 Lean in Project Management

The rudimentary concept of ‘lean’ in PM is geared towards the elimination of waste from project activities to foster project success. It follows the production management philosophy for the optimal delivery of projects. Intended project deliverables are achieved via synergistic and systematic design and building processes and flows; with focus on continuous improvement (Sbiti et al., 2021). Recent studies have posited that project waste adversely impacts both the schedule and the budget (Mohammed and Khodier, 2017; Sarhan et al., 2017). In the delivery of capital projects, the main project phases include design, planning, construction, and control and monitoring (Aziz and Hafez, 2013). Babalola et al. (2019) identified four categories for lean PM tools implementation within these salient project phases; three of which are reviewed in this study. These include: 1) Design and Engineering practices, 2) Planning and Control Practices, and 3) Construction and Site Management Practices.

Under the Design and Engineering practices category, nine lean tools were found and are comprised of the following: 1) Visual design construction (Sarhan et al., 2017), 2) Design structure matrix (Johansen and Walter, 2007), 3) Prefabrication and modularisation (Hermes, 2015), 4) Detailed briefing (Anderson et al., 2012), 5) Design workshops/big room workshops (Vaidyanathan et al., 2016), 6) Integrated project delivery (Rached et al., 2014), 7) Target value design (Franco and Picchi, 2016), 8) Standardisation (Fernandes et al., 2016), and 9) Concurrent engineering (Ansah and Sorooshian, 2017).

The second category of Planning and Control Practices is comprised of nine lean practices. They support strategic decision-making at the preconstruction, construction planning, and control process (Babalola et al., 2019). These include: 1) Last planner system (Salvatierra et al., 2015), 2) Work structuring and scheduling (Murguía et al., 2016), 3) Location-based management system (Vaidyanathan et al., 2016), 4) Benchmarking (Johansen and Walter, 2007), 5) Six sigma (Ogunbiyi, 2014), 6) Value stream mapping or Value based management (El Sakka et al., 2016), 7) Daily cluster or Huddle meeting (Erol et al., 2017), 8) Pull scheduling/planning (Tillmann et al., 2015), and 9) Error proofing (poka-yoke) (Salem et al., 2005).

The third category, described as Construction and Site Management Practices, fosters appropriate management, organisation, and coordination of site activities at the construction phase of project delivery (Babalola et al., 2019). This category consists of 1) Gemba walks (Franco and Picchi, 2016), 2) Total productive/preventive maintenance (El Sakka et al., 2016), 3) Kanban system (Sarhan et al., 2017), 4) 5s onsite management (Li et al., 2017), 5) First run study (Ogunbiyi, 2014), 6) Kaizen (Aomar, 2012), 7) Teamwork and partnering (Erol et al., 2017), 8) Total quality management (Johansen and Walter, 2007), 9) Just-in-time (Nowotarski et al., 2016), 10) Visualisation tools/management (Limon, 2015), and 11) Conference management (Li et al., 2017).

Moreover, recent studies (like, Gomez-Cabrera et al. (2020) and Rosli et al. (2020)) explored the relationship between lean and project delays and identified a host of benefits from employing lean principles during the project’s lifecycle. The slow-paced adoption of lean practices in the project-based industry could be attributable to the fragmented nature of projects (Laryea and Ibem, 2014). This suggests that lean implementation in project-based settings is in the development stages (Babalola et al., 2019). Tzortzopoulos et al. (2020) purported the need for creating a synergistic interface between lean and other disciplines.

2.3 The Productivity Factors

2.3.1 Establishing a Standard Workforce (ESW)

Worker productivity was found to be an important factor affecting the time and cost parameters of projects (Moradi et al., 2017). Low productivity could have adverse effects on project performance (Anees and Sabarinathan, 2016). A recent study conducted by Hassanali and Pun (2022b) proposed methods for accurately computing the number of workers required to perform project activities, stressing the importance of ESW towards productivity improvements during execution.

2.3.2 Optimising the Site Layout (OSL)

Site layout planning is essential for making the most optimum use of the site space available (Ning et al., 2018), and fosters work efficiency and effectiveness by reducing the cost and time wastages present in inefficient site layouts (Said and El-Rayes, 2013). Moreover, OSL fosters improved project productivity (Hassanali and Pun, 2022a) that would facilitate smoother workflow and project processes.

2.3.4 Establishing Reliable Supply Chains (ERSC)

Supply chain management could provide capital projects with the capability to reduce its costs and increase its performance. Luo et al. (2020) highlighted the importance of supply chain planning and workflow control, while Masood et al. (2021) stressed the selection of competent suppliers (for materials and equipment). Hassanali and Pun (2022a) posited that ERSC efforts could facilitate the optimal flow of information from manufacturers and suppliers to project site storage facilities, thereby encouraging project productivity.

2.3.4 Establishing Standard Work Schedules (ESWS)

Standard work schedules can transition a project plan into execution activities (Al Farizi and Latief, 2018). Sobieraj and Metelski (2022) opined that the schedules should be realistic and capable of facilitating the proper coordination of activities. Sobieraj (2020) proclaimed the importance of standard scheduling. Moreover, productivity improvements can be realised by ESWS on project sites (Hassanali and Pun, 2022a).

2.3.5 Employing Motivation Strategies (EMS)

Classical motivation theories are often applied to increase productivity in projects. According to Dwivedula et al. (2012), there are three perspectives to work motivation, namely: 1) needs, drives, and traits (that are biological in nature); 2) context (that explains constructs such as job design and person-context fit, to define work motivation); and 3) cognition (that explains motivation as an outcome of one's (behavioural) self-regulation in relation to the context and needs/drives). Recent studies have emphasised the impact of motivation on worker productivity (Alaghbari et al., 2021; Azize, 2021; Hassanali and Pun, 2022a).

2.4 Matching the Lean Principles with Productivity

Figure 1 depicts the relationship between the lean principles and the productivity factors giving rise to the LP factors.

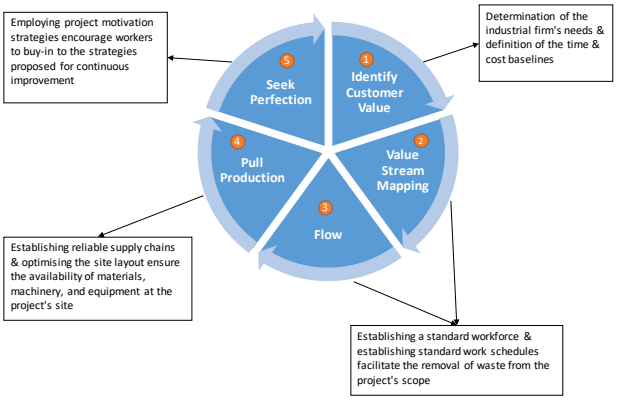

Figure 1. Relationship between the Lean Principles and the Productivity Factors

2.4.1 Lean Principle 1 - 'Value Proposition'

For this study, the "customer" refers to an industrial firm undertaking a capital project(s), while the "contractor" is the entity which serves the industrial firm (i.e., the customer) and is also referred to as "contracting firms" in later sections of this paper. The value proposition is thus geared towards achieving the project's schedule and budget baselines (i.e., without variances) in a sustainable manner. This first lean principle focuses on the contractor's ability to understand the customer's needs, to sustainably secure the project's time and cost baselines (see Figure 1).

2.4.2 Lean Principle 2 - 'Value Stream Mapping'

Value stream mapping (VSM) in a project context is premised on the identification of the non-value adding and/or non-essential activities from the project's scope. This lean principle is associated with two productivity factors, i.e., ESW and ESWS. Moreover, the project's budget (i.e., the cost of labour, material, machinery, equipment, and utilities) could be streamlined (see Figure 1).

2.4.3 Lean Principle 3 - 'Flow'

Flow is defined as the removal of the waste from the activities comprising the scope (Mohammed and Khodier, 2017). This lean principle is associated with ESW and ESWS. The standardisation efforts proclaimed by these productivity factors could allow for the removal of waste from the workforce in terms of overestimation and/or underestimation of workers; and from the project

schedules in terms of ensuring accurate assignment of manpower, materials, machinery, and equipment to the work activities (see Figure 1).

2.4.4 Lean Principle 4 - 'Pull Production'

Supply chain methods such as the supply chain operations reference (SCOR) model (Ntabe et al., 2014), and the plan, source, make, deliver, and return (PSMDR) concept (Venkataraman, 2007) were explored. This supports ERSC and OSL. This also facilitates the deployment of the 'pull production' lean technique to deliver materials, machinery, and equipment at the project site based on requirements stipulated in the standard project schedule (see Figure 1).

2.4.5 Lean Principle 5 - 'Perfection' and 'Continuous Improvement'

The 'perfection' state depended on the success of the previous four lean principles and could be achieved via the development and deployment of continuous improvement strategies. Moreover, EMS could facilitate the recognition and reward of the project workforce. This aspect is intended to encourage workers to buy in to the continuous improvement strategies proposed. Besides, teachings of the work design and motivation (Dwivedula et al., 2012) and the content theories and process theories (Seiler et al., 2012) added potent perspectives toward continuous improvement (see Figure 1).

3. Methodology

The research design consisted of two stages. Stage 1 explored the nexus of lean and productivity for developing the five LP factors (i.e., the literature review of Section 2). Stage 2 utilises the findings of Stage 1 to develop five study hypotheses to determine the impact of each LP factor on project delays in T&T. The findings of both stages were then fused to develop the proposed LPF. Figure 2 shows the relationship between each LP factor (i.e., independent variable) and its ability to prevent project delays (i.e., dependent variable).

Five (5) hypotheses were developed. These are:

- *Hypothesis 1*: Establishing a standard workforce (ESW) prevents delays during the execution of capital projects.
- *Hypothesis 2*: Optimising the site layout (OSL) prevents delays during the execution of capital projects.
- *Hypothesis 3*: Establishing reliable supply chains (ERSC) prevents delays during the execution of capital projects.
- *Hypothesis 4*: Establishing standard work schedules (ESWS) prevents delays during the execution of capital projects.
- *Hypothesis 5*: Employing motivation strategies (EMS) prevents delays during the execution of capital projects.

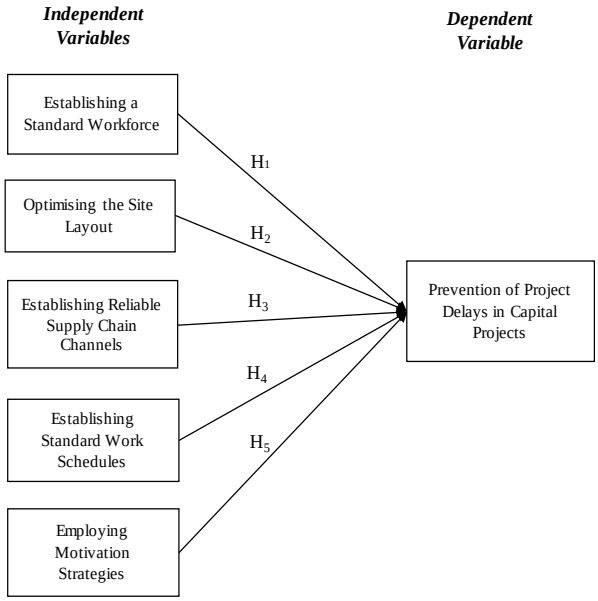

Figure 2. Relationship between the Independent and Dependent Variables

Hypotheses attainment would justify the inclusion of individual LP factors as building blocks of the proposed LPF. A semi-structured questionnaire was distributed to a purposively selected sample comprising of industrial and contracting firms in T&T obtained from 1) The Trinidad and Tobago Manufacturers' Association, 2) The Trinidad and Tobago Contractors Association, and 3) The Energy Chamber of Trinidad and Tobago (Hassanali and Pun, 2021). Contracting firms were included in the survey as their role in executing the industrial firm's capital projects is critical; therefore, their views were deemed necessary and valuable to the study.

The demographic data was obtained via the use of dichotomous questions. The need for effective planning and execution was measured using a five-point Likert scale, from 1-Strongly disagree to 5-Strongly agree. The delay factors were measured using a five-point Likert scale, from 1-Least severe to 5-Extremely severe; and the results indicated the level of severity each factor would have on project performance if it were to occur. The influencing factors were measured using a five-point Likert scale, from 1-Not important to 5-Extremely important; and the results measured the importance of each factor towards productivity improvements. SPSS for Windows, Version 27.0 (SPSS, 2020) was utilised for the statistical analyses of the data generated from the questionnaire survey.

A validity test was applied to the questionnaire construct using factor analysis. Composite reliability tests were then administered on the questionnaire construct. To determine whether to use parametric or non-parametric statistical tests, the Sharpiro-Wilk test was applied to test for normality of the data. Moreover, the weighted mean score and the standard deviation were

used to measure each delay factor and influencing factor. Table 1 depicts the methods adopted for the analysis of the questionnaire data.

In testing the validity of the findings, most of the factor loadings were ≥ 0.50 indicating that the questionnaire items loaded meaningfully on each respective factor category. The Kaiser-Meyer-Olkin (KMO) and Bartlett's test results confirmed sampling adequacy since KMO > 0.60 and $\rho < 0.001$. To elaborate, the recorded KMO value implied suitability of the data, while the significant Bartlett's test indicated the presence of relationships worth investigating within the factor analysis. It was found that the factor categories demonstrated good agreement, suggesting that the questionnaire items in each factor category sufficiently described that category.

Composite reliability was used to determine the reliability of the findings. These include 0.88 for the factor category of 1) Project Planning and Execution; and 0.86 and 0.75 for that of 'Challenges Impacting Project Performance' and 'Factors Influencing Project Productivity', respectively. The score for individual factor categories was found to be > 0.70, which indicated a good reliability status. Therefore, both the validity and the reliability test results substantiated the suitability of the questionnaire design. Moreover, the Sharpiro-Wilk test was performed to determine whether parametric or non-parametric statistical tests are used. It was found that all question items were statistically significant, and therefore the null hypothesis (i.e., the dataset follows a normal distribution) was rejected since $\rho < 0.001$. Since the data did not meet the requirements for normal distribution, a non-parametric inferential test, namely Spearman's Correlation Coefficient, was adopted.

4. Results and Discussion of Findings

4.1 Response Rate and Respondents' Demographics

A total of 152 questionnaires were dispatched, of which 92 complete questionnaires were received, yielding a response rate of 60.5%. This response rate was considered adequate for the purpose of this study. The demographic profile of the respondents is summarised in Table 2. As shown, project practitioners were targeted by two types of firms, namely industrial firms (53.3%) and contracting firms (46.7%). Respondents from small (21%), medium (40%), and large (39%) firms comprising the manufacturing (35.9%), construction (30.8%), and oil and gas (33.3%) sectors in T&T; provided valuable feedback. Most of the respondents resided at the upper management level (62%), which indicated management's commitment to project success; albeit the middle (26%) and the lower (12%) management levels feedback were also important. The respondents' academic qualifications ranged from diplomas to doctorates, where 92.4% of practitioners were found to be qualified at the Bachelor's and the Master's level (combined). Moreover, 60% of the respondents possessed at least 10 years' project experience with 78% of the respondents being older than the age of 35 years. The participants' responses were found to be credible and suggested data validity.

4.2 Analysis of Findings

The study measured the importance of the planning and execution phases toward productivity improvements and delay prevention. The severity of each delay factor was measured along with the importance of individual LP factors towards productivity improvements.

Table 1. Methods Adopted for Analysis of the Questionnaire Data

No.	Tests Performed	Measure	Purpose of the Tests or Analysis
1	Construct Validity Test	Factor Analysis (Principal Components Analysis)	Validity of the Construct
2	Construct Reliability Test	Composite Reliability	Reliability of the Construct
3	Test of Normality	Sharpiro-Wilk Test	Parametric and Non-parametric Tests
4	1) Weighted Mean Score, and 2) Standard Deviations	1) Weighted Mean Score, and 2) Standard Deviations	Validation of the Study Hypotheses
	Tests of Association	Spearman's Rank Correlation Coefficient (ρ)	

Table 2. Profile of Study Subjects

No.	Attribute	Frequency			
1	Type of firms under study	Industrial Firms = 53.3%	Contracting Firms = 46.7%		
2	Size of firms	Small = 21%	Medium = 40%	Large = 39%	
3	Sectors targeted	Manufacturing = 35.9%	Construction = 30.8%	Oil & Gas = 33.3%	
4	Respondents' management level within the firm	Lower = 12%	Middle = 26%	Upper = 62%	
5	Respondents' academic qualifications	Diploma = 6.5%	Bachelor's = 34.8%	Master's = 57.6%	Doctoral = 1.1%
6	Respondents' years of Project Management experience	< 5 years = 12%	5-10 years = 28%	10-15 years = 27%	> 15 years = 33%
7	Respondents' age	25-35 years = 22%	35-45 years = 45%	45-55 years = 16%	> 55 years = 33%

Source: Adopted from Hassanali and Pun (2022a)

The acceptance criteria for each of these were a weighted mean score of ≥ 3.5 and a standard deviation (SD) value of < 1.0. Furthermore, the strength of the relationship between the delay factors and the influencing (LP) factors was measured using Spearman's Rank Correlation Coefficient (ρ). The acceptance criteria were a value of significance $\rho < 0.05$ and a $\rho > 0.35$ (Akoglu, 2018). The results validated the components and elements of the proposed LPF and are summarised in Table 3.

4.2.1 The Need for Project Planning and Execution

Practitioners strongly agreed that incorporating a robust planning element to project delivery could improve productivity during execution since the mean score was found to be 4.57 with a SD of 0.617. Moreover, effective project planning reduced the chance of delays during project execution (mean = 4.63, SD = 0.549) in T&T.

4.2.2 Hypothesis 1 - Impact of Standardising the Workforce on Project Delay

Poor workforce estimation could impact performance during the execution of capital projects. Practitioners found this delay factor to be severe (mean = 4.11 and SD = 0.883). ESW was important for fostering productivity improvements (mean = 4.60 and SD = 0.536). There was a positive and moderately strong relationship between the severity of delays and the importance of ESW (ρ = 0.365). The correlation was significant (ρ = 0.001). By having the right number of workers available to execute the task with the right skillset, productivity could be improved thereby preventing delays attributable to understaffing (or overstaffing) during project execution in industrial firms. Hypotheses 1 was validated and ESW was determined as an important LPF component (see Table 3).

4.2.3 Hypothesis 2 - Impact of Optimising the Site Layout on Project Delay

Inefficient site layout could negatively affect project performance. Practitioners found this delay factor to be moderate to severe (mean = 3.73 and SD = 0.853). OSL was important for stimulating improvements in productivity (mean = 4.02 and SD = 0.771). The correlation was significant (ρ = 0.001) between the severity of delays due to an inefficient site layout and the importance of OSL. The relationship was found to be positive and strong (ρ = 0.547). Organising material, machinery, and equipment in a manner that improves the coordination of site activities could lead to an increase in productivity. The pitfalls related to the poor layout of site resources could be managed during project execution. Hypothesis 2 was validated and ESW was selected for the proposed LPF (see Table 4).

4.2.4 Hypothesis 3 - Impact of Establishing Reliable Supply Chains on Project Delay

Unreliable supply chains could adversely impact performance during project execution. Practitioners found this delay factor to be severe (mean = 4.40 and SD = 0.727). ERSC was important for strengthening productivity (mean = 4.54 and SD = 0.563). There was a positive and strong relationship (ρ = 0.462) between the severity of delays due to unreliable supply chains and the importance of ERSC. The correlation was significant (ρ = 0.001). Productivity could be improved by ensuring that material, machinery, and equipment are readily available on site. The issue of delays appertained to resources unavailability could be managed during the execution of capital projects. Therefore, Hypothesis 3 was validated and ERSC constitutes the proposed LPF (see Table 3).

Table 3. A Summary of the Study Findings

Delay Factors	Mean and Std. Deviation	Influencing (LP) Factors	Mean and Std. Deviation	Spearman's Correlation Coefficient	Significance (2-tailed)	Decision	Results	Inclusion within the Framework?
Severity of delays due to poor worker estimation	Mean = 4.60 SD = 0.536	Importance of establishing a standard workforce	Mean = 4.11 SD = 0.833	0.365	0.001	Reject the Null Hypothesis, since the correlation is significant at the 0.01 level (2-tailed)	There is a positive and moderately strong relationship between both factors	Yes
Severity of delays due to an inefficient site layout	Mean = 4.02 SD = 0.771	Importance of optimising the site layout	Mean = 3.73 SD = 0.853	0.547	0.001	Reject the Null Hypothesis, since the correlation is significant at the 0.01 level (2-tailed)	There is a positive and strong relationship between both factors	Yes
Severity of delays due to unreliable supply chain management	Mean = 4.54 SD = 0.563	Importance of establishing reliable supply chains	Mean = 4.40 SD = 0.727	0.462	0.001	Reject the Null Hypothesis, since the correlation is significant at the 0.01 level (2-tailed)	There is a positive and strong relationship between both factors	Yes
Severity of delays due to inadequate scheduling of resources	Mean = 4.51 SD = 0.564	Importance of establishing standard work schedules	Mean = 4.27 SD = 0.800	0.393	0.001	Reject the Null Hypothesis, since the correlation is significant at the 0.01 level (2-tailed)	There is a positive and moderately strong relationship between both factors	Yes
Severity of delays due to low worker motivation	Mean = 3.98 SD = 0.825	Importance of employing motivation strategies	Mean = 3.97 SD = 0.931	0.565	0.001	Reject the Null Hypothesis, since the correlation is significant at the 0.01 level (2-tailed)	There is a positive and strong relationship between both factors	Yes

4.2.5 Hypothesis 4 - Impact of Establishing Standard Work Schedules on Project Delay

Inadequate scheduling of resources could unfavorably affect performance during project execution. Practitioners found this delay factor to be severe (mean = 4.27 and SD = 0.800). ESWS was important for encouraging increased levels in productivity (mean = 4.51 and SD = 0.564). The correlation between the severity of delays due to inadequate scheduling and the importance of ESWS was significant (ρ = 0.001). The relationship was found to be positive and moderately strong (ρ = 0.393). This association indicated that productivity could be improved by ensuring accurate assignment of manpower, materials, machinery, and equipment to work activities. Inaccurate allocation of work resources could thus be managed during the execution of capital projects. Hypothesis 4 was validated and ESWS was justified for the proposed LPF (see Table 3).

4.2.6 Hypothesis 5 - Impact of Employing Motivation Strategies on Project Delay

Low worker motivation and morale could adversely impact performance during project execution. Practitioners found this delay factor to be severe (mean = 3.97 and SD = 0.931). EMS was important for fostering productivity improvements (mean = 3.98 and SD = 0.825). There was a positive and strong relationship between the severity of delays due to low worker motivation and the importance of EMS (ρ = 0.565). The correlation was significant (ρ = 0.001). Productivity could be improved by trusting, recognising, and rewarding workers. Any demotivated workforce could be managed during project execution. Therefore, Hypothesis 5 was attained, and EMS constituted the proposed LPF (see Table 3).

5. A Proposed Lean Productivity Framework

The study proposes a unique configuration of the five LP factors that foster the delivery of capital projects in industrial firms. From the survey results outlined in subsection 4.2.1, practitioners participating in the T&T-based study endorsed the importance of both the planning and execution project phases. To further this sentiment in the framework's design, the 'Planning' component was derived from the theory of planning advocated by Koskela and Howell (2002a) and the 'Execution' component was borrowed from the theory of execution advocated by Koskela and Howell (2002b). Figure 3 shows the skeleton of a proposed Lean Productivity Framework.

5.1 The Planning Component

Project planning is an essential component of the framework, which is composed of two parts, namely, the planning part (i.e., management-as-planning) and the organising part (i.e., management-as-organising) (Koskela and Howell, 2002a, b). The planning part consists of creation, revision, and implementation of the project plans, and is further categorised into two subparts, namely: a managerial subpart and an effector sub-part, where the principal function of the managerial subpart is planning, and the main function of the effector subpart is to translate the resultant plan into action.

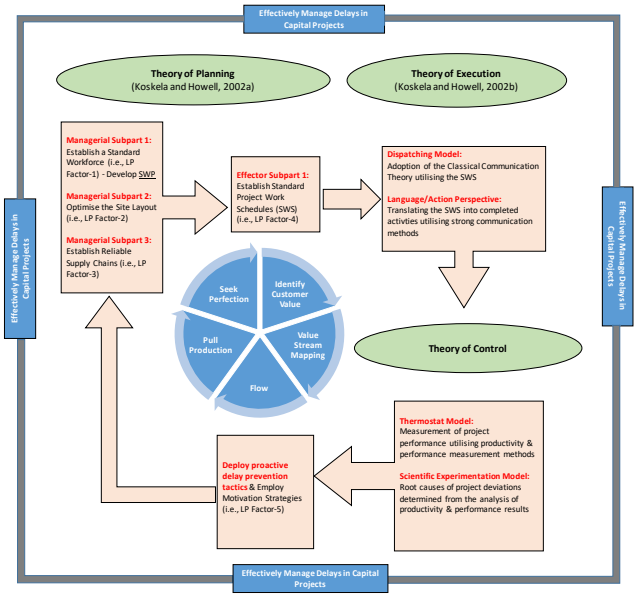

Figure 3. Skeleton of the Proposed Lean Productivity Framework

To incorporate the LP factors, the ESW (LP Factor-1), the OSL (i.e., LP Factor-2), and the ERSC (i.e., LP Factor-3) were categorised as the primary planning elements (i.e., the managerial subpart); while the ESWS (i.e., LP Factor-4) is the method of translating the plan into action (i.e., the effector subpart). Both parts utilised lean principles like VSM, flow, and pull production. A detailed analysis of the relationship between each LP factor and the managerial and effector sub-parts are explained, as follows:

5.1.1 Managerial Subpart 1 – Establishing a Standard Workforce (ESW)

As depicted in Figure 3, several criteria were considered for the ESW design (i.e., LP Factor-1), namely: 1) determining the standard number of workers (SW) with the right skillset required to complete each work activity, 2) defining the standard activity duration (SAD) for each work activity (in hours), 3) defining the standard labour cost per hour (SLC) for each activity, and 4) developing the standard work packages (SWP), inclusive of the SW, SAD, and the SLC components. Moreover, the SWP is the key output of this managerial subpart.

5.1.2 Managerial Subpart 2 – Optimising the Site Layout (OSL)

There were two key elements to OSL (i.e., LP Factor-2),

namely: 1) methods for organising material, machinery, equipment, and utilities to improve the coordination of site activities; and 2) setting predefined work zones both at the industrial firm's (customer) site, as well as at the contracting firm's (contractor) site (see Figure 3). Considerations were given to the guidelines prescribed by Jergeas (2009) for project site optimisation.

5.1.3 Managerial Subpart 3 – Establishing Reliable Supply Chains (ERSC)

This LP Factor-3 incorporated three attributes of Just-In-Time (see Figure 3). These include: 1) methods to ensure material availability, 2) methods to guarantee machinery and equipment availability, and 3) methods to provide the requisite utilities, like electricity, water, and waste disposal units; to ensure smooth site operations during execution. These attributes were in line with the SCOR model (Ntabe et al., 2014) and the PSMDR framework (Venkataraman, 2007).

5.1.4 Effector Subpart 1 – Establishing Standard Work Schedules (ESWS)

The effector subpart 1 was focused on this LP Factor-4. The standard work schedules essentially transitioned the plan into action during execution. There were four ESWS criteria, including:

1) The standard work schedule for a specific day with the specified SWP clearly defined (inclusive of the SW, SAD, and the SLC components of the Managerial Subpart 1),
2) Project work area assigned for each SWP, ensuring smooth coordination efforts on site (i.e., the Managerial Subpart 2),
3) The availability of material, machinery, equipment, and utilities in accordance with the SWP scheduled for the specified workday (i.e., the Managerial Subpart 3), and
4) Prioritisation of the SWP to ensure that the critical work activities are performed prior to the non-critical work activities (as outlined by de Miranda Mota et al., 2009).

Moreover, the generation of a daily standard work schedule confirmed that the necessary resources (i.e., workforce, material, machine, equipment, and utilities) were readily available, and the priorities were properly identified ahead of execution.

5.2 The Execution and Control Components

Project execution and control are two critical components of the framework (see Figure 3), namely: 1) the dispatching model, and 2) the language/action perspective. Execution is related to the dispatching of tasks to workstations and is referred to as the classical communication theory (Koskela and Howell, 2002b). On one hand, the dispatching model requirements were accomplished by way of the standard work schedule, which included daily work activities compartmentalised into specific work areas; indicating the quantum of labour, material, machinery, equipment, and utilities required at each workstation. On the other hand, classical communication theory emphasised the concept of two-way communication and commitment (Koskela and Howell, 2002b). The concept is reliant on the effective use of a defined feedback mechanism, to ensure the successful execution of the standard work schedule. The feedback mechanism comprised the monitoring and controlling component of execution, where the concepts derived from the theory of control were adopted. This feedback loop provided a means to EMS (i.e., LP Factor-5).

Expanding on the theory of control, two models were utilised, namely: 1) the thermostat model, and 2) the scientific experimentation model. For the application of the thermostat model, the standard work schedule was adopted, where its work contents were translated into actual work performed and then measured and controlled by a set of productivity and performance measurement methods (i.e., metrics to be developed). The conditions of the thermostat model were satisfied by the ability to measure and control the progress of work during execution. Moreover, the framework incorporated the aspect of learning i.e., the monitoring and controlling component of execution, which allowed for the identification and qualification of project deviations. Based on the recorded daily results of productivity and performance, the causal impacts of those variations (i.e., the scientific experimentation model) would allow project practitioners to respond.

6. Discussion and Conclusion

6.1 Applying Lean Productivity Concepts to Tackle Project Delays

The LP concept is deficient within the PM discipline. Industrial firms need to know how their capital projects are delivered in line with the global movement towards a clean energy future. The on-time delivery of projects is critical, therefore delay prevention is of utmost importance (Hassanali and Pun, 2021). This study utilised the lean principles advocated by Bertelsen (2002), and the five productivity factors posited by Hassanali and Pun (2022a) within a project context. Practitioners could maximise productivity while minimising waste during project execution.

As depicted in the LPF (see Figure 3), the planning phase includes the ESW (i.e., LP Factor-1) to ensure the right number of workers with the right skillsets are available to perform the project activities. This ensures that the required material, machinery, equipment, and utilities are readily available by way of ERSC (i.e., LP Factor-3); along with the OSL (i.e., LP Factor-2). These three LP factors set the platform for the ESWS (i.e., LP Factor-4) using lean principles like VSM, flow, and pull production. These would facilitate a smooth flow of

work activities during execution and control which could result in a more motivated workforce (i.e., LP Factor-5). Moreover, adopting the proposed framework could foster continuous improvement and mitigate delays for either prevention (i.e., a proactive approach), or immediate correction (i.e., before minor variations become exacerbated).

6.2 LP-Sustainability Implications on Industrial Firms

From both economic and environmental perspectives, factors like ESW (i.e., LP Factor-1), OSL (i.e., LP Factor-2), ERSC (i.e., LP-Factor 3) could assist industrial firms in reducing their wastes in man-hour costs, unnecessary movements on project sites, variability in workflow, and material purchasing; thereby fostering sustainable supply chains. ESWS (i.e., LP Factor-4) ensures that the right project activities are performed in a way that balances the sustainable use of resources on site with a focus on the on-time completion of critical activities to ensure that delays are prevented. These efforts enable improved levels of project quality and environmental considerations. Through a social lens (i.e., relationship-based and people satisfaction), ERSC (i.e., LP Factor-3) could accommodate improved supplier relationships, while ESWS (i.e., LP Factor-4) could facilitate increased work efficiency and improved labour productivity in industrial firms. Optimising the site layout (i.e., LP Factor-2) could encourage efficient coordination on project sites. Moreover, EMS (i.e., LP Factor-5) could be obtained via increased worker satisfaction and cooperation among the project stakeholders.

6.3 Conclusion

In T&T, industrial firms comprising the manufacturing, construction, and oil and gas sectors have a direct influence on the economy, society, and the environment. There is a need to combat the issues of delays in the delivery of capital projects in industrial firms. Factors like poor workforce estimation, inefficient site layouts, unreliable supply chains, absence of standard work schedules, and low worker motivation have had a debilitating impact on project delivery. This paper investigated lean principles and productivity factors and examined them in facilitating PM practices and capital project deliveries in industrial firms. Empirical evidence shows that delays could be managed via establishing a standard workforce, optimising the site layout, establishing reliable supply chains, establishing standard work schedules, and employing motivation strategies. Project wastes could be removed from the project activities, thereby guaranteeing the availability of resources (i.e., manpower, material, and machinery) in the right quantities and at the right time. Adopting the proposed LPF could guide industrial firms towards the attainment of their economic, social, and environmental goals.

A smooth implementation of the LPF would require a pragmatic implementation strategy to support practitioners, service providers, and other users in industry. The development of an implementation guide would thus form an integral part of future work. Besides, the empirical data was acquired from industrial firms representing three selected sectors in T&T. Views from practitioners engaged in the delivery of projects in other sectors were not able to be incorporated into this study. Future studies would thus expand the scope of other sectors in T&T. Moreover, improvements to external validity and the generalisation of the results could validate the efficacy and the suitability of the proposed framework in industry.

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The Use of Cloud Optical Depth in the Assessment of Solar Resource Potential in the Lower Caribbean Region

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Abstract: *This paper proposes a computational method to assess the solar resource potential in the lower Caribbean region. This method uses a novel combination of remotely sensed high-resolution cloud optical depth data and terrain shadowing effects. Clear-sky and all-sky irradiance components are determined from air pressure, precipitable water, aerosol optical depth, Angstrom exponent, and cloud optical depth data. The r.sun algorithm requires digital elevation maps as input and is utilised to examine terrain shadowing effects. The method predicted irradiance with an accuracy that is comparable to, and in some cases better than, corresponding estimates from the National Solar Radiation Database and the Copernicus Atmosphere Monitoring Service Radiation Service. Earlier solar forecasting methods used numerical computer simulations to integrate high-resolution cloud data. In contrast, this approach is more efficient in terms of computational resources. In addition, it may be extended to a finer spatial analysis by increasing the resolution of the digital elevation maps used. The method was also used to determine solar maps for Trinidad and Tobago, which has few ground irradiance measurements. Solar maps for the year 2021 were produced using weekly average data to reduce computation time. The yearly average global horizontal solar map had a mean absolute percentage error of 5.63% when compared to the corresponding map from the Global Solar Atlas. Case studies of photovoltaic energy potential were conducted at seven locations within Trinidad and Tobago. The predicted photovoltaic energy potential had percentage differences between 2.5% and 15.5% when compared to corresponding values from the Global Solar Atlas. The solar forecasts presented in this study have wide applicability because they can be utilised in different locations owing to the wide-spread availability and open-source nature of the required datasets.*

Keywords: *Terrain shadow, solar irradiance map, renewable energy, geographic information systems*

Nomenclature

Symbol	Definition
m	Absolute airmass
T_L	Linke turbidity factor
α	Angstrom exponent
Δ_{cda}	Clean dry atmosphere panchromatic optical depth
Δ_w	Water vapour panchromatic optical depth
Δ_a	Aerosol panchromatic optical depth
I_0	Extraterrestrial irradiance (W/m^2)
B_0	Direct normal irradiance (W/m^2)
G_h, B_h, D_h	Global, direct, and diffuse horizontal all-sky irradiances
G_{hc}, B_{hc}, D_{hc}	Global, direct, and diffuse horizontal clear-sky irradiances
K_c, K_c^b, K_c^d	Global, direct, and diffuse clear-sky indices
δ	Bounded cloud optical depth
n	Fractional cloud cover

Abbreviations

AWS	Amazon Web Services
BSRN	Baseline Surface Radiation Network
COD	Cloud Optical Depth
CPS	Cloud Particle Size
DHI	Diffuse Horizontal Irradiance
DNI	Direct Normal Irradiance
GHI	Global horizontal irradiance
GOES	Geostationary Operational Environmental Satellites
MAPE	Mean Absolute Percentage Error
MRE	Mean Relative Error
MIT	Missing Imputation Task
NOAA	National Oceanic and Atmospheric Administration
ORT	Observed Reconstruction Task
PV	Photovoltaic
RNN	Recurrent Neural Network
SAITS	Self-Attention-based Imputation for Time Series
SARIMA	Seasonal autoregressive integrated moving average
SI	Scatter-index
SVM	Support vector machine
RMSE	Root mean squared error
TFT	Temporal Fusion Transformer
TPE	Tree-structured Parzen Estimator
WCRP	World Climate Research Programme

1. Introduction

Recent advances in solar forecasting, highlighted by McCandless and Jiménez (2020), have underscored the advantages of employing high-resolution satellite data in

recent solar forecasting studies, as opposed to using data of lower resolution. This paper builds on these advances, utilising recent Geographic Information System (GIS) methods (Neteler et al., 2012) which offer a less computationally intensive solution even when processing high-resolution satellite data. This approach contrasts with traditional methods employed in solar forecasting studies, such as those of Cros, Sylvain et al. (2020) and Kallio-Myers et al. (2022), which rely on complex numerical weather prediction (NWP) algorithms. NWP models, while effective, demand significant computational resources due to the complexity of solving partial differential equations that simulate atmospheric physics.

The solar forecasts presented in this study are widely applicable due to the use of readily accessible and open-source datasets. The study uses high-resolution cloud optical depth data from the GOES-16 satellite (GOES-R Series Program, 2017) and terrain shadowing effects derived from digital elevation maps. This wide applicability is underpinned using open-source GIS software and photovoltaic modelling packages (Holmgren et al., 2015), making the methodology accessible for further research and application in various geographical contexts.

In terms of accuracy and reliability, this method compares well with established systems. The Copernicus Atmosphere Monitoring Service (CAMS) Radiation Service (CAMSrad), as discussed by Dragani et al. (2022), provides historical all-sky and clear-sky irradiance time series, drawing upon NWP data from the European Centre for Medium-Range Weather Forecasts (ECMWF) Integrated Forecasting System (IFS). This study demonstrates that the irradiance estimates achieve an accuracy comparable to CAMSrad. Our method determines clear-sky and all-sky irradiance components using a range of atmospheric data including air pressure, precipitable water, aerosol optical depth, and the Angstrom exponent. The r.sun algorithm (Šúri and Hofierka, 2004), integral to the approach, requires digital elevation maps to analyse terrain shadowing effects. Our results, based on these methodologies, predict irradiance with an accuracy that matches or exceeds estimates from the National Solar Radiation Database and CAMSrad.

The following outlines the framework of this study. Section 1.1 provides an energy overview of Trinidad and Tobago. Section 1.2 is a review of past attempts at mapping solar resources in the Caribbean. Section 2.1 describes the satellite reanalysis products, ground irradiance observations and elevation data used to compute irradiance maps. Section 2.2 defines the irradiance components (beam, diffuse and global) considered in this paper. Section 2.3 considers the application of the Linke turbidity factor (which measures atmospheric radiation attenuation due to aerosols and water vapor) to clear-sky irradiance models. Clear-sky irradiance models estimate solar radiation under the assumption of a cloudless sky, whereas all-sky irradiance models incorporate cloud cover. Section 2.4 outlines the DIRINT model which is used to estimate beam and diffuse irradiance components from global horizontal irradiance. Clear-sky indices are defined as the ratio between overcast and clear-sky irradiance values. Section 2.5 considers the computation of all-sky irradiance time series from Linke turbidity, cloud optical depth and clear sky indices. Additionally, elevation data and the r.sun function are used to model terrain shadowing.

The predictions of the all-sky irradiance models are validated against ground observations at five locations in Section 3.1. In Section 3.2, solar irradiance maps for beam, diffuse and global components are developed for Trinidad and Tobago using methods comparable to those used to determine all-sky irradiance time series in Section 2.5. An application example of using the solar irradiance models to estimate photovoltaic yield at seven locations in Trinidad and Tobago with differing cloud cover and terrain is given in Section 3.3.

1.1 Energy Overview of Trinidad and Tobago

Trinidad and Tobago is a twin island country located in the southern Caribbean, approximately 11 kilometres off South America. Its economy is heavily dependent on its energy sector, which is mainly based on oil and natural gas. As shown in Figure 1, since the start of the 21st century, the per capita energy consumption of the country has surpassed that of many developed nations (Ritchie et al., 2014).

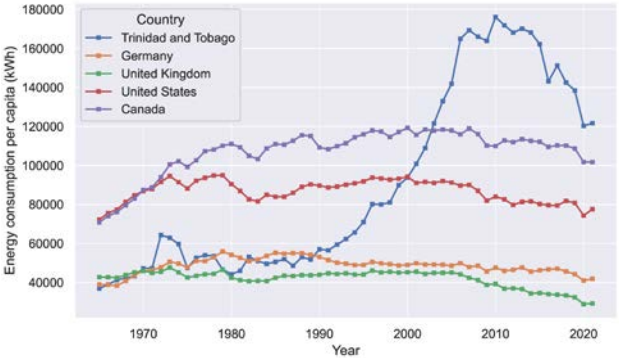

Figure 1. Energy Consumption per Capita
Source: Abstracted from Ritchie et al. (2014)

Most of its 2118 MW electrical capacity (Caribbean Centre for Renewable Energy and Energy Efficiency, 2022) comes from natural gas (Ministry of Energy and Energy Industries, 2022a). The contribution from renewables is usually under 1%, as indicated in Figure 2.

In 2016, Trinidad and Tobago's government announced a plan to source 10% of its electricity from renewable energy by 2021 (Ministry of Finance, 2015). Currently, two solar farms are under construction, and are expected to start operating in late 2024 (Loop News, 2022). Additionally, the government is working on a

wind resource assessment to identify potential wind farm locations (Ministry of Energy and Energy Industries, 2022b). Developing a similar assessment for solar farms will help identify suitable locations in Trinidad and Tobago, aiding in effective energy planning.

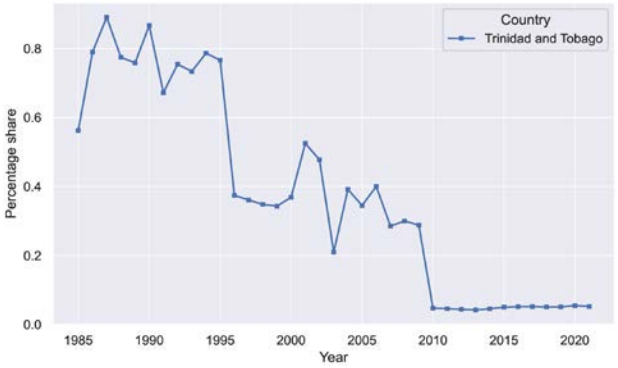

Figure 2. Percentage Share of Electricity Production from Renewables in Trinidad and Tobago
Source: Adopted from Ritchie et al. (2014)

1.2 Previous Solar Resource Studies in the Caribbean

Basnayake (1968) produced two solar maps of Barbados for June 18, 1964, and December 28, 1964, using Ohmura's (1968) method. Basnayake used topographical maps to create slope and aspect maps and approximated optical airmass using solar position. The assumption of constant transmissivity by Basnayake implies that his maps did not account for cloud variation over time and space, nor did they allow for terrain shadowing. The methods in this paper improve upon Basnayake's methods by incorporating spatiotemporal cloud data and terrain shadowing, essential for accurate photovoltaic system assessment.

Amarakoon and Chen (1999) estimated the daytime net surface radiation of Jamaica, utilising meteorological data collected over eight years from three different sites. Their model primarily employs air temperature and global shortwave radiation to detect daytime net surface radiation, omitting the need for surface temperature and long-wave radiation data. The temporal resolution of the estimates is significantly higher than those of Amarakoon and Chen.

De Souza and Andrews (2015) also evaluated several models of estimating solar radiation for the island of Trinidad. These were based on varying temporal resolutions of the Angström-Prescott model (Prescott 1940), which estimates global solar radiation on a horizontal surface using the average fraction of daylight hours. The Angström-Prescott model is best suited for estimating irradiance on longer time scales and cannot be applied to hourly intervals. The models created by De Souza are, however, still applicable to solar assessment methods, which do not depend on intraday time series data. This limitation is not present in this paper as the use of high temporal resolution cloud data allowed for the construction of hourly time series irradiance estimates.

2. Problem formulation

2.1 Data sets

The Modern-Era Retrospective Analysis for Research and Applications Version 2 (MERRA-2) provides hourly global reanalysis data at 50 km spatial resolution that are derived from satellite observations of aerosols. In this study, the M2I1NXLFO (Land Surface Forcings), M2T1NXAER (Aerosol Diagnostics), and M2T1NXSLV (Single Level Diagnostics) datasets of MERRA-2 were used (Global Modeling and Assimilation Office, 2015a, 2015b, 2015c). Variables from these data sets were used to determine Linke turbidity and cell temperatures of solar panels.

The National Oceanic and Atmospheric Administration (NOAA) Geostationary Operational Environmental Satellites (GOES) provide high-resolution satellite images through the noaa-goes Amazon Web Services (AWS) database (GOES-R Series Program, 2017). In particular, the GOES-16 EAST satellite delivers images of several atmospheric measurements (called GOES products) for the western hemisphere at a spatial resolution of 4 km (GOES-R Series Program 2019b). The Cloud Optical Depth (COD) GOES-16 product was used in this study to model cloud cover, as it is a measure of how opaque or transparent a cloud is to sunlight (Heidinger et al., 2020).

The Baseline Surface Radiation Network (BSRN) is a project established in 1992 with the aim of producing, collecting, and archiving high quality ground-based radiation measurements (Driemel et al., 2018). The BSRN consists of 74 stations which measure solar and atmospheric radiation at a high temporal resolution of one to three minutes (The Global Energy and Water Exchanges 2022). In this study, the BSRN data were accessed for the following stations: Paramaribo (Suriname), Desert Rock (United States), Florianopolis (Brazil), Observatory of Huancayo (Peru) and Rock Springs (United States) (Piters 2021, Augustine 2020, Colle 2020).

A digital elevation model (DEM) is a raster containing elevation data that is parameterised by a specified geographic coordinate system. In this study, the utilised DEMs had a 30-metre resolution and originated from data from the Shuttle Radar Topography Mission (Earth Resources Observation and Science Center, 2018).

Global Solar Atlas 2.0 (GSA) is a free web-based application that was developed by Solargis on behalf of the World Bank Group (World Bank, 2017). The GSA average daily total GHI and DHI maps for Trinidad and Tobago were compared with the corresponding maps generated using the methods. Also, the average daily totals for PVOUT and optimal tilt angles for seven locations in Trinidad and Tobago were used to validate

the power estimates. PVOUT is the photovoltaic power potential of a single kWp free-standing PV system with panels inclined at optimum tilt.

The National Solar Radiation Database (NSRDB) is a reanalysis project conducted by the National Renewable Energy Laboratory (NREL) that provides international solar irradiance time series (Sengupta et al. 2018). In this paper, 10-minute GHI, DHI and DNI with a 4-kilometre spatial resolution were obtained from the NSRDB. The solar irradiance time series obtained from the NSRDB were compared with the BSRN data to evaluate the relative performance of the model developed in this paper.

2.2 Irradiance Components

Solar irradiance is the power per unit area received from the Sun that is incident on a surface. The irradiance observed on the surface of the Earth is attenuated by the scattering, absorption, and reflection of light in the atmosphere. Figure 3 shows the global, beam (or direct), and diffuse irradiance components.

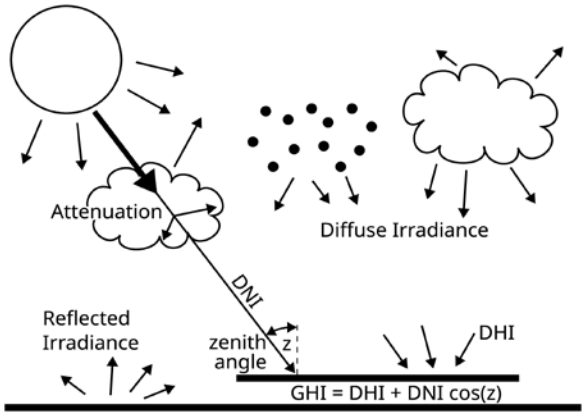

Figure 3. Irradiance Components

The total irradiance observed on a horizontal surface is called *global horizontal irradiance* (GHI) and is denoted by the symbol G_h. GHI may be decomposed as:

$$G_h = D_h + B_0 \cos(z) \quad (1)$$

where z is the solar zenith angle. Beam (or direct) irradiance consists of rays that originate from the direction of the Sun, excluding irradiance that is the result of scattering or reflection. Beam irradiance is usually measured either on a horizontal surface or on a surface normal to a ray from the Sun. In the latter case, it is called *direct normal irradiance* (DNI) and is denoted by the symbol B_0. However, when beam irradiance is measured on a horizontal surface, it is denoted by the symbol B_h. Diffuse irradiance does not originate directly from the Sun but is the result of the scattering of light by molecules and particles. When diffuse irradiance is measured on a horizontal surface, it is called *diffuse horizontal irradiance* (DHI) and is denoted by the symbol D_h.

Irradiance values that are derived under the assumption that there are no clouds are referred to as *clear-sky*, whereas irradiance derived or observed under general cloud conditions are referred to as *all-sky* (or *overcast*). Clear-sky irradiance symbols are indicated with an additional subscript 'c', and therefore clear-sky GHI, DHI and horizontal beam irradiance are denoted by the symbols G_{hc}, D_{hc} and B_{hc} respectively.

2.3 Linke turbidity and clear-sky irradiance

The *Linke turbidity factor* (T_L) measures the attenuation of radiation that occurs in the atmosphere due to aerosol and water vapour particles in relation to a clean and dry atmosphere (Šúri and Hofierka, 2004). In a perfectly dry and clean atmosphere, the Linke turbidity value would be one, while typical Linke turbidity values lie between two and eight (SoDa, 2010).

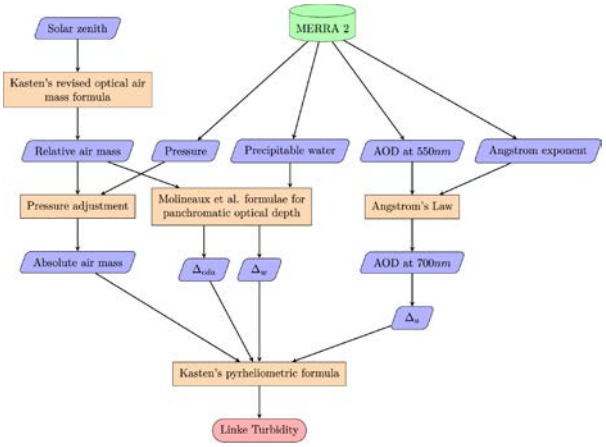

Figure 4. Algorithm to Compute Linke Turbidity

Larger Linke turbidity values correspond to decreased radiation and increased proportions of diffuse irradiance (Rathore et al., 2021), and as such, Linke turbidity values are used in the calculation of clear-sky irradiance estimates. Linke turbidity values were calculated for the five BSRN locations stated in Section 2.1 and for Trinidad and Tobago. Figure 4 illustrates the method of computing Linke turbidity using the pvlib function kasten96_lt (Holmgren et al., 2015).

In this paper, two clear-sky models were used to obtain clear-sky DNI, DHI and GHI irradiance components: the Ineichen-Perez model (Ineichen and Perez, 2002) and the simplified Solis model by Ineichen (2008b). The choice of clear-sky model at each BSRN station was made by comparing the DNI and DHI model components with the BSRN DHI observations. Figure 5 illustrates an example of this comparison where it may be seen that the simplified Solis model provides a more suitable model for clear-sky DHI than the Ineichen

model at the Desert Rock location. The tick marks are placed at the beginning of the day.

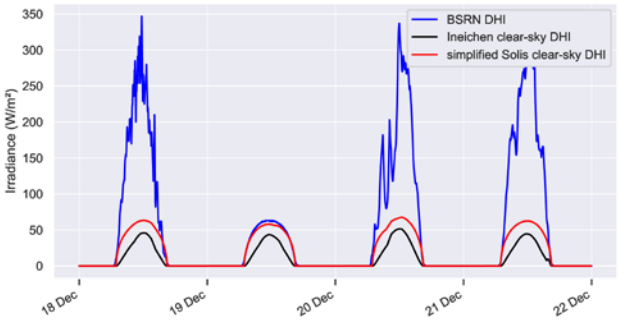

Figure 5. Clear-sky DHI Estimates (Ineichen, simplified Solis) and BSRN DHI Observations at Desert Rock, Nevada (18 December 2019 to 21 December 2019)

Input data for the Ineichen model include solar zenith angle, absolute airmass, and Linke turbidity. The input data for the simplified Solis model includes the solar elevation angle, the AOD at 700nm, and precipitable water. Note that Linke turbidity is not a required input for the simplified Solis model.

2.4. DIRINT Model and Clear-sky Indices

The calculations utilise the DIRINT model developed by Ineichen et al. (1992) to estimate both direct normal irradiance (DNI) and diffuse horizontal irradiance (DHI) using only global horizontal irradiance (GHI) as input. DIRINT enables this by enhancing the earlier DISC model proposed by Maxwell (1987). We implement DIRINT using the pvlib Python library, which requires inputs of GHI, solar zenith angle, and air pressure.

DIRINT also requires clearness indices, which are the ratios of surface radiation to extraterrestrial radiation. Specifically, DIRINT utilises global horizontal clearness index, K_t, and direct normal clearness index, K_n, which are defined as:

$$K_t = \frac{G_h}{I_0 cos(z)} \quad (2)$$

$$K_n = \frac{B_0}{I_0} \quad (3)$$

where I_0 is the extraterrestrial radiation.

Clear-sky indices are crucial for predicting all-sky irradiance, which includes the effects of cloud cover on solar irradiance. Note that the clear-sky indices should not be mistaken for the clearness indices mentioned above, as they are separate measures. Global, beam and diffuse clear-sky indices, as defined by Šúri and Hofierka (2004), are calculated as ratios of overcast to clear-sky irradiance for their respective components. These indices are denoted as K_c (global), K_c^b (beam) and K_c^d (diffuse) and are defined by:

$$K_c = \frac{G_h}{G_{hc}} \quad (4)$$

$$K_c^b = \frac{B_h}{B_{hc}} \quad (5)$$

$$K_c^d = \frac{D_h}{D_{hc}} \quad (6)$$

These clear-sky indices may be ratios of either instantaneous or aggregated irradiances and are required inputs for the r.sun function (see Section 2.5). The following empirical formulae formed a regression method that was used to estimate the clear sky index K_c using Cloud Optical Depth (COD):

$$\delta = min(\text{COD}, 100) \quad (7)$$

$$n = \frac{\delta - min(\delta)}{max(\delta) - min(\delta)} \quad (8)$$

$$K_c = k + (1-k)e^{-\alpha \times n} \quad (9)$$

where n is an estimate of the fractional cloud cover determined from the COD, and *min* (δ) and *max* (δ) are respectively the minimum and maximum of the time series δ in Equation (7). The values of k and α in Equation (9) were determined per location by minimising the root mean squared error of the predicted all-sky GHI time series when compared to BSRN GHI observations.

Given the calculation of the global clear-sky index K_c as described above, the beam and diffuse clear-sky indices K_c^b, K_c^d are subsequently ascertained through the procedure depicted in Figure 6.

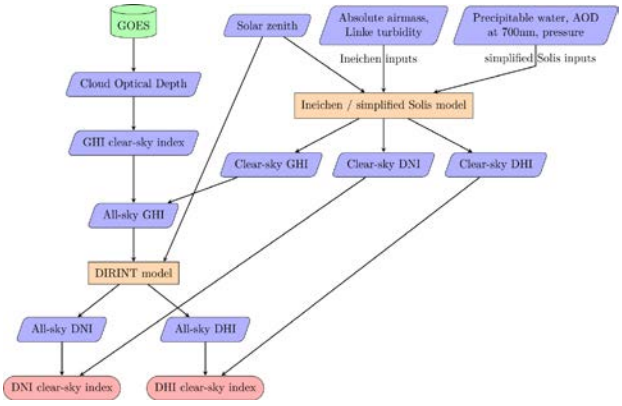

Figure 6. Algorithm for Computing Clear-sky Indices

We briefly describe this procedure. The choice of a clear-sky model (either Ineichen or simplified Solis) is made as described in Section 2.3. This clear-sky model outputs clear-sky estimates of GHI, DNI and DHI. The clear-sky GHI and the global clear-sky index K_c are used to determine all-sky GHI. The DIRINT model is applied to this all-sky GHI estimate to determine all-sky DNI and DHI estimates. Equations (5) and (6) are then used to calculate K_c^b and K_c^d which are required inputs for the r.sun function as examined in Section 2.5. The all-sky irradiance components determined above are henceforth

denoted as pvlib all-sky irradiance components since they were derived using the pvlib python package.

2.5 Determining all-sky irradiance using r.sun

The r.sun function in the GRASS GIS software (Šúri and Hofierka, 2004) utilises elevation data to account for the impact of terrain induced shadowing on the estimation of beam, diffuse, and global irradiance. The r.sun function can be used in instantaneous or daily mode. Figure 7 summarises the use of the r.sun function in this paper. In the following, an irradiance component determined using the r.sun function is called a r.sun all-sky irradiance component.

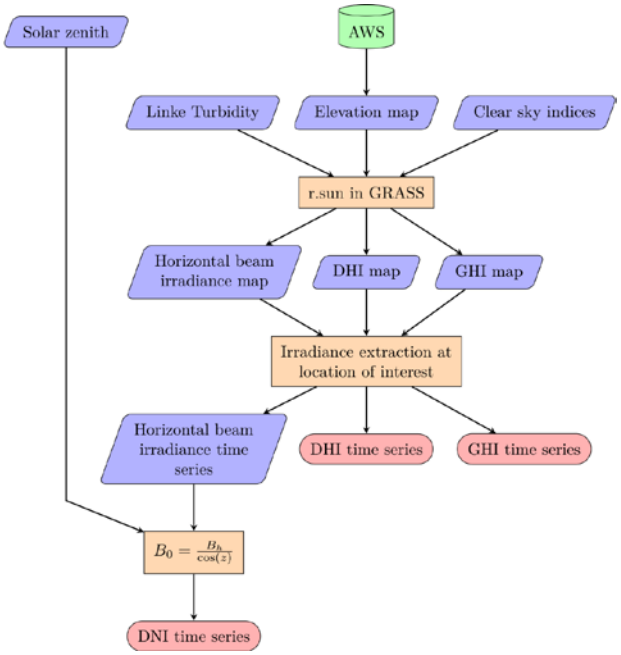

Figure 7. Using r.sun to Compute Beam, Diffuse and Global Irradiance Maps and Time Series

Instantaneous mode determines the irradiance at a specified date and time and was used to determine all-sky irradiance time series predictions. The daily mode determines the total irradiation for a given day and was used to determine the average all-sky irradiance maps, as described in Section 3.2. The r.sun function requires Linke turbidity, clear-sky indices, an elevation map, and panel slope and aspect as inputs. The outputs of r.sun are the irradiance components, which are resolved with respect to the slope and aspect of the panel. For the purposes of this analysis, the panel slope was set to zero to evaluate irradiance on a horizontal surface.

3. Results

3. Accuracy of the Model

This section examines the accuracy of solar irradiance estimates generated by the pvlib and r.sun methods described in Sections 2.4 and 2.5, by comparing them to ground observations from five Baseline Surface Radiation Network (BSRN) stations. Figures 8 to 10 compare the hourly averages of observed GHI, DNI, and DHI (from the Paramaribo BSRN station) with predicted values (from the pvlib and r.sun methods) from December 17-25. This short period of time was selected for visual clarity. These figures indicate that both methods predicted the three components moderately well, although r.sun overestimated the DHI.

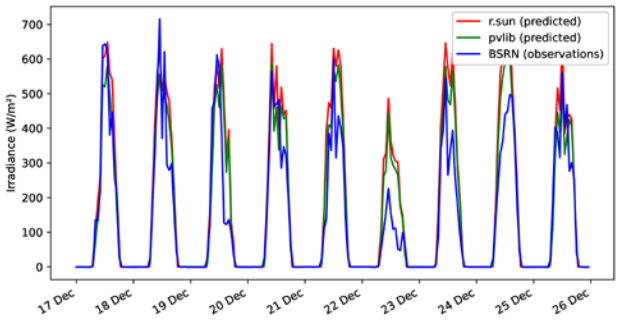

Figure 8. GHI Observations (BSRN) and Predicted Values (r.sun, pvlib) of Irradiance Components at Paramaribo, Suriname (17 December 2019 to 25 December 2019). The tick marks are placed at the beginning of the day.

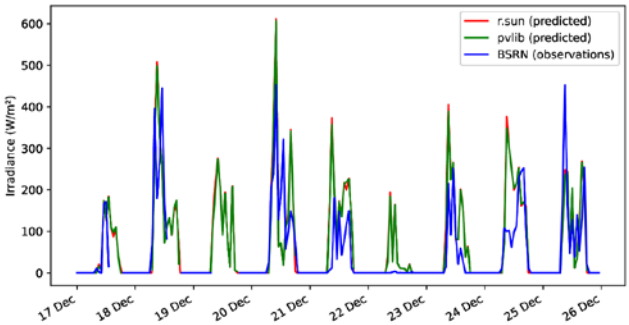

Figure 9. DNI Observations (BSRN) and Predicted Values (r.sun, pvlib) of Irradiance Components at Paramaribo, Suriname (17 December 2019 to 25 December 2019). The tick marks are placed at the beginning of the day.

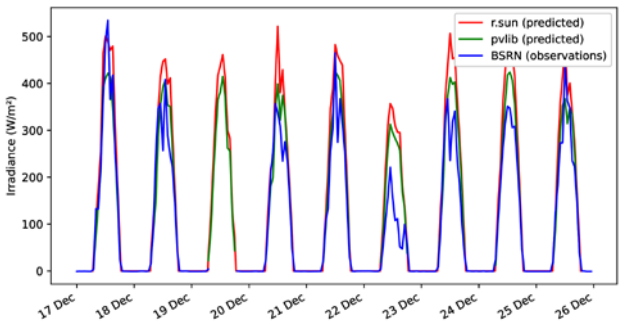

Figure 10. DHI Observations (BSRN) and Predicted Values (r.sun, pvlib) of Irradiance Components at Paramaribo, Suriname (17 December 2019 to 25 December 2019). The tick marks are placed at the beginning of the day.

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Pearson's correlation analyses between predictions of the all-sky irradiance model and BSRN observations were also performed in December 2019 at the five BSRN stations to evaluate the accuracy of the model. These are shown in Figures 11 to 13. These diagrams also contain correlations of NSRDB and CAMSRAD irradiance estimates with BSRN observations. Correlation values approaching one denote stronger positive linear correlations, while values near zero indicate weaker relationships. Overall, moderately strong positive Pearson coefficients were exhibited by both the pvlib and r.sun methods across the different irradiance components and BSRN sites. The pvlib correlations were generally higher than those for r.sun, especially in relation to estimating the GHI. The similar correlations of the pvlib and r.sun methods with the established NSRDB and CAMSRAD databases demonstrate that the methods achieve comparable predictive skill to these existing solar resources.

Regression analyses are performed to further examine the prediction biases exhibited by the pvlib and r.sun models. Figure 14 shows scatter plots of hourly GHI predictions versus BSRN observations, with data from all stations included. The regression slopes are positive but below one, intersecting the 1:1 line within the irradiance range. Both models tend to overpredict at low irradiances and underpredict at high values. The slope and R-squared for the pvlib predictions are closer to one, indicating that it more accurately reproduces the relationship between predictions and observations.

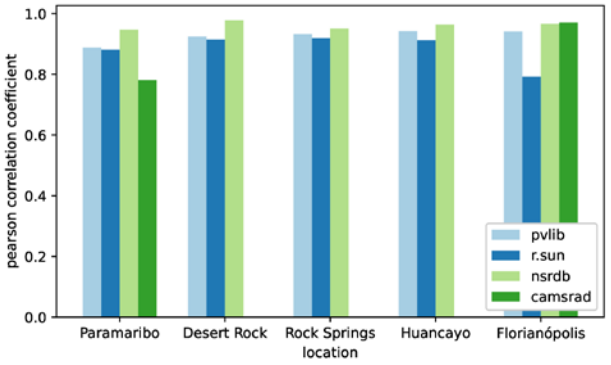

Figure 11. Pearson Correlation Coefficient of Estimated GHI Irradiances at Each Location

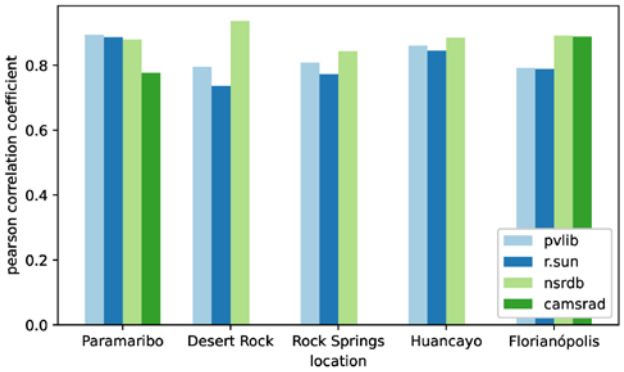

Figure 12. Pearson Correlation Coefficient of Estimated DHI Irradiances at Each Location

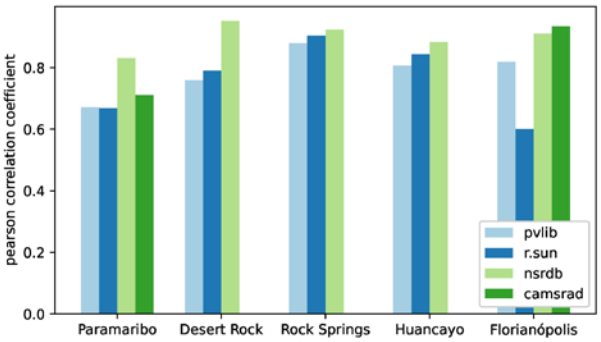

Figure 13. Pearson Correlation Coefficient of Estimated DNI Irradiances at Each Location

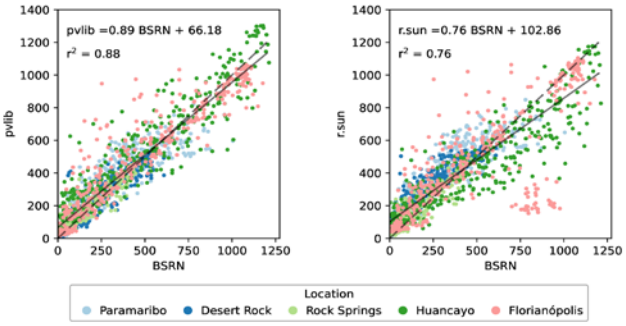

Figure 14. Regression Scatter Plots of Hourly GHI Predictions (pvlib, r.sun) vs Hourly GHI Observations (BSRN)

3.2 Solar Irradiation in Trinidad and Tobago

The solar irradiation maps were generated for Trinidad and Tobago. Raster time series of the MERRA-2 and GOES-16 datasets together with a digital elevation model were used to obtain these maps. MERRA-2 provides aerosol optical depth, Angstrom exponent, precipitable water, and air pressure datasets used in the Linke turbidity calculation. Recall that Linke turbidity accounts for attenuation from aerosols and water vapor. The high frequency GOES-16 cloud optical depth (COD) data enables estimating all-sky irradiance and resolving small-scale spatial-temporal variability in cloud cover. Figure 15 contains the average GOES-16 COD raster for January 2021.

Figures 16-18 show the average daily GHI, horizontal beam irradiation, and DHI solar maps for 2021 produced using r.sun for the northwest peninsula of Trinidad. Recall that the r.sun method (Section 2.5) Figure 19 contains a hillshade map derived from a DEM using the QGIS GIS software (QGIS Development Team 2022). A hillshade map allows for easy discernment of topological features (Horn, 1981). When the solar maps are compared to this hillshade map, the terrain shadowing effects are apparent in the beam and GHI maps. Mountain ridges have higher irradiation values

than valleys, and coastal regions generally have higher irradiation than their inland counterparts because there is less shadowing. However, these topographical features are not apparent in the DHI map, as DHI does not depend on light rays directly emitted by the sun and is less influenced by terrain shadowing.

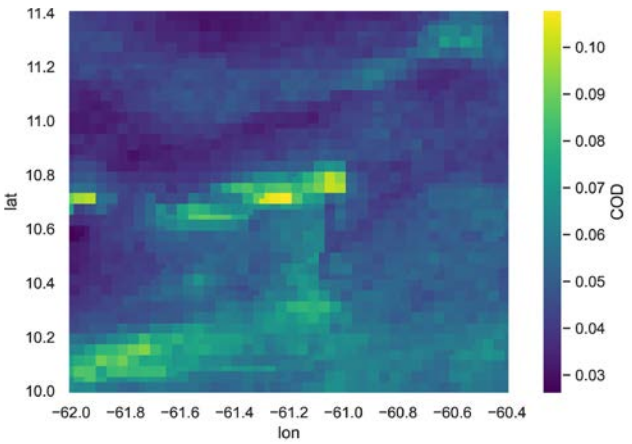

Figure 15. Average GOES-16 Daytime COD Plot for January 2021

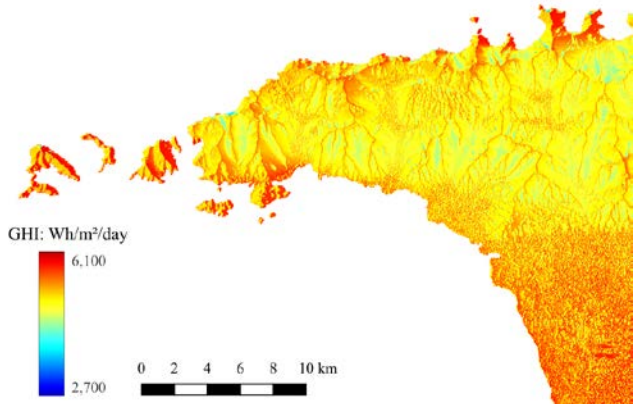

Figure 16. Average Daily GHI for 2021 in the North-west Peninsula of Trinidad

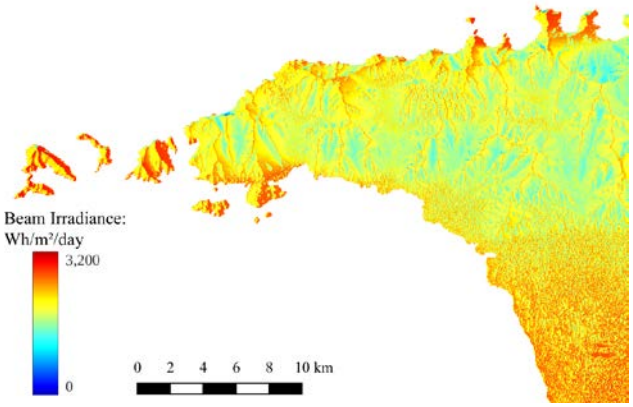

Figure 17. Average Daily Horizontal Beam Irradiance for 2021 in the North-west Peninsula of Trinidad

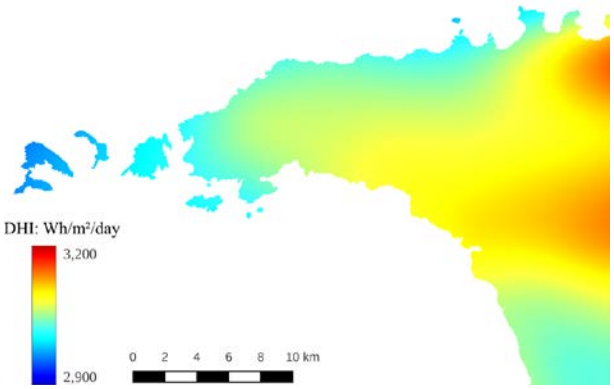

Figure 18. Average Daily DHI for 2021 in the North-west Peninsula of Trinidad

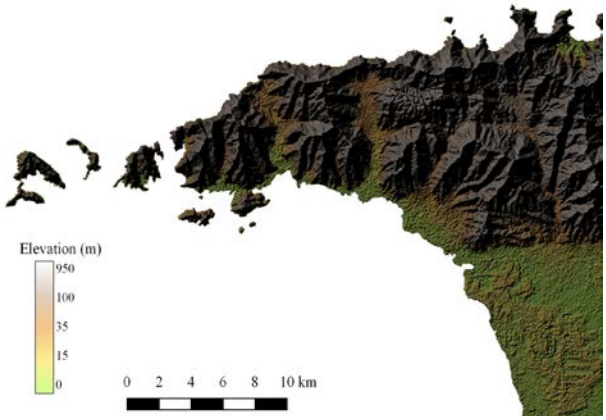

Figure 19. Hillshade Map of the North-west Peninsula of Trinidad (azimuth of 315 degrees, zenith of 45 degrees) created using QGIS computes the solar irradiation considering shading and occlusion by surrounding terrain features based on the DEM.

The GHI raster map (see Figure 16) had a mean absolute percentage error of 5.6% relative to the corresponding GHI raster obtained from the Global Solar Atlas (Solargis, 2019). The DHI solar map had a larger mean absolute percentage error of 32.9% when compared to the DHI map from the Global Solar Atlas.

3.3 Photovoltaic Yield Analysis

Seven locations in Trinidad and Tobago were chosen to demonstrate the utility of the method by computing the projected photovoltaic yield from solar panel arrays. These locations, shown in Figure 20, experience different cloud cover and topography and therefore illustrate how these factors influence solar irradiance modelled by the method.

The photovoltaic yield at a given location was determined from an hourly time series of irradiance components. These hourly time series were generated from Linke turbidity and clear-sky index raster time series (described in Section 3.2) using the instantaneous mode of r.sun (see Section 2.5). The power output of a solar panel array depends on the mounting mechanism used.



Figure 20. Case Study Locations

For each location, three mounting mechanisms were modelled. These are:

1. fixed-axis with azimuth of 180 degrees and optimal tilt angle from the Global Solar Atlas (Solargis, 2019).
2. horizontal single-axis with the axis aligned on a north-south line, and
3. dual-axis.

The pvlib library and the r.sun all-sky irradiance time series were used to determine the plane of array irradiance time series for each location and mounting mechanism. The model of Reindl et al. (1990a, 1990b) was used to model the diffuse irradiance incident on a tilted panel.

Figure 21 contains the daily photovoltaic yield for seven locations using a single-axis mount for 2021 averaged by week. From this diagram, the Crown Point location had the highest yield. This was likely due to the lack of shadowing and lower cloud cover at Crown Point. At Aripo, the photovoltaic yield was always lower than at all other locations. This was likely due to a combination of shadows from the mountain range, in which Aripo is located, and high cloud cover.

Figure 22 contains the average daily yield for different mounting mechanisms together with PVOUT from the GSA (Solargis, 2019). The GSA's PVOUT is the photovoltaic power potential of a one kWp fixed-axis photovoltaic system. By comparing the photovoltaic yield of fixed-axis mounts with the corresponding values given by the GSA, the model predicted a higher photovoltaic yield than the GSA.

Single-axis mounts produced a higher yield than fixed-axis mounts, while dual-axis mounts produced the highest yield. On average, single-axis and dual-axis mounts produced 15.2% and 19.3% more energy than fixed-axis mounts.

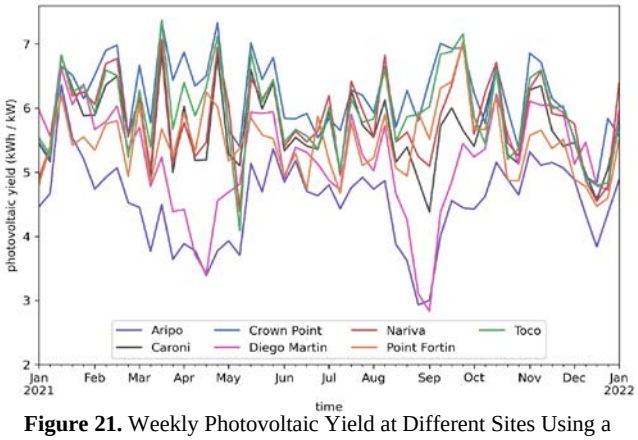

Figure 21. Weekly Photovoltaic Yield at Different Sites Using a Single-axis Mount

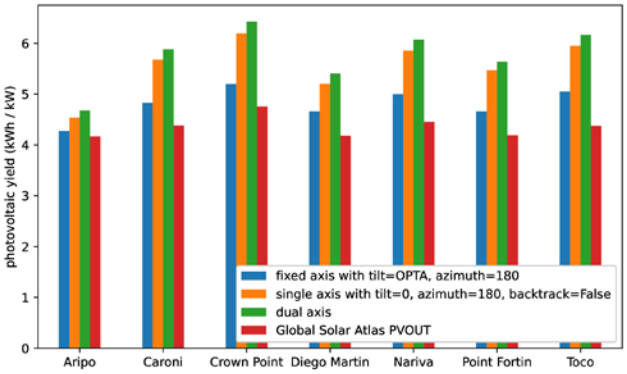

Figure 22. Photovoltaic Yield Using Different Mounting Mechanisms

4. Conclusion and Future Work

As Trinidad and Tobago prepares to transition from fossil fuel dependency, the evaluation of alternative energy sources, particularly solar energy, is imperative. This study contributes to this effort by developing high-resolution solar irradiance maps and solar power estimates for Trinidad and Tobago, using a combination of MERRA-2 aerosol data, GOES-16 cloud data, and elevation maps from the AWS Terrain Tiles database.

To evaluate the precision of the all-sky irradiance model, we conducted Pearson correlation analyses using data from five Baseline Surface Radiation Network (BSRN) stations during December 2019. These analyses included comparing the predictions with BSRN observations and juxtaposing them with irradiance estimates from the National Solar Radiation Database (NSRDB) and the CAMS Radiation Service (CAMSrad). The similarity in performance between the methods and the established NSRDB and CAMSrad datasets underscores that the approaches are on par with these existing resources in terms of predictive accuracy.

The solar maps produced in this study showed clear effects of shadowing and cloud cover. Mountainous areas with more shadows and clouds had less solar irradiance than flatter, windward areas of the twin island

state. Shadowing was noticed on a smaller scale, probably due to the high resolution of the elevation map and uneven terrain. Compared to the GSA's GHI map, the GHI solar map had a mean absolute percentage error of 5.63%.

Seven locations in Trinidad and Tobago were selected to assess the potential of solar resources. For each site, we calculated the energy yields for three types of solar panel mounts: fixed-axis, single-axis, and dual-axis. On average, single- and dual-axis mounts generated 15.2% and 19.3% more energy than fixed-axis mounts. It was also observed how shadowing and cloud cover affected the energy yield at these sites. Crown Point had the highest yield, likely due to less cloud cover and minimal shadowing. The energy yield for the fixed-axis panels was 2.5% to 15.5% higher than the values reported by the GSA PVOUT variable.

The cloud optical depth product of GOES-16 was chosen in this paper by manual inspection of its suitability. However, future work could include the evaluation of other GOES-16 cloud products such as cloud particle size (Heidinger et al., 2020) for irradiance estimation. Machine learning or multivariate time series analysis techniques could be used to develop relationships between cloud products and all-sky irradiance. Furthermore, the DIRINT irradiance decomposition processes can be improved using regional data and statistical methods to tune the DIRINT parameters.

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