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INAT.
INTERNATIONAL NETWORK ON APPROPRIATE TECHNOLOGY.

RE 11th ICAT

Dear ICAT participant:

Thanks to you, the International Network on Appropriate Technology (INAT), held from November 25 to 29, was a success. Over 150 academics and practitioners participated over the five days. The poster competition consisted of 40 quality academic presentations from students and Post-Docs from several countries. Our international keynote speakers came from India, Kenya, Lesotho, the USA, and South Africa.

At each of our 11 International conferences on Appropriate Technology, the highlight is a highly competitive peer review paper competition. The process starts with the submission of abstracts that are blind peer-reviewed. The authors of accepted abstracts received reviews and were allowed to submit full papers. Full papers were double-blind peer-reviewed by 2-4 reviewers. Authors of selected papers revised their papers based on the comments and resubmitted. One of the co-editors of the proceedings was assigned each paper for final review and worked with the authors on any final edits required.

The scientific review committee consisted of over 40 academics and practitioners from 25 different institutions across eight countries. The process started with 75 paper abstracts. After the three-stage review process, we ended with 30 high-quality papers. The authors gave oral presentations and the final papers are included in the conference proceedings with ISBN 978-0-9993666-6-0.

We look forward to your participation in our 12th ICAT in November 2026.
Note: Additional information about INAT and our past conferences can be found on our website (http://www.appropriatetech.net).

Sincerely yours,

John Trimble

Gada Kadoda, PhD
Chair, 11th ICAT
Board Member, INAT

John Trimble, Prof.
President, INAT

SECTION: HEALTH, KNOWLEDGE & TECH TRANSFER

Edited by Brian Stephenson

THE IMPACT OF PANDEMICS ON THE MENTAL HEALTH OF NURSE CLINICIANS IN PRIMARY HEALTHCARE FACILITIES

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ABSTRACT
The study investigated mental health risk factors in nurses working in Covid-19-affected facilities. Self-administered questionnaires were used, with the majority of participants being females aged 25-44. Findings revealed significant proportions reporting anxiety, major depression, and burnout. Participants lacking a support system, with more household occupants, and concerns about exposing family had higher anxiety scores. Similarly, higher depression scores were associated with working in Covid areas and having >2 household occupants, and increased burnout was linked to working in Covid areas, shift work, more household occupants, and exposure concerns. The study underscores the importance of implementing mental health support programs and interventions for healthcare professionals during pandemics.

Keywords: SARS-COV 2**,** Anxiety, Depression, Burnout, Nurse Clinicians

Introduction
The global prevalence of mental disorders stood at 970 million people in 2019, with a significant increase attributed to the Covid-19 pandemic (WHO, 2022). A multitude of factors, spanning biological, psychological, social, and work-related aspects, are linked to poor mental health. Primary healthcare nurses, often in resource-constrained settings, are especially vulnerable to mental health issues (Robertson, 2020).
These nurses are frontline healthcare providers, conducting assessments, diagnosis, treatment, and patient care. During pandemics, their responsibilities extend to aiding in public health responses, providing infection control, risk management education, and ensuring uninterrupted access to health services (Halcomb et al., 2020).

Mental Health Challenges in Healthcare Workers during Covid-19:
Working in healthcare is associated with mental health challenges, exacerbated during pandemics, as observed during the 2003 SARS outbreak and Covid-19. These challenges encompass sadness, anxiety, depression, and more. Factors such as working conditions, organizational structures, long hours, lack of protective gear, and insufficient support contribute to these issues (Hassannia et al., 2021). Other factors, like social distancing difficulties and a surge of anxiety within communities, further strain mental health.

South Africa's healthcare system, marked by inadequate infrastructure, faced unique challenges during the Covid-19 peak. Healthcare workers dealt with overwhelming caseloads and limited resources, resulting in heightened stress, worry, and fatigue. Studies in South Africa highlighted adverse effects on healthcare workers' well-being, with substantial levels of depression, anxiety, and post-traumatic stress (Curran et al., 2021; Dawood et al., 2022).

Monitoring healthcare workers' mental health is crucial for disease management and public health efforts. Addressing their mental health challenges is a global imperative, necessitating tailored support.

Aim and Objectives
The study aimed to assess the risk factors associated with mental health (anxiety, depression and burnout) among primary healthcare nurse clinicians working in facilities affected by the Covid-19 pandemic.

Research Question
What are the factors associated with mental health among nurse clinicians in PHC facilities during the Covid-19 pandemic? What is the prevalence of anxiety, depression and burnout among primary health care nurse clinicians in PHC facilities during Covid-19 pandemic?

Methodology
Study Design and Study Site
This cross-sectional study was conducted in Ekurhuleni Health District. Ekurhuleni Health district is one of six districts in the province of Gauteng. Ekurhuleni is Tsonga word which means a "place of peace"(Our Journey, 2021). The district is subdivided into three health sub-districts, viz. East, South and North, and has a population of approximately 4.1 million people (Macrotrends, 2023) served by one district hospital, four regional hospitals and 93 primary healthcare facilities. The research was conducted within the City of Ekurhuleni's 15 provincial primary healthcare facilities.

Study Population
The study population was primary healthcare nurse clinicians working in Ekurhuleni health district provincial primary healthcare facilities. The South African Nursing Council (SANC) has registered a nurse clinician as a professional nurse with an extra qualification in primary care nursing. Permanent primary healthcare nurse clinicians between the ages of 25-65 years, male or female, who had worked in the selected primary healthcare facilities for at least two years, and who were willing to sign an informed consent were included in this study. A total of 183 primary healthcare nurses were included in this study.

Ethics Approval
The study was approved by the University of Johannesburg research ethics committee (REC-1627-2022), and the Ekurhuleni health district research ethics committee (NHRD: GP_202207_066).

Data Collection
Prior to data collection, a courtesy meeting was held with the heads of the 15 provincial facilities to discuss the study aims, objectives and outcomes. Questionnaires were given to consented participants with a week to complete. A sealed and labelled box was placed in the facility manager's office for participants to drop off their completed consent forms and questionnaires. The self-administered questionnaires included information on socio-demographic characteristics, Covid-19 exposure, and mental health outcomes as shown below:

(iv) *Section A*: Socio-demographic data: i.e., age, race, gender, education, support system, occupational history.

(ii) *Section B*: Occupational history: i.e., length of time employed as a primary healthcare nurse, and number of years working at the current facility.
(iii) *Section C: Mental health outcomes:* Anxiety: Anxiety was assessed using the generalized anxiety disorder (GAD) 7-item. Seven (7) responses were measured using a Likert scale (not at all (0), several days (+1), more than half days (+2) and nearly every day (+3). Depression: Patient Health Questionnaire-2 (PHQ-2) was used to assess the frequency of depressed mood over the past two weeks. Two questions were asked and answers were based on the Likert scale (not at all (0), several days (+1), more than half days (+2) and nearly every day (+3). PHQ-2 has been used to examine mental health among nurse clinicians in South Africa (Posel et al., 2021). Burnout: The Oldenburg Burnout Inventory (OBI) was used to measure burnout. The nurse clinician was presented with a series of 16 statements based on a Likert scale: strongly agree (+1); agree (+2); disagree (+3); strongly disagree (+4).The scores ranged from 16 to 64 These tools have previously been used to assess the mental health status of South Africans (Demerouti et al., 2003; Hoque et al., 2021; Posel et al., 2021).
(iv) *Section D:* Exposure to Covid-19: this section included information on: testing positive for Covid-19, period of testing positive for Covid-19 (first 6 months of the pandemic, after 6 months of the pandemic), family members testing positive for Covid-19, working in a Covid area, doing shift work, concerned about exposing or infecting family members, loss of family/ friends/colleagues to Covid-19, training on Covid-19 and related factors, and receiving de-briefing or counselling during the pandemic.

Data Analysis

All data were cleaned and checked for quality on Microsoft Excel and exported to the Statistical Package for the Social Sciences (SPSS) software, version 28. Descriptive statistics such as frequency tables were used to describe the prevalence of mental illness (anxiety, depression and burnout), and various covariates (age, gender, race, support system, educational level, occupational history, training, and shift work). Non-parametric tests (Mann-Whitney U test and Kruskal-Wallis test) were used to examine the relationship between mental illnesses and associated risk factors. $P < 0.05$ was regarded as the level of significance.

Results

Demographic Characteristics

Table 1 shows the demographic characteristics of study participants. The sample consisted of 183 participants: 42% of the participants were between the ages of 25-44 years, 86% were female primary healthcare nurse clinicians, 87% were black, and 98% of participants had a PHC qualification with 85% having a support system. More than 40% of participants had worked at the current facility for >10 years.

Table 1: Demographic characteristics (n=183)

Characteristics	Total n (%)
Age	
<44 years	76 (42)
45-60	54 (30)
>60	53 (29)
Gender	
Male	24 (13)
Female	158 (86)
Race	
Black	159 (87)
White	1 (1)
Colored	9 (5)
Indian	13 (7)
Highest level of education	
Nursing Degree	1 (1)
Primary healthcare certificate	179 (98)
Other	3 (2)
Number in Household	
1-2	65 (36)
>2	118 (64)
Support System	
Yes	155 (85)
No	28 (15)
Years in current facility	
<10 years	140 (76)
>10 years	43 (24)

In this study when assessing the impact of Covid-19-related exposures and the prevalence of mental health problems among participants, several significant findings emerged. A majority of participants, approximately 60%, tested positive for Covid-19, with a striking 78% of their family members also contracting the virus. The vast majority of the participants were employed in Covid-19-affected areas, and a considerable portion of them were shift workers. Notably, a high percentage, 94%, expressed concerns about infecting or exposing their loved ones, reflecting the pervasive anxiety surrounding the pandemic. Moreover, an alarming 81% of the participants had experienced losses in the form of family, friends, or colleagues due to Covid-19. Shockingly, 81% reported not receiving any debriefing regarding the pandemic, and only 60% received adequate training on Covid-19 and its related factors. These experiences had a pronounced impact on mental health, with 57% experiencing anxiety, 81% exhibiting depressive symptoms, and varying degrees of burnout observed among participants. The study's findings underscore the significant toll of the pandemic on healthcare workers' mental well-being, emphasizing the importance of support systems and interventions to address these challenges.

Discussion

The results of our study reveal a prevalent occurrence of poor mental health among nurse clinicians working in primary healthcare facilities during the Covid-19 pandemic. Our findings align with prior research conducted in various regions, demonstrating elevated levels of mental health issues among frontline healthcare workers amid the pandemic, as reported in studies by Chinvararak et al. (2022), Hu et al. (2020), and Tselebis et al. (2020).

During the peak of the Covid-19 pandemic, the mental health of nurse clinicians emerged as a critical concern. Factors such as workplace anxiety, information overload, the loss of loved ones, colleagues, and patients, coupled with the pervasive fear of the unknown, were identified as contributory elements linked to the pandemic. In our study, among 183 participants, 57% experienced minimal anxiety, 26% reported mild anxiety, 11% reported moderate anxiety, and 6% reported severe anxiety. Furthermore, participants without a support system, those with more than two household occupants, and those concerned about exposing or infecting family members displayed higher median GAD-7 scores. Similar demographic characteristics and Covid-19-related exposures were reported as predictors of anxiety in studies conducted elsewhere (Chinvararak et al., 2022; Tselebis et al., 2020).

Over 80% of the participants reported experiencing mild depressive symptoms, with 19% exhibiting major depressive symptoms. Studies by Shaukat et al. (2020) and GebreEyesus et al. (2021) indicated that working in high-risk Covid-19 areas and living with family were associated with an increased risk of depression, respectively. In our study, participants working in Covid-19-affected areas and those with more than two household occupants had higher median PHQ-2 scores.

Burnout levels observed in our study varied from minimal (14%) to mild (53%), moderate (27%), and severe (2%). Higher median OBI scores were observed among nurse clinicians working in Covid-19 areas, shift workers, those with household occupancy exceeding two, and those concerned about exposing or infecting family members. These findings were consistent with a study in Ghana, which reported increased burnout scores among nurses working night shifts (Konlan et al., 2022). Conversely, our findings did not reveal differences in median scores for social support, contradicting a study in Thailand that linked sex and social support to burnout (Chinvararak et al., 2022).

Notably, median scores for anxiety, depression, and burnout were not influenced by age, gender, years of employment at the facility, testing positive for Covid-19, experiencing loss due to Covid-19, or receiving Covid-19-related training and debriefing. These results diverge from earlier studies (Luo et al., 2020; Pappa et al., 2020; Wang et al., 2020) that suggested access to adequate medical services, up-to-date information, and the adoption of preventative measures contributed to the psychological well-being of healthcare workers. It is conceivable that the limited sample size in our study may have contributed to these findings.

Limitations

According to our knowledge, this was the first study to investigate the prevalence of mental health outcomes and risk factors associated with Covid-19 in Ekurhuleni health district. However, our study was not without limitation, for example, we were not able to conduct multivariate analysis due to a small sample size. We used self-reported questionnaires, and the limitation of these measures is that individuals may overestimate or underestimate exposure and outcome. Our study may be used as a baseline study for future studies focusing on treating nurses working in the district.

Public Health Implications and Further Recommendations

The Covid-19 pandemic emphasized the vital role of frontline healthcare professionals and the limitations of healthcare systems worldwide (Doherty et al., 2021). Protecting the ongoing mental health of primary healthcare nurse clinicians is crucial, requiring evidence-based measures and interventions beyond the pandemic.

This pandemic significantly impacted the mental well-being of healthcare workers, particularly nurse clinicians in primary healthcare (Doherty et al., 2021). Self-care is essential for managing their workload and promoting a work-life balance, encompassing self-awareness, self-compassion, altruism, and various strategies for physical, social, and inner well-being (Callahan et al., 2018).

To prevent burnout and mental health issues, fostering a positive work environment is essential (Wiskow et al., 2010). Healthcare leaders must destigmatize mental health issues, promoting a culture of openness, respect, empathy, and support, while encouraging collaboration over competition.

This study advocates for ongoing employee wellness programs with psychological interventions for primary care nurse clinicians, not just during the pandemic, but in future crises. It also highlights the importance of peer support and government backing, prioritizing fair compensation, adequate protective equipment, and addressing staffing shortages for healthcare workers.

Conclusion

The Covid-19 pandemic has highlighted the essential and required work of frontline staff and other healthcare professionals, as well as the limitations of healthcare systems worldwide. The prevalence of mental health conditions was prevalent in this study, and the median scores differed by certain Covid-19 related exposures. To protect the mental health of primary healthcare nurse clinicians, evidence-based measures and interventions must be put in place and implemented before the memory of the pandemic response fades. Healthcare leaders should create a culture of inclusiveness, collaboration, and support to reduce stigma associated with mental health problems and foster a work environment that values openness, honesty, respect, equality, empathy, and support.

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Declaration

The authors declare that this is their own work; all the sources on this paper have been duly acknowledged and there are no conflicts of interest.

Data set can be made available upon request.

REFERENCES

Chinvararak, C., Kerdcharoen, N., Pruttithavorn, W., Polruamngern, N., Asawaroekwisoot, T., Munsukpol, W., & Kirdchok, P. (2022). Mental health among healthcare workers during COVID-19 pandemic in Thailand. PloS One, 17(5), e0268704. https://doi.org/10.1371/journal.pone.0268704

Curran, R., Bachmann, M., Van Rensburg, A. J., Murdoch, J., Awotiwon, A., Ras, C.-J., Petersen, I., & Fairall, L. (2021). Personal and occupational experiences of COVID-19 and their effects on South African health workers' wellbeing. South African Medical Journal, 111(7), 607–608. https://doi.org/10.7196/SAMJ.2021.v111i7.15733

Dawood, B., Tomita, A., & Ramlall, S. (2022). 'Unheard,''uncared for'and 'unsupported': The mental health impact of Covid-19 on healthcare. Plos One, 17(5).

Demerouti, E., Bakker, A. B., Vardakou, I., & Kantas, A. (2003). The convergent validity of two burnout instruments: A multitrait-multimethod analysis. European Journal of Psychological Assessment, 19(1).

Deng, D., & Naslund, J. A. (2020). Psychological impact of COVID-19 pandemic on frontline health workers in low-and middle-income countries. Harvard Public Health Review.

GebreEyesus, F. A., Tarekegn, T. T., Amlak, B. T., Shiferaw, B. Z., Emeria, M. S., Geleta, O. T., Terefe, T. F., Mammo Tadereregew, M., Jimma, M. S., Degu, F. S., Abdisa, E. N., Eshetu, M. A., Misganaw, N. M., & Chanie, E. S. (2021). Levels and predictors of anxiety, depression, and stress during COVID-19 pandemic among frontline healthcare providers in Gurage zonal public hospitals, Southwest Ethiopia, 2020: A multicenter cross-sectional study. PloS One, 16(11), e0259906. https://doi.org/10.1371/journal.pone.0259906

Halcomb, E., McInnes, S., Williams, A., Ashley, C., James, S., Fernandez, R., Stephen, C., & Calma, K. (2020). The experiences of primary healthcare nurses during the COVID-19 pandemic in Australia: COVID-19 in Australian PHC. Journal of Nursing Scholarship, 52(5), 553–563. https://doi.org/10.1111/jnu.12589

Hassannia, L., Taghizadeh, F., Moosazadeh, M., Zarghami, M., Taghizadeh, H., Dooki, A. F., Fathi, M., Alizadeh-Navaei, R., Hedayatizadeh-Omran, A., & Dehghan, N. (2021). Anxiety and depression in health workers and general population during COVID-19 in IRAN: A cross-sectional study. Neuropsychopharmacology Reports, 41(1), 40–49. https://doi.org/10.1002/npr2.12153

Hoque, A. M., Hoque, A. M., Buckus, S., Hoque, M., ul Alam, A. M., Hoque, M. E., & Singh, N. (2021). Psychological problems experienced by primary healthcare workers during COVID-19 epidemic in South Africa. Psychological Disorders and Research, 1–7. https://doi.org/10.31487/j.pdr.2021.01.01

Hu, D., Kong, Y., Li, W., Han, Q., Zhang, X., Zhu, L. X., Wan, S. W., Liu, Z., Shen, Q., Yang, J., He, H.-G., & Zhu, J. (2020). Frontline nurses' burnout, anxiety, depression, and fear statuses and their associated factors during the COVID-19 outbreak in Wuhan, China: A large-scale cross-sectional study. EClinicalMedicine, 24(100424), 100424. https://doi.org/10.1016/j.eclinm.2020.100424

Luo, M., Guo, L., Yu, M., Jiang, W., & Wang, H. (2020). The psychological and mental impact of coronavirus disease 2019 (COVID-19) on medical staff and general public-A systematic review and meta-analysis. Psychiatry Research.

Macrotrends.net. Ekurhuleni, South Africa metro area population 1950-2023. (n.d.). Retrieved June 18, 2022, from https://www.macrotrends.net/cities/22484/ekurhuleni/population

Mental disorders. (n.d.). Who.int. Retrieved June 18, 2022, from https://www.who.int/en/news-room/fact-sheets/detail/mental-disorders

Okechukwu, E. C., Tibaldi, L., & La Torre, G. (2020). The impact of COVID-19 pandemic on mental health of Nurses. La Clinica Terapeutica, 5.

Our Journey - city of ekurhuleni. (2021, October 13). City of Ekurhuleni - A Partnership That Works; City of Ekurhuleni. https://www.ekurhuleni.gov.za/about-the-city/our-journey/

Pappa, S., Ntella, V., Giannakas, T., Giannakoulis, V. G., Papoutsi, E., & Katsaounou, P. (2020). Prevalence of depression, anxiety, and insomnia among healthcare workers during the COVID-19 pandemic: A systematic review and meta-analysis. Brain, Behavior, and Immunity, 88, 901–907. https://doi.org/10.1016/j.bbi.2020.05.026

Posel, D., Oyenubi, A., & Kollamparambil, U. (2021). Job loss and mental health during the COVID-19 lockdown: Evidence from South Africa. PloS One, 16(3), e0249352. https://doi.org/10.1371/journal.pone.0249352

Robertson, L. J., Maposa, I., Somaroo, H., & Johnson, O. (2020). Mental health of healthcare workers during the COVID-19 outbreak: A rapid scoping review to inform provincial guidelines in South Africa. South African Medical Journal, 110(10), 1010–1019. https://doi.org/10.7196/SAMJ.2020.v110i10.15022

Shah, J., Monroe-Wise, A., Talib, Z., Nabiswa, A., Said, M., Abeid, A., Ali Mohamed, M., Mohamed, S., & Ali, S. K. (2021). Mental health disorders among healthcare workers during the COVID-19 pandemic: a cross-sectional survey from three major hospitals in Kenya. BMJ Open, 11(6), e050316. https://doi.org/10.1136/bmjopen-2021-050316

Shaukat, N., Ali, D. M., & Razzak, J. (2020). Physical and mental health impacts of COVID-19 on healthcare workers: a scoping review. International Journal of Emergency Medicine, 13(1), 40. https://doi.org/10.1186/s12245-020-00299-5

Tselebis, A., Lekka, D., Sikaras, C., Tsomaka, E., Tassopoulos, A., Ilias, I., Bratis, D., & Pachi, A. (2020). Insomnia, perceived stress, and family support among nursing staff during the pandemic crisis. Healthcare (Basel, Switzerland), 8(4), 434. https://doi.org/10.3390/healthcare8040434

Wang, S., Xie, L., Xu, Y., Yu, S., Yao, B., & Xiang, D. (2020). Sleep disturbances among medical workers during the outbreak of COVID-2019. Occupational Medicine (Oxford, England), 70(5), 364–369. https://doi.org/10.1093/occmed/kqaa074

Xiang, Y.-T., Yang, Y., Li, W., Zhang, L., Zhang, Q., Cheung, T., & Ng, C. H. (2020). Timely mental health care for the 2019 novel coronavirus outbreak is urgently needed. The Lancet. Psychiatry, 7(3), 228–229. https://doi.org/10.1016/S2215-0366(20)30046-8

POST WAR TRAJECTORIES: GENDERED ACCESSIBILITY TO PUBLIC SPACE IN SUDAN

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ABSTRACT

This paper delves into the issue of gendered access to public space within the Sudanese context, particularly in light of the ongoing civil war. It posits that this tumultuous period presents an opportunity for new trajectories to be forged, allowing for comprehensive processes aimed at addressing the colonial legacy of inequalities and the structural social stratification that continue to exert a mutual influence on physical space.

Employing an analytical approach, the paper synthesises and analyses existing literature on spatial justice, oppressive structures, the right to the city, and gender accessibility to public space. It specifically hones in on Sudanese women's access to public space and the power structures that serve to restrict their mobility. Understanding these dynamics is crucial in order to pave the way for successful processes geared towards achieving spatial justice.

By shedding light on these complexities and advocating for a more inclusive and equitable approach to public space, this paper seeks to contribute to ongoing discussions surrounding gender equality and social justice in Sudan.

Keywords: gender, spatial justice, accessibility, public space

INTRODUCTION

In April 2023, a harrowing conflict started in the city of Khartoum, subsequently spreading to different regions of the country, Sudan. Since then, the people of Sudan have found themselves caught amidst the heart-wrenching choices of exile, displacement, and enduring severely deteriorated conditions, giving rise to a humanitarian crisis of alarming proportions. Amidst these circumstances, the people of Sudan yearn for the cessation of hostilities, aspiring to transition from the shadows of conflict to the realm of peacebuilding, continuing the process that started in 2019 when a civil revolution triumphed over a three-decade-long dictatorship.

Post-war reconstruction activities have garnered increasing interest in practical implementation and research within national and international politics and development agendas. Historical influences such as the "Marshall Plan" post World War II in 1947, and the mainstream "State-Building Model" in the 1990s, a decade that witnessed numerous conflicts following the Cold War, have been prominent here (IEMed, 2017). These historical antecedents serve as valuable touchstones, offering insights and lessons that contribute to the ongoing discourse surrounding effective strategies for post-conflict reconstruction and development.

Contemporary civil wars are concentrated in a few regions, particularly in poor and weak states with colonial histories. These conflicts lead to widespread destruction of infrastructure, as well as social, political, ethnic, and religious disputes, sustaining the cycle of violence (Rothe, 2008; Walter, 2011).

However, traditional approaches to post-war reconstruction efforts have faced widespread criticism. They are often deemed ineffective, failing to address historical legacies, reproducing pre-conflict systems, being controlled by regional and international interests, and lacking ownership and participation (Barakat, 2005; Fischer & Wang 2011). These shortcomings frequently contribute to the recurrence of civil wars, with some countries experiencing multiple episodes of violence and falling into what is known as the "conflict trap" (Walter, 2011). Therefore, while there is no one-size-fits-all solution for post-war reconstruction processes, comprehensive approaches that ensure community participation are crucial to breaking the cycle of post-conflict relapse (Barakat, 2005).

Consequently, the importance of addressing gender issues in post-conflict reconstruction efforts is widely highlighted. Gender-sensitive approaches are essential for achieving sustainable peace and development in war-torn societies. The limitations and gaps in current development aid practices, emphasise the lack of attention to gender dynamics and the failure to adequately address women's rights and empowerment. Thus, the call for a more inclusive and gender-responsive approach to post-conflict reconstruction that priorities women's participation, access to resources, and protection from violence is crucial long-term peace and stability (Greenberg & Zackerman, 2016) .

Undoubtedly, gender-based inequalities are one of the greatest social justice concerns. It's an issue that faced multiple layers of ignorance at the level of political, social, economic, and cultural structures of power, and again at the level of being relegated to a position of insignificance or receiving a lower priority on the hierarchy of societal concerns. It is not only important, but women's status is also a measure of the efficiency and effectiveness of social justice processes. For the purpose of this paper, the status of accessibility of abled and disabled women in Sudan to public space is discussed to suggest new trajectories for post-war processes that guarantee maximum accessibility for women from a social justice perspective.

METHODOLOGY

This conference paper is based on a secondary research methodology that involved a comprehensive review and analysis of existing literature on the topic of spatial justice and gender, using a geographical approach to analyse Sudanese women's accessibility to public space as a case study. The primary sources of data for this study were academic journals, books, reports, and other scholarly publications related to gendered access to public space. It also involved the author's observation as a participant.

The search strategy for this study involved utilising online databases such as Google Scholar, JSTOR, and other academic repositories to identify relevant literature. Keywords used in the search included gender, space, spatial justice, accessibility, Sudanese women. The search tried in most cases to use articles published in the last two decades to ensure the inclusion of recent research findings.

Data collection involved systematically reviewing and synthesising the identified literature to extract key themes, findings, and insights related to the topic of interest. The analysis focused on identifying common trends, gaps in the literature, and areas of consensus or disagreement among scholars. The data were organised thematically and critically evaluated to provide a comprehensive overview of the current state of knowledge on gender in space.

It is important to acknowledge that this study is limited by the availability and scope of existing literature on the topic. The data on Sudanese women and space is extremely limited or unavailable. A significant limitation in the circumstances of the ongoing conflict is the absence of primary data from focus groups and interviews of different groups. The findings presented in this conference paper are based on the interpretation and synthesis of secondary sources and may be subject to bias or limitations inherent in the original studies.

SPACE AND GENDER RELATED STUDIES

Territorial Justice

David Harvey (1973) introduced the concept of 'territorial justice' as access to social justice. He identified a two-fold approach to social justice composed of just distribution of resources and equitable institutional processes. Harvey's model defines the need to evaluate the distribution of resources among groups, individuals, and territories based on need, contribution to the common good, and merit, and evaluating the mechanisms through which the distribution takes place. He explores what is distributed and who exactly the distribution is concerned with. As it shows, the second part is concerned with the processes which accomplish resource allocation, Importantly, it scrutinises the existing power structures and dominant forces that determine who holds the authority to distribute resources.

Oppression

The concept of domination is integral here, implying that certain groups may be excluded from political decision-making processes; in her book “Justice and the Politics of Difference” (1990), Iris Young identified exploitation, marginalisation, powerlessness, cultural imperialism and violence as the five faces of oppression. She focused on the institutional context emphasising the significance of rules, practices, and norms that guide the processes, language, and symbols that mediate social interactions within the family, society, workplace and the state. The importance of the institutional context comes from determining not only what resources are to be distributed but also the methods and agents of distribution, ultimately influencing the desired outcomes. Thus, social justice requires inclusion of all groups and cannot be achieved without following mechanisms that implies oppression reduction.

Spatial justice

The adoption of a spatial perspective gained momentum in the 1980s, coinciding with the spatial turn that redefined human beings by their spatial existence as well as their historical. As stated by Soja (2010), the concept of spatial justice provides a theoretical framework for understanding the relationship between space, justice, and politics. Soja argues that spatial arrangements such as the distribution of resources, opportunities, and access to public spaces reflect social, economic, and political power dynamics. Hence, spatial arrangements contribute to inequalities, while they have the potential to promote more equitable urban environments. The spatial dimension of justice manifests in the struggles over geographies and locational discrimination of people based on their class, race, and gender. The unequal distribution of rights to physical space and the dictation of women's movement by gender roles imposed by patriarchal systems undermine the concept of equality. This patriarchal influence extends to the political organisation of space, which exists in top-down approaches that result from external processes such as post-colonial policies, or bottom-up approaches that result from local decision-making processes regarding the distribution (Soja, 2010).

The right to public space, the Right to the City

While this conceptualisation may not be entirely novel, the right to public space is deeply rooted in urban theory, serving as a robust conceptual umbrella that scrutinises the intricate social dynamics producing hierarchies and unequal citizenship. The work of Lefebvre’s Right to the City (Le Droit a la Ville 1968) influenced this theoretical framework and the ensuing movement, it emphasises the right to just access to resources and marginalisation of social groups within dominant social relations. Followed by the development of David Harvey, the Right to the City is not limited to mere access to existing resources but a right to participate in the transformative processes that influence urban landscapes. The spatial perspective, thus, provides a critical lens for understanding and addressing the complex intersections of space, justice, and power dynamics in shaping our societies.

The space, as stated by Lefebvre is socially produced, meaning that the spatial pattern of a society is produced to support its reproduction of social relations. Uneven social power and unequal participation in political decisions is a manifestation of uneven geographical and spatial injustice, for example Lefebvre’s perception of space as a social product emphasises that space is a final product rather than a means to an end.

Gender and public space accessibility

In his book *Social Spaces and the Public Sphere*, Harikrishnan (2022) explores the concept of public space and its intersection with issues of gender and disability. The author examines how social spaces are shaped by power dynamics and cultural norms that often marginalise individuals based on their gender or disability status exploring the ways in which public spaces can be exclusionary for women and individuals with disabilities, limiting their access and participation in society. Perspectives from feminist theory and disability studies are crucial in understanding and addressing inequalities in public spaces. The calls for a more inclusive and equitable approach to spatial planning in Harikrishnan's insights is critical for any post-war processes.

Following to the social production of space, and according to Siwach (2020), the way space is utilised is shaped by social and cultural factors. Gender norms established by society manifest in physical space, they define boundaries and dictate women's mobility, allowing them access to spaces only when their presence is deemed necessary, defined by the nature of woman's work for instance; public spaces, being highly contested, require women to justify their presence. The subordination of women by men is a fundamental aspect of patriarchy, perpetuating gender roles and delineating boundaries within gendered spaces, which are represented by the division between public and private space. Women's space is confined as private space, and within the private space, there is also a female space, such as 'Harem' in some Arab society's context. Gender access to space and mobility is also influenced by other factors such as age, appearance, and non-verbal communication, in addition to class and social status. Understanding these complexities is crucial for dismantling the barriers to inclusive and equitable spatial practices, especially in the context of post-war reconstruction, where a re-evaluation of societal structures and spatial dynamics is essential.

Public spaces dominated by men exemplify male dominance over women by controlling their access and limiting their movement, thereby reinforcing power dynamics and resource control. These masculine spaces are reflective of the societal norms that create and endorse them. The way in which space is claimed reflects socio-economic status in society and manifests power structure. Spaces and places are defined by social-spatial practices which result in intersecting places with multiple boundaries, constructed and maintained by power and exclusion to define who belongs and who does not belong to certain places.
The geographical imagination privileged men in public space and confined women under different causes such as vulnerability, and fear. Women were perceived to belong in private spaces, tasked with domestic roles and family care, reinforcing traditional gender roles.

Phadke (2013), disputes the restriction of women mobility to need or type of work, claiming that the right to the city implies women's right in terms of pleasure. He identifies the issue of safety and fear of violence as one that contradicts with the fact that both women and men are exposed to violence in public space, moreover, that more women are subject to violence in private space. Consequently, women should claim the right to risk, and that risk should be eliminated through designating infrastructures that should regard gender and physical disability in access to transport facilities and public space.

One aspect that reinforces patriarchal system, particularly in developing countries is militarism. Militarism is the domination of military values and culture over civilian and peaceful ones. The relationship between militarisation, gender, and oppressive ideologies is exemplified by religious fundamentalism. Fundamentalist groups often embrace militarism to enforce their beliefs. An analysis of militarisation reveals how gender, class, race, nation, ethnicity, and fundamentalism intersect with militarism to create a network of oppressions. Women may be disproportionately affected by war and militarisation based on factors like economic status or ethnic/religious identity. Militarism can lead to negative consequences like patriarchy and authoritarianism, the repercussions of militarisation intersect with patriarchy and other forms of oppression (Henry & Natanel, 2016; Elvereen & Moghadam, 2019).

Feminist movements have historically struggled to claim space; the limitation of these efforts on planning without adequately addressing the underlying power dimensions restricting women's access to space, would not contribute to accessibility. Since the Habitat III and the new urban agenda, the United Nations acknowledges the Right to the City through spatially just distribution, political agency, and cultural diversity as comprehensive approach (http://habitat3.org).

RESULTS AND DISCUSSION

Geographical context: The country's background

Sudan is the third largest country in Africa occupying around 1.9 million square kilometres with a 2.4 per cent growth population of 41 million people. The number of females is almost 50 per cent of the youth-based population. Despite the fact that the country is endowed with many natural resources, huge cultural and ethnic diversity, it is cursed with under development, civil wars, political instability, limited livelihood opportunities, massive migration, and significant influx of refugees from neighbouring disputes. It is believed that, and maybe because of political instability, civil wars and other factors, the different governments that reigned Sudan since its independence failed to build a viable national economy putting the country in the bottom of the least developed countries, moreover, issues of social justice were ignored and the legacy of colonial inequalities accumulated.

The current war has exacerbated these challenges, escalating the humanitarian crisis to unprecedented levels. The repercussions extend beyond immediate human suffering, impacting the economy, social structures, and overall security in profound and far-reaching ways. As Sudan grapples with the consequences of the ongoing conflict, there is a pressing need for comprehensive strategies that address both the immediate humanitarian concerns and the underlying systemic issues that have contributed to the nation's complex socio-economic and political landscape.

However, the modern national Sudan was born in political resistance, marked by pivotal events such as the Mahdiya Revolution, which triumphed over Turkish-Egyptian rule, the Revolution Twenty Four, resisting Anglo-Egyptian rule, and the subsequent national liberation movement that culminated in independence in 1956. Since its independence Sudan has been struggling between short periods of democratic rule and long totalitarian rule that followed military coups. Remarkably, the nation has witnessed three significant popular revolutions in 1964, 1985 and 2018, each of the three succeeded in throwing military regimes. This history of instability and resistance accumulated a huge legacy of patriotism, sacrifice and heroism, throughout these episodes the Sudanese women participation escalated from individual symbols since the 19^{th} century to reach a massive participation in the December Revolution of 2018. This shift underscores the transformative power of grassroots movements and the enduring spirit of Sudanese women in shaping the nation's political destiny (Badri, 2005).

Sudanese women timeline

History

To understand Sudanese women's access to public space, it is important to shed some light on the historical and cultural landscape of Sudan.

Before the Turkish-Egyptian occupation 1821, Sudan was composed of different political entities extended since an ancient history that goes back to several centuries B.C, in these historical pre-colonial kingdoms women held significant roles as governors, exemplified by the queens and princesses of the Meroe Kingdom in northern Sudan and the transmission of leadership through the maternal line in the *Funj* Kingdom in central Sudan. Sudan's cultural diversity is shaped by both maternal cultures with African origins and patriarchal cultures with Arabic roots (Badri, 2005).

Modern profile

In modern Sudan, women access to public participation started in the fields of education and health when girls schooling started in 1907 and more women were trained as teachers, nurses and midwives, in addition to their involvement in political resistance individually or through social relations and leadership kinship as a socially accepted access to public space (Badri, 2005; Siwach, 2020). The foundation of the Women's Union in 1951 was the first formal collective organisation that paved the way for women's political participation. Before the end of the 1960s, Sudanese women were the first in the region to win labour and political rights such as the right to equal pay for equal work in 1967, the right to vote and the right to stand for elections in 1965 which allowed the president of the Women Union to be elected for parliament in 1965.

The public space witnessed fluctuations in women's actual political participation and decision making through different governments that took power in Sudan; according to Hashim 2018, the percentage of women who graduate from higher education is 58% compared to men percentage of 42%; but only 26% of them work in the formal sector. Although the statics of women in decision making positions are not comprehensive, it shows that in both elected and appointed parliaments the percentage of women participation in the period 1955- 1996 was between 0% and 9.2% (Albathani in Osman, 2004), after the peace agreement (CPA) in 2005, the percentage jumped to 18%, then 25% in 2010. According to a press release in 2014 only 16% of the committees' heads were women, even though they were 67% of the voting power (sudantribune.net, 21 January 2014). The first woman to be appointed as minister was in the in the May period reign 1969, then in the democratic period (1986-1989) another woman became a minister. Badri (2005) states that women representation in high positions in civil service and strategic ministries such as Judiciary, Defence, Finance and foreign affairs is insignificant. Despite the foundation of women units in ministries, male domination is constituted, the women who were represented in parliament or top office were from the ruling regime supporters who have not addressed women justice agenda and submitted to the government that restricted women presence in the public space, applied a dress code on women and limited their mobility and freedom with an oppressive law known as the "Public Order Law" (Badri, 2005; Abbas, 2010; Hashim, 2018). Nevertheless, politics in Sudan is still dominated by men (Aziz & Alfaki, 2021) ; despite the contribution of Sudanese women in the December Revolution and the constitutional statement that decided a 40 percent for women representation in power structures, the actual representation of women in the transitional government did not exceed 20 percent.

Despite the lack of accurate statistics on women's access to basic services, some figures indicate that poor accessibility to services affects women more. Although records show almost parity in primary education, women's illiteracy is 45 per cent. While 65 per cent of those below the poverty line are women, rural and poor women have no access to basic services (Badri,2005). Statistics show a high percentage of child marriages leading to school dropouts caused by early marriage. Among Sudanese families is as high as 85 per cent have access to health facilities 30-60 minutes away from home, only half of those who approach the health facility get help from a skilled health worker; limited access to health services, especially for maternal care, results in high maternal mortality and other related conditions such as obstetric fistulas which affects 14 percent of women in Khartoum state and has dire physical and psychological impacts on women that in many cases end their marriages. Regarding WASH status, 68 percent of the total households have access to clean water for domestic uses, while only 32.9 percent have access to sanitation; this has been affecting females in conflict and post conflict zones exposing them to violence while they travel long distances to get water in addition to causing inability to access school classes because of lack of sanitation that is needed for menstrual periods and school dropouts as a consequence.

The presented information highlights the vulnerability of women, particularly those in rural and economically disadvantaged areas, to the lack of accessibility to basic services. Across various sectors such as education, healthcare, water and sanitation, and economic opportunities, disparities persist, disproportionately affecting women in these specific contexts. The challenges faced by Sudanese women underscore the need for comprehensive and targeted interventions to address the unique barriers they encounter in accessing essential services and participating fully in society.

The World's Bank Women Business and Law Index 2022 which is structured around working women cycle further underscores challenges, revealing Khartoum's overall score zero in mobility, workplace, pay and marriage, 20 in parenthood, 40 in assets, 75 in entrepreneurship and 100 in pension with a total score of

29.4% (the average of the regional Sub-Saharan Africa is 71.5%). It indicates that only two areas surpass the Sub-Saharan Africa's average reflecting poor situation regarding agency, freedom and accessibility.
The above statistics shows that Sudanese women are subject to superimposed circles of the five faces of oppression (marginalisation, powerlessness, cultural imperialism, violence and exploitation), as identified by Young (1990). It's worth mentioning that the degrees of oppression are varied among women between urban and rural residence, ethnicity, socio-economic status and affiliation (Hashim, 2018).

Records state the percentage of people with disability as 4.8% of the population; 52.2 males and 47.8 females with variable types of disabilities and percentages around geographical regions. Although Sudan has signed and ratified the UN Convention on the Rights of People with Disabilities (CRPD), they still have limited access to basic services. Sudan registered the highest percentage of mental illness and disabilities due to pregnancy and delivery complications in the regional context of Sub-Saharan African countries. No accommodation for people with disabilities in the spatial organisation in public space. Women with disabilities are 'invisible' among the group of people with disabilities and among women groups.

Current post-war efforts

War in Sudan is still active, making Sudan the largest internal displacement globally, in addition to large numbers mostly women and children forced to flee to neighbouring countries. The humanitarian situation is disastrous, more than 13 million people in need for assistance. Women and girls are facing increased risk of sexual violence. Since the last quarter of the year 2023, different civilian and women groups organised their efforts to call for collective action to stop the war. They can be categorised as three main coalitions according to the 'quota' or women participation in post-war and political processes:

1. *The groups supporting the civilian coalition that led the transitional period post December Revolution, they call for 30% women representation.*
2. *The groups calling for 40% representation claiming the 40 percentage was agreed upon in the constitutional statement of the transitional period.*
3. *The groups calling for 50% representation for women.*

Gender and public space

The intersectionality between gender and public space has been discussed in academia and activism contexts. It can be noted that the public-private segregation and violence discourse in the Sudanese context is weaved by the patriarchal system and militarism. Militarism is an anti-feminism system of ideals and values, it used patriarchy, fundamental ideology and tokens of security to control and commodify the public space with coercive laws such as the Public Order Law. The system is based on masculine dignity and honour and feminine fragility that needs guardians, "wali" -where many females work as gatekeepers for the system. The current war also feeds from these values, and represents a platform where masculinity manifests itself. To illustrate, the following analysis focuses on two relations: (i) spatial justice (ii) the right to the city.

Spatial Justice

Addressing inequalities through spatial justice and oppression reduction processes should involve the existing institutional context in family, society, workplace and the state (Young, 2019). Spatial justice constitutes distribution and its agency, but it cannot be achieved without negotiating the obstacles caused by the patriarchal system.
Both patriarchy and underdevelopment exist in the Sudanese context, according to Moghadam (1992), development has an inverse relation to patriarchy. She defines it as a system "where property, residence and decent proceed through the male line". Conforming to that, property rights reflect power relations and social privilege. To illustrate:

- Historically, land ownership was communal by customary traditional laws, until the British introduced the 1925 Land Law which is based on individual ownership rights and male domination. The national governments followed the colonial legacy and the law remains unchanged. Despite the significant contribution of Sudanese women to farming and food production, their property ownership remains restricted by law.
- The legislative framework in Sudan, despite constitutional provisions, upholds patriarchal norms; the Family and Labour laws are widely criticised for constituting articles that limits women freedom and agency (Tonne
- ssen, 2019). For instance, male guardianship in marriage and work is protected by law. Inconsistencies with international agreements, such as the duration of maternity leave (stated to be 8 weeks, while the ILO's is 14 weeks), further highlight gender inequalities in the legal system.
- According to Harvey's model, achieving gender spatial justice starts by handling the distribution of resources according to just basis such as need, merit and contribution to common good, along with involving women in the distribution processes. In addition, there should be in depth analysis for inequalities and how discrimination is formed through top-down paths "exogenous geographies" such as colonial and post colonial laws, and bottom-up paths "endogenous geographies" as local laws. This social stratification is affected vis-à-vis by the physical spatial segregation, influencing gender roles and power relations.
- In addition, high military expenses added more gender inequalities because it reduced government expenditure on health, eduction and mobility. More burden is added due to the horrible effects of the current war on women.

The Right to the City

In this section, I am going to look into women use and accessibility to physical space as place and time, namely: private space, public space, work place, and the city *oeuvre*.

1. *Private Space between the "Dewan" and "Hosh alniswan"*

Private space is considered women space in most Sudanese cultures, but it is also divided to men's section "Dewan" which is usually larger in area and facing the street at the front side, and women's (and children) section "Hosh alniswan" at the back yard connected to the food preparation area which is typically considered a woman's role. Women access to men's section, where important decisions and discussions go on is restricted specially in the evenings when social visits are expected, if any exception occurred she would appear in proper decorum, non-verbal communication and proper attire. This segregation of private space varies largely among geographical areas, across class, and the rural- urban context. Nevertheless, the physical exclusion from men spheres where most informal practices of power take place degrade women especially those who enter the areas typically regarded as male domain such as politics.

2. *Public space*

In Sudan, public space has been restricted for women by a "Public Order Law" which uses an arbitrary syntax to restrict appearance and behaviour. This law was utilised by the police state to largely discriminate against women. In addition, it was also used within the commodification of public space against street vendors and impoverished urban women. Public spaces and gender discourse is also structured around what is known as "geographies of fear"; a study by Hamid and Taha (2020) conducted in Khartoum showed that women do not use public spaces due to security reasons in addition to lack of amenities and women related activities. Women also said they prefer to go out only in day time because of social norms. As stated by Phadke (2013), fear of violence hinders women's access to public space, although violence is not limited to public space nor it happens exclusively to women. Police records and newspaper reports in Sudan show large numbers of women being victims of domestic violence.

3. Workplace

Sudan's Labor Law designates certain work as unsuitable for women and imposes age restrictions on specific jobs, such as women's salons. However, the law does not protect women from sexual harassment in the workplace. These limitations in the legal framework contribute to gender inequalities in employment opportunities and workplace environments.

4. The city oeuvre or pleasure

Lefebvre's Right to the City identifies play, pleasure or oeuvre as an important right. Women's accessibility to these areas is very low. Two illustrative examples are the Sudanese Women Football Team and the Sudanese Female Cyclers. Public interviews with these women reveal multidimensional barriers rooted in legislation, social norms, and economic factors that restrict their participation and enjoyment in these activities.

CONCLUSION

In summary, Sudan's complex geographical context, characterised by vast territory, diverse population, and abundant natural resources, is marred by decades of underdevelopment, political instability, and civil conflict. Colonial and post-colonial have left lasting imprints on social structures, power dynamics, and cultural norms. Colonial powers imposed their own ideologies and values, including rigid gender roles that reinforced male dominance and female subordination. Despite its rich history of resistance and independence, the nation continues to grapple with systemic challenges that hinder the realisation of its full potential.

Sudanese women, throughout history, have played pivotal roles in shaping the nation's trajectory, from ancient kingdoms to modern political movements. Despite significant strides in education and political participation, women still face persistent barriers to accessing essential services, economic opportunities, and public spaces. The intersectionality of gender, ethnicity, socio-economic status, and disability further exacerbates these challenges, highlighting the need for targeted interventions and inclusive policies.

The ongoing conflict exacerbates existing vulnerabilities, particularly for women and marginalised communities, underscoring the urgent need for comprehensive strategies to address humanitarian crises and promote sustainable peace-building efforts. Women-led coalitions advocating for increased representation and collective action demonstrate the resilience and determination of Sudanese women in shaping their nation's future.

Efforts to promote spatial justice and the right to the city must dismantle patriarchal structures, address legal and institutional barriers, and prioritise the inclusion of women and vulnerable groups in decision-making processes. Only through collaborative and sustained action can Sudan achieve gender equality, social justice, and inclusive development for all its citizens.

REFERENCES

Abbas, S. (2010, September). The Sudanese Women's Mopvement and the Mobilization for the 2008 legislative Quota Aftermath. *IDS Bulletin-Volume 41, No. 5*.

Aziz, A. & Alfaki, A. (2021). Shifting Terrain of Political Participation in Sudan: Elements Dating from the Second Colonial (1898-1956) Period to the Contemporary Era.

Badri, B. (2005). Feminst Perspective in the Sudan: An Analytical Overview. *freie Uniersitat Berlin*.

Barakat. S. (2005). *After the Conflict: Reconstruction and Development in the Aftermath of War*. London: I. B. Tauris.

Elveren, A & Moghadam, V. M. (2019). The Impact of Militarization on Gender inequality and Female Labour Force Participation. *https://ideas.repec.org*.

Fischer, M. & Wang, F. a. (2011). *Spatial Data Analysis: Models, Methods and Techniques*. New York: Springler.

Hamid, G. & Taha, S.(2020). An Expoloratory Study of Women's use of Public Spaces in Greater Khartoum, sudan- Case Study of Althawra Hara 72 Omdurman. *Journal of Building and Road Research Volume 22*, 49-64.

Harikrishnan, S. (2022). *Social spaces and Public Sphere.* Routledge.

Harvey, D. (1973). *Social Justice and the City.* University of Georgia Press.

Hashim, F.(2018). *Political Economy of Violence Against Women in Sudan.* DAWN Discussion paper no. 12.

Henry, M. & Natal, K.(2016, 6 23). Militarialization as Diffusion: the Politics of Gender, Space, and Everyday. *Gender, Place, Culture* , pp. 850-856.

IEMEed. (2017). Post Conflict Reconstruction in MENA: Previous Experiences and Stakeholder's Inclusive Involvement.

Lefebvre, H. (1996). *The Right to the Citu.* The Anarchist Library.

Moghadam, V. M. (2004). Patriarchy in Transition: Women and the Changing Family in the Middle east. *Journal of Comparative Family Studies 35 (2)*, 137-162.

Osman, N. (2004). Political Participation of Sudanese Women. *www.sudan-forall.org.*

Phadke, S. (2013, September 28). Unfriendly Bodies, Hostile Cities: Reflections on Loitering and Gendered Public Space. *Economic and Political Weekly*, pp. 50-59.

Rothe, D. (2008). Ironies of Controlling State crime. *International Journal of Law, Crime and Justice*, 196-210.

Siwach, P. (2020). Mapping Gendered Spaces and women's mobility: A Case Study of Mitathel Village, Haryana. *Volume 20, Issue 1*.

Soja, E. (2010). *Seeking Spatial Justice* . London: University of Minnesota Press.

Tonnessen, L. (2019). The Social politics: International studies . *Gender, State, and Society Vol. 26-No.2*, 223-244.

Walter, B. (2011). Conflict Relapses and the Sustainability of Post conflict Peace. *World Bank*.

OPTIMIZING SPRAY DRYING PARAMETERS FOR TRONA FGD SORBENT USING RESPONSE SURFACE METHODOLOGY

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ABSTRACT

Spray drying flue gas desulphurization (FGD) demands intricate understanding of the influences of various spray drying parameters on sulphur dioxide capture. Drying and evaporation are integral to the process, significantly influencing product quality, especially moisture content. This study focused on assessing Trona ($NaHCO_3.Na_2CO_3.2H_2O$) as a suitable sorbent material for spray drying FGD, utilizing a laboratory-scale spray dryer. The study aimed at optimizing key spray drying parameters i.e., inlet gas temperature (120 - 200 °C), slurry flowrate (16 - 32 ml/min) and slurry solid concentration (5 - 12.5 %) using a response surface methodology (RSM) approach. A systematic experimentation employing Central Composite Design (CCD) was conducted to analyse the interactive effects of these parameters on both the moisture content (Y_1) of the resulting product and exit temperature (Y_2). Results indicated a significant influence of both inlet flue gas temperature and slurry flowrate on the final moisture content and exit temperature. The lowest moisture content (4.41%) was achieved at the highest slurry concentration (12.5%), an inlet gas temperature of 180 °C, and a slurry flowrate of 20 ml/min, resulting in an exit temperature of 73.9 °C. Conversely, the lowest exit temperature (40.5 °C) corresponded to the highest moisture content (14.65%) at an inlet gas temperature of 120 °C. The analysis of variance (ANOVA) confirmed the substantial impact of inlet gas temperature, as indicated by the highest F-values of 129.78 and 192.79 for moisture content and exit temperature, respectively. Predictive quadratic models, established from experimental findings, exhibited strong fits with R-squared coefficients of 0.95 for moisture content and 0.96 for exit temperature.

Keywords: Trona, FGD, spray drying, optimization, moisture content, exit temperature.

INTRODUCTION

In today's energy landscape, many countries continue to rely on fossil fuels for energy production with coal contributing to approximately 37% of the world's electricity as of 2019 (Filonchyk and Peterson, 2023). South Africa in particular, is the 7th largest of coal exporter as of 2020 (IEA, 2021) and generates a greater proportion of its electricity (about 77%) from coal (Jain and Jain, 2017). This global reliance on fossil fuel raises environmental concerns like rising temperatures and disasters (Dlewis, 2020). This has sparked a need to curb harmful gas emissions from fossil fuel use. Coal combustion results in the emission of various pollutant gasses including nitrous oxides and sulfur oxides causing acid rain, smog, and respiratory illnesses (Munsif et al., 2021). As a result, regulations such as the Air Quality Act have been implemented in South Africa. These regulations are further supported by international agreements pushing industries toward more sustainable practices. Industries have therefore been mandated to adopt control measures to curb the emission pollutant gases to the environment.

Flue gas desulphurization (FGD) is a control technology that has been widely used worldwide for active removal of sulphur compounds and other pollutants from industrial flue gases. FGD is categorized into three types i.e., dry, semi-dry and wet FGD technologies based on the handling of the sorbent and the desulphurization products (Kumar and Jana, 2022). Spray drying FGD is a type of semi-dry FGD which utilizes spray drying technique to react the sulphur species contained in flue gases with an alkaline sorbent slurry. The spray drying FGD technology stands out for its lower water consumption and reduced capital investment compared to the wet limestone FGD process (Koech et al., 2021).

The spray drying FGD process involves preparing a sorbent slurry by mixing the sorbent with water, which is then pumped into a spray chamber. In the spray chamber, it encounters a stream of hot flue gases from the boilers. The slurry enters the spray chamber through a spray nozzle, atomizing it into a mist of droplets. This atomization significantly enhances the interaction between the SO_2 in the flue gas and the reactive component in the droplets (Liu et al., 2023). The spray drying process can utilize various absorbents, that are either calcium or sodium-based sorbents, for the removal of SO_2 from flue gas. Trona is a natural mineral rich in both Na_2CO_3 and $NaHCO_3$, with abundant global deposits (Jiang et al., 2019). Its alkaline nature and solubility in water makes it an effective reagent for the scrubbing of SO_2. It has been tested and proven to be highly reactive towards SO_2 and therefore can be used as a sorbent for spray drying FGD (Erdöl-Aydın and Nasün-Saygılı, 2007).

The spray chamber is a critical part of the process facilitating simultaneous drying, evaporation and absorption (Cal and Sollohub, 2010). The effective removal of sulphur dioxide in the chamber is dependent on numerous factors such as the preparation of the sorbent and the reaction conditions within the chamber. As flue gas from the boilers (typically around 140°C) encounters the slurry within the spray chamber, it induces droplet drying and moisture evaporation (Carpenter, 2012). This process leads to the formation of a dry desulphurization product, typically collected at the chamber's bottom. It is therefore essential to establish and utilize appropriate drying and evaporation conditions for specific sorbents. Obtaining dry desulphurization products while maintaining high desulphurization rates within the spray chamber is vital. A thorough understanding of the effect of operational parameters on the performance of the spray dryer is necessary for effective SO_2 removal, including a careful assessment of drying and evaporation within the spray chamber.

Recent advancements in spray drying technologies, particularly in FGD have focused on optimizing the efficiency of SO_2 removal while minimizing the environmental footprint. Various studies have explored different sorbents and process parameters to enhance the FGD process. Li et al. (2018) optimized the deacidification performance in waste incinerator flue gas by rotating spray drying using a mathematical model based on mass and energy conservation and chemical reaction rates. Their model indicated that the deacidification can be significantly improved by optimizing the stoichiometric ratio, flue gas velocity, water spray rate and droplet size. Liu et al. (2023) investigated the gas-solid two-phase flow in an industrial-scale three-dimensional SDA-FGD reactor. The study found that the mass fluxes show a positive correlation with the inlet velocity of flue gas, while the particle mass fluxes are negatively correlated with the Ca/S molar ratio. Desulfurization efficiency negatively correlated with the flue gas inlet velocity and lime slurry size, while showing a positive correlation with the Ca/S molar ratio and flue gas inlet temperature. Hrdlicka and Dlouhy (2018) examined the potential for increasing SO_2 capture in spray drying FGD technology, finding a possibility of achieving SO_2 emission targets beyond 93%, even though the FGD was designed for a 75% capture ratio. The most significant factor affecting SO_2 capture was the temperature difference between the dry-bulb and the flue gas dew point in the spray absorber. Yi et al. (2019) explored a novel semi-dry spray drying absorption method for the simultaneous removal of mercury (Hg) and sulphur dioxide (SO_2) from flue gas using CaO. The study revealed limited effects of changing process parameters on Hg removal, but the use of additives improved Hg removal by about 40%. Koech et al. (2023) investigated the application of sodium-based sorbents in a lab-scale spray drying FGD system, demonstrating superior reactivity towards SO_2 compared to calcium-based alternatives.

Despite the promising findings in this technology, there are limitations related to the optimization of operating conditions and the scalability of the process. Additionally, the technology faces challenges such as the inability to react flexibly to changes in SO_2 concentration and flue gas flow (Hrdlicka and Dlouhy, 2018). While previous studies have demonstrated the potential of trona as an effective sorbent for SO_2 removal, there remains a gap in the optimization of spray drying parameters specifically for trona-based FGD systems. This study focuses on the optimization of spray drying parameters for trona-based FGD sorbents using the Response Surface Methodology (RSM) approach by systematically investigating the effects of key parameters such as inlet flue gas temperature, slurry flow rate, and slurry solid concentration. The significance lies in providing a robust framework for improving the performance of spray drying FGD systems and enhancing their efficiency, contributing to the pursuit of cleaner energy practices.

METHODOLOGY

Materials and Equipment

Trona, in its raw, unprocessed state, was procured from Tata Chemicals, South Africa. It was mixed with water to form a slurry of varying solid concentrations. The mixing process employed a Dragonlab MS-H_20 Pro Magnetic Stirrer. The precise weighing of the sorbent was done using an AE Adam PGL Laboratory scale. The slurry preparation was carried out in a standard 500ml laboratory flask, while the final product resulting from the entire process was collected and stored in 50ml Boston and smooth prep bottles. The analysis of the spray-dried product involved using a Shimadzu MOC63u Moisture Analyzer to determine its moisture content.

Design of Experiments

This study utilized RSM for experimental design with the primary objective of maximizing a response concerning the provided collection of independent variables and to establish the interrelationships between the independent variables and the targeted responses. RSM is as a powerful tool that is widely used for optimizing complex processes by modelling and analysing the effects of multiple variables (Myers et al. 2016). It is based on regression and variance analysis principles enabling the user to improve, develop and optimize the response of interest (Reji and Kumar 2022). Specifically, this study focused on the moisture content of the collected dried trona samples and the exit air temperature as key responses of interest. The chosen independent variables encompassed the inlet air temperature, slurry flow rate, and slurry concentration. The Central Composite Design (CCD) which is a component of RSM was used to generate a matrix of experiments based on the chosen limits of the independent variables as outlined in Table 1. These limits were determined based on trial runs conducted during the study. The inlet gas temperature was based on typical flue gas temperature of around 140-160°C entering the FGD unit.

Table 1: *Ranges experimental variables.*

Variable	Range
Slurry flowrate (ml/min)	16 – 32
Inlet flue gas temperature (°C)	140 – 200
Slurry Concentration (% mass)	7.5– 12.5

The execution of the experimental design followed a three-step process, which involved performing the statistically designed experiments followed by the estimation of the coefficients within the requisite mathematical model and finally predicting the response and assessing the reliability of the model. Equation 2 outlines the expected polynomial model.

$$Y = \beta_0 + \sum_{i=1}^{n} \beta_i x_i + \sum_{i=1}^{n} \beta_{ii} x_i^2 + \sum_{i=1}^{n} \sum_{j=i+1}^{n} \beta_{ij} x_i x_j \quad (2)$$

Procedure

A laboratory scale spray dryer (mod. MSD/EV) was used to carry out the experiments as illustrated in Figure 1. The slurry was first prepared separately by mixing a predetermined mass of the trona sample with water to obtain the desired solution concentration. Mixing of the slurry was allowed to continue for 10 minutes at 500 rpm to ensure complete dissolution of the trona sample in water. The flowrate and temperature of the inlet air were preset, and the spray dryer allowed to stabilize. The slurry was then introduced into the spray chamber using a peristaltic pump through a two-fluid nozzle. The spray nozzle efficiently disperses the slurry into fine mist of droplets allowing interaction with the heated air in the spray chamber.

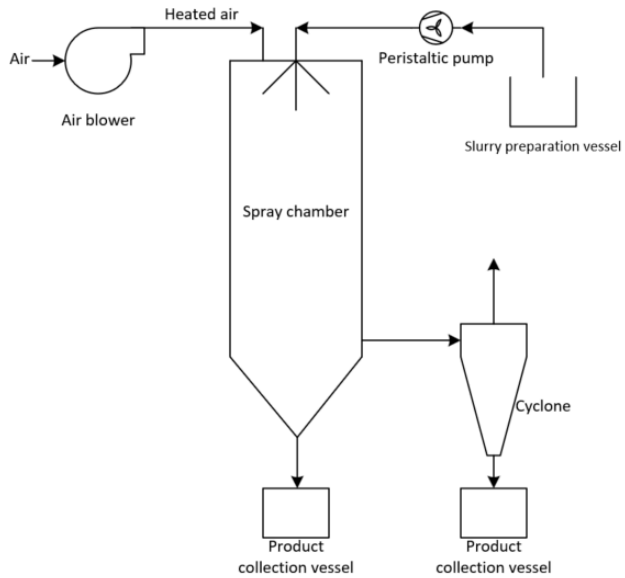


Figure 1: *Laboratory scale spray drying experimental setup.*

The operational parameters in the spray dryer i.e., the slurry flowrate, inlet air temperature, and the heating gas flowrate were preset using the touch screen panel on the spray dryer. Each run involved recording the exit temperature after achieving steady state. The dried samples were also collected and stored for moisture analysis. The sample mass after drying recorded as the initial mass, was subjected to a moisture analyzer at 120 °C for 30 minutes. Subsequently, the final mass was recorded, and the moisture content was calculated using Equation 1.

$$\%\ moisture\ content = \frac{(initial\ mass - final\ mass)}{initial\ mass} \times 100 \qquad (1)$$

Analysis of trona was done using a Malvern Pananalytical Empyrean X-ray diffractometer (XRD) to determine the crystallographic structure of the sorbent. A Philips XL-30S Scanning electron microscopy (SEM) was used to analyze the surface morphology and topography of trona while Energy-Dispersive X-ray Spectroscopy was used to determine the sample's surface elemental composition.

RESULTS AND DISCUSSION OF RESULTS

Characterization of Trona

The X-ray diffractometer (XRD) analysis of the trona sample (Figure 2) revealed a distinctive diffraction pattern marked by multiple peaks. These peaks, representing crystallographic planes of different phases within the trona material, prominently indicated a composition of 65.9% natrite (Na_2CO_3) and 34.1% thermonatrite ($Na_2CO_3.H_2O$). These findings from XRD align with the SEM image mapping analysis of phases presented in Figure 3, illustrating that three phases of NaCO constitute a combined percentage fraction of 90.83%. SEM micrographs in Figure 4 depicted varied particle sizes with rough surfaces, suggesting high surface area and pore volume. The presence of needle-like structures can be attributed to impurities present in the sample. Although the trona used is naturally occurring and may contain impurities, the low concentration is evident in the combined fraction of 90.83% for NaCO.

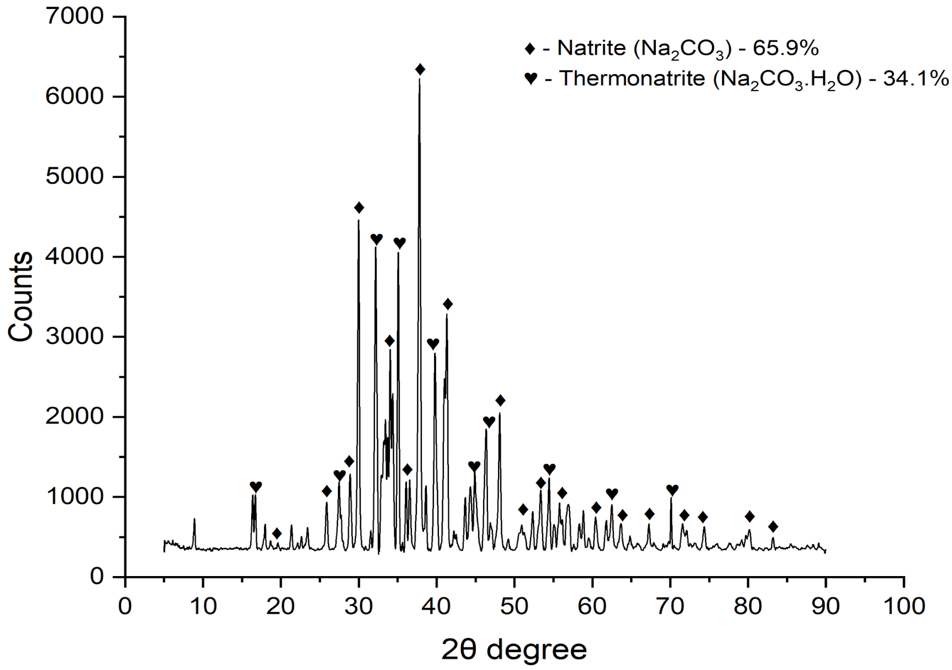
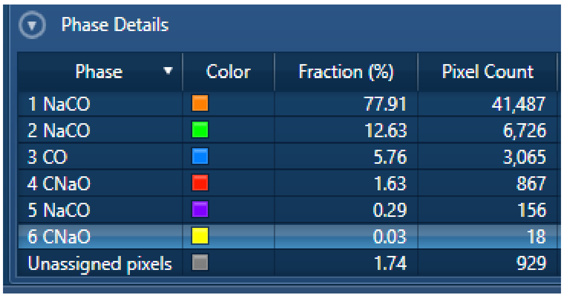


Figure 2: *XRD analysis results of trona.*



Phase Details

Phase	Color	Fraction (%)	Pixel Count
1 NaCO		77.91	41,487
2 NaCO		12.63	6,726
3 CO		5.76	3,065
4 CNaO		1.63	867
5 NaCO		0.29	156
6 CNaO		0.03	18
Unassigned pixels		1.74	929

Figure 3: *SEM image mapping analysis of trona phases*

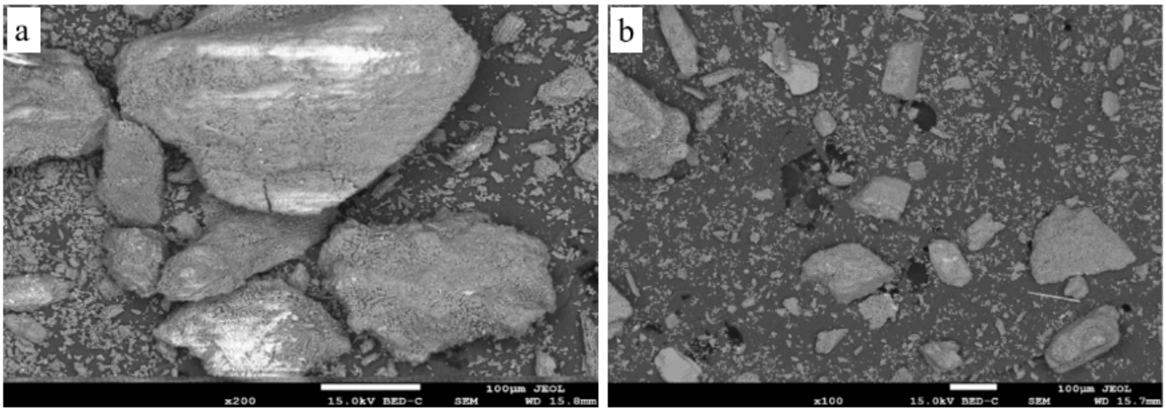


Figure 4: *Trona SEM generated images at (a) X200, and (b) X100 magnification.*

Model fitting

A mathematical correlation (quadratic models) was established to depict the relationships between the set of independent variables and the responses based on the experimental findings. The predictive models, presented as Equations 3 and 4 for moisture content and exit temperature respectively, were developed using CCD.

$$Y_1 = 8.9842 - 0.703932A - 0.038764B + 1.11311C - 0.00012 \qquad (3)$$

$$Y_2 = -147.49659 + 2.95114A + 1.50935B + 3.92685C - 0.016250AB \qquad (4)$$

$Y_1 - Moisture\ content\ (\%)$
$Y_2 - Exit\ temperature\ (°C)$
$A - Slurry\ concentration\ (\%)$
$B - Inlet\ flue\ gas\ temperature\ (°C)$
$C - slurry\ flowrate\ (ml/min)$

The adequacy of the predictive models for both responses (i.e., moisture content and exit temperature) were assessed by comparing predicted data with experimental data. Figure 5(a) for moisture content and Figure 5(b) for exit temperature demonstrate satisfactory results, with most data points closely aligning with the line of unit slope. This alignment underscores the effectiveness of both models in predicting experimental data, evident from the respective R-squared values of 95.01% and 96.04%.

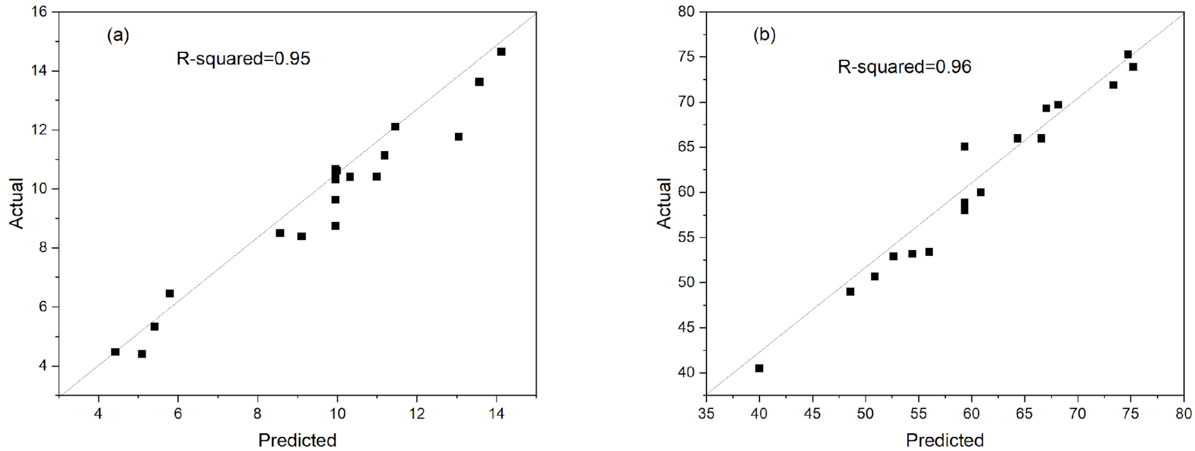


Figure 5: *Plots of the predicted vs experimental values for (a) moisture content and (b) exit temperature.*

Table 2 and Table 3 display the analysis of variance (ANOVA) for moisture content and exit temperature, respectively. In the ANOVA, a p-value less than 0.05 denotes significance, while values exceeding 0.1 indicate insignificance. For moisture content, significant terms include B, C, and C^2, with the highest F-value of 129.78 attributed to inlet flue gas temperature (B), signifying its major influence. The model's reliability is confirmed by an F-value of 21.14. For exit temperature (Table 3), significant terms are B, C, AC, and A^2. Similarly, the most influential term is B (inlet flue gas temperature), with an F-value of 192.79. The overall model is significant with an F-value of 26.97, underscoring the model's validity.

Table 2: *ANOVA for moisture content*

Source	Sum of Squares	df	Mean Square	F-value	p-value
Model	138.13	9	15.35	21.14	< 0.0001
A-slurry concentration	1.46	1	1.46	2.01	0.1869
B-Inlet flue gas temperature	94.24	1	94.24	129.78	< 0.0001
C-Slurry flowrate	36.51	1	36.51	50.28	< 0.0001
AB	0.0003	1	0.0003	0.0004	0.9839
AC	0.0120	1	0.0120	0.0165	0.9002
BC	0.2701	1	0.2701	0.3720	0.5555
A^2	0.6391	1	0.6391	0.8801	0.3703
B^2	0.7315	1	0.7315	1.01	0.3392
C^2	3.64	1	3.64	5.01	0.0491
Residual	7.26	10	0.7261		
Lack of Fit	4.58	5	0.9156	1.71	0.2860
Pure Error	2.68	5	0.5367		
Cor Total	145.39	19			

Table 3: *ANOVA for exit temperature*

Source	Sum of Squares	df	Mean Square	F-value	p-value

Model	1522.64	9	169.18	26.97	< 0.0001
A-slurry concentration	4.95	1	4.95	0.7892	0.3952
B-Inlet flue gas temperature	1209.30	1	1209.30	192.79	< 0.0001
C-Slurry flowrate	159.39	1	159.39	25.41	0.0005
AB	5.28	1	5.28	0.8420	0.3804
AC	41.86	1	41.86	6.67	0.0273
BC	24.15	1	24.15	3.85	0.0781
A^2	59.35	1	59.35	9.46	0.0117
B^2	6.00	1	6.00	0.9571	0.3510
C^2	3.06	1	3.06	0.4878	0.5008
Residual	62.73	10	6.27		
Lack of Fit	24.43	5	4.89	0.6378	0.6832
Pure Error	38.30	5	7.66		
Cor Total	1585.37	19			

Effects of independent variables on the responses

Effects of slurry concentration and inlet gas temperature on the responses

Figure 6 provides insights into the influence of inlet flue gas temperature and slurry concentration on the responses. In Figure 6a, reveals an inversely proportional relationship between inlet flue gas temperature and moisture content. As the temperature increases from 140 to 180 °C, there is a corresponding decrease in moisture content from 12.20% to 7.34%. The relationship is linear, matching predicted trends and validating experimental results. Higher temperatures accelerate moisture transfer in the spray dryer, improving the overall drying process. This bears significance for flue gas desulphurization, offering energy-efficient drying with implications for SO_2 absorption optimization.

The combined effects of inlet gas temperature and slurry concentration demonstrate a notable increase in moisture content at lower temperatures and slurry concentration. In Figure 6b, a linear, directly proportional relationship is observed between inlet gas temperature and exit temperature. A shift in inlet air temperature from 180 to 140 °C results in a decline in outlet temperature from 67.5 to 50.1°C. Higher exit temperatures are associated with lower moisture content and reduced energy consumption in spray drying. However, careful consideration is required to prevent machinery strain or undesirable changes in product characteristics due to excessively high temperatures.

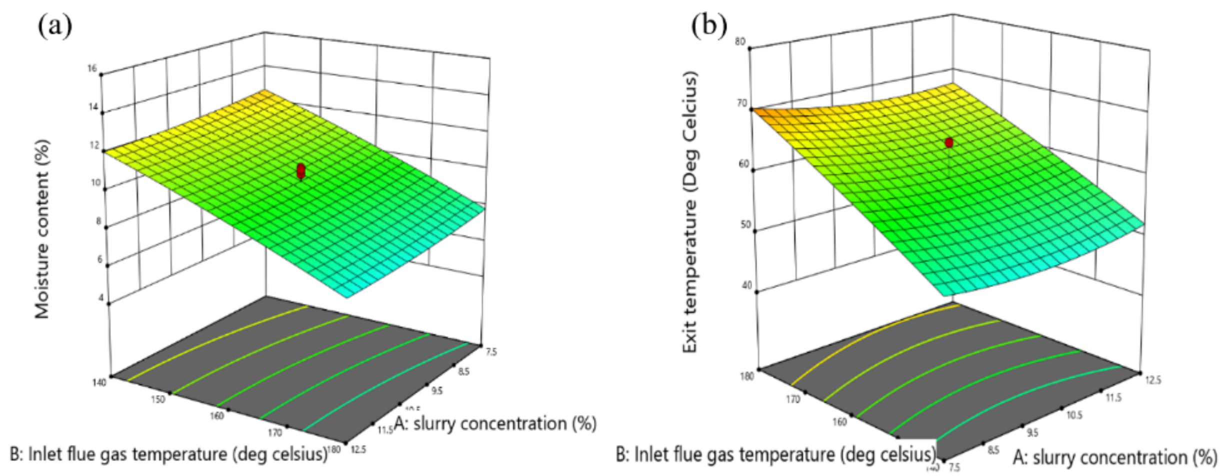


__Figure 6:__ 3D surface graphs of the effects of inlet flue gas temperature and slurry concentration on (a) moisture content and (b) exit temperature.

Effect of inlet flue gas temperature and slurry flowrate on the responses

Figure 8a displays a 3D surface graph demonstrating a slightly linear relationship between slurry flowrate and exit temperature, with a negative gradient. Increasing slurry flowrate causes a decrease in exit temperature, exemplified by the decrease from 62.8 to 60 °C as flowrate increases from 20 to 28 ml/min. This can be attributed to the larger flowrate introducing more moisture, demanding more energy for evaporation and subsequently lowering the exit temperature. The combined effects of both the inlet flue gas temperature and slurry flowrate on exit temperature reveal that the highest exit temperature is achievable when the inlet gas phase temperature is at its highest and moisture content at its lowest, and vice versa. This is evident in the 3D surface plot, where at a constant slurry concentration of 10%, the maximum exit temperature of 72.7°C is achieved at 180°C inlet flue gas temperature and 20 ml/min slurry flowrate, while the minimum exit temperature of 60°C is achieved at 140°C temperature and 28 ml/min flowrate.

Figure 7b illustrates a positive quadratic relationship between slurry flowrate and moisture content. The curved line with a positive gradient suggests that the moisture content gradually increases as slurry flowrate rises. The peak moisture content occurs at the lowest slurry flowrate. For instance, increasing the flowrate from 20 to 28 ml/min results in an increase in moisture content from 5.3% to 8.7%. This relationship is explained by the fact that higher slurry flowrates require more energy to evaporate water, leading to higher moisture content in the final product. The combined effects of inlet flue gas temperature and slurry flowrate on moisture content reveal that the highest moisture content occurs at the lowest temperature and highest flowrate, while the lowest moisture content occurs at the highest temperature and lowest flowrate. These observations show the significance of the slurry flowrate in spray drying FGD which impacts the contact time, absorption capacity, and hydrodynamics within the system, influencing the distribution and mixing of flue gas and sorbent slurry.

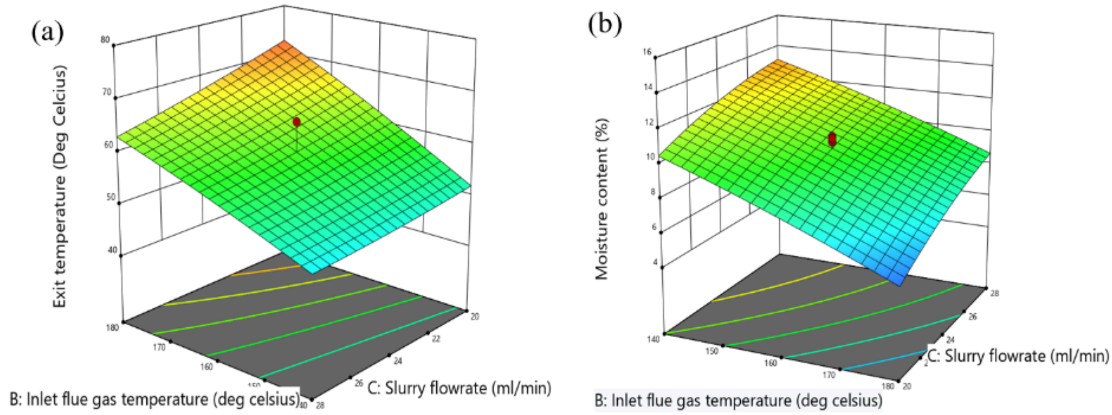


Figure 7: *3D surface graphs of the influence of inlet flue gas temperature and slurry flowrate on (a) exit temperature and (b) moisture content.*

Effect of slurry flowrate and slurry concentration on the responses

The influence of slurry concentration on both exit temperature and moisture content was found to be minimal, indicated by a nearly horizontal, slightly curved line that exhibited little change with increasing slurry concentration as observed in Figure 8. This observation was substantiated by ANOVA analysis, which determined the factor to be insignificant in both models. The combined effects of slurry flowrate and slurry concentration on moisture content revealed that the primary influencing factor was slurry flowrate, while slurry concentration had little to no impact on the graph shape. In contrast, the relationship had a more complex nature for exit temperature. The highest exit temperature was associated with the lowest slurry flowrate and highest concentration, the second highest with the lowest concentration and flowrate, and the lowest with the highest slurry flowrate and concentration.

Despite its insignificance concerning moisture content and exit temperature, the factor of slurry concentration holds importance in flue gas desulphurization. It is directly proportional to the stoichiometric ratio, as demonstrated by Koech et al. (2022), and has been shown to affect absorption efficiency. An increase in the stoichiometric ratio correlates with a rapid rise in desulphurization efficiency, attributed to the high slurry concentration, which reduces the droplet liquid-phase mass transfer resistance for SO_2 (Qu et al., 2021).

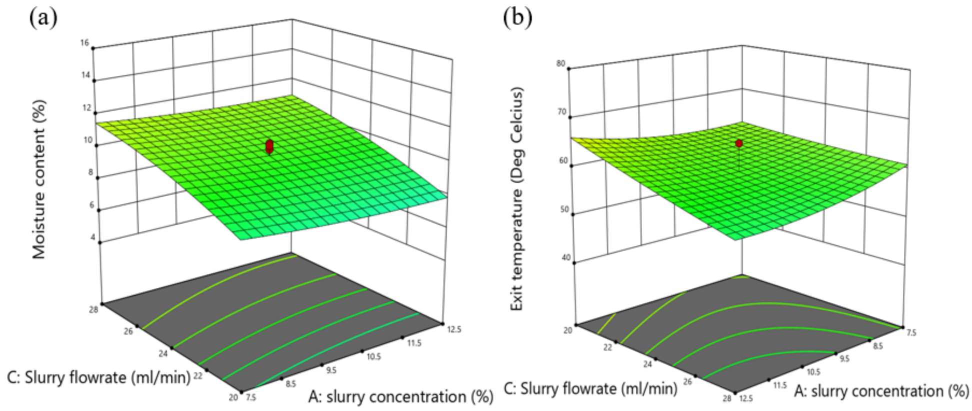


Figure 8: *3D surface graphs of the effects of slurry concentration and slurry flowrate on (a) moisture content (b) exit temperature.*

CONCLUSION

Trona, characterized by a crystalline, particle-like structure, primarily consists of carbon in the form of natrite (Na_2CO_3). While trace impurities such as copper and chlorine are present, they constitute minimal proportions, with NaCO accounting for 90.83%. This composition positions trona as a promising candidate for FGD sorbent applications. This study focused on assessing the effects of key spray drying parameters on the trona product properties using a Response Surface Methodology (RSM) approach. The developed RSM model demonstrated desirable estimation accuracy, evident in the close alignment of predicted data with experimental output values for both moisture content and exit temperature. These predictive models exhibit potential applications in modelling flue gas desulphurization systems, as evidenced by their excellent prediction performance, yielding R-squared values exceeding 95%. Analysing the significance of each independent factor on the responses revealed the following order of importance: inlet flue gas temperature > slurry flow rate > slurry concentration. Changes in inlet flue gas temperature exerted the most significant impact on responses, while variations in slurry concentration had the least effect. The highest air exit temperature coincided with the highest inlet flue gas temperature, resulting in the lowest moisture content. Conversely, varying the slurry flow rate showed that the highest flow rate correlated with the lowest exit temperature and the highest moisture content. Changes in slurry concentration were observed to have negligible effects on both responses. By optimizing the spray drying parameters, the performance of trona as an FGD sorbent can be improved, leading to more effective SO_2 removal and reduced environmental impact.

REFERENCES

Cal, Krzysztof, and Krzysztof Sollohub. “Spray Drying Technique. I: Hardware and Process Parameters.” *Journal of Pharmaceutical Sciences* 99, no. 2 (2010): 575–86.

Carpenter, Anne M. “Low Water FGD Technologies.” *IEA Clean Coal Centre*, 2012. https://usea.org/sites/default/files/112012_Low%20water%20FGD%20technologies_ccc210.pdf.

Dlewis. “Increase in Natural Disasters on a Global Scale by Ten Times.” Vision of Humanity, October 27, 2020. https://www.visionofhumanity.org/global-number-of-natural-disasters-increases-ten-times/.

Erdöl-Aydın, N., and G. Nasün-Saygılı. “Modelling of Trona Based Spray Dry Scrubbing of SO2.” *Chemical Engineering Journal* 126, no. 1 (2007): 45–50.

Filonchyk, Mikalai, and Michael P. Peterson. “An Integrated Analysis of Air Pollution from US Coal-Fired Power Plants.” *Geoscience Frontiers* 14, no. 2 (2023): 101498.

França, Ítalo WL, Samuel JM Cartaxo, Moises Bastos-Neto, Luciana RB Gonçalves, and Fabiano AN Fernandes. "Effect of additives to improve calcium-based sorbents in semi-dry flue gas desulphurization." *Emission Control Science and Technology* 6 (2020): 105-112.

Hrdlička, Jan, and Tomáš Dlouhý. "Full-scale evaluation of SO_2 capture increase for semi-dry FGD technology." *Journal of the Energy Institute* 92, no. 5 (2019): 1399-1405.

IEA. “Coal Information: Overview.” Paris, 2021. https://www.iea.org/reports/coal-information-overview/exports.

Jain, Shilpi, and P. K. Jain. “The Rise of Renewable Energy Implementation in South Africa.” *Energy Procedia* 143 (2017): 721–26.

Jiang, Shifeng, Yuande Zhang, and Zhibao Li. “A New Industrial Process of $NaHCO_3$ and Its Crystallization Kinetics by Using the Common Ion Effect of Na_2CO_3.” *Chemical Engineering Journal* 360 (2019): 740–49.

Koech, L., H. Rutto, L. Lerotholi, R. C. Everson, H. Neomagus, D. Branken, and A. Moganelwa. “Spray Drying Absorption for Desulphurization: A Review of Recent Developments.” *Clean Technologies and Environmental Policy* 23, no. 6 (August 2021): 1665–86. https://doi.org/10.1007/s10098-021-02066-3.

Koech, Lawrence. “Flue Gas Desulphurization by Spray Dry Scrubbing.” PhD Thesis, Vaal University of Technology, 2022. http://digiresearch.vut.ac.za/handle/10352/616.

Koech, Lawrence, Raymond C. Everson, Burgert Hattingh, Hilary Rutto, Letsabisa Lerotholi, and Hein WJP Neomagus. "Comparative Study of Sorbents for Spray Dry Scrubbing of SO2 from Flue Gases." *ACS omega* 8, no. 26 (2023): 23401-23411.

Kumar, Lokesh, and Susanta Kumar Jana. “Advances in Absorbents and Techniques Used in Wet and Dry FGD: A Critical Review.” *Reviews in Chemical Engineering* 38, no. 7 (October 26, 2022): 843–80. https://doi.org/10.1515/revce-2020-0029.

Li, Chunxi, Zhennan Jia, Xuemin Ye, and Shuie Yin. "Simulation on deacidification performance of waste incinerator flue gas by rotating spray drying." *Energy* 152 (2018): 652-665.

Liu, Peng, Shiliang Yang, Jianhang Hu, and Hua Wang. “Numerical Analysis of SO_2 Removal Characteristics in Industrial Flue Gas Desulfurization Reactor by Spray Drying Adsorption.” *Separation and Purification Technology* 323 (2023): 124475.

Myers, Raymond H., Douglas C. Montgomery, and Christine M. Anderson-Cook. “Response surface methodology: process and product optimization using designed experiments.” *John Wiley & Sons*, (2016).

Munsif, Rabia, Muhammad Zubair, Ayesha Aziz, and Muhammad Nadeem Zafar. “Industrial Air Emission Pollution: Potential Sources and Sustainable Mitigation.” In *Environmental Emissions*. IntechOpen, 2021. http://dx.doi.org/10.5772/intechopen.93104.

Qu, Jiangyuan, Nana Qi, Zhen Li, Kai Zhang, Pengcheng Wang, and Lifeng Li. “Mass Transfer Process Intensification for SO_2 Absorption in a Commercial-Scale Wet Flue Gas Desulfurization Scrubber.” *Chemical Engineering and Processing-Process Intensification* 166 (2021): 108478.

Reji, Meega, and Rupak Kumar. “Response surface methodology (RSM): An overview to analyze multivariate data.” *Indian Journal of Microbiology Research* 9(4) (2022): 241-248.

Yi, Honghong, Chengcheng Du, Yueqiang Ma, Xiaolong Tang, Shunzheng Zhao, Fengyu Gao, Zhongyu Yang, Yonghai Huang, Kun Yang, and Xizhou Xie. "A novel semi‐dry method for the simultaneous removal of Hg and SO_2 using spray drying absorption method." *Journal of Chemical Technology & Biotechnology* 95, no. 5 (2020): 1431-1440.

AN ELECTRONIC HEALTH RECORD WEB APPLICATION FOR ADDICTION REHABILITATION CENTRES (REHABAID)

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ABSTRACT

The study focuses on the creation of a web application to be used by rehabilitation facilities that deal with substance-addicted patients. This application aims to bring together addiction treatment centres and guardians who look after their affected family members. Drug abuse is on the rise in Zimbabwe, a country that has very few addiction rehabilitation facilities for housing and treating affected patients, who in many cases are young children and youth of school-going age. The affected (patient and guardian) need to travel long distances to take their family members (patients) for treatment or review. There is a great need for them to know the details of these treatment facilities before travelling, things like; where the facility is situated, what the facility offers, whether there is an admission facility, and other details. Most people will be travelling from as far as the rural areas. People in cities are also not aware of how they can have their loved ones treated in cases of drug abuse. The study assists in linking the facilities and guardians looking to have their family members treated by providing an all-in-one shop for services like patient admissions, their progress, and specialist care through the use of a responsive web application. It also analyses doctor's notes to provide a summary of treatment reviews. These are secured and protected under doctor-patient confidentiality and health regulations.

Keywords*—addiction, rehabilitation facilities, drug abuse, patient, monitoring*

INTRODUCTION

Drug abuse has fast become one of the biggest challenges that Zimbabwe is currently facing and there are limited facilities to help deal with it. Therefore, there is a need to maximise what we have. Drugs are elements that change an individual's mental or physical state, which can influence how they perceive, understand, and react to their surroundings (Rhodes 2002:85). They can affect brain function, emotions, behaviour, and senses, making them hazardous and unpredictable, particularly for adolescents. The results of drug use vary from person to person and depend on the specific drug being used (Degenhardt et al.,2011). Addiction is a condition where a person is unable to cease using a substance or engaging in a particular behaviour (Koob and Volkow,2010:220). Drug addiction or substance use disorder (SUD), is an illness that affects a person's brain and behaviour leading to an inability to control the use of drugs or medication (Mayo Clinic Staff, 2022). Substances such as alcohol, marijuana and nicotine are considered drugs. When someone is addicted, they might continue using the drug despite the harm it causes (West and Brown,2013).

One of the most prevalent ways of dealing with substance use disorder is the use of addiction rehabilitation centres or treatment facilities for drug abuse (Moos,2018). These are facilities where drug abusers are committed to undergoing different treatment regimens to recover from substance use disorder. It was observed that the majority of addicts participate in a variety of crimes, such as killing, raping, robbing, and selling drugs within the neighbourhood (Hunter,2021:63). As a result, helping addicts receive treatment lessens these social issues in society (Alexander,2010). Studies have shown that there are different barriers to the rehabilitation process (Tavakoli, Armat and Akbari,2022:552). One such barrier is that facilities are limited in Zimbabwe. Their information such as locations, services offered and the number of patients they can accommodate or whether they are fully occupied is not readily available. This can prove to be a major hindrance to recovery, particularly as many individuals are only willing to engage in treatment for a brief period. Another barrier arises once an individual is committed to rehabilitation. Guardians are often anxious thinking that as soon as they commit their loved ones to rehabilitation, they are already better and some guardians fail to make it on visitation days, therefore there is a need to track patients' progress remotely to get a general idea of how they are progressing. Removing these barriers and providing comprehensive information about available facilities for addiction treatment, the services they offer, and acceptance criteria, provides a greater deal of help in combating substance use disorder (Appel et al., 2004:133).

RELATED STUDIES

Different ways of using technology to help in the addiction rehabilitation process have been proposed over the years and even though some seemed more helpful than others, all played a role in aiding addiction treatment (Kruse et al.,2020). Different researchers came up with different systems, some only offered educational information on drug abuse while others enabled easy management of rehabilitation facilities.

According to Gustafson et al., (2014:570), Alcohol Comprehensive Health Enhancement System Support (ACHESS), is a mobile application that facilitates communication between alcohol use disorder patients and professionals. It is an embedded application for smartphones. ACHESS offers a platform for patients to communicate, share their tales, and hold discussions. It has static and interactive features (Gustafson et al., 2014:572). It also provides information, decision-making tools, adherence policies, and support services to alcohol use disorder patients. The application looks at assisting patients to develop and maintain motivation for self-respect and connects patients with resources to cope with longing, removal of symptoms, and high-risk situations to avoid deterioration. Patients with alcohol use disorders were the target people for the application. This application has bias because it is only used by alcohol use disorder patients and does not help the community or guardians who would want to check on their loved one's progress. This is one of its flaws.

The Drug and Alcohol Services Information System (DASIS), another resource for information about drug and alcohol services, is present in the United States (US). It consists of three datasets: the Treatment Episode Data Set (TEDS), the National Survey of Substance Abuse Treatment Services (N-SSATS), and the Inventory of Substance Abuse Treatment Services (I-SATS) (SAMHSA, 2008). TEDS gathers demographic data on individuals receiving treatment, N-SSATS conducts a census of all facilities listed in I-SATS, and I-SATS is responsible for compiling a list of all organised facilities providing drug misuse and mental health treatment (SAMHSA, 2014). The three data sets that make up DASIS give information on illnesses related to drug misuse and mental health. The system focuses on giving survey data on drug usage, information on treatment options, and data on persons who are receiving treatment. However, it does not enable user interaction or display the location of treatment centres so that people are aware of where advice and treatment services are offered.

Additionally, there is a national case management database for information on addicts called the Addiction Management Information System (AMIS) in Canada. This was intentionally created to enhance the data collection, processing, and reporting process (Thunderbird Partnership Foundation, 2022). The work done by Canadian treatment facilities is presented. Treatment facilities use the system to feed all actions carried out at the facilities, including information about patients' admission and discharge. The purpose of this system is to provide treatment facilities with sufficient and reliable information about the addicts they serve as well as other activities carried out there. Most related systems either provide educational information on drug abuse such as effects, causes, and rehabilitation or were for the management of a facility's day-to-day record keeping. Few to none factored in the guardian, who, when examined clearly, plays a crucial role in the rehabilitation process. The proposed system aims at bridging the gap between addiction rehabilitation facilities and guardians.

FEATURES OF THE SYSTEM

Available facilities

The system has a carousel showing all the available facilities in Zimbabwe and their details. A guardian seeking rehabilitation services can view the details of these facilities to find one that is best suited to their needs. Details provided for each treatment facility include address, contact details and services. The capacity of each facility is also provided, that is the number of patients each facility can accommodate. There is a notification if the facility is fully occupied and guardians cannot make reservations to these fully occupied facilities.

Creating reservations
The system enables guardians to make a reservation at a facility of their choice. This is crucial since the facilities are limited. After making a reservation, a confirmation email is sent to the guardian.

Sentiment analysis of therapy reviews
Once committed to rehabilitation, individuals undergo therapy sessions where the greater amount of recovery stems from since the root causes of drug abuse in an individual are tracked. Therapists write therapy reviews for each patient during or after every session. Greater progress comes from therapy, therapy reviews convey how much progress an individual has made therefore the reviews are conveyed to guardians to show how their loved ones are progressing through rehabilitation. The therapy reviews though cannot be shown to guardians as they are since they are protected under doctor-patient privilege. Therefore, the system analyses therapy reviews using sentiment analysis to give a general notion of how an individual is progressing through rehabilitation.

Tracking patient's progress through a portal
The system enables guardians to track the progress of their loved ones remotely through a web portal. Information about the medication an individual is taking is shared with his/her guardian. The output of sentiment analysis on the therapy notes is also shown on the portal.

METHODOLOGY
Before launching the web application, a thorough examination of the requirements of the guardians seeking addiction rehabilitation services was made, as well as the requirements of the addiction treatment facilities. This involved conducting interviews and focus group discussions to establish specific user requirements and to develop the user interface designs. Consideration of the pros and cons of creating a cloud-supported native mobile application versus a web-based front-end application was done. Ultimately, a decision was reached to develop a web-based front-end application that can be accessed through mobile devices and desktop computers.
The system design was carried out through the use of UML modelling tools like sequence diagrams to show how the system functions, and how the different components that make up the system interact. Figure. 1 shows the sequence diagram of the RehabAid web application.

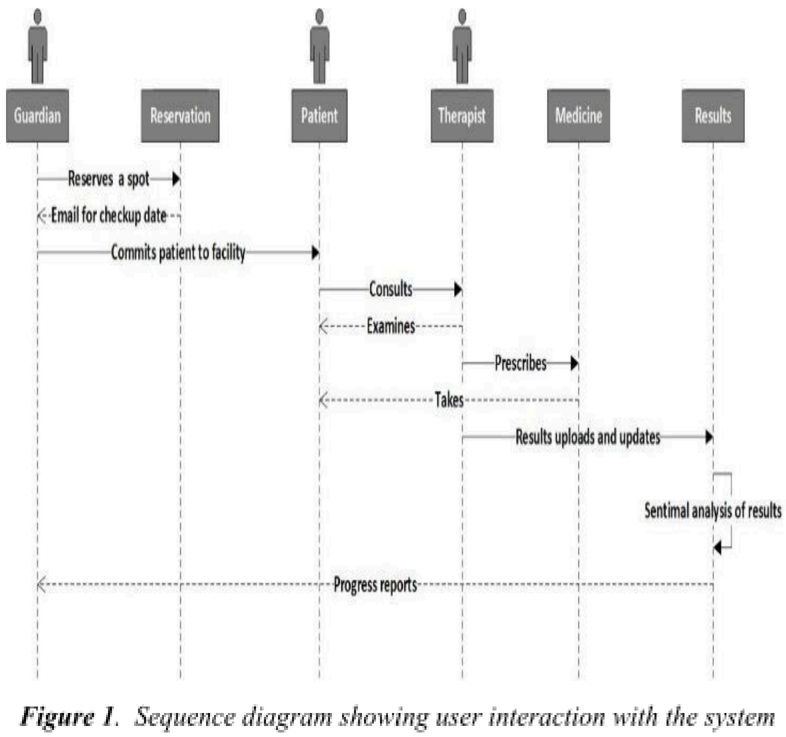

Figure 1. Sequence diagram showing user interaction with the system

The development of the system was carried out in ASP.NET using c# programming. This enabled the simultaneous development of the front end and back end of the system. The database of choice was

PostgreSQL. Send Grid was integrated into the system to enable the sending of confirmation emails by the treatment facility to the guardians who made reservations. The sentiment analysis model was trained on the Kaggle notebook using Python and LightGBM gradient boosting algorithms. A dataset used was obtained from Kaggle. Before training, feature extraction was carried out to extract the features that were necessary for model training. This was carried out using a vectoriser.

After extracting some features that were important in model building, some basic cleaning skills to get the dataset ready for training were done. Text cleaning included lowercasing all the text and removing punctuation. The dataset was first split into training and testing sets in the ratio 80/20 respectively. Eighty per cent of the dataset was used to train the sentiment analysis model to categorise the therapy reviews as positive, neutral or negative and the remaining twenty per cent was used to validate the trained model. Below is a confusion matrix for the LightGBM algorithm which shows a summary of prediction results.

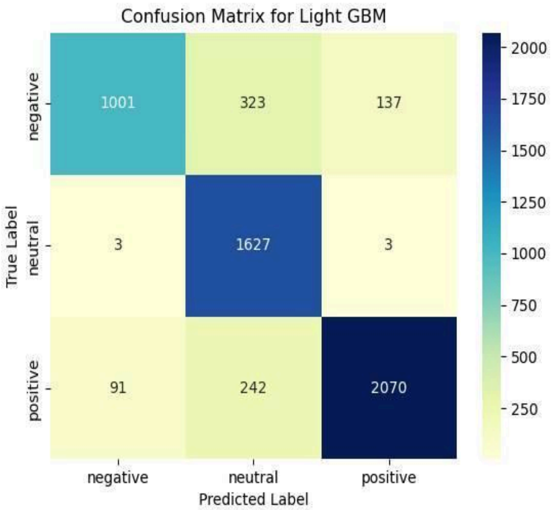

Figure 2: *Confusion matrix*

RESULTS AND DISCUSSIONS

The electronic health record web application for addiction rehabilitation facilities, also called "RehabAid", bridges the gap between addiction rehabilitation facilities and guardians seeking addiction rehabilitation services has been designed. The RehabAid web application helps remove barriers to addiction recovery and factor in the guardians. The RehabAid web application performs sentiment analysis on a patient's therapy review and generates a polarity grading indicating the patient's progress during therapy. The generated grading is then reflected on the portal, which guardians can access to track the progress of their loved ones. The RehabAid web application provides a way for guardians seeking addiction rehabilitation services to reserve an appointment at a treatment facility of their choice from the list of facilities in Zimbabwe. It also enables facilities to carry out their day-to-day record-keeping. The RehabAid web application does not facilitate any kind of payment.

System testing

The test plan included unit testing where each functionality of the RehabAid web application was individually tested. Test cases were used to conduct unit testing and some of these were: Reserve a spot at a treatment facility, sentiment analysis of therapy review and guardian tracking patient progress.

System results

The system aimed to design and develop an electronic health record web application for addiction rehabilitation facilities, also called "RehabAid" and this was successfully achieved. All the objectives of the system were met. Guardians can make reservations to a facility of their choice using the RehabAid web application and they can receive emails confirming their reservations. This is shown in Figure 3.

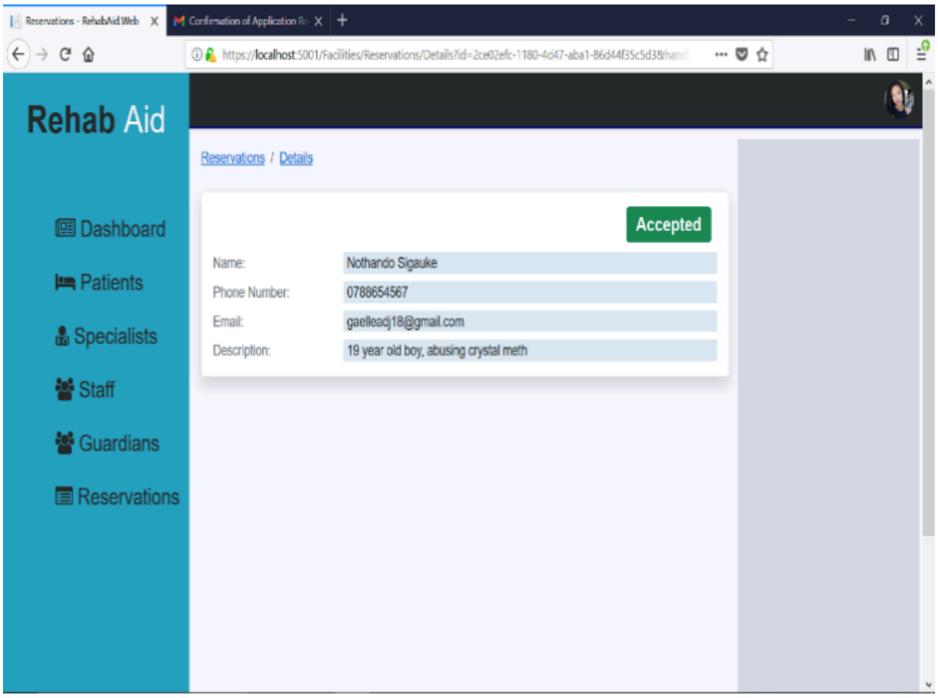

Figure 3: Confirmation of reservation

After a guardian has made a reservation, the system sends two emails. The first email is to confirm that their request to reserve a spot was successfully received and is undergoing consideration. The second email is shown in Figure. 4, is when the reservation is accepted and is to notify the guardian to bring the individual for tests to start the rehabilitation process

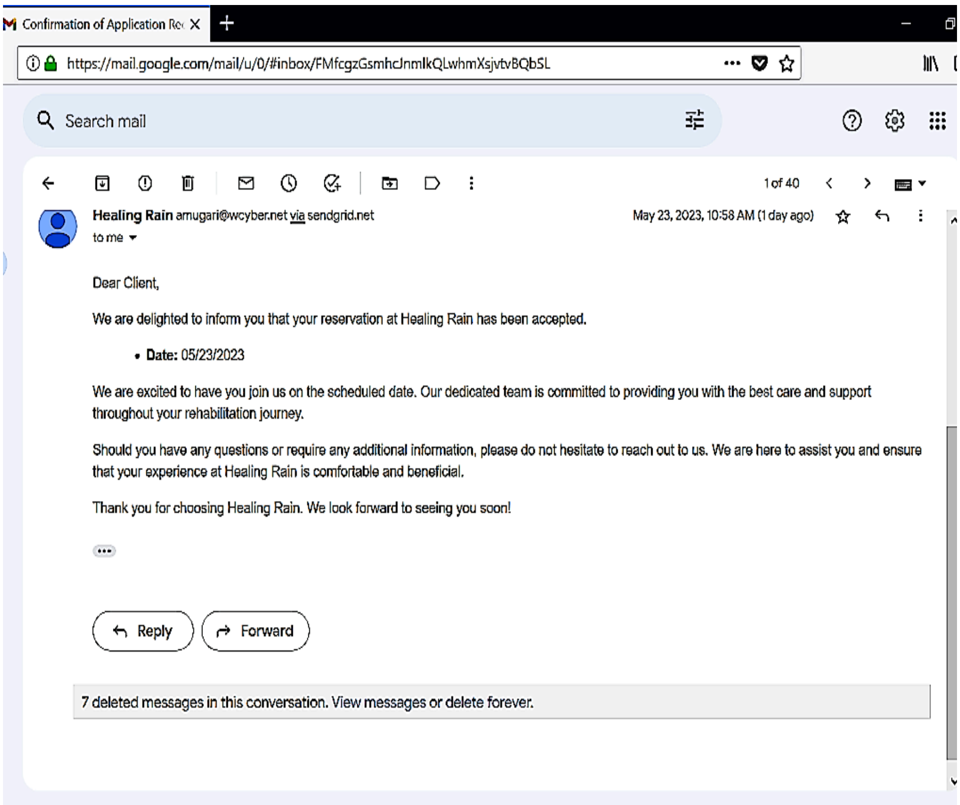

Figure 4: Reservation accepted

The system can analyse the reviews that a therapist writes during the therapy sessions using sentiment analysis to give a polarity rating to say whether the individual undergoing therapy is progressing positively, fairly or negatively. This is depicted in Figure 5.

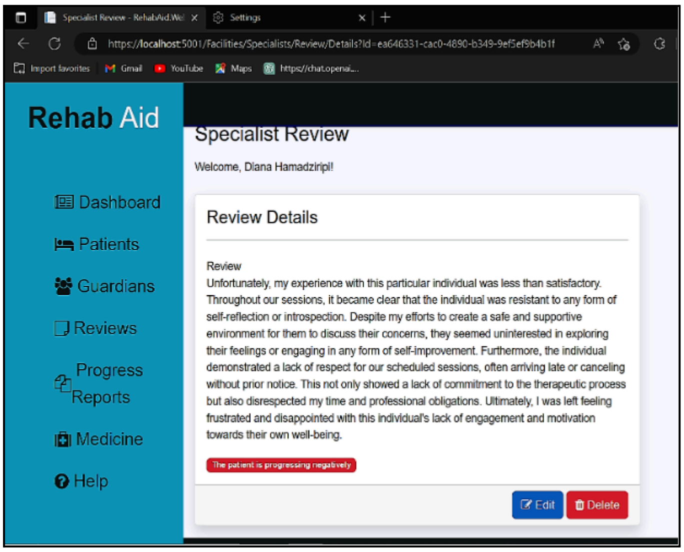

Figure 5: *Therapists review*

The system can create portals for guardians to track the progress of their loved ones remotely. These portals only show each guardian details about their loved one. Figure. 6 shows a guardian's portal with therapy results and prescription.

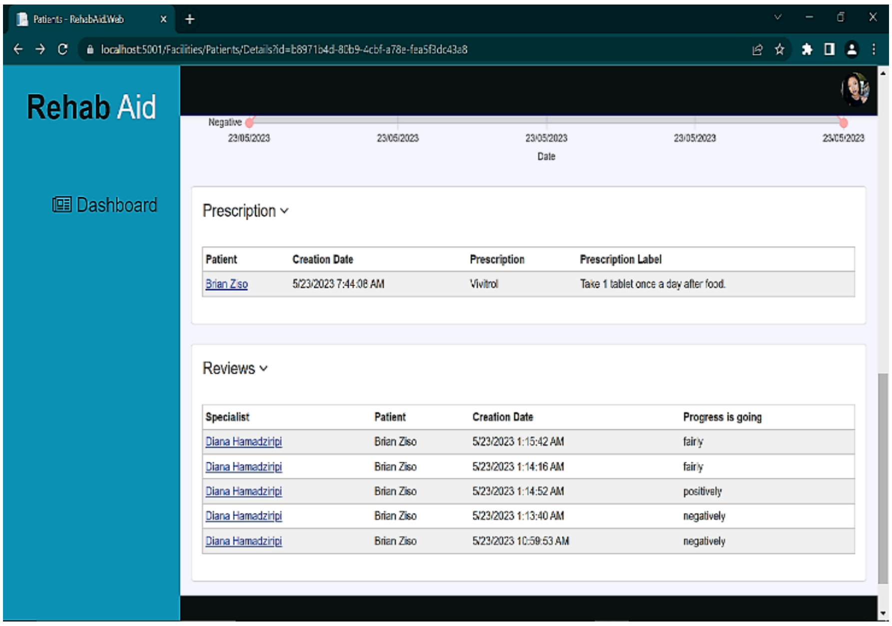

Figure 6: *Guardian Portal*

This research posed different barriers to the rehabilitation process and the RehabAid web application was developed to eliminate these barriers to the rehabilitation process. Its existence means that guardians will not have to travel long distances only to be turned away because the facilities will not match their needs or will be full.
Guardians who cannot make it on visitation days are catered for as they can track the progress of their loved ones through the rehabilitation process. This was not possible with all the related systems that were developed before. Most of the systems that were developed before only enabled the facilities to manage their day-to-day record-keeping.

CONCLUSION AND FUTURE WORK

This paper presented the design and implementation of RehabAid a web application that bridges the gap between addiction treatment centers and guardians who are seeking rehabilitation services for their loved ones. A choice was made to develop the system as a web application because it is easily accessible via both mobile and traditional computers. With a design for clear user interfaces, the application allows guardians to reserve spots at rehabilitation facilities of their choice and to track the progress of their loved ones through the rehabilitation process. It also enables the treatment facilities to carry out their day-to-day record-keeping. The system may be developed further to broaden its scope to increase its functionality. Other functionalities that can be included are integrating PayPal functionality into the system to enable guardians to make payments electronically. Creating a mobile application version of RehabAid's web platform can increase accessibility and convenience for users who prefer to use their mobile devices for making reservations and monitoring patients' progress while on the go. A Chabot can also be implemented to interact with guardians to get the full details of their situations.

REFERENCES

Alexander, B., 2010. The Globalization of Addiction: A Study in Poverty of the Spirit. Oxford University Press.

Appel, P.W., Ellison, A.A., Jansky, H.K., Oldak, R., 2004. Barriers to enrollment in drug abuse treatment and suggestions for reducing them: Opinions of drug injecting street outreach Clients and other system stakeholders. *American Journal of Drug and Alcohol Abuse 30, 129–153*. https://doi.org/10.1081/ADA-120029870.

Bahra, A., 2017. Harmful Effect of Drug Abuse. *INOSR Experimental Sciences* 3, 15–22.

Chawla, S., Srivastava, S., Bedi, P., 2017. Improving the Quality of Web Applications with Web Specific Goal Driven Requirements Engineering. *International Journal of System Assurance Engineering and Management* 8, 65–77. https://doi.org/10.1007/s13198-015-0385-z

Degenhardt, L., Bucello, C., Calabria, B., Nelson, P., Roberts, A., Hall, W., Lynskey, M., Wiessing, L. and GBD Illicit Drug Use Writing Group, 2011. What Data Are Available on the Extent of Illicit Drug Use and Dependence Globally? Results of Four Systematic Reviews. *Drug and Alcohol Dependence*, *117*(2-3), pp.85-101.

Gustafson, D.H., McTavish, F.M., Chih, M.Y., Atwood, A.K., Johnson, R.A., Boyle, M.G., Levy, M.S., Driscoll, H., Chisholm, S.M., Dillenburg, L., Isham, A., Shah, D., 2014. A Smartphone Application to Support Recovery from Alcoholism a Randomised Clinical Trial. *JAMA Psychiatry 71,* 566–572. https://doi.org/10.1001/jamapsychiatry.2013.4642.

Hamilton, J., Lee, J., Canales, J.J., 2015. Chronic Unilateral Stimulation of the Nucleus Accumbens at High or Low Frequencies Attenuates Relapse to Cocaine Seeking in an Animal Model brain stimul 8, 57–63. https://doi.org/10.1016/j.brs.2014.09.018

Hiriyanna, S., Tedor, M.F., Stoddard-Dare, P.A., Zhao, W., 2018. Design and Development of a Web Application for Matching Drug Addiction Treatment Services with Substance Users. *Applied System Innovation* 1, 1–15. https://doi.org/10.3390/asi1040047

Koob, G.F. and Volkow, N.D., 2010. Neurocircuitry of Addiction. *Neuropsychopharmacology*, *35*(1), pp.217-238.

Kruse, C.S., Lee, K., Watson, J.B., Lobo, L.G., Stoppelmoor, A.G. and Oyibo, S.E., 2020. Measures of Effectiveness, Efficiency, and Quality of Telemedicine in the Management of Alcohol Abuse, Addiction, and Rehabilitation: Systematic Review. *Journal of Medical Internet Research*, *22*(1), p.e13252.

Kumar, A., Dangi, I., 2019. Drug Addiction – A Big Challenge for Youth and Children by Ajay Kumar Drug Addiction: A Big Challenge for Youth and Children.

Mayo Clinic Staff, 2022. Drug Addiction (Substance Use Disorder) [WWW Document]. URL https://www.mayoclinic.org/diseases-conditions/drug-addiction/symptoms-causes/syc-20365112#:~:text=Drug%20addiction%2C%20also%20called%20substance,nicotine%20also%20are%20considered%20drugs. (accessed 9.22.22).

Moos, R.H., 2018. Evaluating Treatment Environments: The Quality of Psychiatric and Substance Abuse Programs. Routledge.

Pandya, S., Mehta, P., 2020. A Review on Sentiment Analysis Methodologies, Practices and Applications Dog Acoustic Analysis View Project Pollution Monitoring System, *International Journal of Scientific & Technology Research 9, 2.*

Rhodes, T., 2002. The 'Risk Environment': A Framework for Understanding and Reducing Drug-Related Harm. *International Journal of Drug Policy*, *13*(2), pp.85-94.

SAMHSA, 2014. Treatment Episode Data Set (TEDS). [WWW Document]. URL https://doi.org/10.3886/ICPSR24280.v6 (accessed 10.6.22).

SAMHSA, 2008. About dasis [WWW Document]. URL https://wwwdasis.samhsa.gov/dasis2/aboutdasis.htm (accessed 10.6.22).

Thunderbird Partnership Foundation, 2022. Addictions Management Information System (AMIS) [WWW Document]. URL https://thunderbirdpf.org/about-tpf/scope-of-work/addictions-management-information-system/ (accessed 10.7.22)

Tavakoli Ghouchani, H., Armat, M.R., Akbari, H., Hojjat, S.K., Lashkardoost, H., Asghari, D., Gholizadeh, N. and Saadati, H., 2022. Perceived barriers to addiction treatment: an inductive qualitative content analysis. *Journal of Substance Use*, *27*(5), pp.550-555.

West, R. and Brown, J., 2013. Theory of addiction.

DEVELOPMENT OF A HEALTH 4.0 MATURITY MODEL FRAMEWORK

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ABSTRACT

The concept of Industry 4.0 has its roots in the manufacturing sector. Upon successful implementation, benefits realised by Industry include maximizing profits, minimizing operational costs, and enhanced agility in the digitized business environment. Although the concept of Industry 4.0 was initially pioneered in the manufacturing sector, the dispersion of this concept has sparked interest in other sectors as well. Amongst these sectors is the healthcare, giving birth to Health 4.0.

Adoption of Industry 4.0 does not come based on "one-size fits all". The healthcare sector needs to customise respective concepts, principles, and migration strategies to realise anticipated benefits. For organizations seeking to evaluate their readiness and the adoption of the Industry 4.0 concept, the development of a maturity model is essential. Maturity models serve as structured frameworks that enable organizations to conduct a comprehensive assessment of their current state in terms of their processes and practices within a specific domain. Also, offering organizations with roadmaps to advance towards higher levels of performance. Given the wide application of maturity models and the diversity of organizations with their unique requirements, the development of a maturity model should be customized based on the unique needs and challenges of each individual industry. Accordingly, a design science methodology is employed in the development of the framework following the maturity model guidelines proposed by De Bruin et al., (2005). In this paper we identify the criteria applicable in the development of maturity models as well as develop a framework tailored for the Health 4.0 maturity model.

Keywords: Maturity model, industry 4.0, healthcare 4.0, digital maturity, decision-making

INTRODUCTION

The emergence of Industry 4.0 defined by its unique features of intelligent systems and digital technologies were particularly designed for the manufacturing sector. Embedded production system technologies and intelligent production processes are the two systems that holistically support the concept of Industry 4.0 (Zhong, Xu, Klotz& Newman, 2017), with the objective of delivering and providing end-to-end solutions for organizations aiming to implement this concept at a full scale. The key components of Industry 4.0 include; horizontal integration through value networks - integrated IT systems are implemented in various stages of the organization's operations, vertical integration and networked manufacturing systems - integration of IT systems exists at different hierarchical levels, from sensors and actuators to the entire business levels of the organization and end-to-end engineering across the entire value chain - utilizing relevant IT systems with the aim of providing comprehensive end-to-end assistance for the value chain, from the inception to completion of the product, while taking into account all operations stakeholders from different departments (Kagermann, Helbig, Hellinger & Wahlster, 2013). The design principles of the Industry 4.0 concept were also put forth by Hermann, Pentek, and Otto (2016). These include; interoperability - enables different technological components within the smart factory to seamlessly connect and communicate information on all levels, virtualization – ability of cyber physical systems (CPS) in monitoring physical processes where a digital representation is created to represent the physical world, decentralization – utilizes embedded computers across the manufacturing system to enable CPS to operate autonomously, real-time capability – the systems are designed to process and analyse data in real-time to allow rapid decision-making, service orientation – promotes a customer- centred approach allowing users to access and use the services of the organization, CPS via the use of Internet of Service (IoS) and modularity – through the replacement or expansion of individual modules, modular systems are capable of adapting to changing requirements. Therefore, the concept of Industry 4.0 is not exclusively propelled by technology; rather, the incorporation of the two systems that supports organizational operations and functions at their core both internally and externally.

Notwithstanding the fact that the concept of Industry 4.0 was developed as a high-tech strategy project to transform the manufacturing sector's landscape through the integration of intelligent systems and digital technologies, the Industry 4.0 concept's holistic approach allows it to be widely used and adopted by different sectors, as meeting changing customer demands, maximizing profits and minimizing operational costs within the value chain are all shared goals across different sectors. The concept of Industry 4.0 has sparked significant interest in the healthcare sector resulting in the development of Health 4.0. Inspired by Industry 4.0, Health 4.0 is a tactical deployment and managerial concept for the healthcare industry (Estrela, Monteiro, França, Iano, Khelassi and Razmjooy, 2018). As part of an ongoing process aimed at promoting improvement and transformation in the healthcare industry's value chain, Industry 4.0 principles and innovative technologies have been further implemented and integrated into the concept of Health 4.0 (Pamanik, Lau, Demirkan & Azad, 2017 and Grigoriadis, Bakirtzis, Politis, Danas, Thuemmler & Lim, 2017). The traditional methods of care and the current health systems cannot keep up with the demands of the future health care system, therefore, there is a need for the healthcare sector to embrace the concept of Industry 4.0 to promote improvement and transformation. Even though the concept of Industry 4.0 is regarded as a reference concept for the development of Health 4.0, the adoption of Industry 4.0 does not come on the basis of "one-size fits all". There are different operational requirements across various sectors, thus the concept of Industry 4.0 needs to be tailored for the specific needs of the healthcare sector. The healthcare sector needs to customise respective concepts, principles and migration strategies to realise anticipated benefits. For organizations seeking to evaluate their readiness and the adoption of Industry 4.0 concept, the development of a maturity model is essential.

A maturity model is a tool that an organization or a process can utilize for purposes of conceptualization and evaluating its level of maturity with respect to a specific target state (Schumacher, Erol & Sihn, 2016). A maturity model should consist of clear sequential steps that can be followed by an organization in order to achieve a maturity level in assessing its people/culture, processes/structures and objects/technologies (Mettler, 2011). In this context, the established maturity models within Industry 4.0 plays a pivotal role serving as a backbone in the construction, refinement and enhancement of maturity models specific to Health 4.0. As the concept of Health 4.0 is still in initial stages and initial testbed scenarios for Health 4.0 are currently in the developmental phase (Grigoriadis, Bakirtzis, Politis, Danas, Thuemmler & Lim, 2017). Determining the Health 4.0 implementation guidelines and criteria is a first step first step in supporting healthcare industries in their transitioning to the Health 4.0 concept for enhancing their operational capabilities across the value chain. Therefore, this study aims to identify the criteria applicable in the development of the maturity model as well as developing a framework tailored for the Health 4.0 maturity model, utilizing the fundamental concepts and knowledge obtained from current Industry 4.0 maturity models.

LITERATURE REVIEW

Maturity Models

Maturity models have been extensively applied by researchers and practitioners across diverse sectors, including healthcare, finance, energy, industrial, government, law, education and for broader general application (Tocto-Cano, Paz Collado, López-Gonzales and Turpo-Chaparro, 2020). Additionally, Backlund, Chronéer & Sundqvist (2014) highlighted that maturity model frameworks are increasingly important for assessing organizations. While there are many generic maturity models that exist and are ready to be used and have been validated and tested by different organizations, these models have a limitation in their scope which may only partially address specific needs. Though these generic models are widely applicable, they tend to be generalized and inflexible, in a sense that they have been utilized as they were initially designed (Goksen, Y., Cevik, E. and Avunduk, H., 2015). Organizations are under constant pressure from ongoing business changes, such as competition, operational cost reduction, demand for innovative products and services requirements, time to market and improved product quality, etc. Consequently, this necessitates the development of new maturity models to help decision-makers effectively navigate and manage these dynamics (Mettler, 2011). Applying generic maturity models as a "one-size-fits all" across areas of assessment can create rigidity which might hinder their initial effectiveness in offering customized solutions to changing business requirements. Therefore, if they are to be adopted, it is imperative that they are modified to suit the diverse and evolving requirements of specific industries. In the context of Health 4.0 the generic maturity models can be used as foundational models, but should not be adopted as initially designed instead they can be used as a guide in developing new maturity models aligned to the requirement of Health 4.0.

A maturity model is a tool that an organization or a process can utilize for purposes of conceptualization and evaluating its level of maturity with respect to a specific target state (Schumacher, Erol & Sihn, 2016). Serving as a roadmap, maturity models guides organizations toward a more structured and systematic way of doing things (Proença and Borbinha, 2016). The information obtained from maturity models can be utilized by decision-makers to audit and benchmark regarding to assessment results, the organization has the ability to utilize the information for comparing their organizational current state to best practices in similar business sectors (Duffy, 2001 and Proença & Borbinha, 2016). Ustundag, Cevikcan, Akdil, Ustundag & Cevikcan (2018) mention that the effectiveness of a maturity model is measured by its usability on analysis and positioning.

According to Simpson & Weiner (1989), “maturity” refers to a “state of being complete, perfect, or ready.” The concept of maturity within a process, system or organization can be comprehended as a progressive development or evolutionary stage of a process, system or organization from its inception stage to its end-stage. The inception stage represents the “starting point” of an organization, process or system, the emphasis at this stage is based on areas that require improvement and the establishment of basic aspects that are required to advance to higher degrees of maturity. The end-stage refers to the “desired future state” that represents the most advanced level of maturity that a process, system or organization can reach in specific area or domain.

Before reaching its end-stage, a process, system or organization should undergo several stages of growth known as levels. These levels are designed to measure the fullness of a process, system or organization with the application of several sets of criteria (Wendler, 2012). The criteria are developed during a maturity assessment; the assessment offers the organization a broad overview of the situation to aid in the creation of the criteria (Becker, Knackstedt & Pöppelbuß, 2009). If the maturity model’s criteria are not defined, the intended maturity level will not be fulfilled. Maturity models should possess specific characteristics in order to achieve the desired maturity model (Becker, Knackstedt & Pöppelbuß, 2009). Despite the fact that there are a number of different kinds of maturity models put forth, they all share a common feature of defining a several dimensions or process areas at multiple discrete stages or levels of maturity, together with a description of typical performance at different levels of granularity (Fraser, Moultrie & Gregory, 2002). The majority of maturity models share the following common features, according to Fraser, Moultrie, and Gregory's (2002) based on the extensive review of literature they conducted; *maturity levels* - levels range between 3 to 6, these levels of maturity are linked to capabilities which indicate the achievement of process improvement (Bate, Kuhn, Wells, Armitage, Clark, Cusick, Garcia, Hanna, Jones, Malpass & Minnich, 1995), *level descriptor for each level* – provides a description of each maturity levels in an order from basic to advance stage: initial, repeatable, defined, managed and optimising, *generic description* - characteristics of each level as a whole are described, *number of dimensions*- represents a specific area that is to be evaluated with the purpose to determine a process, system or organization’s maturity level, *number of elements for each dimension* – a dimension can be divided into several processes, each with a different maturity level (De Bruin, Freeze, Kaulkarni & Rosemann, 2005) and *a description of every task as it could be carried out at every maturity level*.

Maturity Model Development Guidelines
The adaptability of a maturity model relies on the fundamental development principles (Lahrmann and Marx, 2010). Different design guidelines have been proposed and adopted to assist researchers and practitioners to develop maturity models following a fundamental design process (De Bruin et al. 2005, Becker et al. 2009 and Mettler et al. 2009). There are three categories of maturity model guidelines: guidelines outlining the design of the maturity model, guidelines outlining the organization’s implementation and learning process utilizing maturity models and those that outline both aspects (Mettler & Ballester, 2021). Since the interests of this study centers on the design of a maturity model framework for Health 4.0, the focus will only be on design guidelines.

With the growing number of new maturity model development across various domains, there has arisen a demand from developers for well-defined guidelines in the development of these models (Lasrado, Vatrapu & Andersen, 2015). These comprehensive guidelines are of great use to developers as they provide structured frameworks for the effective development of maturity models. As a result several guidelines have been formulated to provide guidance in the development of maturity models by researchers (Becker, Knackstedt & Pöppelbuß, 2009, De Bruin, Freeze, Kaulkarni, Rosemann, Campbell, Underwood & Bunker, 2005, Solli-Sæther & Gottschalk, 2010 and Pöppelbuß & Röglinger, 2011). Three guidelines are frequently utilized in the process of developing a maturity model; (i) six-phases (scope, design, populate, test, deploy and maintain) of developing maturity models (De Bruin et al., 2005), (ii) eight-steps (problem definition, study existing models, design strategy, iterative development process, transfer concept and evaluation, implementation of transfer media, evaluation of results and iterative continuation) to developing maturity models (Becker et al., 2009), (iii) five-steps (suggested stage model, conceptual model, theoretical model, empirical model, revised stage model) for developing stage of growth (Solli-Sæther & Gottschalk, 2010). To guarantee practical applicability, these guidelines place a strong emphasis on the validation and implementation of maturity models. There exist no inflexible guidelines for deciding the approach in constructing a model; however, it is crucial to validate the dimensions and the developmental aspects leveraging on existing literature aspects (Monteiro & Maciel, 2020).

Overview of Industry 4.0 Maturity Models/Frameworks

A number of maturity models or frameworks have reportedly been proposed in literature to assess the Industry 4.0 maturity levels. As the concept of Industry 4.0 was pioneered and intended for the manufacturing sector, the majority of models and frameworks were designed to focus on assessing Industry 4.0 maturity from that perspective. Consequently, the application of the concept of Industry 4.0 was very limited in the service sector (Bandara, Vidanagamachchi & Wickramarachchi, 2019). In recent years, it has been observed that the scope of Industry 4.0 has dominantly spread across the service sector, signifying that it has significantly impacted the service sector (i.e. healthcare). As a result, the concept of Industry 4.0 has become the reference point for the service sector. Therefore, it is important that the expertise and insights derived from the concept of Industry 4.0 be utilized as a foundation in the development of tailored maturity models or frameworks for the service sector. Table 1 provides existing maturity models or frameworks of Industry 4.0 that can be used in the development of the proposed model. The common features used to review the existing models presented in Table 1 are those suggested by (Fraser et al., 2002; Bate et al., 1995).

Table 1: *Comparison of maturity models and frameworks for Industry 4.0*

Model name/description	Model Objective	Research Area	Model dimensions	Maturity levels	Maturity items	Maturity definition	Assessment method	Practicality	Model Structure
IMPULS-Industrie 4.0 Readiness Model Lichtblau et al.(2015)	Self-valuation and comparison towards Industry 4.0 readiness.	Industry 4.0 readiness	6 dimensions – strategy & organization, smart factory, smart operations, smart products, data-driven services, employees.	6 maturity levels - outsider, beginner, intermediate, experienced, expert, top performer.	18	Yes	Questionnaire	Yes	Model empirically developed - comprehensive information about the structure of the model is provided.
SIMMI 4.0 Model Leyh et al. (2016)	Enables the classification of an organization's IT system landscape with an emphasis on industry 4.0 requirements.	Industry 4.0 maturity (IT landscape)	4 dimensions – vertical integration, horizontal integration, digital product development, cross-sectional technology criteria	5 maturity stages - basic digitalization level, cross-departmental digitization, horizontal and vertical digitalization, full digitalization and optimized full digitization.	-	Yes	-	No	General information about the model is provided. Comprehensive information about the structure of the model is not provided.
Industry 4.0 Maturity Model Schumacher et al. (2016)	Assessing the Industry 4.0 maturity of industrial enterprises in the discrete manufacturing sector.	Industry 4.0	9 dimensions – strategy, leadership, customers, products, operations, culture, people, governance, technology.	5 maturity levels – where level 1 being "complete lack of attributes" and level 5 being "state-of-the-art attribute".	62	No	Questionnaire	Yes	General information about the model is provided. Comprehensive information about the structure of the model is not provided.

DREAMY Model De Carolis et al. (2017)	Assessing readiness level and identifying strengths, weaknesses and opportunities to provide solutions for addressing the weaknesses that have been identified.	Digital Readiness for Industry 4.0	4 dimensions - Process, monitoring and control, technology, organization.	5 maturity levels - initial, managed, defined, integrated and interoperable, digital-oriented.	-	Yes	Questionnaire	Yes	General information about the model is provided. Comprehensive information about the structure of the model is not provided.
SPICE Model Gökalp et al. (2017)	Measuring readiness level for Industry 4.0.	Industry 4.0	5 dimensions – asset management, data governance, application management, organizational alignment, process transformation.	6 stages - incomplete, performed, managed, established, predictable, optimizing.	-	Yes	-	Yes	General information about the model is provided. Comprehensive information about the structure of the model is not provided.
Acatech – Industry 4.0 Maturity Index Model Schuh et al. (2017)	Aimed at providing manufacturing organizations with guidance for developing their individual strategy for Industry 4.0 implementation.	Industry 4.0	4 structural areas – resources, organizational structure, information systems, culture.	6 stages - computerization, connectivity, visibility, transparency, predictive capacity and adaptability	-	Yes	Questionnaire	Yes	Model empirically developed – comprehensive information about the structure of the model is provided.
Industry 4.0 Maturity Model – Strategy Akdil et al. (2018)	Assessing Industry 4.0 principles and technologies.	Industry 4.0	3 dimensions – smart products and services, smart business processes, strategy and organization.	4 stages – absence, existence, survival, maturity.	13	Yes	Questionnaire	Yes	Model empirically developed – comprehensive information about the structure of the model is provided.

The Industry 4.0/ Digital Operations Assessment Model Geissbauer et al. (2016)	Assessing digital maturity of organizations perspectives on Industry 4.0.	Industry 4.0	7 dimensions – digital business and customer access, digitization of product and service offerings, digitalization and integration of vertical and horizontal value chains, data and analytics as core capability, agile IT architecture, compliance, security, legal and tax, organization, employees and digital culture.	4 maturity levels – digital novice, vertical integrator, horizontal collaborator, digital champion.	-	Yes	Online self-assessment tool	Yes	General information about the model is provided. Comprehensive information about the structure of the model is not provided.
Three-Stage Maturity Model Ganzarain and Errasti (2016)	Guiding and training organization to identify new opportunities for diversification within Industry 4.0.	Industry 4.0	3 dimensions – envision, enable, enact.	5 maturity levels - initial, managed, defined, transform, detailed business model.	-	Yes	-	No	General information about the model is provided. Comprehensive information about the structure of the model is not provided.
Industry 4.0 Readiness Assessment tool. Agca et al. (2017)	Assessing organizational readiness and future ambition to harness Industry 4.0	Industry 4.0	6 dimensions – products and services, manufacturing and operations, strategy and organization, supply chain, business model, legal consideration.	4 maturity levels – beginner, intermediate, experienced, expert.	37	Yes	-	Yes	General information about the model is provided. Comprehensive information about the structure of the model is not provided.

Industry 4.0 – Smart Factory Model Sjödin et al. (2018)	Guiding towards implementing smart factory.	Industry 4.0 -Smart Factory	3 dimensions – people, process, technology.	4 maturity levels - connected technologies, gathering and sharing of structured data, real-time process analytics and optimization, smart predictable manufacturing.	-	Yes	Interviews	Yes	General information about the model is provided. Comprehensive information about the structure of the model is not provided.
DPMM 4.0 Asdecker and Felch (2018)	Assessing the distribution processes in Industry 4.0.	Industry 4.0 – Supply Chain	3 dimensions – order processing, warehousing, shipping.	5 maturity stages – basic digitization, cross department digitization, horizontal and vertical digitization, full digitization and optimized.	-	Yes	Questionnaire	Yes	Model empirically developed – comprehensive information about the structure of the model is provided.
AMM Scremin et al. (2018)	Assessing the Industry 4.0 adoption process in order for organizations to transition to Industry 4.0.	Industry 4.0	8 maturity indicators – business strategy, technology strategy, networking and integration, infrastructure, analytical skills, absorptive capacity, benefits of Industry 4.0, impact on efficiency.	5 maturity stages – zero represents a poor maturity evaluation and four signifying full accomplishment.	35	Yes	Interviews	Yes	Model empirically developed – comprehensive information about the structure of the model is provided.
Three -Stage Model Keskin et al. (2019)	An analytical model that offers an overall estimate of an organization's readiness for Industry 4.0.	Industry 4.0	6 dimensions – product and services, manufacturing and operations, strategy and organization, supply chain, business model, legal considerations.	-	44	-	AHP and TOPSIS	Yes	General information about the model is provided. Comprehensive information about the structure of the model is not provided.

Industry 4.0 - Evaluation Readiness Model Pacchini et al. (2019)	Evaluating the degree of readiness of organizations to adopt Industry 4.0 principles and practices.	Industry 4.0 -Technologies	8 enabling technologies – big data, cloud computing, cyber physical system, collaborative robots, additive manufacturing, augmented reality, artificial intelligence, Internet of Things.	4 maturity levels defined differently for each enabling technology.	-	Yes	Interviews	Yes	Model empirically developed – comprehensive information about the structure of the model is provided.
Industry 4.0 MCDM Model Kaya et al. (2020)	Selection of the best strategy of action for the Industry 4.0 transition.	Industry 4.0	11 dimensions – leadership, customer, product, operation, culture, people, governance, technology, quality, organization, other.	-	35	-	Combination of AHP and TOPSIS based on interval valued intuitionistic fuzzy value. IVIF -AHP (calculating criteria weights),IVIF -TOPSIS (for best strategy selection). Questionnaire	Yes	Model empirically developed – comprehensive information about the structure of the model is provided.
Industry 4.0 Maturity Model Wagire et al. (2021)	Evaluating an organization's "As-Is" state and suggesting areas of improvement for Industry 4.0.	Industry 4.0	7 dimensions – people, industry 4.0 awareness, organizational strategy, value chain and processes, smart manufacturing technology, product and services-oriented technology, industry 4.0 base technology.	4 maturity levels defined differently for each dimension.	38	Yes	Fuzzy AHP, Questionnaire	Yes	Model empirically developed – comprehensive information about the structure of the model is provided.

Industry 4.0 Maturity Model Senna et al. (2023)	Assessing Industry 4.0 using technology-organization-environment framework	Industry 4.0	3 dimensions – technology, organization, environment.	6 maturity levels – digitization, communication, visibility, transparency, predictability, flexibility.	12	Yes	Interviews	Yes	Model empirically developed – comprehensive information about the structure of the model is provided.
Industry 4.0 Maturity Model Hajoary (2023)	Assessing the current status of the organization in Industry 4.0.	Industry 4.0	5 dimensions – strategy and organization, business model, manufacturing and operations, supply chain, product and services, overall Industry 4.0.	4 maturity levels (adopted from the IMPULS model)	-	-	Questionnaire	Yes	General information about the model is provided. Comprehensive information about the structure of the model is not provided.

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METHODOLOGY

The proposed methodology for this study is composed by three main steps (i.e. literature review, criteria indetification and conceptual design of model) which will lead to the development of the proposed conceptual maturity model framework as illustrated in Figure 1.

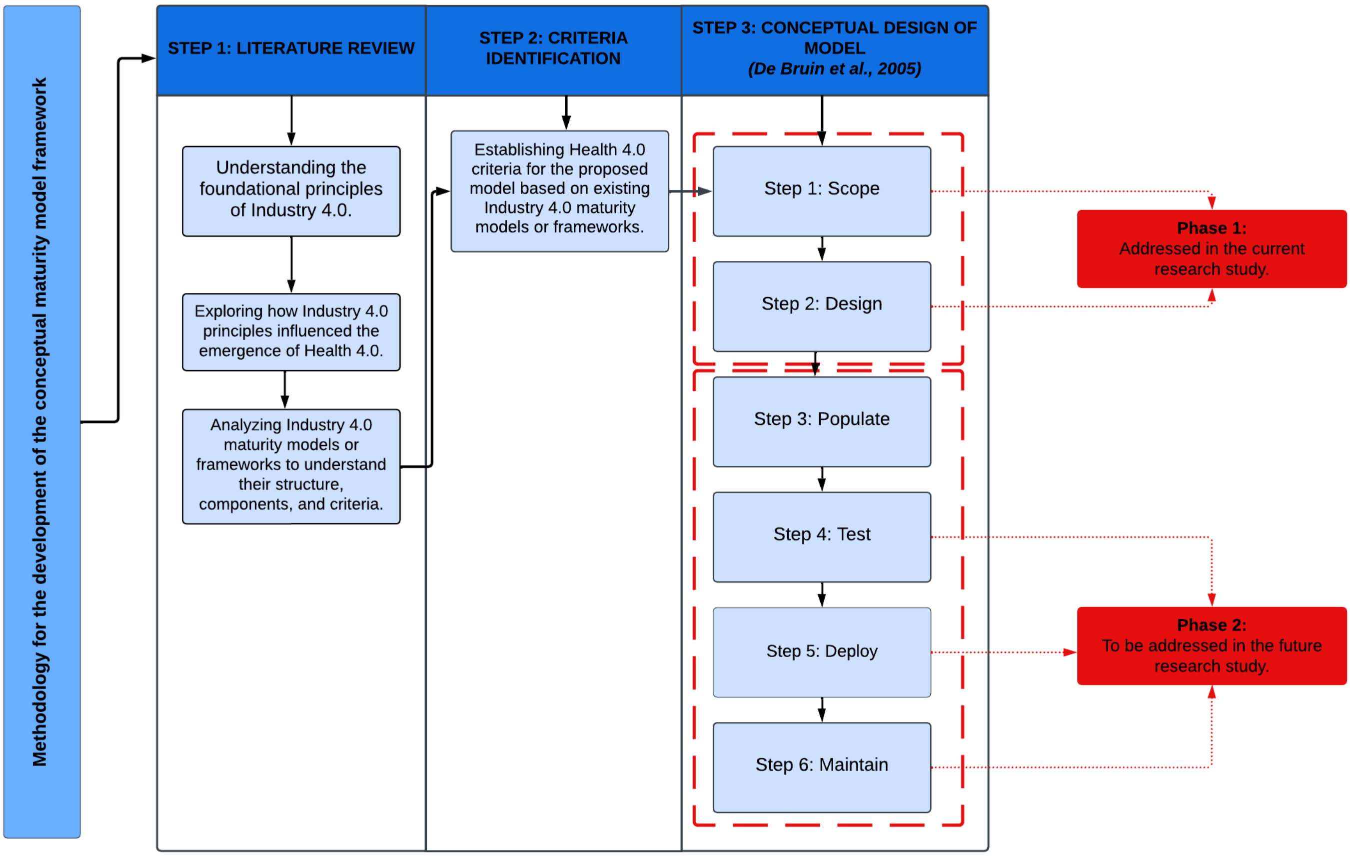

Figure 1: Research methodology for the development of the proposed model.

Step 1 – Review of Literature:
The review was conducted to better understand the concept of Industry 4.0 and how it is associated with Health 4.0. Also, during this step existing maturity models or frameworks were reviewed.

Step 2 – Criteria Identification:
The current maturity models were examined in detail, and the insights gained were used to design the proposed model. Through the evaluation of the existing Industry 4.0 maturity models or frameworks, the key components and criteria were identified. The criteria for the development of the conceptual framework for this study are derived from the different maturity model analysed and are then aligned to tailor for Health 4.0. The criteria appear in Figure 2.

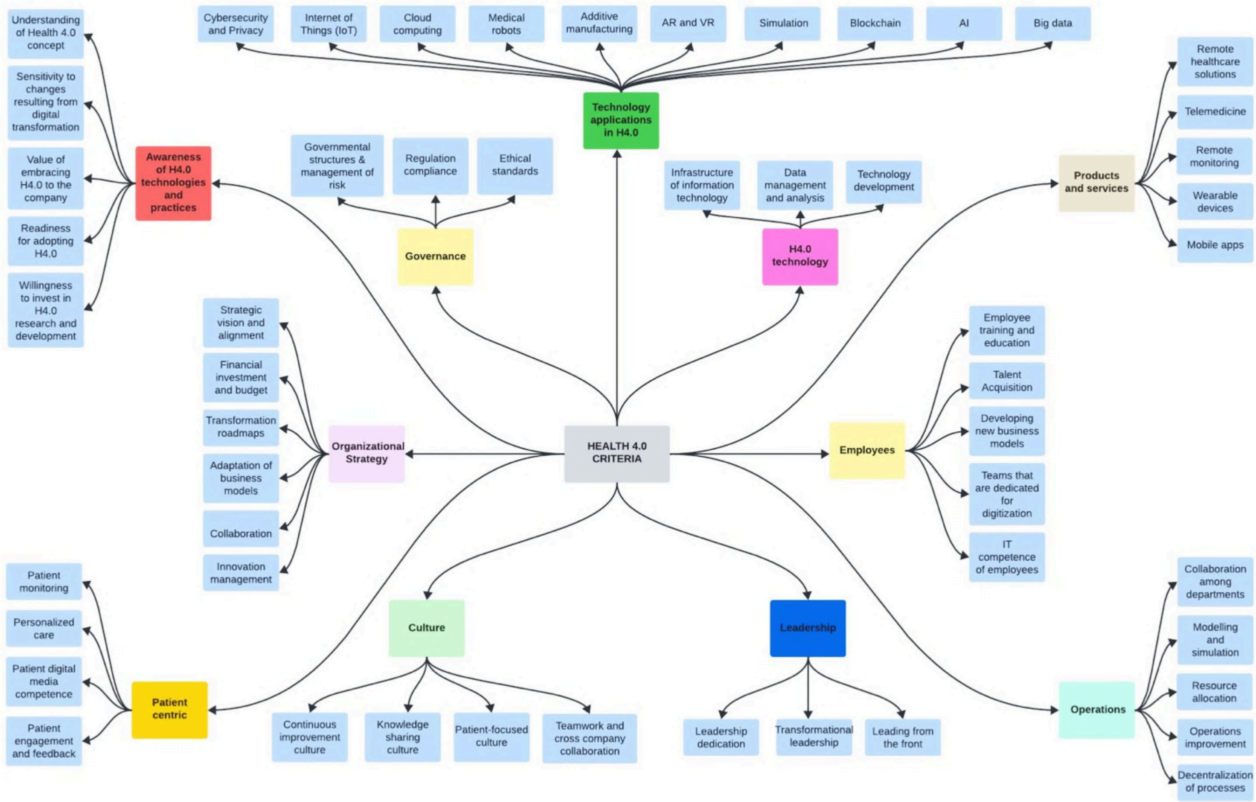

Figure 2: *Suggested maturity model framework criteria.*

Step 3 – Design of Conceptual Model:

The approach used in this study to develop the proposed maturity model framework was based on the development approach of De Bruin., (2005) for developing maturity model; the approach has been widely used and extends beyond specific knowledge domains making it applicable to Health 4.0 as well. The foundation of this approach is grounded in the rigorous methodology established by Hevner, March, Park &Ram (2004) design science research. The design science approach involves the creation or an artifact which can either be a constructs, model or method (Hevner et al., (2004). Therefore, a maturity model is considered an artifact in design science since it offers a systematic approach to problem-solving and development, as well as a concrete representation of knowledge. According to Becker et al., (2009), maturity models are artifacts that address problems and determine the present state of an organization's capabilities, from which improvement strategies are derived. The generic six-step approach of maturity model development by De Bruin et al., (2009) is described as follows:

Step 1 – scope: the first step is focused on determining the model's scope, which includes the criterion and characteristic of the model. The first criterion being the focus of the model highlighting the domain in which the model would be targeted and applied. The focus of model can be characterized by being either domain-specific or general. A general model can be applied to many fields of application (e.g. management models), while domain-specific models are those customized for a specific field of application (e.g. software development - CMM). The second criterion being the development stakeholders which highlights those who have interest and assist in the model development or those who can potentially benefit from the developed model and its implementation. The development stakeholders can either be academics, industry – practitioners, government agencies or a combination.

Step 2 – design: the design step establishes the architecture of the model considering the audience, application method, application driver, respondents and application. During this step, the focus is also on constructing a model that meets the fundamental requirements and outlines the core concept of maturity, which involves establishing the structure of levels, dimensions and sub-dimensions relevant for the model.

Step 3 – populate: once the maturity model's scope and design have been established, then the content must be generated, where a component represents what needs to be measured (De Bruin et al., 2005). Also, De Bruin et al., (2005) mention that determining what needs to be measured and how to measure it for the maturity assessment is vital in this step. The main purpose of this step focuses on identifying the model's content by defining the domain components and sub-components. In a developed domain, an extensive literature review can be utilized to identify the domain components (De Bruin et al., 2005). Identification of domain components is not restrictive to literature review, other empirical methods like focus groups, stakeholder interviews and case studied can also be used (Asdecker & Felch, 2018).

Step 4 – test: this step focuses on testing the populated model for its robustness and usefulness. Both the construct and instruments of the model should be tested for validity, reliability and generalisability, where validity measures the initial intent or purpose and reliability ensures that the results are precise and repeatable (De Bruin., 2005). The validity and reliability of the model can be achieved through the use of literature review, case studies and surveys (De Bruin., 2005).

Step 5 – deploy: after the model has been tested and applied by an involved stakeholder, the model should be deployed to separate entities that were not involved in the development and application of the model at the initial stage. The intent is to determine the model's generalizability (De Bruin., 2005).

Step 6 – maintenance: it is important to prepare the model for a wide range of applications in order to establish its generalisability. The goal of the maturity model significantly impacts the resources required to maintain the model's evolution and utilization (De Bruin., 2005). To accommodate a large number of model users, data repository and other resources are required. The model's standardization and global acceptability will be strengthened by this capacity (De Bruin et al., 2005).

Proposed Model Development: Scope and Design

Figure 1 illustrates step three (i.e. conceptual design of model) of the methodology is divided into two phases as highlighted in red color: phase one deals with the scope and design, while phase two will deal with populate, test, deploy and maintain. For the purpose of this study, this section will focus on the initial two steps (i.e. scope and design) of phase one that have been undertaken for the development of the proposed maturity model framework. The third step (populate) is presently in progress, while the fourth (test), fifth (deploy) and sixth steps (maintain) are planned for future implementation and will be addressed in phase two on other future studies.

Stage 1 – model scope. In this study, the model's scope is designated for healthcare (i.e. hospitals), with special emphasis on the knowledge domain of Health 4.0 thus making the proposed model domain specific. The stakeholders that will assist in shaping the proposed model or benefit from its implementation are academic researchers, industry professionals as well as organizations seeking to understand their standpoint concerning digital transformation. The proposed model initial construction is grounded from an academic perspective; primarily insights were drawn from the literature review. Further refinement of the proposed model, inputs from stakeholders will be essential. Part of the model's scope requires that an appropriate development team be established (De Bruin., 2005). The stakeholders involved in the construction of the proposed model were academics.

Stage 2 – model design. The audience targeted for the proposed model consists of managers (i.e. executives, management) at strategic and tactical levels of the organization. These managers at these levels play a pivotal role as they hold key responsibilities in developing and maintaining Health 4.0 capabilities, making crucial decisions at both strategic and tactical levels. The proposed model was developed to be utilized for self-assessment by the intended users. Third party involvement for the proposed model lies within the discretion of the organization. Drivers of application are internal requirements. The respondents consist of managers and staff from the strategic, tactical and operational levels of the organization, selected for their expertise in assessing the organization's present Health 4.0 capabilities. The proposed model application can be applied to multiple entities. Once the decisions parameters (i.e. the *"why"* and *"how"* the model is applied, *"who"* is involved and *"what"* the model can achieve) pertaining to the design of the maturity model have been addressed, the fundamental requirements, which involves establishing the composition of levels, dimensions and sub-dimensions relevant to the model should be defined. The literature review conducted on the existing Industry 4.0 maturity models highlighted earlier in this study serves as a foundation in identifying the fundamental requirements needed in construction of the proposed Health 4.0 model.

Model dimensions and maturity items

Since the construction of the proposed maturity model framework is based on phase one as highlighted in figure one, the composition of the proposed model was established on the fundamental features of a maturity model namely: the dimensions, maturity items (i.e. known as sub-dimensions), maturity levels. The proposed maturtiy model framework for Health 4.0 comprises of 11 dimensions and 56 maturity items. Table 2 shows an example of the dimensions and maturity items with their specific descriptions.

Table 2: *Maturity dimensions and maturity items*

Dimensions	Maturity Items
1. **Organizational Strategy:** signifies all strategic and conceptual measures the organization has employed to prepare for Health 4.0 implementation…	***1.1 Strategic vision and alignment:*** evaluates the strategic implementation of Health 4.0 within the organization, which explores whether the organization has a clear Health 4.0 vision… ***1.2 Financial investment and budget:*** evaluates the investments incorporated by the organization for Health 4.0 technologies… ***1.3 Transformation roadmaps:*** evaluates the organization's strategic roadmap, which outlines the processes… ***1.4 Adaptation of business models:*** evaluates the organization's capacity to explore and adopt new partnerships… ***1.5 Collaboration:*** evaluates the collaborative initiatives taken by the organization to establish relationship… ***1.6 Innovation management:*** evaluates how well the organization promotes an innovation environment…
2. Leadership: refers to strong dedication to Health 4.0 by the leadership of the organization. Managers at the strategic…	***2.1 Leadership dedication:*** evaluates the organization's leadership commitment towards digital transformation initiatives… ***2.2 Transformational leadership:*** evaluates the organization's leadership style initiatives in the context of Health 4.0… ***2.3 Leading from the front:*** evaluates the leadership of the organization, whether they have the ability to lead and manage change effectively…

3. Health 4.0 technology: represents the technological infrastructure created and developed to contribute to business…	***3.1 Infrastructure of information technology:*** evaluates the technological infrastructure of the organization, including hardware (.i.e. servers and data centers and end-user devices), software (.i.e. EHRs, health information systems and application integration), networks (.i.e. Wide Area Network, Local Area networks and secure reliable connectivity) … ***3.2 Data management and analysis:*** evaluates the organization's use of its resources for collecting, managing, storing and analysing data… ***3.3 Technology development:*** evaluates the utilization of emerging technologies ((e.g. blockchain, IoT, AI, VR, BD etc.)…
4. Operations: refers to the hospital's integration and interconnectivity of various healthcare systems and stakeholders…	***4.1 Collaboration among departments:*** evaluates the organization's initiatives to promote collaboration and communication amongst different healthcare… ***4.2 Modelling and simulation:*** evaluates how the organization utilizes modelling and simulation (.i.e. creation of virtual representation of healthcare scenarios) … ***4.3 Resource allocation:*** evaluates how well the organization efficiently allocates and manages resources, such as personnel, financial… ***4.4 Operations improvement:*** evaluates the organization's efforts to optimize operational processes through the incorporation of Health 4.0 technologies… ***4.5 Decentralization of processes:*** pushing decision-making authority closer to the point of care, including nurses, doctors, and other frontline staff…
5. Patient centric: refers to the service provider putting the patient at the core of healthcare delivery and meeting the distinct requirements of each patient…	***5.1 Patient monitoring:*** evaluates the methods through which the organization delivers additional services to patients without them having to come to the organization… ***5.2 Personalized care:*** evaluates how much attention the organization is giving in delivering personalized care plans and treatment… ***5.3 Patient digital media competence:*** evaluates the strategies the organization employs to guide and assist patients to receive the best service through the utilization… ***5.4 Patient engagement and feedback:*** evaluates the organization's strategies of engaging with customers…
6. Governance: refers to the structures for governing and monitoring of Health 4.0 implementation. It relates in examining the organization's committees…	***6.1 Governmental structures and management of risk:*** evaluates whether the organization's has governmental structures and strategies in place such as steering committees who are in charge of managing projects… ***6.2 Regulation compliance:*** evaluates the organization's compliance to policies, regulations and standards that apply to Health 4.0 practices… ***6.3 Ethical standards:*** evaluates whether the organization is committed to utilizing Health 4.0 technologies in an ethical manner…
7. Employees: refers to the human resources and workforce skills needed for digital transformation to be successful…	***7.1 Employee training and education:*** evaluates the organization's training and education programs. It focuses on ensuring that employees... ***7.2 Talent Acquisition:*** evaluates the organization's strategies, tactics and processes for identifying, attracting, developing… ***7.3 Developing new business models:*** evaluates the ability of employees to develop new business models in accordance with digitization. ***7.4 Teams that are dedicated for digitization:*** evaluates whether there are dedicated teams in the organization that are responsible for driving digitization… ***7.5 IT competence of employees:*** evaluates the employees' level of knowledge, skills…
8. Culture: refers to the pivotal role that culture plays in shaping the organization's ability to embrace and succeed in the digital health environment…	***8.1 Continuous improvement culture:*** evaluates the organization's culture of continuous improvement… ***8.2 Knowledge sharing culture:*** evaluates how the organizational culture emphasizes and supports the sharing… ***8.3 Patient-focused culture:*** evaluates the organization's culture that is dedicated in creating a patient-centric approach that puts the needs… ***8.4 Teamwork and cross company collaboration***: evaluates the organization's efforts to promote collaboration and communication across different stakeholders…
9. Products and services: refers to the use of different digital health products and services that improve…	***9.1 Remote healthcare solutions:*** evaluates how well the organization's portfolio of digital health products and services, which includes telemedicine… ***9.2 Telemedicine:*** evaluates how the organization has adopted and used telemedicine platforms and services… ***9.3 Remote monitoring:*** evaluates the organization's utilization of remote patient monitoring solutions, which aids health professionals to monitor… ***9.4 Wearable devices:*** evaluates how the organization integrates wearable devices (e.g. smartwatches, smart glasses, fitness trackers and other health monitoring devices)…

	9.5 Mobile apps: evaluates the organization's development and use of mobile applications…
10. Awareness of Health 4.0 technologies and practices: refers to level of awareness, understanding…	***10.1 Understanding of Health 4.0 concept:*** evaluates the organization knowledge and familiarity with the concept… ***10.2 Sensitivity to changes resulting from digital transformation:*** evaluates how well-informed the organization is about the impact of digital transformation through Health 4.0… ***10.3 Value of embracing Health 4.0 to the company:*** evaluates the organization's perspective regarding the value which Health 4.0… ***10.4 Readiness for adopting Health 4.0:*** evaluates the organization's preparedness for adopting Health 4.0… ***10.5 Willingness to invest in Health 4.0 research and development:*** evaluates the organization's efforts to invest in research and development related to Health 4.0…
11. Technology applications in Health 4.0: evaluates the technologies of Health 4.0 utilized by…	***11.1 Cybersecurity and Privacy:*** refers to the protection of sensitive data of patients and maintaining their privacy and security… ***11.2 Internet of Things (IoT):*** evaluates the organization's integration and usage of linked sensors, systems and medical devices in the healthcare environment… ***11.3 Cloud computing:*** evaluates how the organization utilizes its cloud-based infrastructure and services in managing and processing… ***11.4 Medical robots:*** evaluates the use of medical robots by the organization in assisting surgeons and other practitioners… ***11.5 Additive manufacturing:*** evaluates the organization's use of various additive manufacturing… ***11.6 Augmented Reality (AR) and Virtual Reality (VR):*** evaluates how the organization uses AR and VR technologies for different clinical… ***11.7 Simulation:*** evaluates the organization's use of simulation application, where the organization can use the obtained data… ***11.8 Blockchain:*** evaluates how the organization utilizes blockchain technology to strengthen data security… ***11.9 Artificial Intelligent (AI):*** evaluates how well the organization has adopted and used AI and related technologies for offering healthcare… ***11.10 Big data:*** evaluates the organization's capabilities in collecting, storing and managing big data…

Model maturity levels

The proposed maturity model framework has six maturity levels, from zero to five, where level zero signifies "non participant" and level five represents "high achiever", Table 3 provides the description of each maturity level. The suggested maturity levels presented in Table 3 should be interpreted and tailored to cater for each maturity dimension with its respective maturity item. Figure 3 shows the proposed maturity levels for this study.

Table 3: *Maturity level definitions*

Maturity Level 0: Non-Participant	*Definition:* None of the principles and practices of Health 4.0 are achieved by the organization. The organization does not participate in any Health 4.0 initiatives, finds Health 4.0 practices irrelevant for their organization, or does not even know and understand what Health 4.0 is about.
Maturity Level 1: Novice	*Definition:* An organization has just begun understanding the concept of Health 4.0 and has limited implementation and experience of Health 4.0. The organization is at an infancy state towards exploring and adopting Health 4.0 principles and practices. The absence of appropriate organizational structure and technological infrastructure hinders the execution of Health 4.0. There is minimal integration of digital technologies across the organization's processes and the organization lacks well-defined strategy for Health 4.0 transformation.

Maturity Level 2: Intermediate	*Definition:* An organization is fully aware of Health 4.0 principles and practices. The organization has begun integrating Health 4.0 into its overall strategy. Implementation strategy for Health 4.0 is being developed and indicators that will be used to measure the organization's progress are identified. The planning and implementation of Health 4.0 principles are carried out to a moderate extent. The organizational structure and technological infrastructure are undergoing adjustments to support the implementation of Health 4.0. The organization has begun exploring and implementing some principles and practices of Health 4.0 across the organization through projects but at a minimal scale as the organization is still in the early phase of adoption. The organization has launched some pilot initiatives (i.e. trial and error) in a small scale across functional departments in support of Health 4.0 but they are executed independently with limited experience. The organization has actively initiated integrating digital technologies across the organization processes and the organization has initiated defining its strategy for the implementation of Health 4.0.
Maturity Level 3: Experienced	*Definition:* An organization has made significant progress and already developed a strategy for Health 4.0. The implementation strategy for Health 4.0 is available and the indicators to measure the organization's progress are available. The organizational structure and technological infrastructure have been adjusted to support the implementation of Health 4.0. In support of Health 4.0 principles, the organization is beginning to undertake initiatives throughout the entire organization rather than only focusing on functional departments. The Health 4.0 initiatives are carried out collaboratively across departments rather than independently, nevertheless, there is still potential for improvement concerning the scope of Health 4.0 within the organization.
Maturity Level 4: Expert	*Definition:* An organization is already implementing a Health 4.0 strategy and monitoring it with relevant indicators. The strategy for Health 4.0 is well-defined and the organization continuous to invest in Health 4.0 initiatives. The organizational structure and technological infrastructure of the organization is well integrated to support the implementation of Health 4.0. The organization has achieved an advanced level of adoption and integration of Health 4.0 principles and practices. Health 4.0 projects are not restrictive to the organization internally but are extended outside the organization involving other stakeholders in the value chain. High degree of standardization in the organizational processes and operations exist, with a high level of system integration and interoperability being established throughout the entire organization.
Maturity Level 5: High achiever	*Definition:* An organization has effectively implemented its Health 4.0 strategy and continues to consistently monitor the progress of additional Health 4.0 projects. The organization is considered to be leading the way in Health 4.0 innovation and implementation. The organization regularly invests in Health 4.0 initiatives. The organizational structure and technological infrastructure of the organization have reached a matured state and are integrated to support the implementation of Health 4.0. The organizational processes and operations are digitally oriented allowing for real-time data exchange and rapid decision making. An organization in the forefront of Health 4.0 continues to explore on new opportunities presented by Health 4.0 transformation.

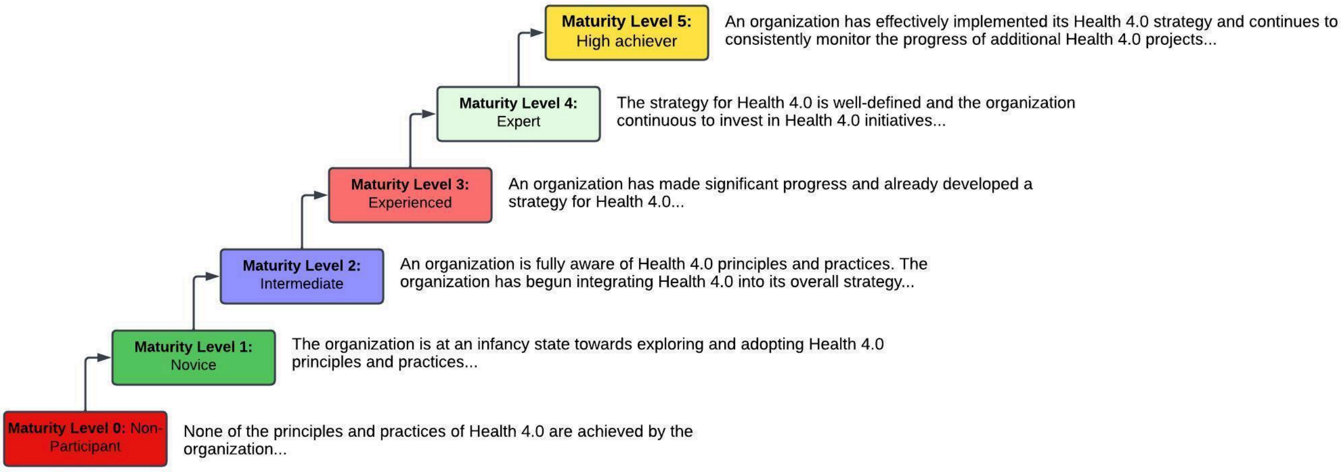

Figure 3: *Maturity model levels for the proposed mode.*

CONCLUSION

Since the concept of Industry 4.0 was pioneered and intended for the manufacturing sector, the majority of models and frameworks developed were intended to focus on assessing Industry 4.0 maturity from that perspective. The concept of Industry 4.0 sparked interest across other sectors, as a result the adoption of this concept spread across different industries, thus, Health 4.0 has emerged for the healthcare sector. Health 4.0 has been embraced by healthcare; however, Industry 4.0 continues to play a pivotal role of serving as a reference point that can be utilized by other sectors to learn from. As highlighted in literature, the concept of Health 4.0 has not yet been fully explored in the healthcare sector as there are still challenges concerning the availability of guidelines and roadmaps for adoption and transitioning to Health 4.0. Therefore, this study has developed a conceptual maturity model framework as a starting point that can be used in healthcare to better understand its Health 4.0 maturity level. Since the Industry 4.0 serves a reference point of Health 4.0, the conceptual maturity model framework was developed on the fundamental concepts and insights of Industry 4.0, hence the literature review conducted focused on maturity models addressing the concept of Industry 4.0.

This study has presented the first phase of the proposed maturity model framework and will require that the second phase to be done in order for the model to be complete and functional. The study was conducted from a literature perspective; hence, the stakeholders involved in the construction of the proposed model are academics. As the process of maturity model development is iterative, the involvement of diverse stakeholders will be taken into consideration as well to enhance the proposed model's comprehensiveness and its practical application. The model's results concerning the second phase are planned for future implementation and will be addressed in subsequent papers in the future.

REFERENCES

Asdecker, B. and Felch, V., 2018. Development of an Industry 4.0 maturity model for the delivery process in supply chains. *Journal of Modelling in Management*, *13*(4), pp.840-883.

Agca, O., Gibson, J., Godsell, J., Ignatius, J., Davies, C.W. and Xu, O., 2017. An Industry 4 readiness assessment tool. *International Institute for Product and Service Innovation*, pp.1-19.

Bandara, O., Vidanagamachchi, K. and Wickramarachchi, R., 2019, March. A model for assessing maturity of industry 4.0 in the banking sector. In *Proceedings of the international conference on industrial engineering and operations management* (Vol. 2019).

Bate, R., Kuhn, D., Wells, C., Armitage, J., Clark, G., Cusick, K., Garcia, S., Hanna, M., Jones, R., Malpass, P. and Minnich, I., 1995. A systems engineering capability maturity model, version 1.1. *Software Engineering Institute*.

Becker, J., Knackstedt, R. and Pöppelbuß, J., 2009. Developing maturity models for IT management: A procedure model and its application. *Business & Information Systems Engineering*, *1*, pp.213-222.

Backlund, F., Chronéer, D. and Sundqvist, E., 2014. Project management maturity models–A critical review: A case study within Swedish engineering and construction organizations. *Procedia-Social and Behavioral Sciences*, *119*, pp.837-846.

Duffy, J., 2001. Maturity models: Blueprints for e‐Volution. *Strategy & Leadership*, *29*(6), pp.19-26.

De Bruin, T., Rosemann, M., Freeze, R. and Kaulkarni, U., 2005. Understanding the main phases of developing a maturity assessment model. In *Australasian Conference on Information Systems (ACIS)* (pp. 8-19). Australasian Chapter of the Association for Information Systems.

Demircan Keskin, F., Kabasakal, İ., Kaymaz, Y. and Soyuer, H., 2019. An assessment model for organizational adoption of industry 4.0 based on multi-criteria decision techniques. In *Proceedings of the International Symposium for Production Research 2018 18* (pp. 85-100). Springer International Publishing.

De Carolis, A., Macchi, M., Negri, E. and Terzi, S., 2017, June. Guiding manufacturing companies towards digitalization a methodology for supporting manufacturing companies in defining their digitalization roadmap. In *2017 International Conference on Engineering, Technology and Innovation (ICE/ITMC)* (pp. 487-495). IEEE.

Estrela, V.V., Monteiro, A.C.B., França, R.P., Iano, Y., Khelassi, A. and Razmjooy, N., 2018. Health 4.0: applications, management, technologies and review: array. *Medical Technologies Journal*, *2*(4), pp.262-276.

Fraser, P., Moultrie, J., & Gregory, M. (2002, August). The use of maturity models/grids as a tool in assessing product development capability. In *IEEE international engineering management conference* (Vol. 1, pp. 244-249). IEEE.

Ganzarain Epelde, J. and Errasti, N., 2016. Three stage maturity model in SME's towards Industry 4.0.

Geissbauer R, Vedso J, Schrauf S (2016) Industry 4.0: Building the digital enterprise. Available from: https://www.pwc.com/gx/en/industries/industries-4.0/landing-page/industry-4.0-building-your-digital-enterprise-april-2016.pdf. Accessed: 10 December 2023.

Gökalp, E., Şener, U. and Eren, P.E., 2017. Development of an assessment model for industry 4.0: industry 4.0-MM. In *Software Process Improvement and Capability Determination: 17th International Conference, SPICE 2017, Palma de Mallorca, Spain, October 4–5, 2017, Proceedings* (pp. 128-142). Springer International Publishing.

Goksen, Y., Cevik, E. and Avunduk, H., 2015. A case analysis on the focus on the maturity models and information technologies. *Procedia Economics and Finance*, *19*, pp.208-216.

Grigoriadis, N., Bakirtzis, C., Politis, C., Danas, K., Thuemmler, C. and Lim, A.K., 2017. A health 4.0 based approach towards the management of multiple sclerosis. *Health 4.0: how virtualization and big data are revolutionizing healthcare*, pp.205-218.

Hajoary, P.K., 2023. Industry 4.0 maturity and readiness-A case of a steel manufacturing organization. *Procedia Computer Science*, *217*, pp.614-619.

Kagermann, H., Helbig, J., Hellinger, A. & Wahlster, W. 2013, *Recommendations for implementing the strategic initiative INDUSTRIE 4.0: Securing the future of German manufacturing industry; final report of the Industrie 4.0 Working Group,* Forschungsunion.

Kaya, İ., Erdoğan, M., Karaşan, A. and Özkan, B., 2020. Creating a road map for industry 4.0 by using an integrated fuzzy multicriteria decision-making methodology. *Soft Computing*, *24*, pp.17931-17956.

Lahrmann, G. and Marx, F., 2010. Systematization of maturity model extensions. In *Global Perspectives on Design Science Research: 5th International Conference, DESRIST 2010, St. Gallen, Switzerland, June 4-5, 2010. Proceedings. 5* (pp. 522-525). Springer Berlin Heidelberg.

Lasrado, L.A., Vatrapu, R. and Andersen, K.N., 2015. Maturity models development in is research: a literature review. Available from: https://www.researchgate.net/profile/Lester-Lasrado-2/publication/281288783_MATURITY_MODELS_DEVELOPMENT_IN_IS_RESEARCH_A_LITERATURE_REVIEW/links/55e00e0e08aecb1a7cc1da2b/MATURITY-MODELS-DEVELOPMENT-IN-IS-RESEARCH-A-LITERATURE-REVIEW.pdf.Assessed: 5 January 2024.

Leyh, C., Bley, K., Schäffer, T. and Forstenhäusler, S., 2016, September. SIMMI 4.0-a maturity model for classifying the enterprise-wide it and software landscape focusing on Industry 4.0. In *2016 federated conference on computer science and information systems (fedcsis)* (pp. 1297-1302). IEEE.

Lichtblau, K., Stich, V., Bertenrath, R., Blum, M., Bleider, M., Millack, A., Schmitt, K., Schmitz, E. and Schröter, M., 2015. IMPULS-industrie 4.0-readiness. Impuls-Stiftung des VDMA, Aachen-Köln. Available from: https://impuls-stiftung.de/wp-content/uploads/2022/05/Industrie-4.0-Readiness-english.pdf .Accessed: 10 January 2024.

Mettler, T. 2011, "Maturity assessment models: a design science research approach", *International Journal of Society Systems Science (IJSSS),* vol. 3, no. 1/2, pp. 81-98.

Mettler, T. and Ballester, O., 2021. Maturity models in information systems: a review and extension of existing guidelines. In *Proc. Int. Conf. Inf. Syst* (pp. 1-16).

Monteiro, E.L. and Maciel, R.S.P., 2020. Maturity Models Architecture: A large systematic mapping. *iSys-Brazilian Journal of Information Systems*, *13*(2), pp.110-140. Accessed: https://scholar.google.com/scholar?hl=en&as_sdt=0%2C5&q=Maturity+Models+Architecture%3A+A+large+systematic+mapping&btnG=. Accessed: 19 August 2024.

Pacchini, A.P.T., Lucato, W.C., Facchini, F. and Mummolo, G., 2019. The degree of readiness for the implementation of Industry 4.0. *Computers in Industry*, *113*, p.103125.

Pederiva, A., 2003. The COBIT® maturity model in a vendor evaluation case. *Information Systems Control Journal*, *3*, pp.26-29.

Pöppelbuß, J. and Röglinger, M., 2011. What makes a useful maturity model? A framework of general design principles for maturity models and its demonstration in business process management. Available from: https://web.archive.org/web/20220716084655id_/https://aisel.aisnet.org/cgi/viewcontent.cgi?article=1027&context=ecis2011. Accessed: 10 December 2024.

Proença, D. and Borbinha, J., 2016. Maturity models for information systems-a state of the art. *Procedia Computer Science*, *100*, pp.1042-1049.

Santos, R.C. and Martinho, J.L., 2020. An Industry 4.0 maturity model proposal. *Journal of Manufacturing Technology Management*, *31*(5), pp.1023-1043.

Senna, P.P., Barros, A.C., Roca, J.B. and Azevedo, A., 2023. Development of a digital maturity model for Industry 4.0 based on the technology-organization-environment framework. *Computers & Industrial Engineering*, *185*, p.109645.

Schuh, G., Anderl, R., Gausemeier, J., Ten Hompel, M. and Wahlster, W. eds., 2017. *Industrie 4.0 maturity index: die digitale transformation von unternehmen gestalten*. Herbert Utz Verlag. Accessed: https://fundacioperlaindustria.org/wp-content/uploads/2021/07/2020.acatech_STUDIE_Maturity_Index.Update.pdf. Accessed: 15 November 2023.

Schumacher, A., Erol, S. & Sihn, W. 2016, "A maturity model for assessing industry 4.0 readiness and maturity of manufacturing enterprises", *Procedia CIRP,* vol. 52, pp. 161-166.

Scremin, L., Armellini, F., Brun, A., Solar-Pelletier, L. and Beaudry, C., 2018. Towards a framework for assessing the maturity of manufacturing companies in industry 4.0 adoption. In *Analyzing the impacts of Industry 4.0 in modern business environments* (pp. 224-254). IGI Global.

Solli-Sæther, H. and Gottschalk, P., 2010. The modeling process for stage models. *Journal of Organizational Computing and Electronic Commerce*, *20*(3), pp.279-293.

Sjödin, D.R., Parida, V., Leksell, M. and Petrovic, A., 2018. Smart Factory Implementation and Process Innovation: A Preliminary Maturity Model for Leveraging Digitalization in Manufacturing Moving to smart factories presents specific challenges that can be addressed through a structured approach focused on people, processes, and technologies. *Research-technology management*, *61*(5), pp.22-31.

Tocto-Cano, E., Paz Collado, S., López-Gonzales, J.L. and Turpo-Chaparro, J.E., 2020. A systematic review of the application of maturity models in universities. *Information*, *11*(10), p.466.

Ustundag, A., Cevikcan, E., Akdil, K.Y., Ustundag, A. and Cevikcan, E., 2018. Maturity and readiness model for industry 4.0 strategy. *Industry 4.0: Managing the digital transformation*, pp.61-94.

Wagire, A.A., Joshi, R., Rathore, A.P.S. and Jain, R., 2021. Development of maturity model for assessing the implementation of Industry 4.0: learning from theory and practice. *Production Planning & Control*, *32*(8), pp.603-622.

Wendler, R. 2012, "The maturity of maturity model research: A systematic mapping study", *Information and software technology,* vol. 54, no. 12, pp. 1317-1339.

Zhong, R.Y., Xu, X., Klotz, E. & Newman, S.T. 2017, "Intelligent manufacturing in the context of industry 4.0: a review", *Engineering,* vol. 3, no. 5, pp. 616-630.

DRIVER DISTRACTION DETECTION USING CONVOLUTIONAL NEURAL NETWORKS

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ABSTRACT

Nowadays, many people have acquired personal vehicles to facilitate movement from one point to another. The increase in traffic has caused a rise in accidents due to various distractions drivers encounter. Distraction can be caused by fatigue due to long periods of driving and lack of rest. Eye detection and heart rate variability are two metrics for detecting drowsy drivers. Driving behaviours such as lane departure, indicators, braking, and steering wheel control could also be used. A distraction detection system was produced, which is a prediction system that integrates eye detection and driver action classification. It uses behavioural and physiological approaches. The system monitors the open or closed state of the drivers' eyes and detects the drivers' actions per video frame using a convolutional neural network (CNN). The system also accurately locates where the driver is at any given time. The results indicated that driver distraction classification accuracy was 64.37%, which is promising for a non-intrusive system.

Keywords: *Resnet50, traffic accidents, driver distraction, CNN, driver drowsiness*

INTRODUCTION

Distracted driving is a serious issue that has drawn the public, authorities, and researchers' attention. It involves drivers diverting their attention from essential driving tasks and focusing on competing activities, which can significantly compromise road safety. (Moslemi et al., 2021). In-car activities such as controlling in-vehicle information systems (IVISs) like navigation and entertainment systems have been identified as potential distractions. The study of driver distraction originated in the early 1990s when the detrimental effects of cell phone use on driving performance became evident (Caird et al.,2018:122). Another aspect of driver distraction is driver fatigue, which poses a significant threat to road safety in Zimbabwe. (Foya, 2019:780). Fatigue leads to drowsiness, creating concerns for all road users, including drivers and passengers. To address these issues and ensure safety on Zimbabwe's roads, this paper seeks to develop a non-intrusive driver monitoring system capable of assessing driver alertness and promoting responsible driving behaviour.

Zimbabwe faces a severe road safety challenge, with an average of five fatalities daily due to road traffic accidents, making it the country with the highest fatality rate in the SADC region. (Deme, 2019:6). In response, the Ministry of Transport and Infrastructure Development sought assistance from the United Nations (UN) to conduct a nationwide road safety performance review. This initiative aimed at enhancing the capacity of governments in developing countries to manage road safety effectively, focusing on identifying the causes of accidents, including driver distraction.

In today's fast-paced society, multitasking has become deeply ingrained in people's lives. However, this increasing tendency to engage in multiple activities simultaneously has led to a rise in distractions, causing road accidents. Two primary factors contribute to inattention: fatigue and distractions from other activities. Fatigue occurs when a driver feels sleepy or drowsy, impairing their mental state and rendering them unfit to drive (Morgenstern et al, 2020). Distraction, on the other hand, occurs when drivers, even while maintaining focus on driving, become distracted by various other activities (Foya, 2019:780) such as using handheld devices, getting dressed, eating, drinking, adjusting the thermostat, or even reaching for objects between the seats while driving. Though drivers are penalised if they exceed a certain threshold of unsafe driving to prevent harm to themselves, others, or the cargo they may be transporting, accidents are still on the rise. The problem of distracted driving significantly contributes to fatal accidents in Zimbabwe (Foya, 2019:781). Shockingly, a distracted driver uses 37% less brainpower to concentrate on driving. At a speed of 80 kilometres per hour, a driver who sends or reads a text message could cover the length of a soccer field without paying attention to the road (Deme, 2019). According to the Traffic Safety Council of Zimbabwe, car accidents occur every fifteen minutes on Zimbabwean roads, resulting in an average of five deaths per day or 153 monthly deaths (Mutethya, 2022). A significant portion of these accidents, approximately 20%, are caused by less attentive drivers, contributing to severe and fatal accidents. (Kayembe, 2017).

A non-intrusive driver distraction classification and monitoring system for heavy motor vehicle drivers was designed and developed. This system monitors drivers' alertness, detects their actions through video analysis using convolutional neural networks (CNN), provides a web portal for administrators to monitor drivers, and accurately track their locations in real-time. The justification for implementing such a system lies in the significant impact that driver behaviour can have on people’s lives.

RELATED STUDIES

Various methods used for driver distraction detection systems can be categorised into four main categories: biological signal processing: subjective report approaches, behaviour signal processing using image processing, and vehicle-based measures.

Biological signal processing

Biological signal processing involves sensors such as electroencephalography (EEG) to monitor drivers' mental states. EEG measures the brain's electrical activity and can detect drowsiness and distraction based on the frequency of EEG waves. However, using intrusive sensors like EEG can be uncomfortable for drivers and may affect their natural behaviour.(Morgenstern, 2020).

Figure 1: *Using EEG to measure the alertness of the driver (Williams, 2019)*

Subjective Report Approaches

Subjective report approaches rely on the driver's estimation of their level of tiredness. The Karolinska Sleepiness Scale (KSS) gauges the levels of sleep. (Åkerstedt et al., 2017:563). Studies have compared subjective reports of sleepiness with physiological signs, and KSS has shown high validity in measuring sleepiness. (Halim & Haryono, 2022).

Behaviour Signal Processing

Behaviour signal processing techniques using image processing involve analysing facial images or videos to detect signs of distraction. (Mehta et al., 2019). Facial landmarks recognition using libraries like Dlib is used to identify specific facial features and compute metrics like eye aspect ratio (EAR), which can indicate driver tiredness. Additionally, CNN-based approaches have been used to classify driver activities from image datasets. (You et al., 2019), enabling the identification of distracted behaviours.

To measure driver sleepiness, vehicle-based measures involve sensors being attached to the steering wheel, accelerator pedal and other components of the vehicle. These measures are often evaluated in simulated environments. Examples include measuring steering wheel movement and the standard deviation of lane position. Devices like SafeTRAC utilise lane departure to detect driver drowsiness (Perkins, Sitaula and Burke,2022).

Base Technologies

Face landmark recognition using Dlib is employed to extract facial landmarks for further analysis. (Mohanty et al.,2019:3.). CNN-based classification is used to categorise distracted driver activities from image datasets.

Eye Aspect Ratio

The section concludes by referencing theories and concepts from renowned authors. For example, the use of the Eye Aspect Ratio (EAR) for detecting tiredness is suggested, and the simplicity and real-time performance of the computation formula are highlighted. (Ramzan et al., 2019.). The concept of Convolutional Neural Networks (CNNs) is also mentioned, emphasising their ability to extract distinguishing features for classification tasks.

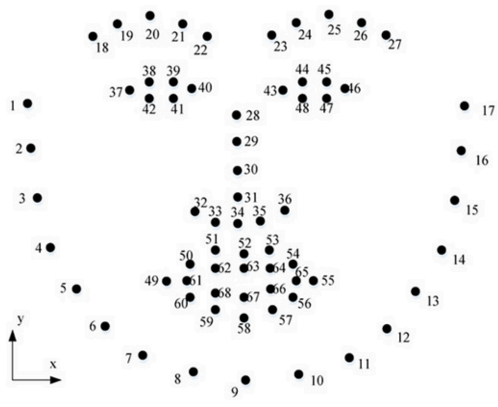

Figure 2: *The 68 facial landmarks identified Dlib (Ramzan et al.,2019)*

$$EAR = \frac{\|p_2 - p_6\| + \|p_3 - p_5\|}{2\|p_1 + p_4\|}$$

Resnet 50
ResNet-50 is a variant of convolutional neural networks (CNNs) developed by Kaiming and his team in 2015. Their study, "Deep Residual Learning for Image Recognition," introduced the concept of residual neural networks (RNNs). ResNet-50 consists of 50 layers, including convolutional layers, a MaxPool layer, and a middle pool layer. It utilises shortcut connections to overcome the vanishing gradient problem when more convolutional layers are added to the CNN.

ResNet-34, which was the original architecture had 34 weighted layers and introduced the idea of shortcut links to create residual networks. These links allow skipping over several layers, transforming a regular network into a residual network. ResNet-50 follows the same principles but with a bottleneck design for its building blocks. This design reduces the number of parameters and matrix multiplications, leading to faster layer training. The architecture of ResNet-50 maintains the same number of filters in each layer, irrespective of the magnitude of the output feature map. (He et al., 2016:770)

Compared to other CNN architectures like VGGNet, ResNet requires fewer filters, making it less complex. A 34-layer ResNet achieves 3.6 billion floating-point operations (FLOPs) (Zhang et al., 2019:1260). An 18-layer ResNet accomplishes 1.8 billion FLOPs, considerably faster than a VGG-19 Network which has 19.6 billion FLOPs.

ResNet-50's unique properties lie in its bottleneck design, residual blocks with shortcut connections, and the uniform number of filters across layers. These characteristics contribute to its improved training efficiency and ability to handle deeper network architectures (Lanjewar, Panchbai and Patle,2024).

METHODOLOGY
Deep learning models were employed for the classification of driver actions. Model training was done on a large dataset of driver behaviour images, including everyday driving, talking on the phone, and drowsiness. The training process involved fine-tuning the pre-trained ResNet-50 model on our specific dataset using the State Farm Driver Classification Dataset after using CNN from scratch gave unsatisfactory results.

OpenCV, an open-source computer vision toolkit, was used for traffic optimisation procedures. Dlib, a C++ toolkit with machine learning algorithms, was also employed. (Ruczyński, 2021). Visual Studio Code, a code editor, was used in debugging, task execution, and version control. Python, a general-purpose programming language, was used due to its ease of use and versatility (Saabith, Vinothraj and Fareez, 2021:22). Django, a web framework, was utilised to create the web portal (Ghimire,2020).

RESULTS AND DISCUSSION
The study obtained the following results, which aimed to classify driver actions using the ResNet-50 model and measure the Eye Aspect Ratio (EAR) using the Dlib library.

Driver Action Classification with ResNet-50
The accuracy of the ResNet-50 model for driver action classification was evaluated using a separate test dataset. We achieved an overall accuracy of 64.34% incorrectly classifying driver actions. The results demonstrate the effectiveness of the ResNet-50 model in the classification of driver actions, indicating its potential for real-time monitoring and detection of risky behaviour on the road.

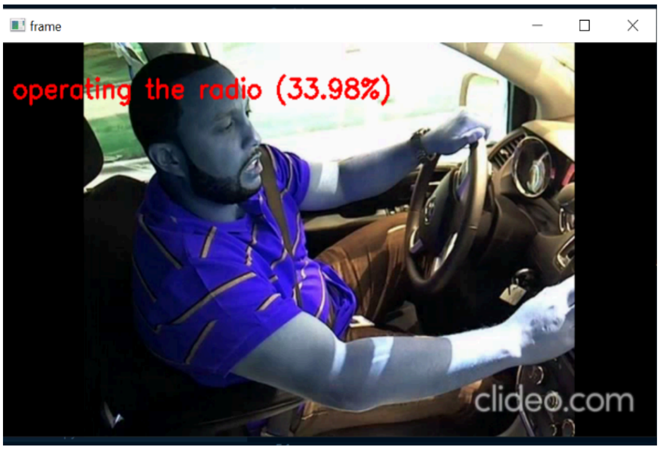

***Figure 3**: System classifying that the driver is operating a radio*

Figure 3 shows the system classifying that the driver is multitasking by operating a radio. This increasing tendency to engage in multiple activities simultaneously has led to a rise in distractions hence causing accidents on the road. Figure 4 also shows the System classifying that the driver is reaching for something at the back of the car. The driver is distracted while maintaining focus on driving and is distracted by various other activities.

***Figure 4:** System classifying that the driver is reaching for something at the back of the car*

Eye Aspect Ratio Measurement with Dlib

Eye Aspect Ratio (EAR) technique implemented with the Dlib library, quantifies eye openness, where lower values indicate higher levels of drowsiness. Figure 6 shows open and closed eyes with landmarks automatically detected by Dlib. By analysing the landmarks of facial features captured from video streams, the Dlib library calculated the EAR values for each frame (Mehta et al., 2022)

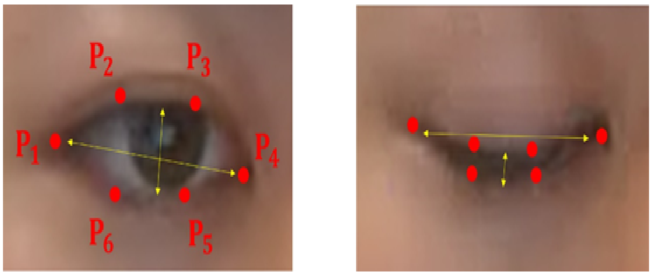

Figure 6*: Open and closed eyes with landmarks automatically detected by Dlib (Mehta et al., 2022)*

These values were then used to track the driver's eye condition over time. While evaluating the EAR measurement, we observed that as the EAR decreased, indicating a more closed eye, the self-reported drowsiness increased accordingly as shown in Figure 7, the system identifying drowsiness.

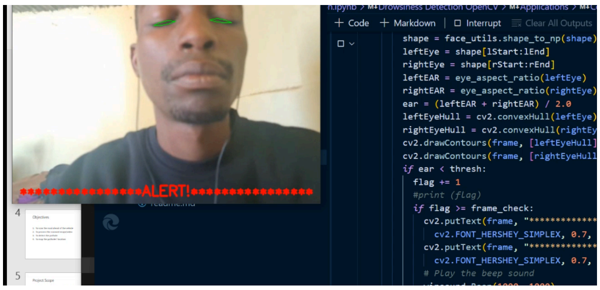

Figure 7: *System identifying drowsiness*

Driver Action Classification

The utilisation of the Re9sNet-50 model for driver action classification yielded significant outcomes. With an accuracy of 90%, the model demonstrated its capability to accurately classify various driver actions in real-time. This finding suggests that deep learning models, specifically ResNet-50, can effectively capture and interpret complex patterns and features in driver behaviour, contributing to the development of robust driver monitoring systems.

Eye Aspect Ratio (EAR) Measurement

Integrating the Dlib library for measuring Eye Aspect Ratio (EAR) proved valuable for assessing drowsiness levels. The strong correlation between EAR and drowsiness levels indicates that monitoring changes in eye behaviour can be a reliable indicator of driver fatigue. This insight has crucial implications for detecting and preventing drowsy driving, a significant cause of road accidents.

Enhancing Road Safety

By combining the ResNet-50 model for driver action classification and EAR measurement using Dlib, this research offers valuable insights for enhancing road safety through advanced driver monitoring systems. These systems can detect and classify various driver actions, such as distracted driving or improper lane changes, while also alerting drivers to their drowsiness levels. The integration of these techniques can contribute to preventing accidents by providing real-time feedback and warnings to drivers, promoting safer driving behaviours.

Further Research and Development

While this study achieved significant progress in driver monitoring, several areas warrant further exploration. Firstly, developing a comprehensive dataset encompassing diverse driving scenarios and driver populations can enhance the model's generalisability and effectiveness. Additionally, investigating the integration of other physiological and environmental sensors, such as heart rate monitors or environmental conditions, may offer additional insights into driver behaviour and improve the accuracy of drowsiness detection.

CONCLUSION

This study developed a driver monitoring system using the ResNet-50 model for driver action classification and the Dlib library for Eye Aspect Ratio (EAR) measurement. The ResNet-50 model achieved an accuracy of 64.37% in classifying driver actions, demonstrating its effectiveness in real-time monitoring. The EAR measurement using Dlib showed a strong correlation with drowsiness levels, indicating its potential for detecting driver fatigue. Combining these techniques offers insights for developing driver monitoring systems to enhance road safety.

REFERENCES

Åkerstedt, T., Hallvig, D., & Kecklund, G. (2017). Normative Data on the Diurnal Pattern of the Karolinska Sleepiness Scale Ratings and its Relation to Age, Sex, Work, Stress, Sleep Quality and Sickness Absence/Illness in a Large Sample of Daytime Workers. *Journal of Sleep Research*, *26*(5), 559–566. https://doi.org/10.1111/jsr.12528

Caird, J.K., Simmons, S.M., Wiley, K., Johnston, K.A. and Horrey, W.J., 2018. Does Talking on a Cell Phone, with a Passenger, or Dialing Affect Driving Performance? An Updated Systematic Review and Meta-Analysis of Experimental Studies. *Human Factors*, *60*(1), pp.101-133.

Deme, D. (2019). Review on Factors that Causes Road Traffic Accidents in Africa. *Journal of Civil Engineering Research & Technology*, 1–8. https://doi.org/10.47363/JCERT/2019(1)101

Foya, David. "Road Traffic Accidents, Causes, Trends and Preventive Measures: The Case of City of Harare (2012-2018)." *International Journal of Research and Innovation in Social Science* 3, no. 10 (2019): 776-792.

Ghimire, D., 2020. Comparative study on Python web frameworks: Flask and Django.

Halim, W, and Haryono,H E. "Analisa Kantuk dengan Karolinska Sleepiness Scale dan Denyut Jantung saat Mengemudi dengan Tiga Tahap Kesulitan Jalan Menggunakan Driving Simulator." *Opsi* 15, no. 1 (2022): 77-84.

He, K., Zhang, X., Ren, S., & Sun, J. (2016). Deep Residual Learning for Image Recognition. *Proceedings of the IEEE Computer Society Conference on Computer Vision and Pattern Recognition*, *2016-December*, 770–778. https://doi.org/10.1109/CVPR.2016.90

Kayembe, C. (2017). Road Traffic Challenges in Kinshasa.

Lanjewar, M.G., Panchbhai, K.G. and Patle, L.B., 2024. Fusion of Transfer Learning Models with LSTM for Detection of Breast Cancer using Ultrasound Images. *Computers in Biology and Medicine*, *169*, p.107914.

Mehta, S., Dadhich, S., Gumber, S., & Bhatt, A. J. (n.d.). Real-Time Driver Drowsiness Detection System using Eye Aspect Ratio and Eye Closure Ratio Fatigue Detection Non-Intrusive Methods Driver Monitoring System. https://ssrn.com/abstract=3356401

Mohanty, Shruti, Shruti V. Hegde, Supriya Prasad, and J. Manikandan. "Design of Real-Time Drowsiness Detection System Using dlib." In *2019 IEEE International WIE Conference on Electrical and Computer Engineering (WIECON-ECE)*, pp. 1-4. IEEE, 2019.

Morgenstern, T, Elisabeth M. Wögerbauer, FN, Josef F. K, and Andreas K. "Measuring Driver Distraction–Evaluation of the Box Task Method as a Tool for Assessing In-Vehicle System Demand." *Applied Ergonomics* 88 (2020): 103181.

Moslemi, N., Soryani, M., & Azmi, R. (2021). Computer Vision-Based Recognition of Driver Distraction: A Review. Concurrency and Computation: Practice and Experience, *33*(24). https://doi.org/10.1002/cpe.6475

Mutethya, E. (2022). Zimbabwe Records Troubling Rate of Road Crash Deaths.

Perkins, E., Sitaula, C., Burke, M. and Marzbanrad, F., 2022. Challenges of Driver Drowsiness Rrediction: The Remaining Steps to Implementation. *IEEE Transactions on Intelligent Vehicles*, *8*(2), pp.1319-1338.

Ramzan, M., Ullah Khan, H., Awan, S. M., Ismail, A., Ilyas, M., Mahmood, A., & Khan, H. U. (n.d.). A Survey on State-of-the-Art Drowsiness Detection Techniques. https://doi.org/10.1109/ACCESS.2019.2914373.

Ruczyński, Ł. (2021). ML Frameworks Compared: Scikit-Learn, Tensorflow, PyTorch and More [Updated]. https://www.netguru.com/blog/top-machine-learning-frameworks-compared

Saabith, S., Vinothraj, T. and Fareez, M., 2021. A Review on Python Libraries and Ideas for Data Science. *International Journal of Research and Engineering Science 9*(11), pp.36-53.

Venable, J. R., Pries-Heje, J., Baskerville, R. L., Venable, J. R., Pries-Heje, J. ;, & Baskerville, R. (2017). Choosing a Design Science Research Methodology. In *Australia Choosing a Design Science Research Methodology* (Vol. 2). https://aisel.aisnet.org/acis2017/112

You, F., Li, X., Gong, Y., Wang, H., & Li, H. (2019). A Real-Time Driving Drowsiness Detection Algorithm with Individual Differences Consideration. *IEEE Access*, *7*, 179396–179408. https://doi.org/10.1109/ACCESS.2019.2958667

Zhang, L., Cheng, X., & Xu, Y. (2019). Non-Intrusive Driver Distraction Detection with Channel-Wise Attention al Convolutional Neural Network. *IEEE Transactions on Intelligent Transportation Systems*, *21*(3), 1253–1263.

TECHNOLOGY AND ENERGY ENGINEERING VALUES, A NEW DIMENSION FOR APPROPRIATE TECHNOLOGY

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ABSTRACT

Since its inception in the 1970s, the Appropriate Technology (AT) movement has gained substantial traction, enabling it to grow. This study examines the literature from the last decade, as well as the history of AT, in order to determine whether it can be used in the energy generation industry. The emergence of contemporary, dependable, and cost-effective renewable energy (RE) systems increased the share of utility-scale RE solutions over small solutions to fulfill individual needs. A critical approach to technical appraisal was utilized. A community engagement strategy is required by governmental institutions, shareholders, and energy ponds. According to the study, increased collective engagement will help the African renewable industry thrive, which represents a new AT method.

Keywords: Appropriate technology, collective engagement, energy incentive

INTRODUCTION

The definition of appropriate technology (AT) as the technology that can be created at a feasible cost by regular individuals using existing assets to conduct valuable work in ways that cause the least amount of harm to both human community and the ecosystem. This definition is valid to any industry or human innovation. In this study, the associated literature on the concepts of AT is introduced in a critical manner, along with the concept in certain historical tradition. Renewable energy provides energy that produces no greenhouse gases from oil and gas, reduces environmental pollution, expands energy sources, and reduces dependency on imported fuel. Renewable energy will boost economic growth and create opportunities in manufacturing, installation, and other sectors. The author focuses on the use of solar energy to generate power, both on a utility and small scale. The cost of generating one kWh, as well as other economic indicators are considered for evaluation. Small-scale solar is considered a suitable technology, however it is more cost-effective than utility-scale solar. Now, as a new dimension of AT model of solar PV will be applied.

LITERATURE REVIEW

There have been several attempts to define appropriate technology, (Tables 1 and 2).The early clear definition of Appropriate Technology (AT): "it is a soft technology that is appropriate to a specific condition encountered by a particular set of people, with consideration given not only to economic circumstances and available resources but also regarding priorities. It is technology that falls somewhere between traditional village technologies and the modern capital-intensive technologies of the West." (Long 1980). The early literatures (Menck 1973), (John M. Kalbermatten et al. 1980) talked that it is for the least developed nations. (Kelvin Willoughby 2005) stated that it not clearly defined. Story according to tradition, 14 centuries ago, a man from the Ansar approached the Prophet Mohamed, peace and blessings be upon him, and begged him. The Prophet urged him to sell the only things he owned: a blanket and a wooden bowl. One of the Prophet's companions purchased them for two coins. The prophet instructed him to buy food for his family. Buy an axe and go gather firewood to sell, and do not see me for a fortnight. The man walked away, collected firewood, and sold it. When he had ten coins, he came to purchase a garment and food, (Anas ibn Malik 2011). That was a true demonstration of the concept of appropriate technology.

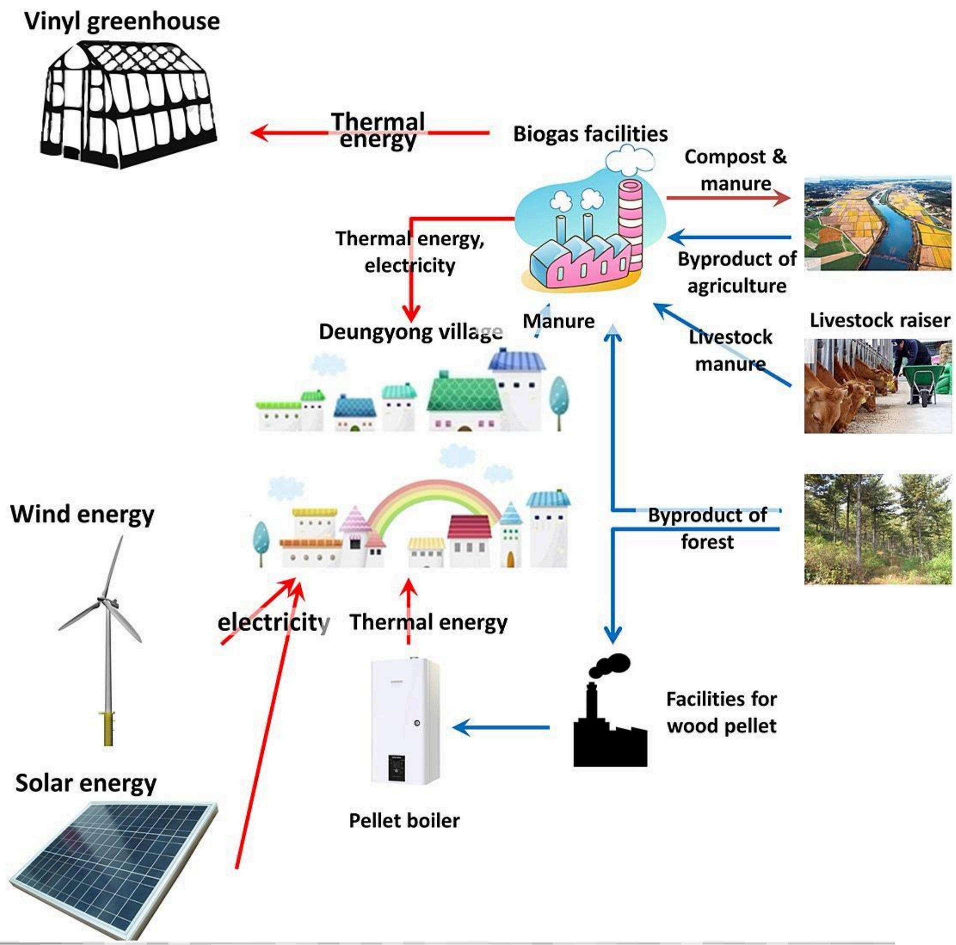
Table 1: Early literature Definitions of appropriate technology

Source	Title	Theme, Remark
(Menck 1973)	The Concept of Appropriate Technology	The idea of AT that: some of Least developed countries; (LDCs) were unable to apply certain technologies due to a lack of qualifications, while most received capital-intensive methods that contradicted widespread under-employment. Additionally, many receiving countries found technical aid to be too expensive due to the need for imports from industrialized countries. For this aim, the LDCs have had to spend some of their already precious foreign exchange.
(Long 1980)	Appropriate Technology and Social Values: A Critical Appraisal	Is a soft technology that is appropriate to a specific condition encountered by a particular set of people, with consideration given not only to economic circumstances and available resources but also regarding priorities. It is technology that falls somewhere between traditional village technologies and the modern capital-intensive technologies of the West.
(John M. Kalbermatten et al. 1980)	Appropriate Technology for Water Supply and Sanitation	a method or approach that gives a socially and environmentally acceptable degree of service, or quality of projects with full wellness advantages and at the least cost to society.
(Kelvin Willoughby 2005)	Technological Semantics and Technological Practice	The term "appropriate technology" was adopted by a slew of organizations, interest groups, individuals, and schools of thought during the 1970s and 1980s, and its application grew vague and perplexing. A technology designed to meet the psychosocial and biophysical circumstances prevalent in a specific region and period.

Table 2: Concept of Acceptable Technology from the Preceding Ten Years.

Source	Title	Theme, Remark
(Park and Ohm 2015)	A. T. for Sustainable Ecosystems: Case Studies of Energy Self-Reliant Villages and the Future of the Energy Industry	Case stories: This city (approximately 4000 population) is regarded as a successful energy-independent community that employs appropriate energy technologies, with renewable energy as the fundamental concept. The city generates electricity through small-scale power plants powered by biogas, small hydropower, wind, and solar energy, with residual electricity distributed to surrounding regions by electric power companies. To reduce the usage of oil and gas, relevant technologies such as wood pellets and heat pump boilers powered by geothermal heat or water are frequently used. See Figure 1.
(Bishop 2021)	Sustainability lessons from appropriate technology	Appropriate technology provides factual proof for sustainability. Impacts of suitable technology across time are still relevant.
(Bashirpour Bonab, Bellini, and Rudko 2023)	Theoretical and analytical assessment of smart green cities	While environmental sustainability is normally an integral aspect of smart city aims, smart technology tools (artificial intelligence, the Internet of things, blockchain, and others) may contribute more to the other pillars of sustainability.

In the literature review above the definition of appropriate technology is illustrated from the point of view of the 1970 and 80's; and the newer concepts in recent years. Now, as a new dimension of AT model of solar PV will be applied. Residential PV systems are an ideal technology to meet the owner's specific concern, and at the other side large scale PV plant will serve as a solution for unstable electricity grid. The solar PV market is separated into two segments: utility-scale solar photovoltaic and distributed solar photovoltaic solutions (home owners' modest PV systems). Figure 2 will further describe the two options.



METHODOLOGY

The economic appraisal of Solar PV

The economic appraisal of a project involves a measure of its net benefits in monetary terms. The cost of electricity or levelized cost of electricity (LCOE) is common measure to evaluate energy projects. It is computed using the equation:

$$LOCE = \frac{\sum_{t=1}^{n} \frac{It+Mt+Ft}{(1+r)^{t}}}{\sum_{t=1}^{n} \frac{Et}{(1+r)^{t}}} \quad \text{where:}$$

It $\longrightarrow$ investment in year t (including financing cost)
Mt $\longrightarrow$ maintenance expenditures in year t
Ft $\longrightarrow$ fuel cost in year t
Et $\longrightarrow$ electricity generated in year t
r $\longrightarrow$ discount rate

n $\longrightarrow$ life span in years.
For renewable energy the fuel cost Ft diminishes.
Other well-known economic indicators, such as payback period (PB), internal rate of return (IRR), and net present value (NPV), can also be applied.

Solar PV

The feasibility of utility-scale photovoltaic (PV) versus small PV applications depends on various factors, including the project goals, location, available space, and energy demand. Utility-scale PV installations or solar farms are typically larger and designed to generate electricity for the grid, offering commercial and economies scale. They are well-suited for areas with ample space and high solar irradiance, providing systems of a size in terms of megawatts and cost-effective energy production, Figure 2. Small PV applications, such as rooftop solar panels on homes or businesses, are more decentralized and can be implemented in a distributed manner. They are beneficial for on-site electricity generation, reducing transmission losses and promoting energy self-sufficiency. Ultimately, they are preferred by people in countries of unstable grid in order to solve the self-problem. As in Figure 2 the Small PV applications may connect to the gird; then no need for back up, of off grid which may need storage backed such as batteries. Figure 3 illustrate the main subject of the comparison, namely Utility scale vs small household pv systems.

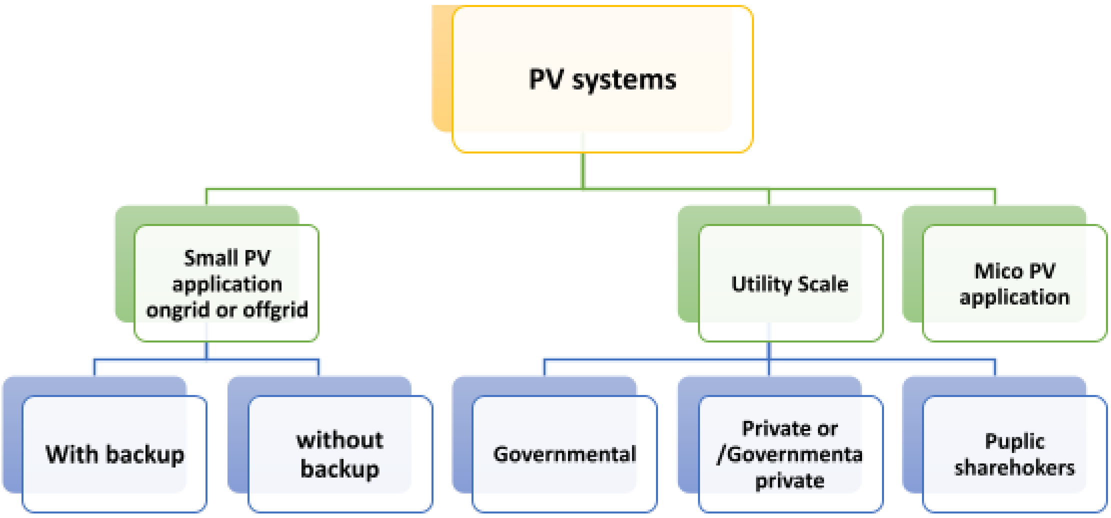


Figure 2: Photovoltaic systems application

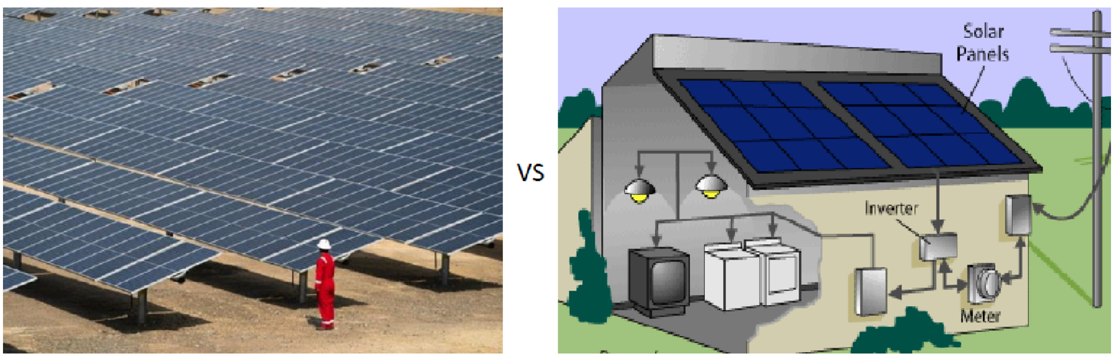


Figure 3: Utility scale vs household pv systems, (Onsa and Iman 2022)

Utility scale PV plant

Normally are built using Power Purchase Agreement (PPA). Power Purchase Agreement is a long-term contract in which a company commits to directly purchase electricity from a renewable energy plant. PPAs may last anywhere from 5 to 20 years. Major advantages of PPA to the user are: he can buy clean electricity at a lower cost than local tariffs; he delegates solar system maintenance to an experienced provider and guarantees savings on utility bills for up to 25 years. On the other side, there are various benefits for the solar system provider: Having customer buy energy on a long-term contract, can get solar tax breaks and rebates, and earning money via solar projects. The other type to finance is to prepare the cost and to build the plant yourself, or through, build, own, operate and transfer, BOOT system.

Table 3 shows that the major item of a PV plant is the module. This is typical for other power plants all over the world. Some items may differ when considering PV for small applications like house rooftop system. Ultimately, the feasibility of either option depends on the specific context and objectives of the project.

Table 3: Division of the cost items of a utility solar power plant, (Lee and Ahn 2020)

Items of Hhardware Costs	%	Items of Soft Costs	%	Items of O&M Costs	%
Modules	40.9	License and permits n insurance	6.7	Land lease costs	1.0
Inverters n wiring	9.9	Standard facility charges	5.5	Inverters	0.4
Connection bands	1.4	Design n Supervisory costs	1.0	Fuses, etc.	0.1
Mechanical Structures	3.9	General management costs	4.6	Parts replacement costs	0.2
Installation construction costs	15.7	Others n Profits	7.0	Safety management costs	0.8
Total	71.8	Total	25.8	Total	2.5

Small scale Solar PV and Appropriate Technology

A small-scale solar photovoltaic (PV) system converts solar energy into electricity by mounting it on the roof or integrating it into the building's façade. This can be used to meet the building's own energy requirements or, in some situations, fed back into the power grid. The system is simple to install and run for the average person who can follow the instructions. Now are considered cheap and become cheaper with time.

RESULTS AND DISCUSSION

The average cost of kWh from utility PV plant is \$0.08 and goes to \$0.10-0.77, Table 4. The real offers given by companies go to as low as \$0.024, Table 5. Now even less prices can be found.

Table 4: Cost of kWh in published papers

Source	Date	$/kWh	Remark
(Lee and Ahn 2020)	2020	0.10-0.15	LCOE for residential solar
(Onsa and Iman 2022)	2022	0.08	LCOE for utility solar
"	2022	0.15-0.77	LCOE for residential solar
(Ismail and Hashim 2018)	2018	0.05	Grid connected house

Table 5: Cost of kWh in commercial offers, (Jack Colreavy 2021)

#	$/kWh	Project name	Capacity [MW]	Country	Date	Company
1	0.024	ADWEA	350	UAE	2019	ADWEA
2	0.029	-	120	Chile	2019	Solarpack Corp. Tecnologica
3	0.030	Maktoum Solar Park Phase III	800	UAE	2020	Dubai Electricity and Water Authority (DEWA)

CONCLUSION AND RECOMMENDATIONS

- Literature suggests that appropriate technology is most effective for small-scale applications in rural and underserved areas, such as rooftop solar systems; which many Africans still see it as a viable solution for poor electrical grids. However, in terms of cost, utility-scale PV will outperform both initially and in the long run, regardless of how the national electricity system expands.
- Residential PV systems are cost-effective, solve individual issues, and align with appropriate technology. But they are less economically viable than utility-scale PV power plants, based on BPB and LCOE calculations. The use of smart meters to completely utilize all generated energy will increase the system's utilization value in the grid-connected zone by fourfold, allowing for an acceptable LCOE.
- African governments ought to create suitable, potent, and dependable incentive schemes to **stimulate public funding** for the creation of utility-scale renewable energy projects. If everyone works together to create a strong, secure, and dependable electricity system, the African renewable energy sector will prosper.
- Further works are necessary to strategize the improvement of collaboration among African nations and their community financial organizations in order to promote utility scale renewable energy alternatives. Regardless of size, and the targeted community, any novel and inventive technology that fosters community development should be incorporated into the AT as part of this new approach to AT. For instance, utility-scale and residential PV systems are both feasible choices that should be taken into account.

REFERENCES

Anas ibn Malik. 2011. "The Prophet Helps a Man Work for a Living." Daily Hadith Online, The Teachings of Prophet Muhammad . 2011. https://www.abuaminaelias.com/dailyhadithonline/2011/10/13/prophet-helps-man-work/.

Bashirpour Bonab, Aysan, Francesco Bellini, and Ihor Rudko. 2023. "Theoretical and Analytical Assessment of Smart Green Cities." *Journal of Cleaner Production* 410 (July): 137315. https://doi.org/10.1016/j.jclepro.2023.137315.

Bishop, Catherine P. 2021. "Sustainability Lessons from Appropriate Technology." *Current Opinion in Environmental Sustainability* 49 (April): 50–56. https://doi.org/10.1016/j.cosust.2021.02.011.

Ismail, Elaff ALfadil, and Samah Mohammed Hashim. 2018. "An Economic Evaluation of Grid Connected Photovoltaic System for a Residential House in Khartoum." In *2018 International Conference on Computer, Control, Electrical, and Electronics Engineering (ICCCEEE)*, 1–6. Khartoum: IEEE. https://doi.org/10.1109/ICCCEEE.2018.8515807.

Jack Colreavy. 2021. "Large-Scale vs. Small-Scale: A Solar PV Debate." Barclay Pearce Capital. June 5, 2021. https://www.barclaypearce.com.au/blog/large-scale-vs-small-scale-a-solar-pv-debate.

John M. Kalbermatten, DeAnne S, Duncan Mara, Charles G, and Gunnerson. 1980. "Appropriate Technologyfor Water Supply and Sanitation." Washington. https://fr.ircwash.org/sites/default/files/201-80AP-19010.pdf.

Kelvin Willoughby. 2005. "Technological Semantics and Technological Practice: Lessons from an Enigmatic Episode in Twentieth-Century Technology Studies." In *Theory of Technology*, edited by Klarke David, 1st ed. Routledge. https://www.taylorfrancis.com/chapters/edit/10.4324/9781315135571-9/technological-semantics-technological-practice-lessons-enigmatic-episode-twentieth-century-technology-studies-kelvin-willoughby?context=ubx.

Lee, Chul-Yong, and Jaekyun Ahn. 2020. "Stochastic Modeling of the Levelized Cost of Electricity for Solar PV." *Energies* 13 (11): 3017. https://doi.org/10.3390/en13113017.

Long, Franklin A. 1980. "Appropriate Technology and Social Values: A Critical Appraisal." *Bulletin of the American Academy of Arts and Sciences* 33 (4): 4. https://doi.org/10.2307/3823175.

Menck, Karl-Wolfgang. 1973. "TMenck, Karl-Wolfgang. 1973. 'The Concept of Appropriate Technology.' Intereconomics 8 (1): 8–10. Https://Doi.Org/10.1007/BF02927517.He Concept of Appropriate Technology." *Intereconomics* 8 (1): 8–10. https://doi.org/10.1007/BF02927517.

Onsa, Mahmoud H., and Onsa Iman. 2022. "ANALYSIS OF RESIDENTIAL SOLAR PV IN GRID CONNECTED ZONES VS UTILITY SCALE PV POWER PLANT, SUDAN CASE STUDY." In *10th ICAT International Conference on Appropriate Technology, International Network on Appropriate Technology (INAT)At: Khartoum* , edited by G Daoda et al., 312–19. Khartoum: INAT.

Park, Eunil, and Jay Y. Ohm. 2015. "Appropriate Technology for Sustainable Ecosystems: Case Studies of Energy Self‐Reliant Villages and the Future of the Energy Industry." *Sustainable Development* 23 (2): 74–83. https://doi.org/10.1002/sd.1574.

STRUGGLING IN SILENCE: THE UNTOLD STORIES OF MENSTRUATORS IN CONFLICT-AFFECTED AREAS IN SUDAN

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ABSTRACT

Sudan is a politically unstable country with a long history of armed conflicts and a recent outburst of conflict displacing many. Conflicts have a toll on individuals' health and well-being, yet little is captured on the effects of conflicts on menstrual experiences. This study aims to study how conflicts might affect menstrual health by studying menstruators' experiences, the role of social and community factors, as well as service provision in trying to meet menstruators' needs in conflict-affected settings.

A literature review was conducted of peer-reviewed and grey literature from Sudan and similar contexts between 2003 and 2023. Data was abstracted from VU electronic library, Google Scholars search engine, and humanitarian agencies websites, among others. The Menstrual Health framework was used to guide and answer the research objectives.

Social norms and taboos restrict menstrual health and hygiene management, and armed conflict further limits access to acceptable menstrual resources and services. Despite having access to interventions targeted to menstrual needs, menstruators didn't utilise these services and products unless they were culturally appropriate. Humanitarian interventions often focus on products and sanitation solutions. Only a few were found to address knowledge needs and gender inequalities.

To have effective humanitarian responses, menstruators need to be consulted and engaged in designing, implementing, and monitoring the interventions. Menstrual education, products, and infrastructure need to be addressed together while planning programs. A cross-sectoral collaboration between sectors like education and protection should be followed.

Keywords: Menstruator, Menstrual Experience, Menstrual Health, Armed Conflict, Sudan

INTRODUCTION

Menstruation marks the beginning of the menstrual cycle. While menarche is an indicator of a girl's entrance to womanhood. Regular menstruation signifies a healthy reproductive system. It's sign of fertility and the ability to conceive and give birth to children.[1] Over 800 million menstruators of the reproductive age (15-49) are menstruating on any given day.[2] Menstruators in low- and middle-income countries (LMICs) face challenges concerning menstruation like limited access to menstrual education or facilities. Additionally, menstrual products are expensive. Nevertheless, it's still considered a taboo and social stigma that is not talked about.[3] Sociocultural norms influence menstruators' access to essential health services and their participation in the community by excluding them from social events or performing certain tasks.[3] Menstruation stigma is exacerbated by gender inequalities,[4] which are further exacerbated by conflict.

Politically, Sudan is a highly unstable country and civilians pay the cost of conflicts.[5] Armed conflict has direct effects like morbidity, mortality and displacement, and indirect effects like disrupting the health and economic systems.[6,7] The negative indirect effects are considerably worse because they affect a larger population.[5] Conflict is to 'develop in reverse' which means it reverses the development achieved over time through loss of infrastructure, disruption of systems, and breakdown of social structures.[5,7] Effects of conflict on health include injuries, mental illnesses, and limited access to SRH services among others.[6,8]

In Sudan, only a third of households use improved sanitation.[9] Approximately 24 million people across the country lack access to adequate sanitary facilities due to the nation's deteriorating WASH infrastructure.[10]

Access to menstrual health is a human right.[11] Human rights and international laws are breached during conflicts.[6.] Along with the limited access to menstrual resources, menstruators face social and societal restrictions.[4] For instance, in Nepal, menstruators are prohibited from praying, participating in social activities, cooking, and doing household activities.[12] Changes in the surrounding environment, social networks, and socioeconomic level can affect displaced menstruators' capacity to manage their periods. Particularly young menstruators who might encounter menarche during displacement. Social taboos that discourage conversation about menstruation, combined with a lack of comprehensive SRHR information, present additional barriers to managing menstruation safely, hygienically, and with dignity.[13]

RELATED STUDIES

While menstruation is a fundamental aspect of human existence, it has only recently begun to receive attention. Most of the existing literature primarily focuses on menstruation in young and humanitarian settings leaving other age groups and aspects underrepresented. The link between menstruation and conflict is rather minimal. While a lot is known and said about the effect of conflict on health, menstruation seems to be underserved.

Although armed conflict started in Sudan in the last century, a notable lack of academic literature concerning the intersection with menstruation exists. Most of the literature focuses on menstruators in Khartoum. However, limited attention has been given to exploring regions significantly affected by conflict, such as the Nuba Mountains, Darfur, and the Blue Nile. The available literature primarily consists of grey literature generated by international humanitarian agencies, focusing on reproductive and maternal health situations.

It’s crucial to study the effect of conflict on public health in general and in SRH in specific, especially given the ongoing conflict. This study sheds light on the effect of conflict on menstruation by collecting literature from Sudan and similar settings. It focuses on the menstrual experiences and needs of IDPs and refugees. Through this research, we aim to study this intersection from a public health perspective, a right-based approach using a gender lens. By delving into menstruators’ needs, challenges, support, access to resources, and how these factors shape their menstrual experience, we seek to generate a comprehensive understanding of this topic. We also aim to contribute to the existing body of research in this area. This contribution can help inform evidence-based policies and targeted interventions to effectively address the needs of menstruators in conflict-affected areas. Furthermore, our efforts align with the goals of promoting inclusivity, gender equality, empowerment, and combatting negative social norms.

OBJECTIVES

General Objective

To explore the effect of armed conflict on menstrual experiences and access to resources, in order to present recommendations for improved humanitarian responses.

Specific Objectives

1. To explore menstruators’ experiences in terms of changes, challenges, and support in conflicted-affected areas.
2. To study the influence of social and community factors on menstruators’ experiences in conflict-affected areas.

3. To examine the access to knowledge, products, and sanitation in conflict-affected areas.
4. To present recommendations to humanitarian organisations to improve their responses and better target menstruators' needs in conflict-affected areas.

METHODOLOGY

Study Design and Approach

To achieve the study objectives, a thorough literature review was conducted using a variety of resources. Google and Google Scholar search engines were used to abstract data. For peer-reviewed published articles, the VU Electronic Library and PubMed online databases were utilised. Additionally, reports and grey literature were accessed from reputable international organisation websites, including UNHCR, UNFPA, IWAG, Wash Aid, Menstrual Health Hub, and the World Bank.

To address the limitation of available literature specific to Sudan, literature from other countries in the region with IDPs and refugees was included, such as Uganda and Tanzania. To gain more specific insight from conflict-affected settings, literature from other LMICs, like Myanmar, was included where there was insufficient literature available from settings closer to Sudan.

Exclusion criteria were applied to narrow down the data. Annex 1 shows an overview of the criteria. Due to the limitation in the literature from Sudan, two exceptions were made in terms of the publication year. One study was included to provide insight into the age of menarche over the past 50 years. The other study was the only one exploring menstruation among Sudanese and other nationality refugees and migrants. However, the findings weren't categorised by refugee status. The literature search was conducted systematically, and the data obtained were organised based on the themes derived from the conceptual framework.

Search Term Combination

Annex 2 shows the search term combinations used in detail.

Study Area

This study seeks to investigate the menstrual experiences of refugees, IDPs, and people residing in conflict-affected areas of Darfur, Khartoum, Nuba mountains, and the Blue Nile State.

Conceptual Framework

The study utilises an adapted Menstrual Health Conceptual Framework. The framework was originally developed by the Bill and Melinda Gates Foundation and FSG in 2016. The framework explores the journey of menstruators from premenarchal phase to menopause. It considers the interplay between education, sanitation, and products as the three pillars of menstrual health. It delves into the influence of 'community and influencers' and 'social norms and taboos' on menstruators' experiences. It examines the role that interventions play in promoting MHH. The framework also analyses the role of policy and research. However, some adaptations were made to capture the complexities of MHH in conflict-affected areas where gender, age, and interventions play a significant role. Annexes 3 and 4 show the original and the adapted frameworks.

RESULTS

Gender, Menstruation, and Conflict

The type of emergency whether human-made or natural disasters, length and the location of the emergency contribute to different circumstances for those affected.[14] Displaced menstruators face difficulties expressing their needs to humanitarian teams, mostly males, who may not be trained to deal with menstruation.[14] Transgender, intersex, and non-binary people face stigma, violence, and marginalisation from their communities, which reduces their chances of accessing essential services.[15] In the African context, there is a lack of literature exploring MHH and gender identities. In displacement, young menstruators avoid using bathrooms because men and boys are around. It was hard for Syrian menstruators to locate safe and private places to change pads, so they wore them for longer.[16] Menstruators avoided buying menstrual products from male sellers. Gender of the seller, affordability, and accessibility are issues facing menstruators when purchasing products. Even in emergencies, menstruators felt uncomfortable buying or getting pads from males or seeing male doctors.[17] The level of education and occupation of fathers influence access to and affordability of products.[16]

A Menstruator's Journey During Armed Conflict

During displacement, menstruators find difficulties to carry with them menstrual products.[14] Unfortunately, the needs of menstruators are placed last when it comes to family priorities.[18] After being exposed to conflict in Lebanon for a short period, menstruators experienced menstrual abnormalities that persisted for more than a cycle. The duration of exposure had a direct correlation with the severity of menstrual abnormalities which resolved without any intervention.[19] Following displacements, menstruators in Nigeria reported experiencing heavier and irregular periods.[20] Menstruators residing in Uganda indicated that their menstrual experience changed significantly. Prior to displacement, they used to work and buy menstrual products, but now they're given free products.[21] The conditions of camps in Uganda, like poor housing, shortages of food, and financial struggles have affected how menstruators perceive and prioritise their menstrual needs.[22] Menstruators in Tanzania had restricted movements during their periods because of the mental and physical conditions they experienced.[17] Leading them to stay home fearing that they smell bad.[17,23] Similarly, young menstruators in Uganda skipped school because they lacked access to products, feared leaking, teasing, or experienced pain. [21,22] Which affected their education.[21]

Menstruators in different contexts supported each other. They sought each other's assistance with household tasks or with items like menstrual supplies and products.[17,18,22] Moreover, they respected each other's dignity.[18] In Tanzania, while some menstruators tried their hardest to deal with discomfort, others stocked up on supplies. However, many of them were dependent on their families.[17] Males acknowledge their partners go through pain and feel restricted.[17]

'Social Norms and Taboos' and 'Community and Influencers'

Displaced menstruators face challenges and barriers that are intensified by gender inequality, discriminatory sociocultural norms, poverty, and lack of essential services.[14,16] Additionally, the social and power dynamics they face make them less likely to ask for improved menstrual resources.[16] As a result, many menstruators don't have their menstrual needs met.[14] Displacement can further worsen the situation by restricting movements and opportunities,[14] whereas menstrual needs seem to increase as the analysis in the previous section revealed.

Restriction in Movement and Mobility

The primary reason for lost livelihoods and people's severe vulnerability in conflict-affected areas is their inability to move freely due to insecurity.[24] Refugees and IDPs are affected more than other groups by restrictions on mobility. Which can sustain and reinforce taboos about menstruation and negatively influence menstruators' attitudes and practices.[24] Menstruators' perception and management of periods depend on sociocultural norms.[25] In several cultures, menstruation is viewed as something filthy, shameful, dirty, and private that shouldn't be talked about.[14,16,17,21,26] This can lead to physical exclusion of menstruators from their home or prohibit them from performing certain activities like cooking, fetching water, bathing, praying, or having sex.[16,17,27] Additionally, they might be excluded from participating in social gatherings or eating certain food.[16,27] Menstruators reported other restrictions, such as pain, and fear of leaking and staining.[28] Pain made it difficult for them to do tasks like cleaning, cooking, or performing daily activities like gathering firewood or water. [17]

Secrecy and Shame

Sociocultural norms influence how menstruators approach menstruation, including what products they use, how they dispose of them, and how they wash and dry them.[16] All these restrictions contribute to the negative feelings menstruators experience making it harder for menstruators to raise concerns, ask for help, or buy menstrual products.[14,16,29]

Due to secrecy and shame, menstruators performed unhygienic practices exposing them to risks. In Myanmar, menstruators continued the practice of burying their pads as they did before being displaced, even though there were ample large rubbish bins accessible. This was due to social norms that prohibited period blood and pads from being seen by others. It was made worse by the lack of gender-segregated bathrooms which increased the chances of men and boys seeing their waste. Despite advocacy from WASH staff, menstruators refused to use these bins. The small space of the camp and the lack of privacy made it difficult for menstruators to bury their pads during the day, leading some to do it at night or to dispose of them in latrines which led to clogging of pipes. Male workers responsible for dislodging pipes refused to remove the clogged pads due to stigma and taboo.[16] Similar issues were reported in Nigeria, where menstruators feared witchcraft or becoming infertile if anyone saw their waste. Moreover, they feared getting diseases if they burned their waste.[20]

In Bangladesh, menstruators make sure they have daily baths and use underwear during periods. However, over a third followed sociocultural taboos like not wearing new clothes and using separate bed covers.[29] Menstruators in Uganda believed that getting their menstrual status known places them in danger of psychological and physical assault from men and children. They also feared that others would find their used pads and use them to humiliate and degrade them publicly.[30] In Syria, menstruators used black plastic bags to hide the used pads and then threw them away in their household bathrooms. The displacement and conditions menstruators in Syria went through made it hard for them to follow their taboo normal routine. Which helped in demolishing them. Conversely, the displacement in Myanmar didn't affect their adherence to taboos.[16]

Menstrual Education

Pre-menarche Knowledge and Source of Information

Prior to menarche, some menstruators did not know about menstruation. For those who did, it was through female family members. In Syria and Uganda, the majority of menstruators learned about menstruation from their female family members, peers, and teachers, while only a few in Bangladesh did so. [16,29,21] However, the information they received was insufficient or mixed with misconceptions.[16,21] In Uganda, some menstruators were confused during menarche.[21] In Myanmar, menstruators reached out to their mothers and sisters for guidance on how to manage their periods.[16]

Ready to Learn

Menstruators expressed their desire to receive menstrual education, despite feeling that the staff providing it is incompetent. In Syria, mothers indicated that they feel unprepared to educate their daughters. Moreover, they showed interest in receiving reproductive and menstrual health education that prepares them to educate their daughters and covers a broad range of topics, including menopause.[16] In Uganda, a mixed method study revealed that 75% of adult menstruators feel they lack knowledge and all of them wanted to learn more, preferably from female sources.[21] Similarly, in Myanmar, menstruators expressed their interest in receiving culturally appropriate MHH education due to a lack of other resources.[16]

The UNFPA in Sudan is educating menstruators about MHH, Gender-Based Violence (GBV), and protection from sexual exploitation as part of risk mitigation tools. They focus on protecting from GBV, eliminating stigma, and enhancing access to specialised services.[31]

Effect of Menstrual Knowledge on Practices

Having knowledge on menstruation is crucial for maintaining good hygienic practices. However, when distributing MHM materials, there was insufficient education on MHH.[14,16] A study in Bangladesh showed a positive correlation between level of knowledge and hygiene practices.[29] Menstruators with high levels of knowledge were more likely to use disposable pads compared to others. However, there was no correlation between the level of knowledge and seeking medical care, taking daily baths, or practising sociocultural taboos.[29] In another study in Bangladesh, menstruators didn't change their pads regularly because they weren't instructed on the frequency of changing pads or how and where to dispose of them. It was their first time using disposable pads, and this lack of knowledge led some to flush the used pads in the bathrooms.[18] A similar case occurred in Myanmar.[16]

Product Solutions

Products Used Before and After Conflict

Displacement affects type and availability of products used. Several studies have indicated how menstruators had less choice over products, or their need to use different products. In Bangladesh and Uganda, disposable pads weren't commonly used prior to displacement.[29,21] The reasons in Bangladesh varied including affordability, availability, and lack of awareness, while in Uganda it was mainly due to affordability.[29,21] Alternatively, menstruators in Syria used reusable pads regularly.[16] In Myanmar, pre-conflict menstruators used cloths. The situation was similar in Nigeria and Tanzania, where the majority of menstruators used cloths.[17,20] Menstruator's choice of menstrual products post-displacement was affected by multiple factors like what was provided in the dignity kit, the frequency of distribution, mobility, ability to wash pads, and financial situation.[16]

Dignity kits seem to be the most common way of providing menstrual products to menstruators. In Tanzania, Bangladesh, and other humanitarian settings, United Nations Children's Fund (UNICEF), UNFPA, Oxford Committee for Famine Relief (Oxfam), and other NGOs distribute dignity kits to menstruators, GBV survivors, and women who gave birth.[17,32] Even though menstruators received dignity kits, they reported insufficient resources to manage menstruation.[18]

Availability

Menstrual products are being made available and accessible in all humanitarian settings assessed in this review by humanitarian organisations through dignity kits. The frequency of distribution and the type of products provided depends on the context. In Sudan, although the UNFPA is distributing dignity kits and there's an urgent need, there are restrictions on availability. [31]

In numerous settings, there was a lack of menstrual products.[18] Menstruators in Bangladesh, Myanmar, Nigeria, Tanzania, and other settings were introduced to disposable pads after displacement.[14,16,17,20,29] They had positive reviews about disposable pads in Tanzania and Myanmar.[16,17] They felt comfortable using them with no concerns about leaking.[16] In Nigeria, NGOs distributed reusable pads, while in Uganda they distributed disposable pads.[20,21,28]

Menstrual products were sometimes distributed regularly, and this gave the menstruators the duty of taking care of them.[20] Menstruators in Uganda and Tanzania reported facing challenges accessing products and expressed their needs for products and underwear.[17,28]

Accessibility

During displacement, menstruators had a severe lack of access to necessities like menstrual products and supplies.[30,33] They also needed access to safe and hygienic storage to store reusable pads.[20] A systematic review found that 34% of menstruators in humanitarian settings lacked access to menstrual products.[18] However, in Tanzania, menstrual products were available and accessible to menstruators within walking distance to the distribution centres within the camp, and menstruators didn't mind walking or standing in queues.[17]

Acceptability and Adequacy

Menstruators had different preferences for using products that differed according to age and context and showed a willingness to try new products. A systematic review found that 54% of menstruators in humanitarian settings had access to adequate disposal facilities.[18] Menstruators in Myanmar and Nigeria liked using reusable pads, although it was a challenge caring for them. [16,20] Adult menstruators in Nigeria perceived reusable pads as a better option than cloths.[20] They appreciated that reusable pads didn't stain, were securely fastened and didn't shift in position. The only negative aspect was they required several pairs of underwear. Which they needed to buy because the quantity provided by NGOs was insufficient.[20] In Tanzania, menstruators enjoyed using reusable pads, particularly when water and soap were available. They perceived them as cheaper, and cost-effective. Moreover, reusable pads reminded them of cloths, but with no leakage.[17]

Conversely, young menstruators in Nigeria preferred using disposable pads because they're thrown away after use. They didn't like to wash the reusable pads, and they felt they were less absorbent. They indicated avoiding changing reusable pads outside home.[20] Although menstruators in Nigeria used pads, they were open to trying other products if they were comfy and would make their lives easier.[20]

Affordability

Money plays a major factor in product choice, the direct cost of pads was expensive.[17] Most menstruators couldn't afford them, considered them luxury items, and had to rely on NGOs to get them.[17,21] As for the indirect cost, no menstruator mentioned bribes or having to engage in transactional sex.[17] Menstruators preferred using disposable pads in Syria and Uganda, but they couldn't afford them.[18,21] In Lebanon, because kits weren't distributed regularly, mothers who could afford them got them for their daughters and those who couldn't, used tissue paper.[16]

Quality and Durability

Menstruators faced challenges accessing soap to care for reusable pads and good-quality pads.[18] In Tanzania, menstruators were told that reusable pads can last up to a year. However, the pads started getting smelly and worn down after six months. To extend the life of products, menstruators took good care of them and requested buckets for personal hygiene.[17]. In Nigeria, menstruators had challenges maintaining their products which affected their durability.[20]

Quantity

Menstruators reported insufficient pad provision. Menstruators in Tanzania complained that the number of pads wasn't sufficient, and the frequency of distribution wasn't adequate. They used between 4-24 pads per period.[17,18] In Tanzania, they were given one or two pairs of underwear which wasn't enough.[17] In Lebanon, menstruators noted that the distribution of dignity kits wasn't frequent, and some adult menstruators didn't receive any pads for a year.[16,18] Due to the insufficient distribution, young menstruators saved disposable pads to use outside home.[16]

Sanitation

Water and Soap

During conflicts, there is limited access to water and soap for drinking, bathing, and toilet use.[16-18] As the cost of commodities rises, many menstruators choose not to use hygienic menstrual products to save water and other resources.[10] In Tanzania and Uganda, menstruators expressed their need to access water and soap and their preference for taking showers at least twice a day. However, the majority didn't have access to menstrual supplies. Less than 25% of menstruators in Uganda reported having access to adequate handwashing facilities.[17,21,34] In Tanzania, menstruators had to prioritise water for drinking, cooking, and other family members' needs before their hygiene.[17] The lack of water made it a challenge for menstruators in Bangladesh to wash their reusable pads.[35] In Lebanon, menstruators suggested distributing baby wipes or pre-wet napkins.[16]

In Bangladesh, water points were far from bathing facilities, making it hard to carry water to bathing places.[35] In Nigeria, Uganda, and other contexts, soap wasn't provided regularly in camps, and it wasn't affordable in the local markets.[18,20,34] To wash their reusable pads, some menstruators soaked their reusable pads in water and scrubbed out the blood, but it didn't get rid of the smell.[20] Others washed their pads using salt or ash.[18,20] And some chose to throw away their reusable pads.[20] After displacement in many settings, young menstruators missed school because they didn't have soap to clean their reusable pads.[23]

Privacy, Safety, and Dignity

During humanitarian emergencies, menstruators struggle to find safe and private spaces to manage their periods with dignity.[30] In Tanzania and Bangladesh, they expressed their need for privacy.[17,35] It was their first concern and was essential for them to feel clean to keep their dignity intact.[17,35]

Menstruators faced challenges that latrines were far and had no lights at night.[16,18,20,35] Some menstruators feared being attacked or subjected to sexual violence while others were intimidated by the idea of using latrines at night without lighting. Menstruators coped differently, In Lebanon, they woke up early (4-5 am) to use the latrines, although it was still dark and a long distance to walk.[16] In Bangladesh, menstruators don't eat or drink at night, so they don't use latrines. Moreover, they didn't change their pads during the night because they feared the stigma of being seen.[35] In Uganda, menstruators asked for lights to protect their safety.[30] In Nigeria, menstruators used flashlights which were hard to handle especially while changing pads. NGOs provided battery-operated flashlights, but batteries weren't affordable.[20]

Menstrual-friendly Toilets

Conflicts put pressure on the already limited WASH infrastructure.[10] In March 2023, the bulk of menstrual facilities in South Kordofan state were found to be poorly managed and inadequately maintained as a result of looting, shortage of supplies, and lack of maintenance.[10]

Menstruators have raised many concerns regarding menstrual facilities. Some of them were: inadequate in number, focused on quantity rather than quality, located far away, crowded, and communal resulting in long queues, uncomfortable, not segregated by sex, had no locks, were dirty, lacked cleaning materials, not maintained regularly, lacked water, and had wide gaps between the walls making it visible from outside.[16-18,30,33,35] All these factors led menstruators to wash less and rush during bathing which was stressful during period.[17,20,21] The majority of menstruators in Bangladesh felt latrines were the main issue, and if fixed it would have a positive impact on their lives. However, they also expressed their concerns that men and boys don't follow the rules of segregated bathrooms.[35]

Often school bathrooms in Nigeria and Uganda were dirty, lacked water and locks, and weren't segregated, leading young menstruators to go home to change their pads which affects their attendance.[20,21] In Tanzania, menstruators avoided using shared latrines due to the fear that a man could walk in. Some menstruators had to hold urine and faeces for a long that caused them stomach pain. Sometimes they had to urinate in the bushes. Single women didn't have latrines in their household because there was no one to dig it for them. They resorted to using their neighbours' toilets, who weren't happy about it.[17] In Myanmar, some families constructed small washrooms near their homes to access sanitation easily and be able to change pads at night.[16,18]

Waste and Disposal Management

In numerous humanitarian contexts, menstruators lacked methods to dispose of the used menstrual materials.[17,18] In Nigeria, the unavailability of disposal methods led menstruators to throw pads in toilets, burn, or burying them. This resulted in clogged pipes, and difficulties emptying septic tanks which eventually led to decreased toilet capacities. Menstruators were asked by community elders and WASH staff not to throw pads in latrines. But they weren't given other alternatives. So, they resorted to burying pads like they used to do. Covered bins were suggested as a disposal method inside bathrooms but menstruators had concerns about others opening them. They didn't prefer burning because they believed fumes might harm their health. But it was a better option for them than a trash bin.[20] Similarly, in Bangladesh, menstruators preferred burying used products as they used to do. They viewed their menstrual products as private and they didn't want others to see them.[32] Menstruators in Uganda didn't want to use bins without locks as they felt uncomfortable with their waste secure.[30]

Washing and Drying Facilities

In various contexts, menstruators encountered difficulties in accessing safe, and dignified private facilities for washing and drying their reusable pads, and they reported their need to access them.[17] In Bangladesh, the lack of access to these facilities exposed menstruators to increased risks of health issues and exploitation.[18,34]

In Tanzania and Nigeria, menstruators hid washing and drying pads. They wanted to care for them without anyone rushing them or facing the danger of having them stolen.[17,20] Similarly, in Bangladesh, menstruators were ashamed of washing their reusable pads in bathing facilities because men could see them.[35] Everyone stood in line and menstruators didn't have enough time to wash their clothes.[35] There were no separate washing facilities, so they washed them in the shower.[35] In Nigeria, most menstruators used bathrooms to wash their pads.[20] This ensured their privacy and the ability to dump the bloody water into the drainage system.[20] Sometimes the soakaway filled up due to overuse which made it challenging to use bathrooms. [20] In Myanmar, some washing facilities had an extra space covered by a curtain to allow menstruators privacy when washing pads.[18]

In Myanmar, Nigeria, and Tanzania, some menstruators hung their pads inside houses or outside underneath other pieces of clothing.[16,17,20] In Tanzania, this piece is called Kanga.[17] In Bangladesh and Myanmar, menstruators dried their pads inside their households where it was dark and had no air. They worried their pads could get stolen if left unattended.[16,35] While in Nigeria, menstruators dried reusable pads at night on the roof and woke up early to take them.[20] In Myanmar, because they put pads under mattresses, it took longer to dry. As a result, menstruators had to wear them wet, which caused them irritation and discomfort.[16] Similarly in Nigeria, the pads weren't completely dry, especially in rainy seasons and sometimes menstruators didn't have enough time to wash them. When this happened, menstruators used cloths. This increased their fear of staining or smelling bad.[20]

DISCUSSION

Education, Products, and Sanitation

Menstruators in various contexts faced similar challenges in accessing menstrual resources leading them to perform unhygienic practices. The lack of menstrual products led menstruators to wear pads for longer, reuse dirty pads, or free bleed. The lack of guidance on product use led menstruators to wear pads for longer times affecting their health. It also led them to dispose of them in the toilets which clogged the pipes and reduced their capacity. The limited access to menstrual supplies has led menstruators to soak their pads in water and salt to clean them. Others had to throw away their reusable pads prematurely due to a lack of supplies. The lack of culturally appropriate disposal methods led menstruators to bury or burn pads or throw pads in toilets which caused further issues. The lack of washing and drying facilities led menstruators to use cloth or dirty and wet pads and not change them frequently which compromised their health. Because these methods weren't hygienic or reliable, they affected menstruators' health and community participation. Menstruators feared they would leak or smell bad. Moreover, young menstruators skipped school which affected their education. This self-exclusion along with the sociocultural norms exclusion reinforces gender inequalities and negatively affects their quality of life and most importantly their mental health and well-being.

Addressing the Menstrual Experience in Sudan

Based on the findings, Sudan's diversity, the presence of two types of conflict, and considering the limited resources, I have proposed two plans, one for each setting. For both settings, the plan involves supporting cross-sectoral collaboration in designing and implementing humanitarian responses and recruiting and training female staff.

For the acute settings of Khartoum and Darfur, the plan involves distributing standard dignity kits containing disposable pads, as access to menstrual supplies is limited. Demonstrations on how to use and dispose of the pads will be made. A distribution schedule will be available, so menstruators know when to expect their kit. Additionally, menstrual supplies and menstrual-friendly toilets will be provided, along with safe, and private disposable methods, and washing and drying facilities. The toilets will be located away from boys' and men's toilets and made sure they don't access them.

For the protracted settings of Nuba Mountains and the Blue Nile, the plan is like the acute settings, but with room for more activities. It will start by conducting consultations with menstruators to capture their preferences. A culturally appropriate menstrual and reproductive health education will be provided, and the community will be engaged to dismantle stigma. Reusable pads will be provided through voucher-cash assistance programs to ensure sustainability and agency. Menstruators will be made aware of the availability of healthcare services. Ad hoc structures and leakproof bags will be provided.

Throughout the implementation phase, a room will be kept for unexpected challenges like in procurement, transportation, or communication. As a result, the plan will be flexible to allow for adjustments based on feedback received and changing circumstances. Ultimately, I hope to provide IDPs with sustainable, inclusive, and equitable MHM that fosters agency.

Strengths and Limitations

My research focused on the emergency context in LMICs, specifically on IDPs and refugees. Although they have different definitions, I discussed them together because they share many characteristics in terms of menstrual experience, humanitarian needs, and access to resources.

Sudan is a unique and diverse country with both Afro-Arab characteristics.[36] To supplement my research, I drew on literature from other conflict-affected contexts with similarities to Sudan in terms of geographic location, language, religion, and ethnic reasons. I included neighbouring countries like Kenya and Uganda. Additionally, Muslim and Arab countries like Syria and Lebanon share the same language and religion as Sudan. I also looked at literature from Myanmar due to its ongoing ethnic protracted conflict, which is like the conflict in Darfur, Nuba Mountains, and the Blue Nile. However, it's crucial to exercise caution when applying research findings or designing humanitarian responses in Sudan since none of these countries are Afro-Arab like Sudan. Differences in culture, social norms, education, and other factors should be considered. While there are differences, I found more similarities than differences in terms of MHM, even though the nature of cultural preferences and practices differed.

Additionally, sociocultural norms have a significant influence on the menstrual experience, which differs between and within each country. Menstruators in Khartoum won't be receptive to using reusable pads. While in Darfur, the Blue Nile and Nuba Mountains, menstruators will appreciate using reusable pads. As for disposal methods, the majority in Khartoum throw pads in trash bins, and a few burn them. However, in the other conflict-affected areas they throw them in pit latrines or burn them. Therefore, it's necessary to acknowledge the differences within Sudan and consult menstruators on their needs and preferences regarding MHM.

Furthermore, there is a distinction between the recent conflict in Khartoum and the flare-up in Darfur, as well as between the protracted conflicts in Nuba Mountains, and the Blue Nile. In Khartoum and Darfur, the need is for humanitarian aid, while in the Nuba Mountains and the Blue Nile, the need is for humanitarian-development nexus. Although there was already a humanitarian nexus in Darfur for the last 20 years, the needs have shifted to purely humanitarian.

The conditions menstruators go through whether related to conflict, social norms exclusion, or self-exclusion, all combine to produce a significant effect on menstruators' mental health and well-being. All these factors play a stressor role and impact hormonal balance causing menstrual irregularities. This stressor can exacerbate the existing menstruation-related disorders further and affect menstruators' mental health and well-being further. Despite being a significant factor in influencing the menstrual experience, none of the literature I analysed has addressed this issue.

The menstrual experience covers a life journey approach starting from menarche to menopause. Although menopause is a part of the menstruators' journey, it hasn't been addressed in any of the literature I studied. In one study, menstruators expressed their desire to learn about menopause. Most of the literature focused on menstruation and menarche but none on menopause.

CONCLUSION

This study aims to explore the effect of armed conflict on menstrual experiences and access to resources, to present recommendations for improved humanitarian responses. Menstruation is viewed as a topic that is taboo, shameful, and private. These sociocultural norms have a significant influence on how menstruators manage their periods and perceive their experiences. Socioeconomic and sociocultural factors heavily impact access to menstrual resources. Even with the occurrence of armed conflict and displacement, accessing and utilising these resources relied heavily on sociocultural norms. During conflicts, menstruators faced additional challenges in accessing menstrual education, supplies, products, and facilities. It's important to recognise that these resources are interconnected, and lack of access can have a significant impact on how menstruators manage their periods. The interplay between sociocultural norms, and the limited resources to manage periods, make MHM additionally challenging for menstruators in conflict-affected settings.

The lack of adequate menstrual education has resulted in menstruators engaging in unhygienic practices like wearing pads for long or throwing them in the toilets, leading to clogged toilets. The lack of menstrual supplies led menstruators to use cloth, reuse dirty pads, or free bleed. The unavailability of private and safe washing and drying facilities has exacerbated the situation, forcing menstruators to continue using unhygienic methods. All these unhygienic practices don't only negatively affect menstruators' health, but also lead to self-isolation, affecting well-being, mental health, and overall quality of life.

Despite menstruation being a normal physiological process and the protracted conflict in Sudan, there is a notable lack of literature addressing this intersection. There is a huge knowledge gap in research, policy, menopause, and the intersection with mental health. Therefore, future qualitative research should focus on these areas.

REFERENCES

1. Muralidharan A. Constrained Choices? Menstrual Health and Hygiene Needs Among Adolescents in Mumbai Slums. Indian Journal of Gender Studies [Internet]. 2019 [cited 2023 Jul 24];26:12–39. Available from: http://journals.sagepub.com/doi/10.1177/0971521518808104
2. WaterAid. We Can't Wait: A Report on Sanitation and Hygiene for Women and Girls [Internet]. 2013. Available from: https://washmatters.wateraid.org/publications/we-cant-wait-a-report-on-sanitation-and-hygiene-for-women-and-girls
3. Sommer M, Hirsch JS, Nathanson C, Parker RG. Comfortably, Safely, and Without Shame: Defining Menstrual Hygiene Management as a Public Health Issue. Am J Public Health [Internet]. 2015 [cited 2023 Jul 24];105:1302–11. Available from: https://ajph.aphapublications.org/doi/full/10.2105/AJPH.2014.302525
4. Alexandra Geertz, Lakshmi Iyer, Lucero Quiroga, Jennifer McCleary-Sills. Gender and Sanitation Evidence Review May 2018.pdf [Internet]. 2018. Available from: https://www.gatesgenderequalitytoolbox.org/wp-content/uploads/Gender-and-Sanitation-Evidence-Review-May-2018.pdf
5. Gates S, Hegre H, Nygård HM, Strand H. Development Consequences of Armed Conflict. World Development [Internet]. 2012 [cited 2023 Jun 26];40:1713–22. Available from: https://www.sciencedirect.com/science/article/pii/S0305750X12001015
6. Levy BS, Sidel VW. Documenting the Effects of Armed Conflict on Population Health. Annu Rev Public Health [Internet]. 2016 [cited 2023 Jul 23];37:205–18. Available from: https://www.annualreviews.org/doi/10.1146/annurev-publhealth-032315-021913
7. impact of conflict on women unfpa.

8. Garry S, Checchi F. Armed Conflict and Public Health: Into the 21st Century. Journal of Public Health [Internet]. 2020 [cited 2023 Jul 23];42:e287–98. Available from: https://academic.oup.com/jpubhealth/article/42/3/e287/5672679

9. Ministry of Cabinet, Centeral Bureau of Statistics. Sudan Multiple Indicator Cluster Survey 2014 Final Report.pdf [Internet]. 2014. Available from: https://mics.unicef.org/files?job=W1siZiIsIjIwMTYvMDUvMTgvMjEvNTkvNTEvODg3L1N1ZGFuXzIwMTRfTUlDU19FbmdsaXNoLnBkZiJdXQ&sha=32907fc39e6e2e6e

10. Care International. Rapid Gender Analysis Policy Brief: Sudan Conflict Response [Internet]. 2023. Available from: https://www.care-international.org/sites/default/files/2023-05/Sudan%20RGA%20Brief_May%202023_CARE.pdf

11. Winkler IT. Menstruation and Human Rights: Can We Move Beyond Instrumentalization, Tokenism, and Reductionism? Columbia Journal of Gender and Law [Internet]. 2021 [cited 2023 Jul 4];41:244–51. Available from: https://journals.library.columbia.edu/index.php/cjgl/article/view/8842

12. Mukherjee A, Lama M, Khakurel U, Jha AN, Ajose F, Acharya S, et al. Perception and Practices of Menstruation Restrictions Among Urban Adolescent Girls and Women in Nepal: A Cross-Sectional Survey. Reprod Health [Internet]. 2020 [cited 2023 Jul 24];17:81. Available from: https://reproductive-health-journal.biomedcentral.com/articles/10.1186/s12978-020-00935-6

13. Pathfinder International. Improving Menstrual Hygiene Management for Rohingya Adolescent Girls in Cox's Bazar, Bangladesh [Internet]. 2022. Available from: https://www.pathfinder.org/wp-content/uploads/2022/04/PI-BD_MHM-Rohingya_2022-04-25.pdf

14. Tina Nelis. Humanatarian Learning Center, Menstrual Hygiene Management in Humanitarian Emergencies, Operational Practice Paper 3 [Internet]. 2018. Available from: https://menstrualhygieneday.org/wp-content/uploads/2018/07/HLC-OPP_MHM-in-HumanitarianSettings-2018.pdf

15. International Labour Organization. Inclusion of lesbian, gay, bisexual, transgender, intersex and queer (LGBTIQ+) persons in the world of work: A learning guide [Internet]. 2022. Available from: https://www.ilo.org/wcmsp5/groups/public/---dgreports/---gender/documents/publication/wcms_846108.pdf

16. Schmitt ML, Clatworthy D, Ratnayake R, Klaesener-Metzner N, Roesch E, Wheeler E, et al. Understanding the Menstrual Hygiene Management Challenges Facing Displaced Girls and Women: Findings from Qualitative Assessments in Myanmar and Lebanon. Confl Health [Internet]. 2017 [cited 2023 Jul 23];11:19. Available from: http://conflictandhealth.biomedcentral.com/articles/10.1186/s13031-017-0121-1

17. Nielsen JK. Women and Girls' Experiences with Safety, Hygiene and Sanitation in Connection with Menstrual Health Management in Nyarugusu Refugee Camp, Tanzania. 2017; Available from: https://womena.dk/wp-content/uploads/2019/07/Women-and-girls'-experiences-with-safety-hygiene-and-sanitation-in-connection-with-Menstrual.pdf

18. Patel K, Panda N, Sahoo KC, Saxena S, Chouhan NS, Singh P, et al. A Systematic Review of Menstrual Hygiene Management (MHM) During Humanitarian Crises and/or Emergencies in Low- and Middle-Income Countries. Front Public Health [Internet]. 2022 [cited 2023 Jul 23];10:1018092. Available from: https://www.frontiersin.org/articles/10.3389/fpubh.2022.1018092/full

19. Hannoun AB, Nassar AH, Usta IM, Zreik TG, Abu Musa AA. Effect of War on the Menstrual Cycle. Obstetrics & Gynecology [Internet]. 2007 [cited 2023 Jul 23];109:929–32. Available from: https://journals.lww.com/00006250-200704000-00021

20. Schmitt ML, Gruer C, Clatworthy D, Kimonye C, Peter DE, Sommer M. Menstrual Material Maintenance, Disposal, and Laundering Challenges Among Displaced Girls and Women in Northeast Nigeria. Journal of Water, Sanitation and Hygiene for Development [Internet]. 2022 [cited 2023 Jul 23];12:517–28. Available from: https://iwaponline.com/washdev/article/12/7/517/89384/Menstrual-material-maintenance-disposal-and

21. Norelius H. Managing Menstruation During Displacement, Uganda. 2017; Available from: https://womena.dk/wp-content/uploads/2019/07/Managing-menstruation-during-displacement.pdf

22. Kemigisha E, Rai M, Mlahagwa W, Nyakato VN, Ivanova O. A Qualitative Study Exploring Menstruation Experiences and Practices Among Adolescent Girls Living in the Nakivale Refugee Settlement, Uganda. IJERPH [Internet]. 2020 [cited 2023 Jul 23];17:6613. Available from: https://www.mdpi.com/1660-4601/17/18/6613

23. Rahma D. Reproductive Health KAP Survey among Communities Affected by Conflict in Darfur. 2009; Available from: https://sudan.unfpa.org/en/publications/reproductive-healthgbv-kap-survey-among-communities-affected-conflict-darfur

24. Young H, Osman AM. Challenges to Peace and Recovery in Darfur, A Situation Analysis of the Ongoing Conflict and its Continuing Impact on Livelihoods. 2006; Available from: https://fic.tufts.edu/assets/Young-Challenges-to-Peace-and-Recovery-in-Darfur-A-Situation-Analysis-of-the-Ongoing-Conflict-and-its-Continuing-Impact-on-Livelihoods.pdf

25. Hawkey AJ, Ussher JM, Perz J, Metusela C. Experiences and Constructions of Menarche and Menstruation Among Migrant and Refugee Women. Qual Health Res [Internet]. 2017 [cited 2023 Jul 23];27:1473–90. Available from: http://journals.sagepub.com/doi/10.1177/1049732316672639

26. Chandra-Mouli V, Patel SV. Mapping the Knowledge and Understanding of Menarche, Menstrual Hygiene and Menstrual Health Among Adolescent Girls in Low- and Middle-Income Countries. Reprod Health [Internet]. 2017 [cited 2023 Jul 23];14:30. Available from: http://reproductive-health-journal.biomedcentral.com/articles/10.1186/s12978-017-0293-6

27. Roose S, Rankin T, Cavill S. Breaking the Next Taboo: Menstrual Hygiene within CLTS. 2015; Available from:

https://opendocs.ids.ac.uk/opendocs/bitstream/handle/20.500.12413/6578/Issue%206%20-%20%20MHM%20FINAL.pdf?sequence=5&isAllowed=y

28. Emilly L. Assessment of Knowledge, Perceptions, and Practices of Menstrual Hygiene Management Among Females Aged (15-49) in Bidibidi Refugee Settlement, Yumbe District, Uganda. 2019; Available from: http://makir.mak.ac.ug/handle/10570/7851

29. Huda MdN, Hossain SZ, Mohsin M, Azim S, Rahman M, Ferdous A, et al. Exploring Knowledge and Practices Regarding Menstrual Hygiene Management Among Bihari Women In The Geneva Camp In Bangladesh. women midwives & midwifery [Internet]. 2022 [cited 2023 Jul 23];2:84–97. Available from: https://wmmjournal.org/index.php/wmm/article/view/57

30. YLabs. Cocoon, Project Overview and Oppurtunities for Future Investment and Scale [Internet]. 2021. Available from: https://iawg.net/resources/cocoon-mini-provides-a-private-space-for-menstruators

31. UNFPA Sudan. Emergency Situation Report No.1 .pdf [Internet]. 2023. Available from: https://arabstates.unfpa.org/sites/default/files/pub-pdf/unfpa_-_sudan_emergency_situation_report_no.1.docx.pdf

32. Schmitt ML, Wood OR, Clatworthy D, Rashid SF, Sommer M. Innovative Strategies for Providing Menstruation-supportive Water, Sanitation and Hygiene (WASH) Facilities: Learning from Refugee Camps in Cox's Bazar, Bangladesh. Confl Health [Internet]. 2021 [cited 2023 Jul 23];15:10. Available from: https://conflictandhealth.biomedcentral.com/articles/10.1186/s13031-021-00346-9

33. UNFPA, Government of Nigeria. Gender Based Violence Sub Sector Addressing Critical Needs of Dignity and Menstrual Hygiene: Through the Nigeria Humanitarian Fund (HNF) [Internet]. 2019. Available from: https://reliefweb.int/report/nigeria/gender-based-violence-sub-sector-addressing-critical-needs-dignity-and-menstrual

34. WHO. World Report on the Health of Refugees and Migrants [Internet]. 2022. Available from: https://www.who.int/publications/i/item/9789240054462

35. Oxfam. Women's Social Architecture Project - Phase 1 Final Report, Oxfam Rohingya Response Cox's Bazaar, September 2018 [Internet]. 2018. Available from: https://reliefweb.int/report/bangladesh/oxfam-rohingya-response-womens-social-architecture-project-phase-1-final-report

36. Embassy of the Republic of Sudan, London. About Sudan [Internet]. 2023 [cited 2023 Aug 2]. Available from: https://sudanembassy.org.uk/about-sudan/#

ANNEXES

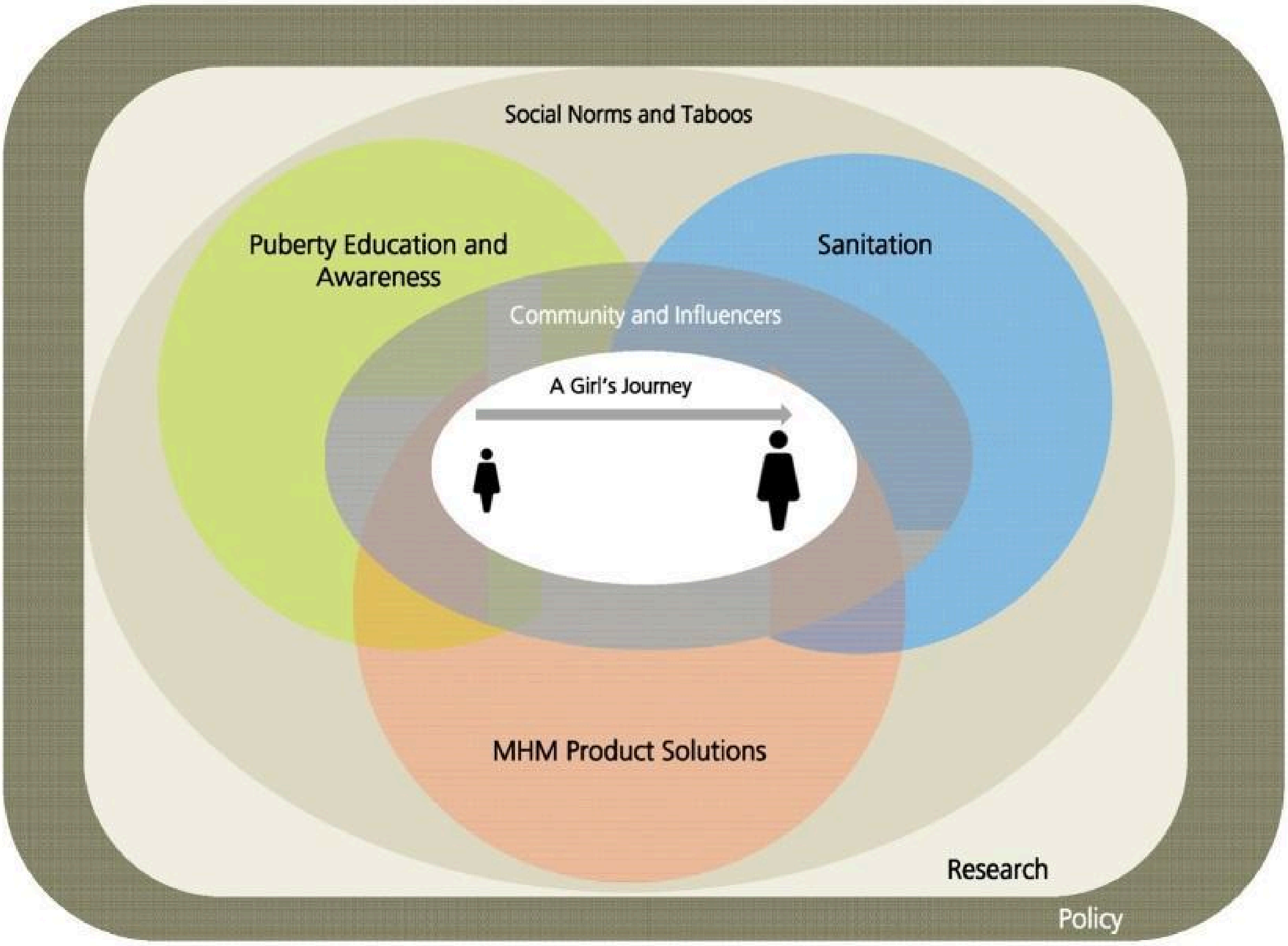
Annex 1: Overview of Inclusion and Exclusion Criteria

Criteria	Inclusion criteria	Exclusion criteria
Language	English	Other languages
Year of publication	2003-2023	Before 2003
Geographic location	Sudan, Africa, Asia, LMIC	Europe, North America, HIC
Study design	Qualitative, Quantitative, mixed, case studies	Non-empirical articles

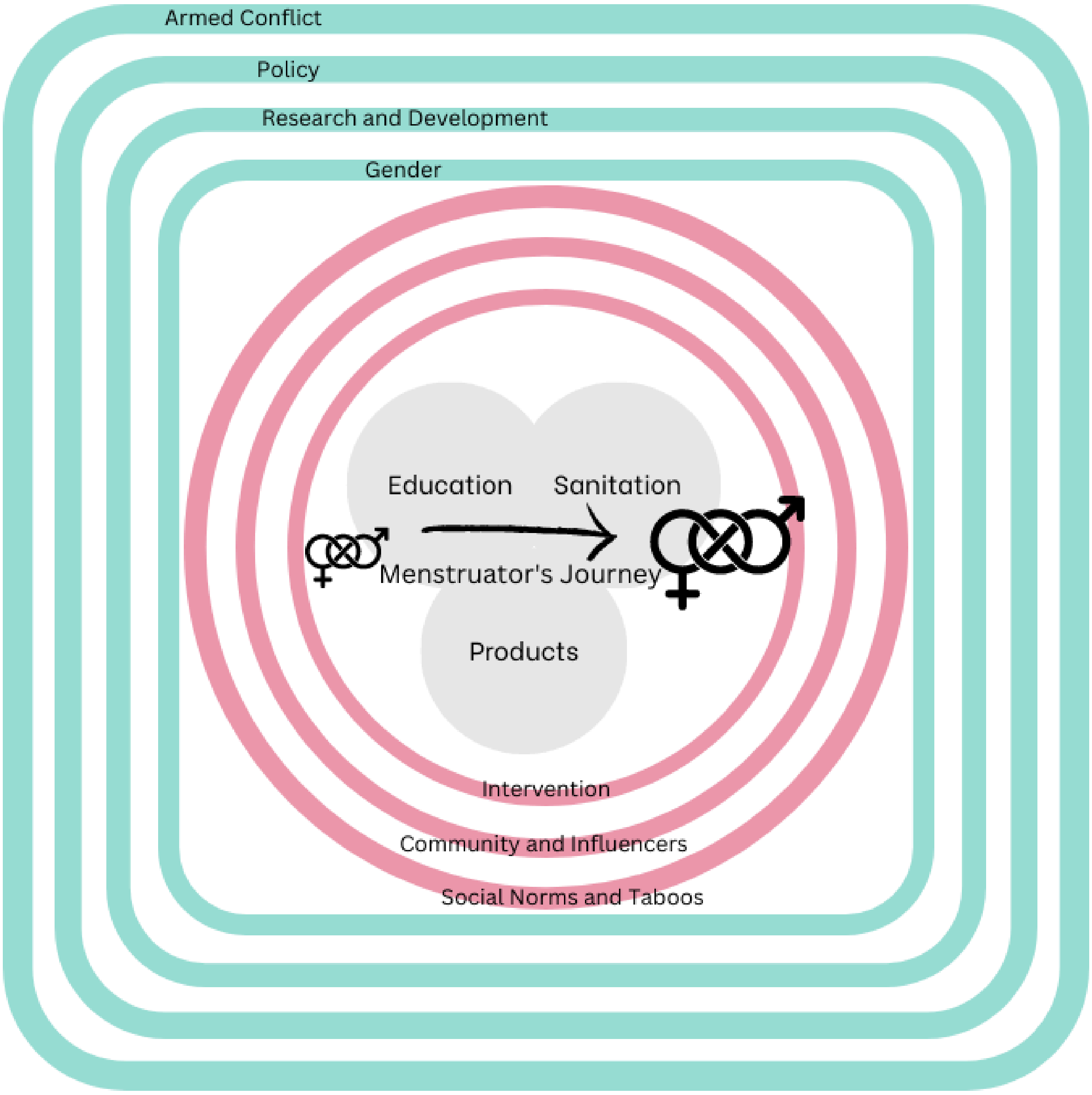
Annex 2: Keywords Combination Used for Literature Search Using Boolean Operators 'AND' and 'OR'

<table>
<tr><td>Specific Objective</td><td rowspan="4">OR</td><td>Key words</td><td rowspan="4">AND</td><td>Theme</td><td rowspan="4">AND</td><td>Geographical Location</td></tr>
<tr><td>1</td><td rowspan="3">Menstruation, Menstrual cycle, Menstrual health, Menstrual health and hygiene, Menstrual hygiene management, Menstruator,</td><td>Gender, Experiences, Challengers, Changes, Enablers, Menarche, Menopause, Menstruation-related disorder, Support, Culture, Religion, Taboos, Stigma, Gender norms, Socioeconomic,</td><td rowspan="3">Sudan, Darfur, Nuba, Khartoum, Blue Nile, North Africa, Sub-Saharan Africa, SSA, Middle East and North Africa MENA, Conflict-affected areas, LMICs, Tanzania, Uganda, Nigeria, Bangladesh, Myanmar, Syria, Lebanon</td></tr>
<tr><td>2</td><td>Culture, Religion, Taboos, Stigma, Gender Norms, Socioeconomic, Sociocultural, Social Norms, Community, Influencers, Society Expectations, Gender Expectations,</td></tr>
<tr><td>3</td><td>Gender, Knowledge, Awareness, Education, School, Products, Disposable, Reusable, Availability, Accessibility, Acceptability, Adequacy, Affordability, Quality, Durability, Quantity, Sanitation, Water, Soap, Gender-segregated, Communal, Privacy, Safety, Dignity, Agency, Violence, WASH, Menstrual-friendly toilets, Female-friendly toilets, Violence, Safety, Waste, Disposal, Washing, Drying, Infrastructure, Facilities,</td></tr>
</table>

Annex 3: *The Original Menstrual Health Framework Developed by the Bill and Melinda Gates Foundation and FSG (reimagining social change) in 2016.*



Annex 4: The Adapted Menstrual Health Framework. It Shows the Added Themes and Menstruator's Journey.



AIR QUALITY MONITORING IN SUDAN: LEVERAGING LONG-RANGE COMMUNICATIONS (LORAWAN) FOR SUSTAINABLE SMART CITIES & VILLAGES

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ABSTRACT

Air quality monitoring in smart cities and villages is crucial in peace as well as in war times. The ongoing armed conflict in Sudan poses health risks due to the release of gases from explosions, weapons, deliberate combustions of markets, buildings, and vehicles. This research explores possibilities for potential deployment of LoRaWAN in Air Quality Monitoring System in Sudan during post-conflict reconstruction.

International air quality monitoring platforms like IQAIR and AccuWeather raise the alarm of poor air quality in Sudan, primarily relying on satellite data to estimate the air quality index (AQI). The absence of ground sensors in Sudan poses a hurdle to the functioning of these platforms in Sudan. The lack of ground-level sensors and insufficient air quality stations has created a gap in research in air quality in Sudan, as this limits the scope of research and affects data accuracy.

To address the gap in research, this paper presents findings from research that aims to design an air quality monitoring system, to ensure access to comprehensive data for evaluating the current air quality in Sudan. Data-driven insights can inform efforts to improve air quality in post-war Sudan. I argue that LoRa, which enables long range communications, indoor penetration at a low-power consumption is suitable for air monitoring in post-war Sudan.

This research is based on an experimental investigation in the author's personal lab in Rijkevorsel in Belgium. Findings demonstrate the effectiveness of LoRaWAN in terms of high signal strength and quality, long reach, and short delay. The Things Console records high CO_2 *that requires proper ventilation. Future work involves surveying the coverage and effectiveness of available stations in Sudan. Collaborating with future government and research institutions to build a holistic air monitoring system based on LoRaWAN that enables indoor and outdoor coverage.*

Keywords— *LoRa, Smart rural and urban areas, Air Quality Monitoring, Sudan, Africa*

INTRODUCTION

Clean air has a pivotal role in fostering sustainable rural areas and cities. Clean air significantly enhances human health by reducing respiratory and cardiovascular issues which in turn increase human well-being and minimizes their footprint on the earth (Sustainable cities Health at Heart of the Urban Development n.d.). Ensuring clean air in cities and among communities in Sudan and elsewhere in Africa and globally is important. It is and should be a collective endeavor as it resonates with several Sustainable Development Goals (SDGs), including goal 11, which aims to "make cities inclusive, safe, resilient and sustainable," including through fostering healthier urban environments; goal 3, which centers "good health and well-being", and with a multitude of other goals which center decent work, better education, and climate action.

The conflict that erupted in April 2023 in Sudan has created one of the world's worst humanitarian crises. According to the recent United Nations Office for the Coordination of Humanitarian Affairs (OCHA) reports (4 February 2024), more than 10.7 million individuals were displaced in and outside Sudan (OCHA, 2024). Children constitute half of the total affected population, setting a global record for child displacement. The conflict was concentrated in the capital, Khartoum and Darfur regions. In December 2023, Gezira emerged as a focal point of conflict, forcing 500.000 people to seek refuge in nearby regions such as Sinnar and Gadarif, and in neighboring countries.

There is a mounting health concern within IDP camps with Cholera cases surpassing 2,525 claiming 78 deaths in states like Kassala, Gadarif and Red Sea (OCHA, 2024). In Kassala, IDPs suffer from the shortage of food, healthcare, and shelters. Importantly, air pollution due to gases released by heavy armed conflict are projected to negatively impact the health and well-being of current and future generations.

While accurate data on pollution in wartime Sudan is lacking, the World Health Organization (WHO) reports alarming statistics regarding air pollution and its impact. The combined effects of ambient (outdoor) and indoor air pollution contribute to 6.7 million premature deaths annually (WHO) 2020). During wars and conflicts, this toll tends to escalate due to fires caused by guns and other weapons, tanks, and bombs. It is against this backdrop that the 11th International Conference on Appropriate Technology *"Building Sustainable Rural and Urban Cities for Economic Growth, Enhancing Health and Eradicating Poverty,"* is convened. Air pollution compounds the humanitarian and public health crises I described earlier in this paper.

Table 1 summarizes gases released during armed conflicts. The air becomes laden with smoke and particulate matter (a combination of liquid droplets and solid particles found in the air) are predominant. Pollutants include CO which is a highly toxic gas released during incomplete combustion of carbon containing fuels like gasoline and natural gas and wood. The impact of CO includes cardiovascular health issues and neurological impairments. Prolonged exposure to CO results in headache, dizziness, impaired coordination, memory loss, coma, and Parkinson disease. Other Pollutants include CO_2 sulfur dioxide (SO_2), nitrogen oxides (NO_x).

Table 1: *Summery of gases released during armed conflict.*

Category	Gases released
Smoke and Particulate Matter	Carbon dioxide (CO_2), carbon monoxide (CO), sulfur dioxide (SO_2), nitrogen oxides (NO_x), and various other particulates.
Explosive Residues	Traces of explosives such as TNT, RDX, and PETN.
Fuel and Propellant Gases	Various hydrocarbons, including butane, propane, and others from fuel and propellant combustion.
Oxidizing Gases	Oxygen (O_2), ozone (O_3), and other oxidizing
Chemical weapons	(e.g., Sarin, VX), blister agents (e.g., Mustard gas), and choking agents (e.g., Chlorine)

Low-income countries in Southeast Asia West Pacific countries and countries in Sub-Saharan Africa bear the brunt of air pollution, which contributes significantly to premature deaths. This is due to a lack of robust air monitoring systems, health care, and policies and guidelines to prevent air pollution. Implementing robust air quality monitoring systems is, thus, imperative in understanding the complexities of air pollution and finding effective interventions.

An air quality monitoring system is a network of devices and instruments designed to measure the concentration of air pollutants in the atmosphere (Barot, 2020, Thu, 2018). It has sensors that gather data on air pollutants such as CO, CO_2, Sulfur, Nitrogen, etc. An end-device connected to the sensor then sends the data gathered via a telecommunication network to the servers for further analysis and insight. The air monitoring system may include stationary air quality stations (al M. H., 2023) and ground-level sensors and satellite data (al, 2016) (al., 2022).

Air quality monitoring platforms such as (https://aqicn.org/map/sudan/), (htt1) show information about air quality in Sudan as shown in Figure 1. Due to the absence of ground sensors, they rely on satellite data or on a few stationary air quality stations owned by the government or by certain institutes. These platforms provide general information; however. Accurate readings require ground sensors. Further, these satellites and stationary air quality stations do not provide indoor readings as demonstrated in Figure 2.

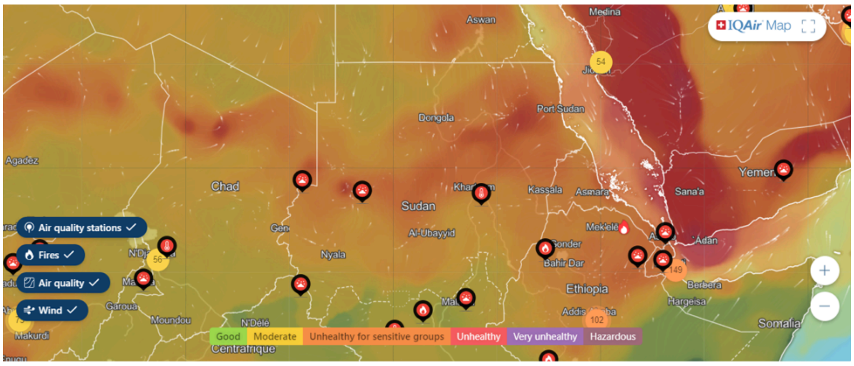

Figure 1: *Air Quality in Sudan viewed on https://www.iqair.com/sudan. date: 15.7.2024*

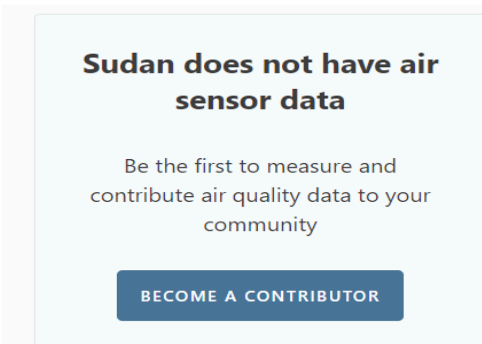

Figure 2: *Information on the absence of ground sensors obtained from https://www.iqair.com/sudan.Date: 15.07.2024*

The Significance of Using LoRa and LoRaWAN:

Using LoRa and LoRaWAN is important for monitoring air quality, especially in settings like Sudan, given that implementing the air quality monitoring system in such context of poses several challenges. The first challenge is that the vast area of the country necessitates deploying numerous sensors spread over several regions. A second challenge is that some of the regions lack coverage of the public electricity network. This necessitates frequent battery replacement, which takes extensive time, requires extra expenses and causes overall additional complications to air quality monitoring systems. Many of the existing solutions depend on WiFi, GSM and LTE, and thus suffer from the high-power consumption. Technologies like LTE, GSM and WiFi6 and above work in licensed spectrum which entail extra cost. Further, indoor monitoring demands technology that penetrates the walls, reaches upper floor, and assess the air in basements.

LoRa and LoRaWAN address the above-mentioned challenges by deploying and utilizing a low frequency spectrum which extends the coverage, and by deploying cutting-edge techniques that reduce power consumption.

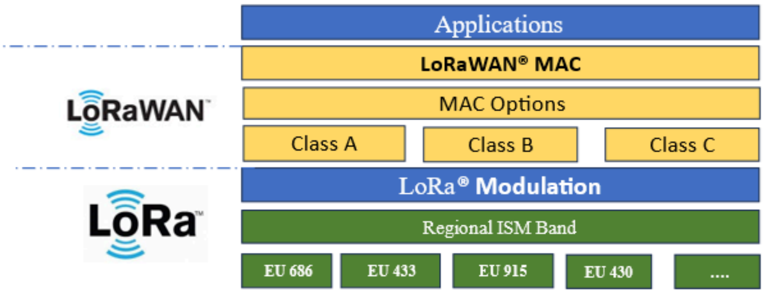

***Figure 3:** LoRa and LoRaWAN OSI model*

LoRa and LoRaWAN are shown in Figure 3. LoRa (Noreen, Umber and Bounceur, Ahcène and Clavier, Lauren 2017) is the physical layer modulation that enables the transmission of LoRa signals to extremely long range that surpasses WiFi and BLE. Invented by Nicolas Sornin and Olivier in 2009, LoRa utilizes the chirp spread spectrum inspired by the communication procedure among whales and dolphins. Distinct from Direct Sequence Spread Spectrum (DSSS), Chirp Spread Spectrum (CSS) encodes the data into linearly modulated chirps which requires less accurate clock synchronization, providing efficient communication between the LoRaWAN device and the gateway (Committee 2018).

The high Processing Gain for LoRa, enables robust reception for signals with extra low signal to noise ratio.

LoRa utilizes the license-exempt sub-GHz frequency spectrum. The choice of the frequency band depends on the region of the LoRaWAN device and specified in the regional parameters document (Workgroup 2022).

The Bandwidth in LoRa is limited by the standard to 125, 250, 500 kHz which is suitable for IoT applications. For higher data rates, LoRa enables 2.4GHz frequency band.

The choice of the data rate is empowered by the Adaptive Data Rates (ADR) mechanism which adjusts the data rate. The distance between the LoRaWAN device and the Gateway influences the choice of the Spreading Factor which in turns impacts the data rate. The spreading factor ranges from 7 to 12. The lower the spreading factor, the higher the bit rate and vice versa. In this paper, we configure the recommended spreading factor 9 on The Things Stack. However, the actual spreading factor may vary during the transmission session.

LoRaWAN is the MAC protocol developed by LoRa Alliance in 2015 (Committee 2020) LoRaWAN is positioned on top of LoRa. It defines the way end devices use the LoRa hardware. LoRaWAN has interesting features such as security, management, device activation, frame counting, acknowledgment, and the synchronization window.

Finally, The Things Stack supported by The Things Industries has extended capacity with powerful servers processing millions of messages weekly. LoRaWAN networks could be deployed publicly or privately. This encourages public companies and entrepreneurs to deploy LoRaWAN networks for Air Quality Monitoring, especially in the context of post conflict reconstruction and beyond.

Figure 4 demonstrates the topology of the air quality monitoring system. It consists of a gas sensor attached to an end LoRaWAN device. The messages transmitted from the LoRaWAN device will be received by the Gateway which forwards the messages to the Network Server. The message will be routed to the appropriate Application Server.

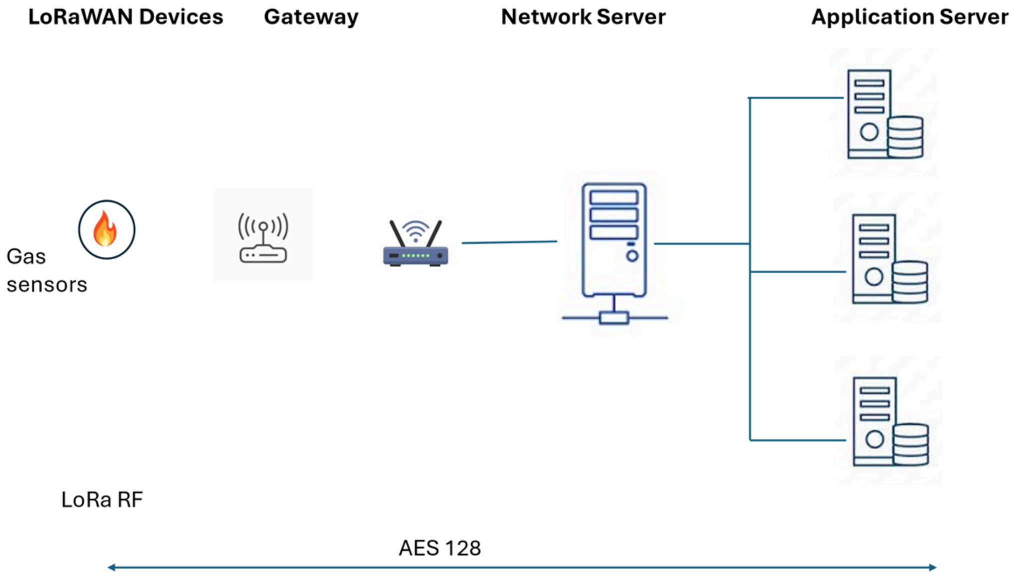

Figure 4: *The topology of the Air Quality Monitoring System*

LITERATURE REVIEW:

Air quality monitoring has gained notice among scholars due to its importance to human health and the environment. Most of the literature focuses on stationary air monitoring which depends on the Arduino boards such as Arduino Uno. Vasuki (2023) and Agullo (2022), for example, developed a prototype for measuring gases inside automobiles and for an air purification system. Another example of using Arduino Uno is (Khadim n.d.) that studied a wide range of gases and the correlation among them. M. Ibrahim (2015) designed a stationary air quality station based on a Raspberry pi single board computer. Some researchers utilized NASA's remote sensing satellite data to study air quality in Sudan (cf. Ibrahim, 2020). Others studied mobile air monitoring systems GSM (Tariq 2020). With the proliferation of LoRa, other groups studied the deployment of LoRa modules for air monitoring (Rochadiani 2022) and (Meli 2020). These groups developed a LoRa based indoor quality system at the University of Malta campus. Meraz (2020) developed a LoRa-based air monitoring system at the National Polytechnic Institute in Mexico City.

The research on which this paper is based involved setting up a ground-based LoRaWAN sensor-based air monitoring system. The system measures both indoor and outdoor readings. Further, the system enables users to view the readings everywhere in the world by utilizing The Things Stack provided by The Things Industries, surpassing the limitations of local display.

METHODOLOGY:

This research is based on an experimental investigation of the conformance of state-of-the-art LoRaWAN technology to an Air Monitoring System. The investigation, which took place in a personal lab situated in Rijkevorsel in Belgium, is motivated by the imperative need to measure both indoor and outdoor air quality – especially in war affected areas like Sudan.

The proposed air quality monitoring system is composed of strategically positioned gas sensors over a broad area in Sudan. These gas sensors are placed both indoors and outdoors, are connected to gateways strategically placed to ensure comprehensive coverage. These gateways are connected to the servers provided by the Things Industries via the backbone network.

Figure 5 shows a demonstration of the air monitoring system deployed in the author's personal laboratory.

The LoRaWAN system includes an Air Quality Monitoring sensor MQ135 which is a cost-effective and stable electromechanical gas sensor. It detects a Volatile Organic Compound (VOCs). It also detects gases. MQ135 is sensitive to CO2, Ammonia, and Benzine. The sensor is widely used in air quality monitoring and in the detection of harmful gases. We connected the MQ135 to the LoRaWAN device which is a MKRWAN 1310 based on the Microchip® SAMD21 with lower power processor, Murata CMWX1ZZABZ LoRa® module. We used the Things LoRaWAN TTNv3 Indoor Gateway which is embedded with an omnidirectional antenna and with frequency range 868 MHz. This is suitable for Europe and Africa as specified in the regional parameter document (Workgroup 2022). The indoor gateway has a low sensitivity -140 dBm in Europe which means that it can receive extremely weak signals. We connected the Gateway to the Things Stack via a stable and fast WiFi router from Proximus service provider.

We registered the TTNv3 indoor gateway via the universal identifier (EUI) to the network server The Things Industries (TTI). We further configured the LoRaWAN application key and universal identifier (App EUI) on the end-device and The Things Stack.

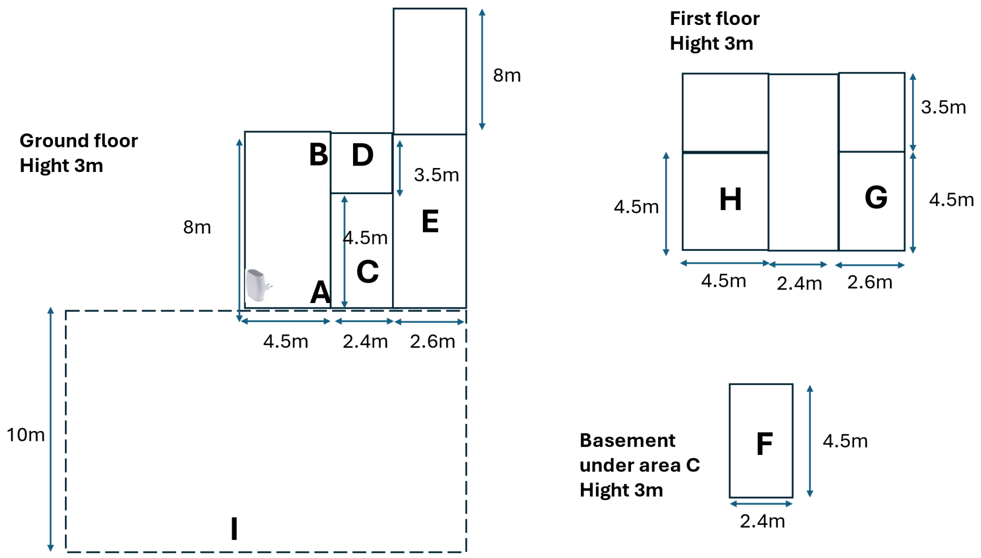

Figure 5: *Experimental Setup- the gateway is placed on the ground floor. The letters A-I denote the position of LoRaWAN end-device.*

The coverage of LoRaWAN:

Experimental Setup:

We used the setup in Figure 5. We measured the quality of the received signals. We measured the Received Signal Strength Indicator (RSSI) which measures the power of the signal received by the antenna of the gateway in dBm, and Signal to Noise Ratio (SNR) which measures the level of the received signal to the background noise time on air which is the elapse time on air for the LoRaWAN packet between the end-device and the gateway for each position shown in Figure 5. We extracted the readings by associated downloading the JSON file from The Things Stack.

RESULTS AND DISCUSSION:

Table 2: *The coverage of LoRaWAN*

Position	RSSI (dBm)	SNR(dB)	SF	Time on Air (s)
A	-33	7.5	12	1.155072
B	-65	6.5	12	1.155072
C	-40	8.5	12	1.155072
D	-55	8.75	12	1.155072
E	-52	7.5	12	1.155072
F	-66	7	12	0.164864
G	-37	8.75	12	1.155072
H	-33	9.5	7	0.046336
I	-53	9.75	7	0.051456

Table 2 shows the results obtained from the experimental setup. Results show that the RSSI ranges from -65 to -33 dBm which is much greater than the sensitivity of the TTN indoor gateway (-140dBm). This means that the signal could be received at a much greater distance. Further, readings are received at outdoor position I with high RSSI -53dBm and short time on air 0.051456. This shows that the indoor gateway also covers the outdoor area with less time on air. We attribute this to the absence of obstructions in the outdoor environment.

The SNR ranges between 6.5 and 9.75dB. Figure 6 shows that RSSI with respect to the positions of the end device. We notice two critical positions where we obtained low RSSI compared to the other positions. The first is critical position B which is in the opposite direction of the hall where we placed the gateway. The hall is full of furniture and the gateway is placed at a lower level for worst-case scenarios. The second position is F which is the basement.

The average time on air is 0.799232 seconds, which makes LoRaWAN suitable for real time applications. When we place the end node in position F (the basement) the signal reaches the gateway with RSSI -66dBm and time on air 164.864 ms. This demonstrates the ability of LoRaWAN signals to penetrate multiple concrete walls in a short time on air and high RSSI.

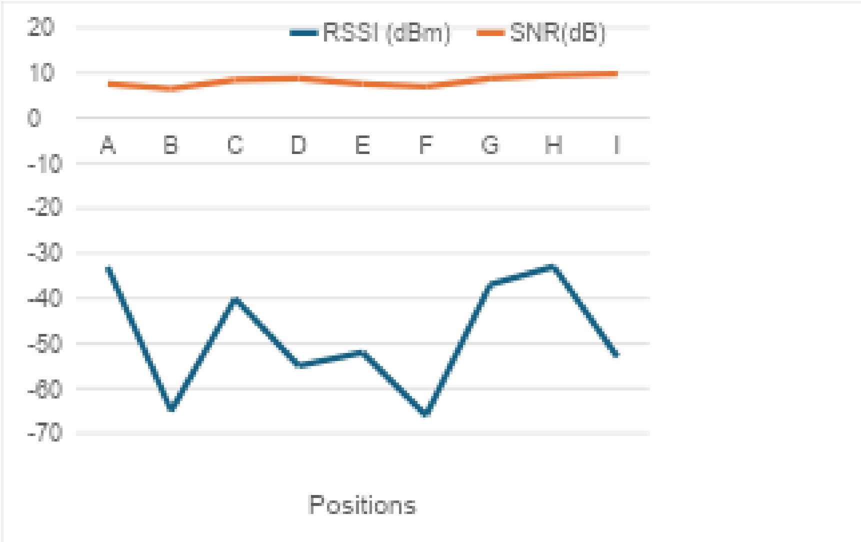

Figure 6: *The LoRaWAN coverage measurements and results*

We further show the position of the end device as viewed from The Things Console as shown in Figure 7.

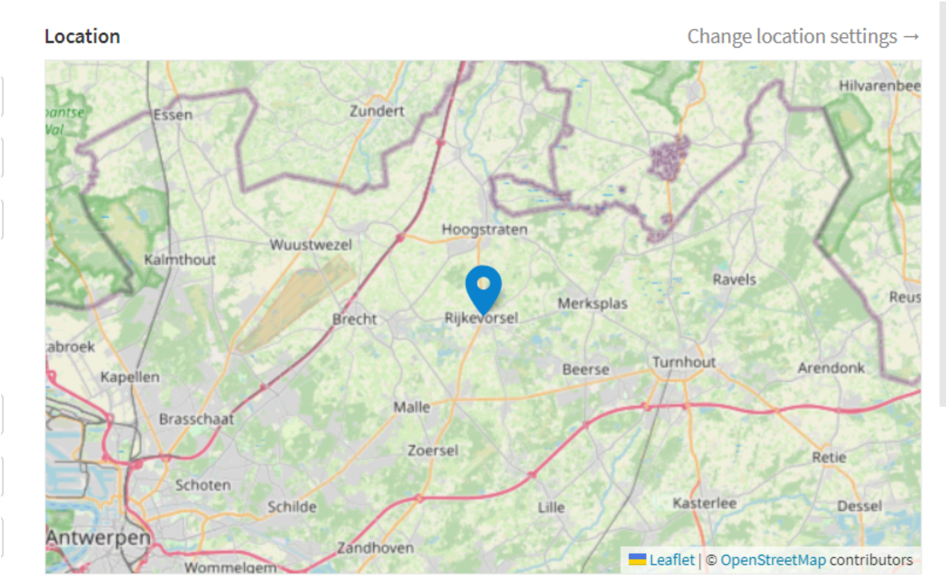

Figure 7: *The position of the end-device on the world map- as shown on the things console.*

Next, we use the above system to measure the air quality.

Air Quality Measurement:

Experimental Setup:

Before measuring the air quality, we need to calibrate the air quality sensor to ensure accurate measurements.

Sensor Calibration:

MQ135 sensor is highly sensitive to environmental conditions such as temperature and humidity (Kalra 2016). MQ135 has a positive correlation with the temperature, which means that it provides readings higher than the original at high temperature levels. Further, the MQ 135 correlates negatively with humidity, which means that at high humidity the readings are lower than the original ones. For this reason, we calibrated the readings with a temperature level set to around 20 °C as shown in Figure 8 by adjusting the heating system of the building. We, then fixed the humidity to around 40% as shown in Figure 9 by utilizing an autronic air dehumidifier. We heated the inbuilt heater of the MQ135 sensor for 24 hours and we then started the actual measurement sessions.

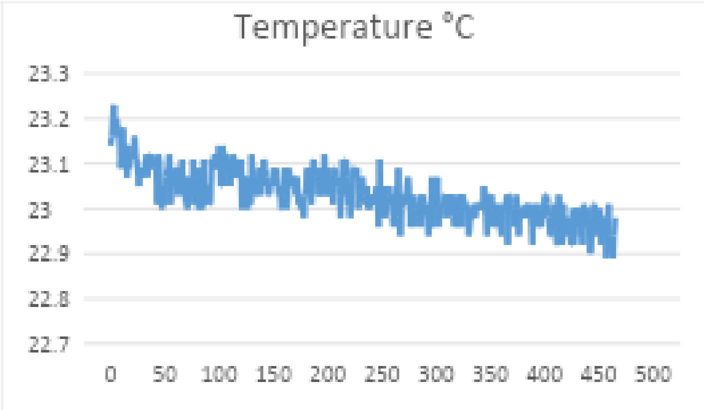

Figure 8: *Temperature levels measured in random moments.*

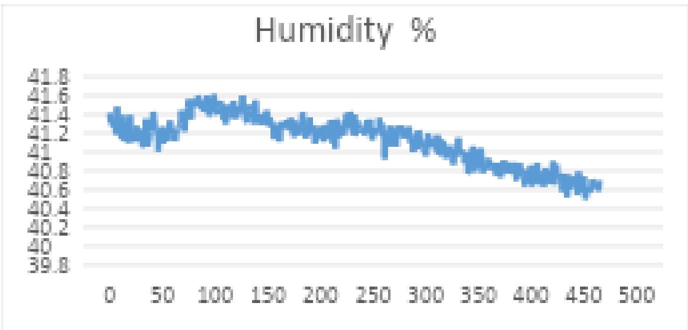

Figure 9: *Humidity levels measured in random moments.*

Results and Discussion:

Figure 10 demonstrates the CO_2 concentration in parts per million ppm as recorded on The Things Console. The readings range from 7378.78 to16424.53 which is considered high concentration compared to the values shown in Table 3.

Table 3*: The impact of the levels of CO2 on the health.*

CO2 concentration in ppm	Air Pollution Status
>450	**Good**
451-600	**Acceptable**
601-1000	**Moderate**
1001-2500	**Poor**
2501-5000	**adverse health effects**
5001 - 10000	**maximum allowed concentration within a 8 hour working period**

10001 - 40000	**slightly intoxicating, breathing and pulse rate increase, nausea**
40001-50000	**above plus headaches and sight impairment**
50001-100000	**unconscious, further exposure causes death**

Figure 10: *The CO2 concentration as viewed on The Things Console*

We then implemented the ventilation measures by opening the doors from two opposite sides in the building followed by another CO2 measurements. As shown in Figure 11, The CO2 levels dropped dramatically after ventilation.

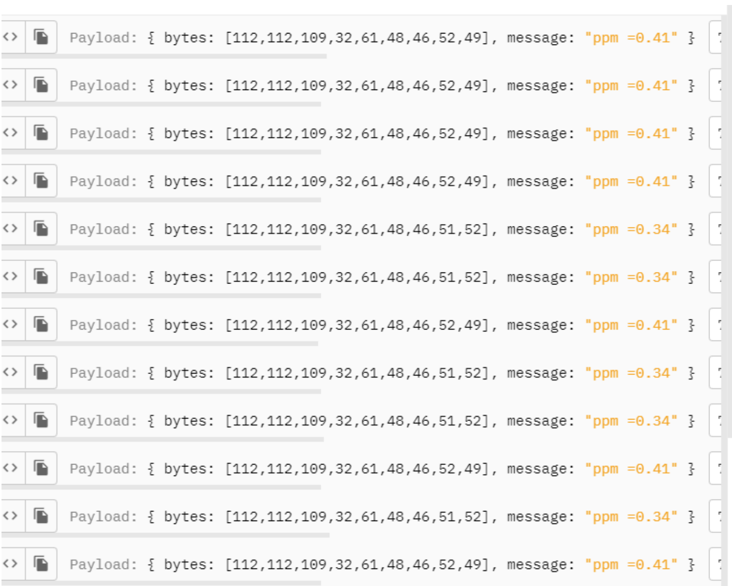

Figure 11: *The CO2 levels as shown on The Things Stack after ventilation!*

CONCLUSION:

The conflict in Sudan has affected the population in drastic ways. The impact of this conflict on air pollution adds to the atrocities that people experience. Its impact will affect the health and wellbeing of current and future generations. The war will eventually come to an end.

During the phase of post-conflict reconstruction, air monitoring systems become crucial, to mitigate risks to health and well-being arising from war-related air pollution. We propose an air monitoring system that leverages LoRaWAN, providing extended coverage and ultra-low power consumption.

The result of our experiment demonstrates the great potential of LoRaWAN in terms of RSSI, SNR and time on air. Considering several positions, The Things Console recorded RSSI values that range from -65 to -33 dBm, surpassing the TTN indoor gateway sensitivity of -140 dBm which indicates long reach of LoRaWAN packets. The SNR ranges between 6.5 and 9.75 dB. This highlights a good signal quality and fast data transmission. Moreover, the average time on air is less than one second. We tested worst case scenarios through positioning the equipment in the basement. Results showcased the ability of LoRa signals to penetrate walls.

Upon deploying our Air Quality Monitoring System, we measured the CO_2 as a key indicator of the harmful gases released during conflict. Recorded CO_2 concentrations displayed on The Things Console ranged from 7378.78 to 16424.53 ppm. This is a notably high concentration. Implementing a straightforward ventilation measure such as opening two doors from opposite sides within the building resulted in significant reduction in CO_2 levels. This finding highlights proper ventilation as a simple, yet impactful strategy for improving air quality.

Future research includes gathering data from Sudan to plan for an efficient air quality monitoring system that conducts a comprehensive assessment in collaboration with key stakeholders such as a future government, industry, and research institutions to identify the impact of the conflict on the air quality in Sudan. This provides a holistic understanding of the long-term effects of poor air quality and proposes appropriate interventions which promote sustainability in post-conflict Sudan, and in similar conflict-affected regions.

BIBLIOGRAPHY

World Health Organization (WHO). 2020. *Household air pollution.* https://www.who.int/news-room/fact-sheets/detail/household-air-pollution-and-health#:~:text=The%20combined%20effects%20of%20ambient,6.7%20million%20premature%20deaths%20annually.

n.d. https://www.iqair.com/sudan.

A.YEGIN (Actility), O.SELLER (Semtech). 2020. *LoRaWAN® L2 1.0.4 Specification.* Copyright © LoRa Alliance, Inc. (2020). All Rights Reserved. https://lora-alliance.org/resource_hub/lorawan-104-specification-package/.

Abderahman Rejeb, Karim Rejeb, Steve Simske, Horst Treiblmaier, Suhaiza Zailani,. 2022. "The big picture on the internet of things and the smart city: a review of what we know and what we need to know,." *sciencedirect.* doi:https://doi.org/10.1016/j.iot.2022.100565.

Agullo, Kyle Vonmar T. and Sasis, John Patric A and Sese, Julius T. 2022. "Air Purification System for Air Quality Monitoring In-Vehicle." doi:10.1109/IES55876.2022.9888466.

n.d. *Air Pollution in Sudan: Real-time Air Quality Index Visual Map.* https://aqicn.org/map/sudan/.

M. Haris et al. 2023. "Design and Development of IoT Based Weather and Air Quality Monitoring Station." International Conference on Robotics and Automation in Industry (ICRAI). doi:10.1109/ICRAI57502.2023.10089568.

S. Zhang et al. 2016. "A dual-phase air quality monitoring system based on satellite data: Framework and preliminary evaluation." 2016 IEEE International Geoscience and Remote Sensing Symposium (IGARSS). Beijing, China. 4074-4076. doi:10.1109/IGARSS.2016.7730060.

J. H. Crawford et al. 2022. "The Airborne and Satellite Investigation of Asian Air Quality (Asia-Aq): An Opportunity for International Collaboration." IGARSS 2022 - 2022 IEEE International Geoscience and Remote Sensing Symposium. Kuala Lumpur, Malaysia. doi:6506-6509, doi: 10.1109/IGARSS46834.2022.9883819.

T. H. Rochadiani et al., 2022. "Design of Air Quality Monitoring Using LoRaWAN In Human Settlement." Boracay Island, Philippines: Communication and Control, Environment, and Management (HNICEM). doi:10.1109/HNICEM57413.2022.10109605.

Barot, Virendra and Kapadia, Viral. 2020. "Air Quality Monitoring Systems using IoT: A Review." *International Conference on Computational Performance Evaluation (ComPE).* Shillong, India. 226-231. doi: 10.1109/ComPE49325.2020.9200053.

LoRa Alliance Technical Committee. 2020. *TS001-1.0.4 LoRaWAN® L2 1.0.4 Specification.* https://resources.lora-alliance.org/technical-specifications/ts001-1-0-4-lorawan-l2-1-0-4-specification.

LoRa Alliance Technical Committee. 2017. *LoRaWAN™ 1.0.2 Regional Parameters.* LoRa Alliance. https://lora-alliance.org/wp-content/uploads/2020/11/lorawan_regional_parameters_v1.0.2_final_1944_1.pdf.

Committee, LoRa Alliance Technical. 2018. *LoRaWAN™ 1.0.3 Specification.*

n.d. *https://aqicn.org/map/sudan/.*

Ibrahim, Muntasir & Curci, Gabriele & Habbani, Farouk. 2020. "Air Quality Assessment over Sudan using NASA Remote Sensing Satellites Data and MERRA-2 Model." *Journal of Environmental Science and Pollution Research.*

Kalra, Vandana and Baweja, Chaitanya and Simmarpreet, Dr and Chopra, Supriya. 2016. "Influence of Temperature and Humidity on the Output Resistance Ratio of the MQ-135 Sensor." *International Journal of Computer Science and Software Engineering.*

Khadim, Hussein J. and Obaed, Faik K. and Abd Ali, Ziad T. n.d. "Khadim, Hussein J. and Obaed, Faik K. and Abd Ali, Ziad T." *2021 International Conference on Intelligent Technology, System and Service for Internet of Everything (ITSS-IoE).* doi:10.1109/ITSS-IoE53029.2021.9615333.

Ibrahim, M., A. Elgamri, S. Babiker and A. Mohamed. 2015. "Internet of things based smart environmental monitoring using the Raspberry-Pi computer." *Fifth International Conference on Digital Information Processing and Communications (ICDIPC).* Sierre, Switzerland, 159-164. doi:doi: 10.1109/ICDIPC.2015.7323023.

Thu, W. Htun, Y. L. Aung, P. E. E. Shwe and N. M. Tun. 2018. "Smart Air Quality Monitoring System with LoRaWAN." *IEEE International Conference on Internet of Things and Intelligence System (IOTAIS).* Bali, Indonesia. 10-15. doi:10.1109/IOTAIS.2018.8600904.

Meli, Matthew and Gatt, Edward and Casha, Owen and Grech, Ivan and Micallef, Joseph. 2020. In *2020 International Conference on Computational Science and Computational Intelligence (CSCI)*. doi:10.1109/CSCI51800.2020.00070.

Meraz, Miguel Sánchez and Gutiérrez, Miriam Guadalupe Juárez and Juárez, Iván Moreno. 2020. "2020 IEEE International Smart Cities Conference (ISC2)." *020 IEEE International Smart Cities Conference (ISC2).* doi:10.1109/ISC251055.2020.9239009.

OCHA. 2024. *Sudan Humanitarian Update (4 February 2024).* February 4. https://reports.unocha.org/en/country/sudan/.

OCHA. n.d. *Sudan Humanitarian Update.* https://reports.unocha.org/en/country/sudan/.

OCHA. n.d. *Sudan: Cholera outbreak Flash Update No. 3, As of 14 November 2023 [EN/AR].* https://www.unocha.org/publications/report/sudan/sudan-cholera-outbreak-flash-update-no-3-14-november-2023-enar.

Rochadiani, Theresia Herlina and Olivia, Deasy and Santoso, Handri and Haryono and Tanuwijaya, Piter and Aprilia, Novia Pramesti and Laurenso, Justin and Rico. 2022. "Design of Air Quality Monitoring Using LoRaWAN In Human Settlement." In *2022 IEEE 14th International Conference on Humanoid, Nanotechnology, Information Technology, Communication and Control, Environment, and Management (HNICEM)*. doi:10.1109/HNICEM57413.2022.10109605}.

Semtech. 2019. *LoRa and LoRaWAN: A Technical Overview.* technical paper, February 11, 2020. https://lora-developers.semtech.com/uploads/documents/files/LoRa_and_LoRaWAN-A_Tech_Overview-Downloadable.pdf.

n.d. *Sustainable cities Health at Heart of the Urban Development.* https://www.who.int/docs/default-source/documents/publications/sustainable-cities.pdf?sfvrsn=2accfb68_1.

Tariq, Hasan and Abdaoui, Abderrazak and Touati, Farid and E Al-Hitmi, Mohammed Abdulla and Crescini, Damiano and Manouer, Adel Ben. 2020. "A Real-time Gradient Aware Multi-Variable Handheld Urban Scale Air Quality Mapping IoT System." doi:10.1109/DTS48731.2020.9196131.

Twahirwa, Evariste and Mtonga, Kambombo and Ngabo, Desire and Kumaran, Santhi. n.d. *2021 IEEE World AI IoT Congress (AIIoT).* IEEE. doi:10.1109/AIIoT52608.2021.9454232.

UNICEF. n.d. *UNICEF supports evacuation of 253 vulnerable babies and children from Madani battle lines.* https://www.unicef.org/sudan/press-releases/unicef-supports-evacuation-253-vulnerable-babies-and-children-madani-battle-lines#:~:text=These%20two%20centres%20housed%20many,50%20caretakers%20and%20medical%20personnel.

Vasuki, A. and Christaline, J.Anita and Akila, V. and Sathiya, R. 2023. "A Low-Cost Air Quality Tracking System Design." doi:10.1109/ICIDCA56705.2023.10099569.

Workgroup, LoRa Alliance Technical Committee Regional Parameters. 2022. "LoRaWAN® Regional Parameters RP002-1.0.4." https://resources.lora-alliance.org/home/rp002-1-0-4-regional-parameters.

Yang, Y., Y. Jiang and C. Du. 2022. "Design of Temperature Monitoring System of Fresh Product Self-collection Cabinet Based on LoRa," Shenzhen, China: 4th International

Conference on Communications, Information System and Computer Engineering. 196-199. doi:10.1109/CISCE55963.2022.9851010.

MANUFACTURING SECTION
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RENEWED BY DESIGN: THE CIRCULAR DESIGN OF A SUSTAINABLE EGGSHELL-BASED PILL BOTTLE

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ABSTRACT

Product design has massively contributed to the global problem of waste, with many products designed for overconsumption, single-use, or planned obsolescence. The aim of this paper is to illustrate how engagement with material experimentation can contribute to sustainability in product design, resulting in greater access to manufacturing processes and technologies, and stimulating economic growth and social upliftment. Product waste has significant environmental, social, and economic impacts; however, waste also has the potential to be viewed as a valuable resource. Engaging with waste value chains provides the opportunity to contribute to industry innovation, sustainable cities, economic growth, and reduced inequalities. With the need to reach net zero, sustainability has been a core consideration in manufacturing and design practice. This paper provides insights into vital sustainable design practices and illustrates the role that waste value chains have in advancing a circular economy. The study brings key Sustainable Development Goals (SDGs) into focus and outlines how circular design can lead to sustainability and social upliftment. The paper details the practice-led process of low-tech and context-aware biomaterial experimentation for new product development, illustrated through a design project undertaken at a South African university, where a pill bottle was effectively designed and manufactured from waste material, specifically spent eggshells. The research project was undertaken in two parts and guided by the theory of Circular Design. Part 1 encompassed the development of the biomaterial through the iterative undertaking of action research. In Part 2, the developed biomaterial was applied to the design of a suitable product using the Double Diamond design process and outlines the development of low-tech tooling utilised for the product production, further engaging with appropriate technology. Although these parts are described separately, they were interdependent and informed each other. The project illustrates how biomaterial innovation could result in effective substitutes for single-use plastic products.

Keywords: Biomaterials, Waste Value Chain, Sustainability, Circular Design, Product Design

Introduction

In the words of Kate Raworth, "today's economy is divisive and degenerative by default. Tomorrow's economy must be distributive and regenerative by design," (2017). This philosophy advocates for an economic paradigm that benefits everyone while positively contributing to the well-being of both humanity and the planet. This underscores the urgent need for a shift away from the current disposable culture towards an eco-efficient, closed-loop production approach, with a focus on waste and recovery processes beyond the typical product life cycle (Wasser, 2024). Failure to make this transition poses challenges in preserving our planet's finite reserves for future generations, potentially leading to detrimental impacts on human health, society, and the environment (Wasser, 2024).

In alignment with this imperative, the paper delves into a practice-led process of low-tech and context-aware bio-material experimentation for new product development. It aims to showcase how bio-material innovation can effectively replace single-use plastic products. In this paper, the project at the forefront of eco-conscious design centres on developing an environmentally friendly pill bottle, placing emphasis emphasising the value stream of spent eggshells. The initiative also aims to address the detrimental effects of waste generation

within the healthcare industry. The paper also seeks to illustrate how engagement with material experimentation contributes to sustainability in the field of product design.
This study addresses the critical issue of product waste and its environmental, social, and economic ramifications by presenting a novel approach to sustainable product design through material experimentation. The research highlights the untapped potential of waste, particularly spent eggshells, as a valuable resource in the creation of biomaterials that can replace single-use plastics. By employing a low-tech and context-aware approach, this study not only advances the field of sustainable design but also demonstrates how such innovations can be accessible and beneficial to communities with limited technological resources. The integration of Circular Design theory with practical, low-tech methodologies offers a unique contribution to sustainable product development, emphasising economic growth and social upliftment. This research aligns with key Sustainable Development Goals, promoting industry innovation, sustainable urban development, and reduced inequalities, thus offering a comprehensive model for future sustainable design practices.

Related Studies
Humanity's relentless pursuit of immediate gratification and over-consumption has intensified into the 21st century, fostering a mindset focused on swift acquisition and disposal of goods (de Wit, 2018, p. 6). This trend has given rise to the linear economy, commonly known as the "take, make, and waste" model, with far-reaching negative consequences (de Wit et al. 2018:6). While the linear economy has generated considerable wealth, its sustainability is in doubt, and it is not a legacy we wish to pass on to future generations. In contrast, the idea of a circular economy advocates for constructing an economic framework rooted in meaningful values, promoting interconnectedness, and necessitating radical collaboration to unlock the full potential of humanity (de Wit, 2018, p. 6).

The 4th Industrial Revolution has brought with it the rapid development of new technologies that blur the line between digital, biological and physical words such as artificial intelligence and smart home devices (Schwab, 2017). While these advancements have shown promising potential for aiding in the sustainable development of how products are designed and produced, they also pose a threat to increasing socio-economic disparities in developing countries where access to and adoption of these new technologies is limited (Patnaik & Tarei, 2022, p. 1). As South Africa is a country that experiences large economic disparities among its population (Baker, 2019; Hurlbut, 2018), it is important to consider how sustainable development is approached.

In order to encourage global sustainable development, the United Nations (UN) outlined 17 Sustainable Development Goals (SDGs) which holistically address sustainable growth in social, economic and environmental areas (United Nations, 2024). Included in these goals is the focus on eliminating poverty and hunger, diminishing disparities among developing nations, tackling climate change, ensuring access to education, and fostering inclusivity (United Nations, 2024; Patnaik & Tarei, 2022, p. 1). Goal 9 specifically aims to "build resilient infrastructure, promote inclusive and sustainable industrialisation and foster innovation," (United Nations, 2024) which supports local innovation and technology development in order to grow technical, economic and social capacities. Through the evaluation of this SDG, appropriate technology emerges as a framework that encourages this advancement without a developing industry being reliant on having access to emerging digital technologies.

The term appropriate technology was devised by Schumacher in his book Small is Beautiful (1973). His description included the development of low-cost technologies, manufactured using locally available materials and tools and produced by local labour and skills resulting in job creation (Schumacher, 1973). This would enable the innovation to be controlled and maintained by the community it was intended for without them needing further education or training (Patnaik & Tarei, 2022; Clot, 2014). Furthermore, the resulting technology should be affordable for consumers within the given context, while considering the cultural and contextual norms (Clot, 2014). While the definition of appropriate technology has evolved and varied, it generally refers to establishing self-sustaining systems where users effectively address their local requirements (Patnaik & Tarei, 2022, p. 3). As a result, appropriate technology intends to support social innovation by developing technology suitable to the economic, political, social, and cultural conditions of a specific region (Patnaik & Tarei, 2022, p. 2). Patnaik and Tarei claim that the appropriateness of a technology can be measured by its economic, ethical, social, and environmental impact (Patnaik & Tarei, 2022, p. 3).

When evaluating how the field of product design can make use of appropriate technology, Circular Design offers a framework for sustainable product development. Design has been viewed as a useful tool for moving the lifespan of products away from this traditional linear model known as "take-make-dispose" and towards being more restorative and regenerative (Moreno, et al., 2016, p. 1). Victor Papaneck describes the field of Industrial Design as one of the most harmful professions and puts the responsibility on designers to consider the impact their products have (Papanek, 1985). As design has evolved into a more human-centred field, awareness of its ability to improve our environment has aided in making it a more sustainable profession (Moreno, et al., 2016, p. 1; Roy, 2006). Through knowledge of technology and human needs, the field of design can function as a holistic approach to sustainable development and in opposition to the linear design approach, Circular Design has emerged as a guiding framework for achieving this (Moreno, et al., 2016, p. 1). Circular Design is defined as designing for a closed-loop system, where products generate zero waste and contribute to the circular economy (Moreno, et al., 2016). When engaging with Circular Design, designers must look at an entire system in order to be effective (Moreno, et al., 2016). It is evident that considering appropriate technology as a framework for engaging with Circular Design would be an effective way of sustainably contributing to the circular economy.

Waste value chains serve as a practical avenue for engaging with the principles of the circular economy. Examining the various stages of waste management, from generation and collection to transportation, treatment, and disposal, reveals potential areas where waste can be transformed into valuable resources (Singh, et al., 2014, p. 800). South Africa has established waste treatment systems that include recycling, composting, landfilling, and waste-to-energy technologies (Godfrey & Oelofse, 2017). While some of these systems contribute to renewed value, many remain linear and ultimately generate costs in order to be processed to landfills (Lange & Nahman, 2015, p. 167). Johannesburg, does however, recycle a significant amount of its plastic waste through small-scale plastic waste reclaiming (Godfrey & Oelofse, 2017), which indicates that the value of small-scale waste management systems are recognised. While waste such as plastic, cardboard and glass are already being revalued (Godfrey & Oelofse, 2017), one untapped area in South Africa with significant potential lies in addressing food waste (Lange & Nahman, 2015, p. 167). Lange and Nahman explain that food waste is increasingly recognized for its economic, social, and environmental costs (2015, p. 167). The field of industrial design has acknowledged this potential and sustainable product design has been explored through the development of biomaterials

(Materiom, 2023). The use of bio-based composites emerges as a crucial factor in embracing the circular economy (Shanmugam, et al., 2021), emphasizing the importance of avoiding new material extraction for creating products. Biomaterials offer a promising avenue for sustainable material exploration that considers the planet's health, recycling costs, and overall environmental impact (Shanmugam, et al., 2021). There is a growing interest in the value of biomaterials in South Africa, often produced on a small scale, which aligns with the principles of appropriate technology within the South African context.

South Africa demonstrates significant potential in the realm of biomaterial development, offering an opportunity to extract value from food waste. Embracing circular design principles is central in this context, as it facilitates the creation of appropriate products and technologies that contribute to the sustainable development of circular communities. By integrating biomaterials derived from food waste into the field of product design, South Africa can not only address environmental concerns related to waste but also promote economic and social sustainability. This dual focus on biomaterials and circular design positions South Africa to play a key role in advancing innovative and sustainable solutions for both waste management and community development. The design project discussed in this paper illustrates how the effective implementation of relevant design processes can lead to appropriate product design outcomes.

Methodology

The research project was undertaken in two parts and guided by the theory of Circular Design. Part 1 encompassed the development of a low-tech and context-aware biomaterial which was undertaken through Kemmis and McTaggart's methodology of action research (1988, p. 5). In Part 2, the developed biomaterial was applied to the design of a suitable product using the Double Diamond design process (British Design Council, 2024). While these parts are described as separate, it is important to note that they were not undertaken independently, but rather that they overlapped and informed each other.

Action research is a qualitative research methodology that engages participants in a cyclic process of *planning, acting, observing*, and *reflecting* to address specific issues or challenges (Zuber-Skerritt, 2001, p. 15). The iterative nature of this approach allows for ongoing refinement and adaptation based on real-world experiences. In the context of the development of biomaterials in this study, three action research cycles were undertaken. Initially, in Cycle 1, extensive experimentation with various waste materials identified from research into South Africa's waste streams and existing waste management systems resulted in the creation of 34 new biomaterials. Building on this, Cycle 2 focused on analysing the most successful biomaterial recipes, leading to the identification of spent eggshells as the optimal direction. The material was then further refined through the exploration of four additional material variations. Guided by the product direction identified in Part 2, Cycle 3 involved adapting the final biomaterial to meet the specific material qualities required for its application in the intended product.

In order to apply the developed biomaterial to the design of a suitable product, the study made use of the Double Diamond methodology. This design process was developed by the British Design Council and describes the four steps undertaken during design and innovation, namely *discover, define, develop* and *deliver* (British Design Council, 2024). The *discover* phase used a divergent process of broad inquiry in order to identify a relevant design problem (British Design Council, 2024). During this phase, research was conducted to understand the environmental impact, energy consumption, and waste generation associated with various operations of the healthcare industry. Through this, a clear problem was *defined* with a specific focus on materials utilised in the packaging of medicine, specifically those of pill containers storing everyday supplements in households. Thereafter, a design solution could be *developed* through extensive ideation. This phase included designing a pill container for ergonomic use and using design ideation methods such as ideation sketching, mockups, and the development of low-tech tooling in the form of silicone and plaster moulds for the pill container. Through the narrowing of feasible product concepts, the developed biomaterial was implemented in the making of the designed product in the *deliver* phase, resulting in a sustainable and biodegradable pill bottle.

By integrating action research for biomaterial development with the Double Diamond process for product design, the methodology leverages the strengths of both approaches. The iterative, experimental nature of action research complements the structured, user-centric framework of the Double Diamond process, resulting in a comprehensive and effective methodology for developing and applying sustainable biomaterials in practical, impactful ways.

Results

The intention of this project was to develop bio-based materials derived from waste, specifically food waste, identified as an untapped value stream for product production. Food waste occurs throughout the entire food supply chain (Tatjana von Bormann, 2017, p. 8). In South Africa, an alarming 10 million tonnes of food are wasted annually, constituting one-third of the total annual production of 31 million tonnes (Tatjana von Bormann, 2017, p. 8). This poses a clear and multifaceted problem. Subsequently, this project follows a practice-led process of low-tech and context-aware bio-material experimentation implemented into the production of a product. This section illustrates how bio-material innovation, specifically crafted from spent eggshells, could result in effective substitutes for single-use plastic products, with a focus on the production of medicine bottles for the purposes of this project.

Part 1

During cycle 1 the planning phase involved gathering precedent data regarding understanding the basics of biomaterials and their applications and gaining knowledge on different types of household food waste and their properties (Figure 1). In this phase, the gathering of precedent data on previously developed biomaterials was a key aspect. Materiom played a valuable role in this regard, serving as a platform that provides an online database containing recipes, products, and workshops (Materiom, 2023). The information gathered proved valuable in understanding various material properties and proper disposal of biomaterials after their lifecycle, aiming for a minimal neutral impact on the environment and the potential for beneficial outcomes (Materiom, 2023). The research included an investigation into suitable locations for waste material collection. It was determined that small amounts of waste could be collected at the individual and community levels. Consequently, the researcher chose to collect organic waste from households and restaurants in Linden, a suburb of Johannesburg.

Figure1: *The material collection process, performed by author*

During the acting phase, extensive experimentation with diverse waste materials sourced from research into South Africa's waste streams, particularly identifying food waste as a potential area, led to the development of 34 new biomaterials see Figure 2. In the creation of these materials, low-tech methods were employed, utilizing basic kitchen appliances and store-bought binding ingredients such as agar-agar, gelatine, and glycerine.

Figure 2: *34 biomaterial tests, conducted by author*

During the observation phase, it was determined that the biomaterial crafted from fine eggshell powder exhibited the highest level of success. Eggshells, sourced from egg processing plants, egg stations, chicken hatcheries, industries, and households in substantial quantities, have versatile applications across various fields (M Waheed, 2020). Despite their potential, this calcium-rich resource is often discarded into landfills, contributing to environmental problems (M Waheed, 2020). Addressing the proper management of eggshells is essential to mitigate these issues. Consequently, eggshells emerge as a promising waste stream within the wider category of food waste, primarily due to their abundant availability.

Upon reflection of this cycle, it was discovered that the eggshell material possesses exceptionally hard and rigid characteristics. When the quantity of the material is carefully controlled during casting, it can achieve a lightweight composition while retaining strength and durability, aligning with the properties of plastic. Recognizing food waste as an untapped value stream, eggshells, in particular, stood out. In the commercial farming of eggs, a significant number are lost and broken, underscoring the potential of spent eggshells in biomaterial innovation.

After recognizing the potential of eggshells, a second cycle of action research was initiated to refine the eggshell recipes conducted in cycle 1. This involved conducting further material testing and experimentation, encompassing four tests to explore additional material variations.

During the acting phase, further testing was undertaken. The initial test focused on assessing the durability of the material, involving a comparison between fine eggshell powder and larger broken eggshell pieces (Figure 3). The second test aimed to determine the most effective adhesive material for the eggshell biomaterial, utilising potato starch, cornstarch, and gelatine, which were then dried. Following this, a flexibility test was conducted with the objective of ensuring that the material could bend without breaking (Figure 4). Lastly, research was conducted on incorporating a SCOBY (symbiotic culture of bacteria and yeast) into the eggshell recipe. A SCOBY, known for its durability and antimicrobial properties, also offers resistance to oxygen, moisture, and other gases, making it a flexible and multifunctional material (Nyiew, 2022).

***Figure 3**: Comparison test, performed by author*

***Figure 4:** Flexibility test, performed by author*

Examining the results of this hands-on experimental involvement, the first test revealed that the fine eggshell powder utilized in creating the eggshell-based biomaterial performed exceptionally well in the durability test. Consequently, gelatine emerged as the optimal binding material. Removing glycerine from the material mixture, and allowing it to cure, resulted in a more flexible material that could bend without breaking, resembling a natural rubber. Lastly, the successful drying of the SCOBY material, retaining its flexibility and durability akin to leather, indicated that a SCOBY would be a viable option for developing a product.

The tests conducted in this cycle unveiled a diverse range of material characteristics achievable by using eggshells in the form of a powder as the primary ingredient. It was concluded that this material could potentially be adapted and manipulated to meet the requirements for producing a product, based on this newfound knowledge.

In alignment with the product direction outlined in Part 2, Cycle 3 focused on customizing the final biomaterial to align with the specific material qualities necessary for its intended application in the product. During the planning phase of Cycle 3, research was conducted to comprehend the requirements for materials used in pharmaceutical packaging production, pill bottles. These criteria included the necessity for the packaging to exhibit resistance to both moisture and increased temperature. Research was also conducted to explore the incorporation of biodegradable antimicrobial agents aimed at preventing the growth of bacteria and other microorganisms that could lead to contamination.

After analysing all the tests and comparing recipes in the earlier cycles of Part 1, it was determined that coating the eggshell-concrete recipe (Test 21, Figure 5) with the bioplastic mixture in Test 9 (Figure 6) could enhance its barrier properties against moisture. Additionally,

***Figure 5**: Eggshell recipe test*

***Figure 6**: Bioplastic test*

***Figure 7**: SCOBY test*

the SCOBY test (Test 25, Figure 7), which resulted in a flexible and durable, leather-like material, was found not only to possess antimicrobial properties but also to demonstrate resistance to moisture and other gases, making it a suitable option for protecting medicines and products.

Concluding Cycle 3 involved adapting the final biomaterial to align with the specific material qualities required for its application in the intended product. This collaborative effort with Part 2 utilised low-tech tooling to experiment and cast the biomaterial (Figure 8).

***Figure 8:** Low-tec tooling, utilized for biomaterial production*

Part 2

Within the scope of this project, the Circular Design framework facilitated the identification of a critical problem, specifically, the waste contribution stemming from the pharmaceutical and healthcare sectors. Subsequently, it guided the creation of a product solution that considered the entire lifecycle of the pill bottle, encompassing its production, usage, and end-of-life stages.

During the *discover* phase, the use of single-use plastic medicine containers in people's homes was identified as a problem. Through research, valuable insights were obtained, revealing the detrimental environmental impact associated with medicine bottles made from single-use plastics. The high turnover rate, driven by the expiration dates of medicines in these bottles, emphasised the necessity for alternative packaging solutions to address this pressing issue.

The healthcare industry's role in exacerbating sustainability challenges is evident in its involvement in medicine production, medicine packaging, and the manufacturing of medical technological equipment (Llano, 2012, p. 3). A significant concern revolves around the widespread use of single-use plastic for storing medical supplies (McClure, 2021). Corporate entities have long promoted the idea that single-use plastic is an essential component in our rapidly moving, consumer-centric society that they have cultivated (McClure, 2021). Under this narrative, they have advocated for superficial solutions like recycling to address the vast volumes of disposable plastic waste (McClure, 2021). However, the harsh reality is that much of the single-use plastic ends up being incinerated, contributing to detrimental greenhouse gas emissions (McClure, 2021).

In response to this information, Part 2 addresses this pressing issue. Within the scope of this project, the Circular Design framework facilitated the identification of a critical problem, specifically, the waste contribution stemming from the pharmaceutical and healthcare sectors. In the discovery phase, the research conducted points out the environmental impact of medicine bottles manufactured using single-use plastics. This impact is exacerbated by a high turnover rate resulting from medicine expiration dates and a low recycling rate. This issue raises the question of how waste challenges in the pharmaceutical and healthcare sectors can be addressed. Subsequently, it guided the creation of a product solution that takes into account the entire lifecycle of the pill bottle, encompassing its production, usage, and end-of-life stages. The proposed solution created in the developing phase was designing a pill bottle that is a sustainable and eco-friendly alternative to single-use plastic containers. The aim of this product is to raise awareness and encourage the healthcare industry to reduce environmental impact in their packaging choices.

During the development phase of the pill bottle, ideation took the form of sketches, 3D models, and physical prototypes. This phase encompassed testing various design solutions and options to ensure that the product adhered to the requirements of a medicine bottle. The product was mandated to be child-resistant, airtight, moisture-resistant, ergonomically functional, stackable for transportation purposes, lightweight, and equipped with the necessary labelling.

Low-tech tools, specifically silicone and plaster moulds, were used in the delivery phase of the product. The product body mould was a two-part mould replicating the injection moulding tool, where the product has a split line. This was done to illustrate how this could be implemented in the industry if the product were to be developed on a large scale. These moulds were used for casting the biomaterial and allowed it to dry. This practical step showcased how bio-material innovation could lead to viable alternatives for single-use plastic products.

Discussion

The paper follows an iterative cycle, beginning with material testing, and progresses to identify a relevant area of material application. Within this framework, the project focuses on addressing the potential of waste value streams in South African food waste. The study illustrates how bio-material innovation can serve as an effective substitute for single-use plastic products such as waste issues in the pharmaceutical and healthcare sectors.

***Figure 9**: Pillpod, final prototype*

The two intertwined processes used in this project, represent a novel approach to developing design solutions. In combination, they illustrate the value in the explorative and experimental nature of action research as well as the successful implementation of an experimental outcome by following a traditional design process such as the Double Diamond method. The process used in this project proved to be a highly successful method of engaging with Circular Design as it addressed both the development of a sustainable material as well as the holistic implementation of such a material, considering the production, use and disposal of the resulting product. The project's concept also encompassed a broader perspective regarding a circular community, demonstrating the potential of waste materials and how they could promote the concept of a circular economy. The suggested concept entails a circular community system that independently manages its resources by collecting spent eggshells from households, restaurants, grocery stores, and small farms. These eggshells are then repurposed to create an eggshell biomaterial for manufacturing products, illuminating new economic opportunities as value is added to an otherwise costly waste value chain. Furthermore, at the end of such a product's life cycle it can be easily biodegraded or reused, making it an environmentally conscious solution.

The design project also considers the low-tech contexts of parts of South Africa that have limited access to advanced technology. A low-tech approach proves valuable for practical and accessible problem-solving. By using available materials like silicone and plaster, the project developed its tools for casting biomaterials and creating a new product. This resourceful approach empowers individuals and communities to own the innovation process, showcasing a self-sufficient and sustainable model aligned with local context and resource constraints. Moreover, the low-tech tooling approach highlights the versatility of biomaterial innovation. Beyond addressing immediate project needs, it paves the way for future endeavours in similar contexts, fostering a culture of innovation and problem-solving within communities.

The product solution exemplifies how a practice-led approach can result in an outcome that is context-appropriate. The developed Pill Pod (Figure 9) is a direct illustration of appropriate technology as it addresses the adaptability of design outcomes through the process of iterative material testing. The identified area of application is also contextualised, ensuring that the resulting product is appropriate for its intended purpose. By focusing on the waste value stream of food waste in South Africa, the study also illustrates how sustainable solutions can be used to meet human needs while reducing environmental footprints and contributing to the potential for economic growth.

Conclusion

This paper addresses the need for the field of product design to strongly consider the environmental and social impact of its outputs. As the problem of waste generation increases, it is imperative that sustainable solutions are engaged with. In line with this necessity, appropriate technology offers a holistic design approach that addresses economic, social and environmental needs. Likewise, Circular Design takes a systematic approach to product development and encourages closed-loop systems that prevent disposed products from ending up in landfills, while considering the context they are used within.

This study reports on a design project that is guided by appropriate technology and Circular Design in order to develop a product that addresses the need for sustainable development. The paper documents the practice-led process of the development of a biomaterial made from spent eggshells that is implemented in the design of a pill bottle, a traditionally single-use plastic item. The paper seeks to demonstrate how involvement in material experimentation can enhance sustainability within the realm of product design. This, in turn, can lead to increased accessibility to manufacturing methods and technologies, fostering economic growth and contributing to social upliftment.

Based on the outcome of this study, we recommend that product industries explore sustainable alternatives like utilising waste materials such as spent eggshells. Developing and supporting low-tech, context-aware solutions for manufacturing processes can empower local communities, especially in developing countries, to innovate using locally available resources. Additionally, fostering collaborations between academia, industry, and government is crucial to advancing research and development in sustainable materials and Circular Design, facilitating knowledge and resource exchange.

Future studies could therefore include the investigation methods to scale biomaterial production to meet industrial demands, optimising manufacturing processes, and ensuring consistent material quality. Alongside this, the assessment of the economic feasibility of biomaterial production across various industries would be relevant and done by exploring cost-effectiveness, market demand, and potential economic benefits. Additionally, future studies could explore technological advancements to enhance biomaterial properties and applications such as research into new binding agents, material treatments, and production techniques. Finally, developing and testing community-based models for waste collection and biomaterial production to demonstrate potential local economic development and resource management would serve as a relevant investigation.

REFERENCES

Baker, A., 2019. The Story Behind TIME's Cover on Inequality in South Africa. *TIME Magazine*, 2 May.

British Design Council, 2024. *The Double Diamond: A universally accepted depiction of the design process.* [Online]
Available at: https://www.designcouncil.org.uk/our-resources/the-double-diamond/

Castro, G., Fernandez, M. & Colsa, A., 2021. Unleashing the convergence amid digitalization and sustainability towards pursuing the Sustainable Development Goals (SDGs): A holistic review. *Journal of Cleaner Production,* 280(1), pp. 1-40.

Clot, N., 2014. *Appropriate Technology to Reduce Risks and Protect Assets: An Example from Development Cooperation in Bangladesh.* s.l., Springer Cham, pp. 245-261.

de Wit, e. a., 2018. *An analysis of the Circular state of the Global Economy,* s.l.: circle economy.

Godfrey, L. & Oelofse, S., 2017. Historical Review of Waste Management and Recycling in South Africa. *Resources,* 6(4), pp. 2-11.

Hurlbut, B., 2018. *Overcoming Poverty and Inequalities in South Africa,* Washington DC: World Bank.

Kemmis, S. & McTaggart, R., 1988. *The Action Research Planner.* 3rd ed. Victoria: Deakin University Press.

Lange, W. & Nahman, A., 2015. Costs of food waste in South Africa: Incorporating inedible food waste. *Waste Management,* Volume 40, pp. 167-172.

Llano, G., 2012. *Environmental.* s.l.:Packaging Logistics Lund University.

M Waheed, M. Y. A. S. ,. M. I.-U.-R. ,. M. K. I. K. ,. M. R. K. ,. N. A. ,. A. ,. R. M. A., 2020. Channelling eggshell waste to valuable and utilizable products: A comprehensive review. *Trends in Food Science & Technology,* Volume 106, pp. 78-90.

Massey, R., 2020. Urban Renewal in South African Cities. In: *Urban Geography in South Africa.* s.l.:Springer Cham, pp. 265-282.

Materiom, 2023. *materiom vision.* [Online]
Available at: https://materiom.org/vision
[Accessed 24 January 2024].

McClure, M., 2021. *Everything you should know about single-use plastic.* [Online]
Available at: https://www.greenpeace.org/africa/en/blogs/14052/everything-you-should-know-about-single-use-plastic/
[Accessed 24 January 2024].

Moreno, M., De los Rois, C., Rowe, Z. & Charnley, F., 2016. A Conceptual Framework for Circular Design. *Sustainability ,* 8(9), pp. 1-15.

Nyiew, K. Y. K. P. J. &. Y. Y. Y., 2022. An overview of antimicrobial properties of kombucha. *Comprehensive reviews in food science and food safety,,* Volume 21(2), 1024–1053. https://doi.org/10.1111/1541-4337.12892.

Papanek, V., 1985. *Design for the Real World: Human Ecology and Social Change.* Chicago: Academy Chicago.

Patnaik, J. & Tarei, P., 2022. Analysing the appropriateness in approriate technology for achieving sustainability: A multi-sectorial examination in a developing economy. *Journal of Cleaner Production,* Volume 349, pp. 1-17.

Raworth, K., 2017. *Doughnut economics : seven ways to think like a 21st century economist.* Vermont: Chelsea Green Publishing, White River Junction.

Roy, R., 2006. *Products: New Product Development and Sustainable Design.* Milton Keynes: The Open University.

Schumacher, E., 1973. *Small is Beautiful: Economics as if People Mattered.* London: Blond & Briggs.

Schwab, K., 2017. *The fourth industrial revolution.* London: Penguin UK.

Shanmugam, V. et al., 2021. Circular economy in biocomposite development: State-of-the-art, challenges and emerging trends. *Composites Part C: Open Access,* Volume 5, pp. 1-16.

Singh, J., Laurenti, R., Frostell, B. & Sinha, R., 2014. Progress and challenges to the global waste management system. *Waste Management & Research,* 32(9), pp. 800-812.

Tatjana von Bormann, :. L. d. V. N. J. N. T. I. M. P. P. B. C. P. N., 2017. *Food Loss and Waste: Facts and Futures,* Cape Town: WWF South Africa.

United Nations, 2024. *Department of Economic and Social Affairs, Sustainable Develpment.* [Online]
Available at: https://sdgs.un.org/goals

Wasser, 3., 2024. *Circular economy: Intelligent production, use and waste routes for the environment and society.* [Online]
Available at: https://wasserdreinull.de/en/knowledge/water-and-wastewater/circular-economy/?gclid=CjwKCAiAzc2tBhA6EiwArv-i6VMu4L6Nm4fcy6KpAHx_3n-3uymgn4ZmaHWlvp3uexHh54ze4xcmghoCWtAQAvD_BwE
[Accessed 23 January 2024].

Zuber-Skerritt, O., 2001. Action learning and action research: paradigm, praxis and programs. In: S. Sankaran, B. Dick, R. Passfield & P. Swepson, eds. *Effective Change Management using Action Research and Action Learning: Concepts, Frameworks, Processes and Applications.* Lismore: Southern Cross University Press, pp. 1-10.

AGILE ASSEMBLY LINES IN FURNITURE MANUFACTURING: OPTIMIZING PRODUCTIVITY FOR SUSTAINABLE URBAN AND RURAL ECONOMIC ECOSYSTEMS

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ABSTRACT

In the pursuit of "Building Sustainable Rural and Urban Cities for Economic Growth, Enhancing Health, and Eradicating Poverty," this research delves into the critical role of the furniture industry in national trade and economy, particularly within the context of South Africa. As urban populations continue to expand, this sector becomes increasingly crucial, facing escalating competition and challenges related to productivity, resource efficiency, workflow optimisation, and lead-time reduction. Small and medium-sized enterprises (SMEs) in furniture manufacturing are yet to fully embrace methodologies addressing these challenges.

The study employs a methodology integrating lean principles, value stream mapping (VSM), and simulation techniques to identify and rectify inefficiencies in current manufacturing processes. Time studies and bottleneck analysis are conducted to pinpoint specific areas of inefficiency. VSM is utilized to map out the production process, highlighting these bottlenecks and areas for improvement. The integration of simulation, utilizing Anylogic software, validates proposed improvements

The objective of this study was to enhance productivity and propose an agile assembly line, aligning with the broader goal of fostering sustainable cities. These cities are integral components of urban and rural economic ecosystems. The outcomes of the study demonstrate a 25% reduction in average cycle time, from 957 seconds to 714 seconds for a cut list. This underscores the significance of lean principles and simulation in enhancing productivity in the South African furniture manufacturing industry.

An in-depth assessment of the broader impact of the proposed solution across various project focus on the development of new software that empowers users to optimize their processes seamlessly without the need to segregate data.

Keywords: Furniture manufacturing, lean manufacturing, value stream mapping.

INTRODUCTION

In the dynamic landscape of contemporary living, the furniture industry stands at a pivotal juncture, holding the key to not only economic growth but also the enhancement of health and the eradication of poverty. The furniture industry contributes 0.95% to manufacturing gross domestic product (GDP) and 1.6% to manufacturing employment, giving it the potential to play an essential role in economic development and job creation within the small, medium, and micro enterprises (SMMEs) in South Africa (Furniture Sector, 2014). With the urban population on the rise, the furniture industry now holds a substantial share in national trade and economy.

The allure of modern homes, coupled with the increasing trend of real estate investments and house renovations, has propelled the demand for furniture that aligns with diverse tastes and styles. However, the traditional furniture manufacturing industry finds itself grappling with challenges such as backlogs in order deliveries, overwhelming workloads, and the necessity to adapt to rapidly changing consumer demands.

This study is significant as it addresses the critical need for optimization in production lines within the furniture industry, specifically focusing on the assembly process of furniture manufacturing by taking multiple orders, businesses can enhance production capabilities, serve a larger customer base, improve customer satisfaction, and increase revenue potential. However, the challenge lies in effectively managing these orders without compromising efficiency or quality.

The novelty of this research lies in the application of advanced simulation techniques, particularly using Anylogic, to design and optimize the production line. This approach not only provides a detailed understanding of the production dynamics but also offers practical solutions for improving operational efficiency.

Agile manufacturing is a concept that has garnered increasing attention in recent years, primarily for its capacity to elevate overall manufacturing efficiency while simultaneously reducing lead times. The rise of the agile manufacturing paradigm mirrors the imperative faced by panel furniture companies to address customer demands swiftly. This approach encompasses several crucial facets, including the rapid design, enhancement, and production of products. It is closely intertwined with complementary technologies essential for agile manufacturing, such as modular product design. It is a production philosophy that emphasizes flexibility and responsiveness to changing market demands and customer needs while also emphasizing the importance of collaboration and communication between different departments within a manufacturing facility (Sephardi, 2018).

In the fiercely competitive realm of the furniture industry, businesses grapple with challenges such as bottlenecks and extended lead times, often endangering client retention and resulting in revenue loss (Alzubi et al., 2019). The industry faces inefficiencies stemming from outdated or insufficient cutting tools and equipment, contributing to prolonged processing times and increased material wastage (DTIC, 2021b). Standard furniture manufacturing plant layouts in small to medium enterprises often suffer from low efficiency, a consequence of designs not aligning with time studies, a prevalent issue (Nyemba & Mbohwa, 2017).

Compounding the complexity is the unpredictability inherent in the furniture sector, coupled with suboptimal manufacturing processes, resulting in a high error rate and extended lead times (Sujová, 2017). Limited facilities pose a significant obstacle, preventing many furniture manufacturing companies from producing large quantities of furniture, and necessitating unsustainable solutions such as hiring more employees or renting additional space (Botti et al., 2017). In this landscape, the imperative emerges for furniture companies to streamline assembly processes, maintain a lean workforce, and implement systems fostering efficiency and skill retention (Nouri & Abdul-Nour, 2019).

The exigencies faced by the company under investigation are multifold, with issues ranging from on-time delivery challenges to the need for additional staff during extensive projects, often leading to subsequent layoffs. Prolonged waiting times before assembly initiation, owing to extended lead times in preceding processes, further compound the challenges faced. The company grapples with the complexity of predicting lead times reliably, resulting in scheduling difficulties and, at times, leading to delivery and installation delays.

In response to these challenges, the research endeavors to address the following crucial questions:

-What is the current state of lead-time, and what factors contribute to these conditions?
-How would modifying process flow parameters impact lead time improvement?

-To what extent can the implementation of modified workflow parameters enhance the output of furniture manufacturing?

These inquiries form the cornerstone of an exploration into the complexities of the wood furniture industry, with the ultimate goal of providing insights that can drive improvements in efficiency, lead times, and overall competitiveness within the sector.

This study focuses on improving productivity and introducing an agile assembly line for SMEs in the South African furniture manufacturing industry. The research aims to identify, investigate, and enhance current process systems employing tools such as VSM, discrete manufacturing, and time studies. The objectives include analyzing existing systems, developing a model highlighting bottlenecks, and comparing outcomes for improvement. The transformative approach seeks to achieve increased order handling capacity, expanded potential in supplying chain stores, sustainable job creation, cost savings on machinery, streamlined cutting processes, cost-effectiveness, and optimize profit margins. The study anticipates that implementing an agile assembly line will not only enhance productivity but also contribute significantly to the competitiveness and sustainability of SMEs in the sector.

As the world grapples with the imperative to build sustainable rural and urban cities, the furniture industry emerges as a linchpin in this transformative journey. By embracing agility, innovation, and lean manufacturing practices, the industry not only contributes to economic development but also becomes a catalyst for positive societal outcomes – improved health, poverty eradication, and a pathway toward sustainable urbanization. This research serves as a beacon, guiding the way toward a future where the furniture industry not only survives but thrives in the face of evolving consumer dynamics and global challenges.

RELATED STUDIES

Furniture products refer to objects such as tables, chairs, desks, cabinets, shelves, and cupboards, mainly meant for storage or to organize living or office spaces. Most are moveable and intended to support human activities. The primary material used is all types of wood. Furniture from the Italian Renaissance has religious connotations and could even be passed from generation to generation (Judith, 2005). Today, in the 21st century, furniture is modern, trendy, and bespoke. It is based mainly on the customer's peculiar needs and preferences. Wood-based furniture manufacturers work in a dynamic environment for people with peculiar tastes; therefore, work cannot be standardized (Nouri & Abdul-Nour, 2019). Agile manufacturing is a methodology that emphasizes the ability to quickly meet changing customer demands, needs, or wishes, creating a competitive advantage from speed, response, and agility. The fundamental principles of agile manufacturing include iteration, bottom-up planning, and flexibility. Agile manufacturing can aid manufacturing operations by focusing on personalized customer products. It has helped manufacturers access faster time to value and increase resilience during disruption. Agile manufacturing (AM) is the ability to thrive and flourish in a fiercely competitive atmosphere rife with constant and unforeseeable alterations. This is achieved by the prompt and effective response to evolving markets fuelled by consumer-designed commodities and amenities (Potdar, Routroy & Behera, 2017).

The Current State of Furniture Manufacturing

In South Africa, furniture manufacturing is significant to the economic sector and an integral part of daily life. It is a labour-intensive business that provides employment possibilities in South Africa. Furniture production uses local resources and skills and provides a market for the South African style. South African homeowners have been spending substantially more on furniture and built-in units in their houses, which has been particularly noticeable after COVID-19, with options for individuals to work from home (DTIC, 2021a).

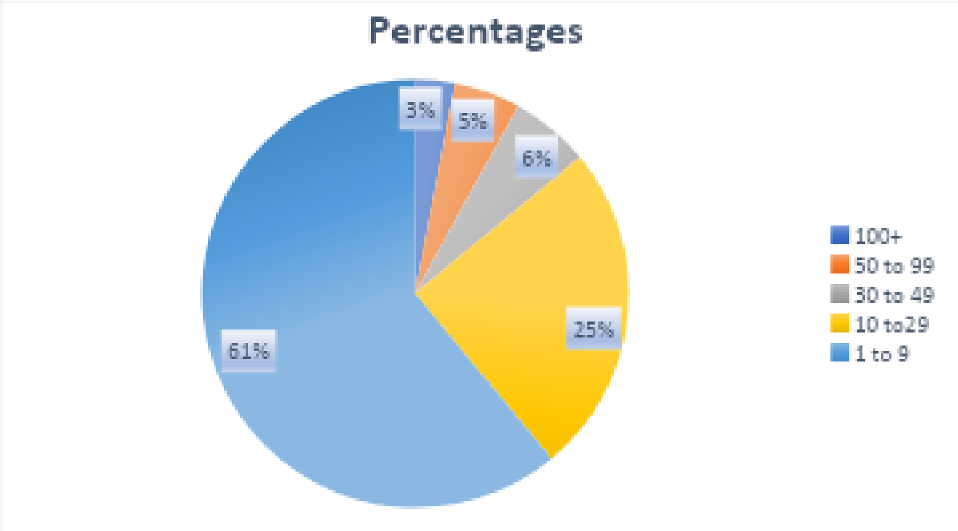

Figure 1: *Pie chart of SA furniture manufacturers in 2020 classified by the number of employees.*

Figure 1 shows that 61% of the businesses registered with the furniture bargaining councils employ fewer than ten individuals. It is found that only 35 businesses employ 100 or more people. The distribution of businesses based on the number of employees, as illustrated by the data provided, underscores the significant role that SMEs play in the economy. The fact that 61% of businesses employ fewer than ten individuals shows that SMEs are a major source of job opportunities. Collectively, they contribute to a significant portion of overall employment, helping to reduce unemployment rates and provide income for a wide range of individuals. Small businesses represent an important source for creating new jobs and expanding new business practices by significantly contributing to economic growth (Spremo, 2016). Also, in the last ten years, the global furniture trade has developed more rapidly than production of furniture. It only amounts to 1% of the world trade of manufacturers. This study serves to change the narrative and increase furniture production in South Africa (Furniture Sector, 2014). To date, not much research has been conducted on furniture-making from a production system point of view (Zhao & Li, 2014). The literature review chapter in this study focuses on manufacturing systems and production processes, specifically addressing (VSM) and simulation theory. The review draws on relevant books, research papers, and journals to explore the research questions.

Data Collecting

Data collection and analysis provide a basis for obtaining empirical information that can be useful for characterizing and predicting the performance of a system. Data can generally be observed, generated, or created to validate original research findings or form new ones. In the case of a furniture manufacturing system, data can be collected from existing furniture businesses. (Mbohwa, 2016) collected data from a local furniture manufacturing company in Harare, Zimbabwe. They used specially designed data collection tools, and the data analysis was done using statistical methods. Their study was focused on machine utilization, available skills, processing time, and material movements of furniture products. Thus, the stochastic behaviour of the data collected from various manufacturing operations was fitted to data standard probability distribution functions, from which statistical inferences and predictions could be made. The obtained probability distribution functions were intended as input variables for designing experiments and planning for simulation experiments. Figure

2-3 demonstrates the investigation for the utilization flows for bunk beds. This method of investigation involves considerable data and time management. The drawback in this study was due to the time spent after processing per workstation, which was found to consume the most time in the overall production rate. This is because the work for the next station must be completed, or it could be waiting to be carried out by a forklift. A functional and sustainable system can alleviate the waiting or lag time.
Value stream mapping (VSM) is defined as a business improvement technique where one can visualize the complete production process by representing the information and the material flow based on the current state of the business production line. VMS is also known as a tool that reveals waste in the manufacturing process. A study by Zhao and Li (2014) focused on creating an assembly line that can modularise the process flow of furniture so that it becomes semi-automated by using a conveyor belt. The main objective of the study was to investigate several existing processes and find ways to decrease lead and flow times using simulation. Discreet event simulation (DES) is usually chosen for modeling and designing manufacturing systems (Al-Aomar et al., 2020). A case study employing DES investigated the current situation in the company and was used to identify bottleneck areas that impeded the production rate. The paper analyses three variables: waiting time, utilization and scenario-based. The results show bottlenecks at assembly, painting, and wrapping; hence, VSM was used to increase the number of workers in the identified problematic areas. VSM's advantage is that it validates and explores various scheduled changes to the future. However, VSM is a static tool as it only shows the current characteristics of one product, meaning any proposed changes that can have a good impact on the business cannot be analyzed in a future state map (Goren, 2017).

Computer simulation systems are one of the popular tools used to implement the 4th Industrial Revolution (Pawlewski, 2019). The simulation consists of mapping the actual system, analyzing its behaviour, and pattern-testing ideas by conducting experiments to make informed decisions based on the readings used to simulate the production and assist in optimizing the production flow. Bambura, Sujová and Čierna (2020) aimed to improve the production system for the Slovak furniture manufacturing enterprise. The simulation was based on the current analysis of the enterprise, and a discrete event simulation model was used. Tecnomatrix plant simulation used software to collect the actual data, which was simulated and analyzed. A more powerful device was used to improve the shortfalls of the production line. Tecnomatrix plan simulation (TPS) is a Siemens simulation product that aids in creating digital models. The advantage of using discreet event simulation for statistical mathematical calculations is that it can perform system monitoring and analyze resources for a specified period. The results of DES are set information, which can be used to implement proposed changes to increase production (Bambura, Sujová & Čierna, 2020). Basic mathematical equations are used to model the production planning in a simulation model. Using a simulation model, one can estimate the operating characteristics such as idle and lead times and productivity. Evaluating the operating parameters of new manufacturing equipment is completed by assessing its financial impact (Freiberg & Scholz, 2015).

The shortfall of the results of this study is that no workers were included, and the woodworking industry is highly dependent on manual labour. The success of a higher production rate depends on purchasing new equipment, for example, a CNC machine, thereby adding costs to the project. This industry is also known for lacking skilled employees and the length of project deadlines (Nouri & Abdul-Nour, 2019). This model-based design utilizes the Taguchi design and simulation. The study has nine independent and three dependent variables. The aim is to reduce lead time and improve productivity using colours to determine FIFO. A Taguchi plan was used by incorporating the Minitab software to analyze the relevant results, while DES was chosen for the many stochastic parameters. This process accommodates many software types; it is costly and tedious to learn.

METHODOLOGY

The research design employed a mixed-methods approach, integrating qualitative and quantitative methods. The qualitative aspect involved conducting observations to gather in-depth insights into the current furniture assembly manufacturing process and identify challenges and bottlenecks. The quantitative element included data collection on key performance indicators (KPIs) such as productivity, lead times, and resource utilisation.

The choice of a mixed-methods approach was motivated by the need to leverage the strengths of both qualitative and quantitative research. Qualitative methods provided rich, contextual understanding, while quantitative methods offered precise, measurable evidence. This combination ensured that the research findings were robust, comprehensive, and actionable. Additionally, using Anylogic simulation for the quantitative analysis allowed for the modeling of various scenarios, further enhancing the study's ability to propose optimized solutions for the furniture assembly process. To accomplish the objectives of this study, the methodological foundations of Abed (Abed SY, 2008) are adopted and modified for the furniture manufacturing industry. The comprehensive methodology unfolds as follows:

The primary goal was to enhance the efficiency of the cabinet assembly factory, particularly addressing the prolonged waiting times for assembly operators, a challenge with far-reaching consequences on production deadlines, profitability, and customer satisfaction.

- Thorough Production Line Study: The entire production line, comprising various departments, was scrutinized. Activities, processes, resources, materials, and timings were meticulously identified and documented.
- Data Identification and Collection: All data related to activities and resources within the production line were identified and collected, laying the groundwork for a comprehensive understanding of the existing processes.
- Simulation Model Development: A simulation model, accurately mirroring the real production line and its dynamic behaviour was designed and developed. Figures 8 and 9 presented a comparison between the current state and the simulated future state.
- Simulation Experimentation: Once a valid model was established, a series of simulation experiments were designed and conducted. The goal was to explore feasible solutions that would maximize the capacity of the production line and increase production rates within existing constraints.

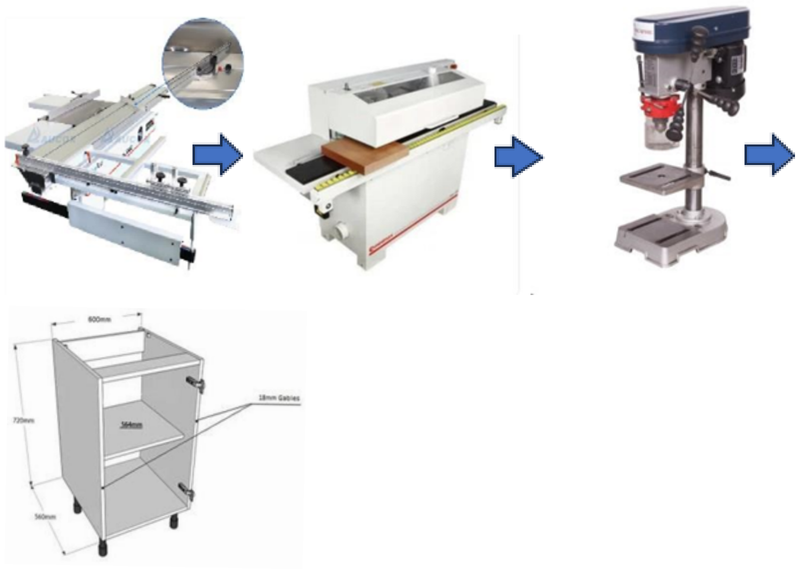

Figure 2: *Process flow of furniture manufacturing and assembly*

Table 1: *The furniture process assembly line explained in sequence*

No.	**Process Name**	**Resource**	**Description**
1	Cutting	Panel saw	Cutting chipboard sheets using a manual panel saw
2	Edge banding	Edge bander	Applying edge bands to straight edges of chipboard elements
3	Drilling	Bench drilling press	Drilling holes in chipboard elements
4	Assembly	Assembly line	Assembling carcasses

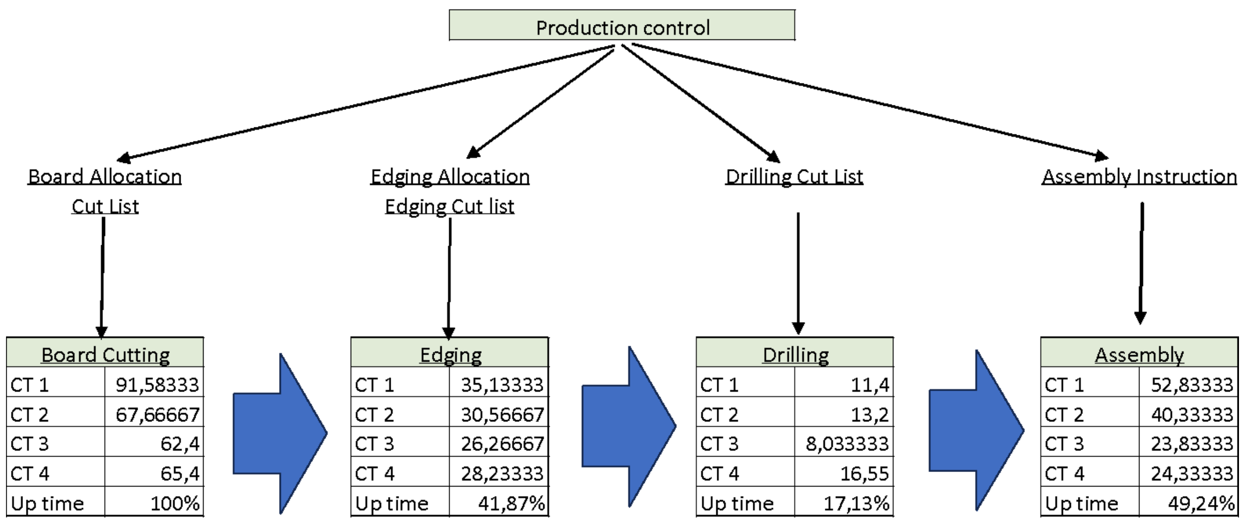

Figure 3: *VSM analysis of the current state*

Figure 3 presents a Value Stream Mapping visualization of the production line process flow, highlighting the current state and identifying potential issues such as bottlenecks, cycle time problems, and capacity limitations. The structure of the VSM is divided into four main parts: On the top diagram is Production Control, diagram illustrating a production process, with clear labels for each stage; Board Allocation Cut List, Edging Allocation Edging Cut List, Drilling Cut List and Assembly Instruction. Each stage led to a summarizing output, including cycle time 1to cycle time 4 and up time. The processes are connected with an arrow showing a product (cupboard) which is made from six main parts: Two sides, two doors, bottom, shelf, back, and top. As shown in the VSM below, the first process was cutting, followed by edging., drilling and then moved to the next process which is assembling. This analysis focuses on the time taken for each process within the production line, providing a comprehensive overview of where inefficiencies may lie

The results of the analysis are as follows:

- The cutting process is identified as the most time-consuming, taking 203% longer compared to the assembly process. This indicates a significant bottleneck within the production line.

The edging and drilling processes together account for an average of 59% of the time taken compared to the cutting process.

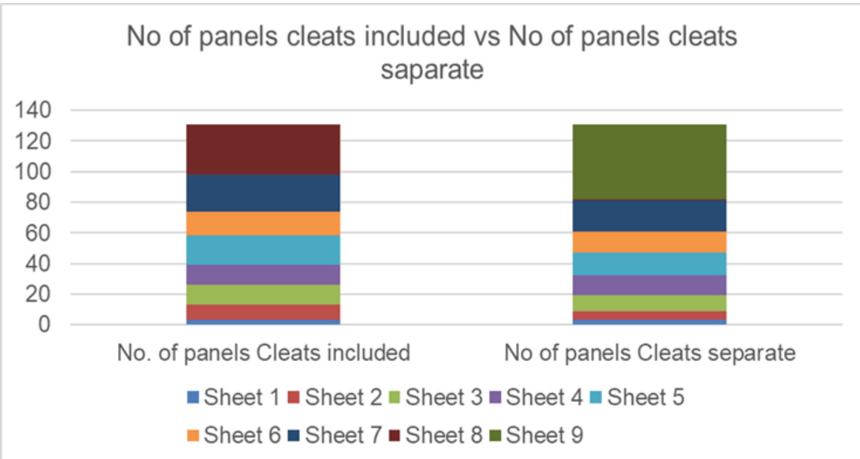

***Figure 4**: Graphical representation of the number of panels with cleats included vs the number of panels with separate cleats.*

Figure 4 presents a comparative analysis of panel configurations with respect to cleat integration. The graph illustrates the distribution of panels between two distinct categories: those incorporating built-in cleats and those designed for separate cleat attachment.

In this graphical representation, the x-axis denotes the two distinct cleat configurations: 'Panels with Cleats Included' and 'Panels with Separate Cleats.' The y-axis quantifies the number of panels in each category. As depicted, the number of panels integrating cleats directly is contrasted with those employing separate cleats, providing a clear visual distinction between the two methodologies.

The total sample size comprises 131 panels, providing a consistent baseline for comparison. This uniform panel count ensures that any observed differences are attributable to the cleat configuration rather than variations in overall panel quantity.

The visual representation clearly compares the two panel types, effectively communicating the project's strategy to group cleats separately rather than incorporating them directly into the panel structure.

This visualization serves as a valuable tool for assessing the potential implications of the chosen design approach, such as manufacturing complexity, assembly requirements, or performance characteristics.

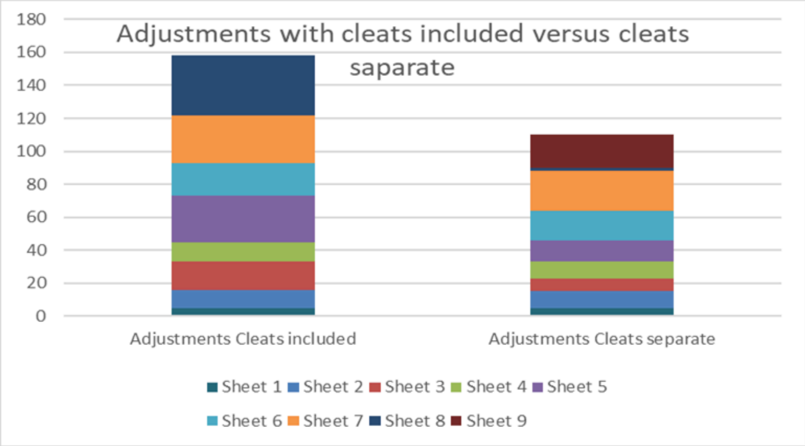

***Figure 5**: Graphical representation of adjustments with cleats included versus cleats separate.*

Figure 5 provides a detailed graphical representation of the adjustments required when cleats are included directly in the panels versus when cleats are separate. The data analysis underscores a significant optimization in the system, as evidenced by the reduction in the total number of required adjustments.

The x-axis of the graph categorizes the adjustments into two groups: 'Adjustments with Cleats Included' and 'Adjustments with Cleats Separate.' The y-axis quantifies the number of adjustments needed for each category.

Initially, the system required 158 adjustments when cleats were included directly in the panels. However, by adopting the configuration where cleats are separate, the number of adjustments was markedly reduced to 110. This change reflects a substantial improvement, with a 30.38% reduction in the total number of adjustments required.

This graphical depiction not only highlights the efficiency gained through the new configuration but also visually communicates the project's success in optimizing the adjustment process. The significant drop in required adjustments indicates a more streamlined and effective system, validating the decision to separate cleats from the panels.

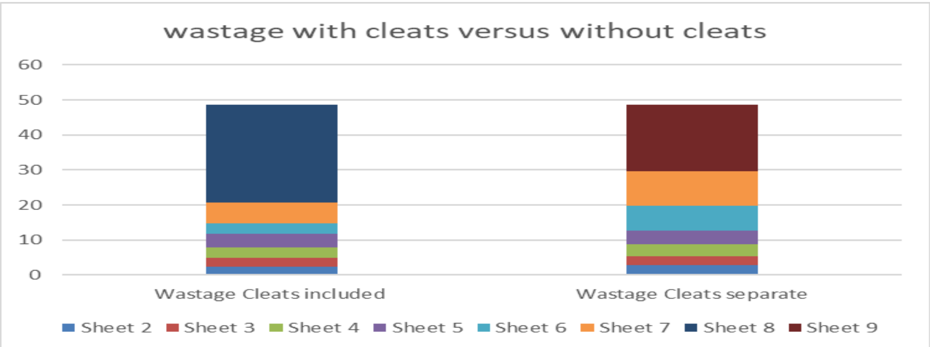

***Figure 6**: Graphical representation of wastage with and without cleats*

Figure 6 presents a graphical representation of wastage in two scenarios: panels with cleats included and panels with cleats grouped separately. This analysis was conducted on projects involving 131 panels under both configurations.

Despite a notable reduction in the number of adjustments—from 158 to 110, representing a significant 30.38% decrease—Figure 6 reveals that the total wastage remained unchanged between the two scenarios. The x-axis of the graph delineates the two configurations ('With Cleats' and 'Without Cleats'), while the y-axis measures the amount of wastage observed.

The constant level of total wastage in both configurations suggests that while the overall inefficiency in material usage did not improve, the specific areas or components contributing to this wastage may have differed between the two scenarios. This insight is crucial for fine-tuning resource allocation and optimizing processes to minimize inefficiencies within the system.

By maintaining the same total wastage, the graphical representation in Figure 6 indicates that further examination is necessary to identify and address the specific sources of wastage in each configuration. Understanding the distribution of wastage can help in developing targeted strategies to enhance resource efficiency and improve overall system performance.

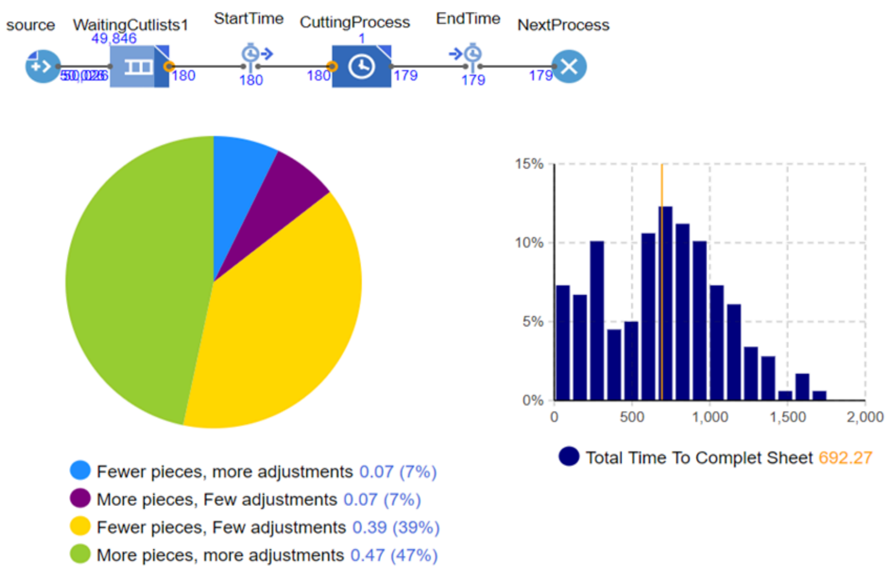

Figure 7: *Current state of Simulating the cut -lists*

Figure 7 offers a comprehensive visual analysis of the current state of simulating cut-lists within a production line. The graphical elements, including diagrams, pie charts, and histograms, collectively provide an in-depth overview of the cutting process and its associated metrics.

The average cycle time for completing the cutting process is 692.27 seconds, which translates to approximately 11.53 minutes per cycle. In terms of throughput, the system processes 180 sheets over a total duration of 124,560 seconds. This equates to the handling of 36 sheets per shift, reflecting the system's capacity and efficiency.

The process begins with a significant waiting time, labeled as WaitingCutlists1, which amounts to 49,846 units. This initial stage is followed by:

The cutting process itself, which takes another 180 units, An end time of 179 units.

Subsequently, this leads into the next process stage, which also requires 179 units. This sequential breakdown highlights the time allocation for each phase within the cutting process. The pie chart included in Figure 8 categorizes the production scenarios into four distinct segments:
Fewer pieces, more adjustments: 7% (0.07)
More pieces, few adjustments: 7% (0.07)
Fewer pieces, few adjustments: 39% (0.39)
More pieces, more adjustments: 47% (0.47)
This categorization provides insight into the distribution of production types, revealing that a substantial portion of the process involves handling more pieces with more adjustments (47%), followed by fewer pieces with few adjustments (39%).

The histogram in Figure 8 illustrates the distribution of the total time taken to complete a sheet. The average completion time is 692.27 units, with the highest frequency of completion times falling within the range of approximately 500 to 1000 units. This distribution highlights the variability in processing times and helps identify the most common time frames for completion.

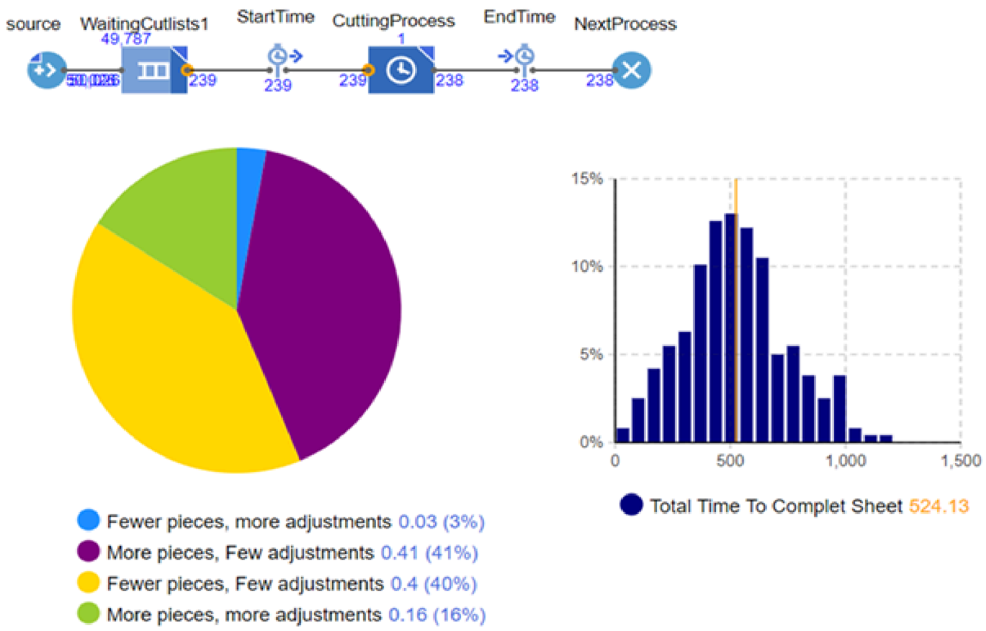

***Figure* 8:** *Future state of Simulating the cut -lists*

Figure 8 illustrates the performance improvements in the cutting process of the production line achieved through simulation modeling and optimization. Simulation is a well-established technique for modeling complex manufacturing systems and evaluating proposed changes before implementation. The selection of simulation software and methods for this study was based on their ability to accurately replicate real-world manufacturing scenarios and provide actionable insights, as demonstrated prior studies (Martinez-Garcia:2021).
The average cycle time for processing a cut list in the current state simulation was recorded at 692.27 seconds (11.5 minutes). This is consistent with prior research showing cutting as a bottleneck in furniture manufacturing due to inconsistencies and frequent adjustments (Marques et al. 2018).

Through optimization of board layouts, the simulation demonstrated a 25% reduction in average cycle time to 524.13 seconds (8.7 minutes). Correspondingly, the production rate or throughput increased from 36 to 48 sheets processed per shift. The simulation results indicate that reducing the proportion of cut lists requiring "more pieces, more adjustments" from 47% to 16% drove most of the cycle time and throughput enhancements.

CONCLUSION

In furniture manufacturing SME processes, the study embarked on a multifaceted journey. Initially, the focus was set on identifying the existing process system, leveraging time studies and (VSM). This approach not only unveiled the most time-consuming facets but, more crucially, directed our attention to the impactful bottlenecks across multiple projects in various manufacturing stages.

Following this, intricate models of the existing manufacturing systems were crafted, prioritizing the bottlenecks affecting lead time. The cutting process emerged as the epicenter, with a thorough analysis of cut lists and their influence on cycle times. A deep dive into cut lists unraveled pivotal parameters prolonging cycle times, setting the stage for transformative improvements.

The pinnacle of our study manifested in the development of a solution model that proposed a paradigm shift in board optimization. The efficacy of this proposed change was rigorously evaluated through a simulation model, revealing a remarkable 25% enhancement in the manufacturing process during the transition from the current to the envisioned future state. This significant leap underscored the tangible success in realizing our study's objectives and the positive impact poised to reshape manufacturing dynamics.

The paramount significance of this research materializes in the empirical evidence it provides, illuminating the path to heightened efficiency in the manufacturing or assembly cycle. The tangible outcomes translate into the ability of companies to produce more products in less time, presenting a dual boon of amplified profits and elevated customer satisfaction. By meticulously addressing and reducing average cycle times and boosting assembly uptime, our study introduces pivotal Key Performance Indicators (KPIs) that stand as benchmarks for efficiency, promising a paradigm shift in profits and customer contentment.

In essence, our research encapsulates valuable insights into the nuanced realm of manufacturing and assembly processes, paving the way for a transformative journey toward heightened efficiency and productivity. Implementing our findings emerges as a strategic key to unlocking optimized production processes and ushering in superior outcomes in the ever-evolving landscape of manufacturing excellence.

Future research scope may include birthing new software solutions that seamlessly integrate our methodology, ensuring a streamlined implementation devoid of data segregation and independent optimizations.

REFERENCE

ABED SY, 2008. A simulation study to increase the capacity of a risk production line, International Journal of mathematics and computers in simulations, Issue 3,Volume 2, pp 228-237

AL-AOMAR, R., ALSHWAILAT, A., ALFARRAJ, A. & ODEH, T. 2020. A simulation-aided lean application to an automated production line. Proceedings of the International Conference on Industrial Engineering and Operations Management, 1641-1652.

The average cycle time reduced from 692,27 seconds to 524.13 seconds to complete a cut lis
time

ALZUBI, E., ATIEH, A.M., ABU SHGAIR, K., DAMIANI, J., SUNNA, S. & MADI, A. 2019. Hybrid integrations of value stream mapping, theory of constraints and simulation: Application to wooden furniture industry. Processes, 7(11).pg. 1-15.

BOTTI, L., MORA, C. & REGATTIERI, A. 2017. Integrating ergonomics and lean manufacturing principles in a hybrid assembly line. Computers & Industrial Engineering, volume111,pp 481-491.

GUNER GOREN, H. 2017. Value stream mapping and simulation for lean manufacturing: A case study in furniture industry. Pamukkale University Journal of Engineering Sciences, 23(4):462-469.

Martinez-Garcia, M. (2021). Key technologies towards smart manufacturing based on swarm intelligence and edge computing. Computers & Electrical Engineering, volume 92, pp107-119

Marques, A. C., Silva, J. F., & Costa, J. (2018). Impact of Cutting as a Bottleneck in Furniture Manufacturing. International Journal of Production Research, 56(18), 6312–6327. DOI: 10.1080/00207543.2018.1431666.

NOURI, K. & ABDUL-NOUR, G. 2019. Optimization via computer simulation of a mixed assembly line of wooden furniture - A case study. Procedia Manufacturing, volume 39:pp956-963.

NYEMBA, W.R. & MBOHWA, C. 2016. Data collection and statistical data analysis in preparation for simulation of a furniture manufacturing company. Lecture Notes in Engineering and Computer Science, volume 2224:pp 727-732.

NYEMBA, W.R. & MBOHWA, C. 2017. Process Mapping and Optimization of the Process Flows of a Furniture Manufacturing Company in Zimbabwe Using Machine Distance Matrices. Procedia Manufacturing, volume 8:pp 447-454.

PAWEL PAWLEWSKI, M.A. 2019. Relational-Database template in the simulation modeling ,IFAC-Papers on line volume 52 (13), pp 1744-1748.

POTDAR, P.K., ROUTROY, S. & BEHERA, A. 2017. Agile manufacturing: a systematic review of literature and implications for future research. Benchmarking: An International Journal, volume 24(7), pp 2022-2048.

SOEPARDI, A., PRATIKTO, N.A., SANTOSO, P.B. & TAMA, I.P. 2018. An updated literature review of agile manufacturing: classification and trends. International Journal of Industrial and Systems Engineering, volume 29(1) ,pp95-126.

ZHAO, C. & LI, J. 2014, Modeling, analysis, and improvement of a multi-product furniture assembly line. IFAC Proceedings Volume 47, Issue 3, 2014, pp1672-1677

IN-SITU LENS FABRICATED TI-AL-SI ALLOYS AFTER ISOTHERMAL ANNEALING HEAT TREATMENTS: NANOMECHANICAL, WEAR, AND OXIDATION PROPERTIES

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ABSTRACT
University of Johannesburg are known for their lightweight with particular focus for applications to replace heavier Ni-based superalloys for high-temperature components. in the next generation of aircraft and automotive combustion engines. Aimed components are turbine blades and turbocharger turbine wheels. However, silicon additions as allotting elements are quite controversial but known to improve TiAl mechanical and oxidation properties when present in certain amount. Recently, technologies known as additive manufacturing (AM) have been adopted to process TiAl alloy with one particularly appealing AM technology called laser engineered net shaping (LENS) has been used to fabricate metals, ceramics, and composites. Thus, this work is focus on the study of the nanomechanical, wear and oxidation properties of intermetallic Ti-Al-Si alloy produced via laser in situ alloying from elemental powders by applying the laser engineered net shaping (LENS) technique. The effects of 0.25g/min Si feed rate were studied before and after LENS in-situ alloying with the isothermal annealing heat treatment conducted at 1200°C and 1400°C for 1h, followed by furnace cooling (FC). It was observed that Si addition causes the formation of ζ-Ti_5Si_3 ascribed to increase in the nanoindentation hardness of the Ti-Al-Si alloys especially after the heat treatment at 1200°C with a duplex microstructure. However, the alloy heat-treated at 1400°C demonstrated a lamellae microstructure comprising of α_2-Ti_3Al and γ-TiAl with ζ-Ti_5Si_3-phase at the grain boundaries. The mechanical properties from the nanoindentation results of the heat-treated samples in this study were relatively better than the non-heat treated sample. However, the alloy heat-treated at 1200°C gave better tribological and oxidation properties from all the samples with non-heat-treated sample performing better than the sample heat-treated at 1400°C. Hence, this study established that laser in-situ alloyed sample heat-treated at 1200°C would perform better in service for the development of TiAl-based alloys.

Keywords: Laser Engineered Net Shaping (LENS); Titanium Aluminide Alloys; Nanomechanical Properties; Titanium Silicide (ζ-Ti_5Si_3); Additive Manufacturing (AM); Tribological Properties

INTRODUCTION
Due to its fascinating properties, alloys based on titanium aluminide (Ti–Al) have garnered a lot of research during the past thirty years. Because of their exceptional light weight and stability at high temperatures, this class of intermetallic alloys is regarded by several industries, including the chemical, aerospace, marine, and automotive sectors. As a result, they are thought to be the best material to replace nickel (Ni)-based super alloys in the future (Raji, Popoola, Pityana and Popoola, 2020; Raji, Popoola, Pityana and Tlotleng, 2021a). This alloy has multiple stable phases, but the gamma phase alloy is thought to have significant technical uses (Kastenhuber, Klein, Clemens and Mayer, 2018; Musi, Graf, Clemns and Spoerk-Erdely, 2023). The titanium-Ti and aluminum-Al elemental powder mixtures in the

gamma phase alloy are chemically balanced, according to the binary Ti–Al phase diagrams (Raji *et al.* 2021a). At room temperature (RT), the binary Ti–Al alloy, which is composed of 52 Ti and 48 Al (at.%), is not ductile. Their industrialization initiatives have been hampered by this room temperature characteristic, which makes them challenging to produce into completed goods. They also have a reputation for having poor wear resistance, particularly oxidation resistance at high temperatures (Ahmadi, Hosseini and Hadavi, 2016; Kanyane, Popoola, Pityana, Raji and Tlotleng, 2023; Qu, Tang, Feng, Feng, Shen and Chen, 2018). The addition of micro-alloying metallic elements that can stabilize the alpha, gamma, or both phases, resulting in a super-stable alloy with improved machinability and engineering properties, has been the subject of extensive research aimed at improving the ductility, mechanical, and electrochemical behaviour of these binary Ti–Al alloys. Ti-Al-Si (Raji *et al.* 2021a), Ti-Al-Nb (Kanyane, Raji and Tlotleng, 2024; Tlotleng, Lengopeng, Seerane and Pityana, 2017), Ti-Al-Mo (Huang, Zhu, Cai, Liu and Jin, 2017), Ti-Al-Cr (Gong, Chen, Fang, Ding, Guo, Su and Fu, 2018; Kanyane *et al.* 2023), and other ternary Ti–Al–X alloys are among the ones that have been studied.

It has been reported that fine silicide (ζ-Ti_5Si_3) particles precipitated within the declining α_2-phases in Si-containing TiAl-based alloys, which effectively improves the properties of FL materials by mitigating dislocation motions (Musi *et al.* 2023). Si-based TiAl alloys have garnered interest because of their improved mechanical characteristics brought about by the formation of the strengthening ζ-Ti_5Si_3 phase. The limited solubility of Si in the γ-phase is the reason behind the precipitation of ζ-Ti_5Si_3-phase formation. Some researchers like Knaislová, Novák, Linhart, Szurman, Skotnicová, Juřica and Čegan (2021) and Raji *et al.* (2021a) have looked into how Si affects intermetallic alloys based on TiAl. It has been found that the use of Si as an alloying element enhances the fine lamellar microstructure stabilization, creep resistance and oxidation resistance (Huang, 2013; Qu *et al.* 2018). It is known that adding 0.5 at.% Si to TiAl-based alloys causes the precipitation of small Ti_5Si_3 particles, whereas adding 2–6% Si results in whiskers or big Ti_5Si_3 particles (Raji *et al.* 2020).

Si has a positive effect on strength, which can be explained by both dissolved Si and these fine ζ-Ti_5Si_3 silicides stiffening precipitation (Musi *et al.* 2023). Interfacial drag processes and the ζ-Ti_5Si_3 silicides' ability to impede dislocation movement both account for the higher creep resistance. According to Noda, Okabe, Isobe and Sayashi (1995), there are two potential phase changes that lead to the creation of silicides: at lower temperatures, a eutectoid $\alpha_2 \rightarrow \gamma +$ ζ-Ti_5Si_3 transformation, and during solidification, a eutectic $L \rightarrow \beta +$ ζ-Ti_5Si_3 transformation. In particular, silicides are formed at the α_2/γ and γ/γ interfaces in the lamellar α_2/γ colonies as a result of the eutectoid transition, which has been seen in a variety of alloys both before and after creep exposure (Musi *et al.* 2023). The growth of the silicides continues into the α_2 lamellae after nucleation at the contact. However, because of their inherent differences in solubility for this element, the development of silicides inside the colonies is strongly dependent on the current ratio of α_2 and γ phase. Specifically, in the event that the γ phase content is excessively low—for instance, due to an Al-lean alloying idea—all Si can stay in a solid solution and no ζ-Ti_5Si_3 silicides can form. You may find information in the literature (Kahrobaee and Palm, 2022; Kastenhuber *et al.* 2018; Musi *et al.* 2023) on isothermal sections and the liquidus projection of the Ti–Al–Si system regarding the effect of Si on phase changes in γ-TiAl based alloys. The phase equilibria in the Al range of engineering γ-TiAl based alloys, or 42 to 48 at%, will probably stay mostly unchanged when compared to the binary Ti–Al system by isothermal sections of the Ti–Al–Si system at high temperatures, with the presence of ζ-Ti_5Si_3 silicides being the only exception. In addition, the fact that Si additions stabilize the γ phase over the α_2 phase is supported by isothermal heat treatments; that is, $\alpha_2 + \gamma \rightarrow \alpha_2 + \gamma +$ ζ-$Ti_5Si_3 \rightarrow \gamma +$ ζ-Ti_5Si_3 (Musi *et al.* 2023; Noda *et al.*

1995). TiAl alloys' mechanical characteristics are primarily dictated by their composition, which is also dependent on the microstructural morphology as a result of various heat treatment techniques.

The use of TiAl-based alloys for rotating compressor and low-pressure turbine (LPT) blades, which has recently been implemented in GEnx and LEAP engines, might result in significant weight savings. The cutting-edge manufacturing process known as Laser Engineered Net-shaping (LENS) in Additive Manufacturing (AM) offers the potential to transform how people view design and production in general. Layer-by-layer melting of TiAl alloys and the ability to build intricate parts for automotive and aerospace applications are made possible by LENS production. The method is also known for cutting down on the amount of labor and resources needed for machining in these kinds of operations. The extent of LENS technology's industrial use is primarily determined by process efficiency, design-to-build accuracy, build consistency, and repeatability—all of which are dependent on a deep understanding of the powder's properties and process parameters. It has been found that the LENS method could decrease capital as well as labor equipment expenditures in addition to cutting manufacturing time by 40%. However, because of the process's quick cooling, large thermal stresses are encountered during LENS, which might result in highly stressed alloys being produced. The Ti-Al binary phase diagram indicates that various heat treatment temperatures and approaches may be employed to create various microstructures. This depends on how the alloy or composition is cooled as well as how much aluminum present.

However, manufacturing complexly shaped parts using the usual forging and casting methods of processing TiAl-based alloys is exceedingly challenging (Raji *et al.* 2020). This results from expensive machining and high energy usage (Yu, Zhou, Yin, Tu, Feng, Nan, Lin and Ding, 2022), which has a significant effect on production costs. Similarly, alloys based on titanium have limited wear resistance, low fracture toughness, and poor resistance to oxidation above 750 ºC by nature. Lately, technologies known as additive manufacturing (AM) have been developed to address the drawbacks of traditional production methods. One particularly appealing kind of laser AM technology that has been used to fabricate metals, ceramics, and composites is called laser engineered net shaping (LENS) (Raji *et al.* 2021a). It is said that this technology can be used to create thin-walled, complexly formed components. This is accomplished by melting metallic powders and applying them directly onto a metallic substrate, creating a melt pool layer by layer in accordance with a pre-made computer-aided design (CAD) model. Thus, Ti, Al, and Si elemental metal powders were used to create sample coupons in this work using LENS. However, the current study's goal is to investigate how heat treatment affects the nanomechanical wear and oxidation parameters of Ti-48Al-1.0Si alloy that is synthesized in-situ via LENS. The alloy following the isothermal heat treatment will be the focus.

METHODOLOGY

Materials

In this work, pure metal powders of Ti, Al, and Si were employed as feedstock. The Ti and Si powders were spherical in shape and had a 45–90 µm particle distribution size range. TLS Technik (Germany) provided the powders, and Weartech (Johannesburg, South Africa) provided the spherical Al. Using LENS technology, powders were deposited onto 100 x 100 x 5 mm3 Ti6Al4V substrates.

LENS Fabrication

Ternary Ti-Al-Si alloy was fabricated using the LENS® Optomec 850-R system, which was equipped with a computer integrated 1000 W IPG fibre laser. The LENS's deposition head, which was attached to the laser fibre, was managed by Optomec software control, version 3.1.6 (Optomec, Albuquerque, NM, USA). The laser in situ alloying method was used to create the manufactured Ti-Al-Si alloy. The ability of the Optomec software to automatically regulate the deposition head, powder feeders, and laser beam made this possible. The substrate was a grade 5 titanium alloy metal plate (Ti-6Al-4 V). Table 1 lists the deposition parameters that were utilized to complete this job. The base plate was cleaned with acetone and subjected to sandblasting prior to deposition. The experimental procedure makes sense in light of Raji *et al.* (2021a) and Raji, Popoola, Pityana, Popoola, Arthur, and Tlotleng (2021b)'s research.

Table 1: Deposition parameters for the fabrication of Ti-Al-Si alloy

Parameter	Values		
Laser Power (W)	450 W		
Scan Speed (mm/s)	10.58 mm/s		
Centre Purge (l/min)	25 l/min		
Stand-off Distance (mm)	8.0 mm		
Laser Spot Size (mm, diameter)	1.35 mm		
Layer Thickness (mm)	0.2 mm		
Hatch Distance (mm)	0.675 mm (50% overlap)		
	Al	**Ti**	**Si**
Powder Feed Rate (g/min)	0.48	2.21	0.025
Carrier gas (l/min)	2.4	4.2	2.0

Isothermal Heat Treatment

Heat treatment was done in a muffle furnace in an argon-rich environment (Kejia Furnace, China). The sample was heated to temperatures between 1200 and 1400 degrees Celsius. The temperature was raised to 20 °C per minute and held there for an hour prior to furnace cooling (FC).

Nano-indentation Testing

The Anton-Paar TTX-NHT3 nano-indentation tester was used to examine how the produced alloys behaved during nano-indentation. The device has a Berkovich indenting tip with a radius of 20 nm. When indenting, a 3 by 4 matrix array, or 12 indents, was recorded. A holding and unloading time of 20 seconds was noted, along with a maximum loading force of 200 mN. The load-displacement curves were analyzed using the Oliver and Pharr (1992) method to determine the mechanical parameters of the material, including stiffness (S), yield strength (YS), young's modulus (E), and ultimate tensile strength (UTS).

Wear Testing

The synthesized Ti–Al–Si's tribological behaviour was investigated using the Anton Paar tribology testing apparatus (Anton Paar, TRB3), in accordance with the ASTM G99–95 standard. A pin-on-disc made of stainless steel was used in the test. For every test sample, a sliding distance of 3000 mm was covered in 900 seconds with an applied stress of 15 N. Data on wear rate and coefficient of friction (CoF) were obtained from the test.

Thermogravimetric Analyzer (TGA) Test

The properties of oxidation of these samples were investigated using a thermogravimetric analyzer (TGA) on the produced alloy. Utilizing a PerkinElmer thermogravimetric analyzer

(TGA 4000; PerkinElmer Inc., USA), the weight of the specimen was changed in relation to temperature throughout time. At a rate of 20 millilitres per minute, an inlet gas consisting of 79% and 21% N2 and O2 correspondingly was infused. The test reached a maximum temperature of 900 ºC at a heating rate of 50 ºC/min. Based on the data, TGA graphs were created and the oxidation resistance was evaluated.

RESULTS AND DISCUSSIONS

Nanomechanical Results

Figure 1 displays the load-displacement curves for the as-built and heat-treated TiAl-0.025 g/min Si alloy, and Figure 2 displays the real stress-true strain curves. Figure 2's curves were used to calculate the UTS and YS of the alloys based on the load-displacement curve as examined by Oliver and Pharr (1992). As per Oyen and Cook's (2009) review report , every sample that was included in this study demonstrated elastic-plastic activity. It is anticipated that the sample heated to 1400 ºC for 60 minutes will exhibit higher plastic deformation than the as-built and heat-treated samples at the same temperature. The unloading section (Figure 1), which discusses the material's stiffness, shows that the as-built and 1400 ºC/60 mins/FC material stiffness were essentially the same.

The stiffness of the as-built sample is 0.91988 x 10^6 N/m, that of the 1200 ºC/60 mins/FC sample is 0.69887 x 10^6 N/m, and that of the 1400 ºC/60 mins/FC sample is 1.08046 x 10^6 N/m. In comparison to the as-built and 1200 ºC/60 mins/FC samples, Figure 2 shows that the 1400 ºC/60 mins/FC sample had the lowest YS and UTS. Although the readings were quite comparable, the 1200 ºC/60 mins/FC sample revealed much higher UTS than the as-built sample. This was ascribed to the 1200 ºC/60 min/FC alloy sample's dual or duplex phase (DP) microstructure. Refer to reference (Raji *et al.* 2021a) for a description of the phases and microstructure seen in these ternary Ti-Al-Si alloys that were synthesized in-situ using LENS. The YS and UTS of the alloys were ascertained using the true stress-true strain curves for each sample, which are displayed in Figure 2. The as-built alloy has an E of 159 GPa with UTS and YS values of 489 MPa and 301 MPa, respectively. The as-built sample's E value of 159 GPa was 5.4% lower than the E value of the GE commercial alloy at RT when compared to Lerch, Draper, Pereira and Zhuang (2003). Furthermore, the YS was approximately 7.7% lower than the 326 MPa YS of GE. Nonetheless, the as-built sample's UTS was approximately 18% higher than the GE's UTS of 422 MPa. This demonstrates that the as-built sample would bear higher stress at room temperature (RT) before breaking, but would deform plastically at considerably lower stress than GE. This was explained by the strengthening mechanism of ζ-Ti_5Si_3 brought about by the Si content.

The heat-treated sample at 1200 ºC for 60 minutes had UTS and YS values of 498 MPa and 280 MPa, respectively, and an E of 166 GPa. The 1200 ºC/60 mins/FC sample's E value of 166 GPa was nearly identical to the GE commercial alloy's E value of 168 ±2 GPa at room temperature (approximately 1.2%< GE). However, the YS of the 1200 ºC/60 mins/FC sample is roughly 14% lower than the YS of the GE sample, suggesting that plastic deformation would occur in the 1200 ºC/60 mins/FC sample at a significantly lower stress than in the GE alloy. Nonetheless, the 1200 ºC/60 mins/FC sample's UTS was almost 18% higher than the GE sample's UTS. As a result, before breaking, the 1200 ºC/60 mins/FC sample would be able to endure greater tension at RT and experience more plastic deformation. The mechanical characteristics of the as-built ternary Ti-Al-Si alloy were inferred to be the same as those of the 1200 ºC/60 mins/FC sample. The heat-treated sample at 1400 ºC for 60 minutes and FC had an E of 155 GPa and a UTS and YS of 419 MPa and 262 MPa, respectively. Approximately 7.7% less was the E value of the 1400 ºC/60 mins/FC sample than the E of the GE commercial alloy at RT. Comparing the YS of the 1400 ºC/60 mins/FC sample to GE, it was found to be approximately 20% lower, suggesting that the 1400 ºC/60 mins/FC sample would require less stress to undergo plastic deformation than the GE sample. Moreover, the UTS of the 1400 ºC/60 mins/FC sample and the UTS of the commercial GE alloy were nearly identical (about 0.7%< GE). As a result, the commercial GE alloy at RT and the 1400 ºC/60 mins/FC sample stress limit are identical.

While plastic deformation would occur in all ternary Ti-Al-Si alloy samples at lower stress than in GE, the as-built and 1200 ºC/60 mins/FC sample's UTS value shows superior fracture toughness compared to GE alloy that is sold commercially. As a result, these alloys would be able to withstand stress deformation more effectively than the GE alloy. However, because of the ζ-Ti_5Si_3 phase's strengthening process, it is anticipated to have higher high-temperature performance and creep resistance. It has been documented that Si influences ζ-Ti_5Si_3-assisted strength enhancement by precipitation hardening or solution strengthening (Kastenhuber *et al.* 2018). However, following HT, it is clear that the produced alloy's young modulus parameters improved in comparison to the as-built samples. The precipitation of ζ-Ti_5Si_3 phase at grain boundaries, which leads to a secondary phase strengthening process, may be the cause of the high stiffness qualities. Thus, the mechanical properties of the alloys are enhanced by the addition of Si.

These findings unequivocally demonstrate how the temperature of the isothermal heat treatment affects the mechanical characteristics of the Ti-Al-Si alloy. It is commonly known that for the majority of metals and alloys, at higher temperatures, ductility rises while YS and E decrease (Mengis, Grimme and Galetz, 2019). The mechanical qualities are often improved as a result of this thermal softening effect, which also affects other performance characteristics including oxidation and wear. These results disagree with macroscopic tests on the studied alloy, which reveal a somewhat brittle behaviour (Knaislová et al. 2021). According to Burtscher, Alfreider, Schmuck, Clemens, Mayer and Kiener, 2021)'s research, strengthening the weakest interface type is necessary to increase the fracture toughness of the entire α_2/γ colony. Furthermore, by applying enough heat treatment to reduce the lamellar gap, the number of α_2/γ contacts can be enhanced. This alloying approach could further optimize the amount of α_2 phase and ζ-Ti_5Si_3 silicides to increase the number of reinforced α_2/γ contacts. However, strain localization at colony boundaries and an increased potential for fracture initiation would come from macroscopically thinner lamellae within the α_2/γ colonies (Burtscher et al. 2021). Moreover, the existence of tiny globular γ grains at various interfaces could potentially enhance the behaviour of fractures. In order to achieve optimal mechanical behaviour and balanced mechanical properties, it is necessary to take into account and assess every aspect of the length scale.

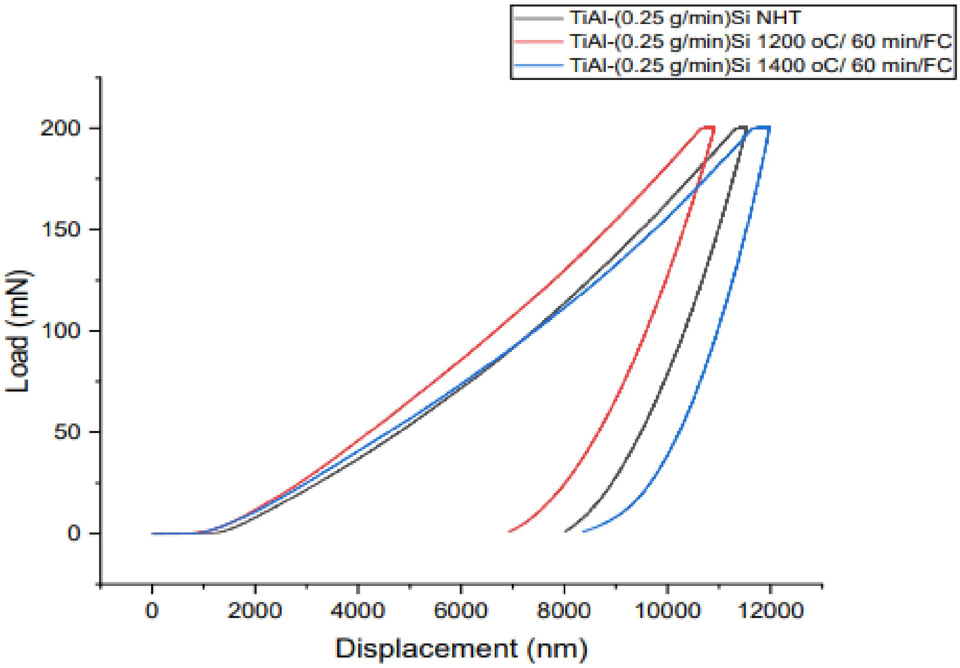

Figure 1: *Nanoindentation Load-Displacement Curves of Ti-Al-0.025 g/min Si Alloy*

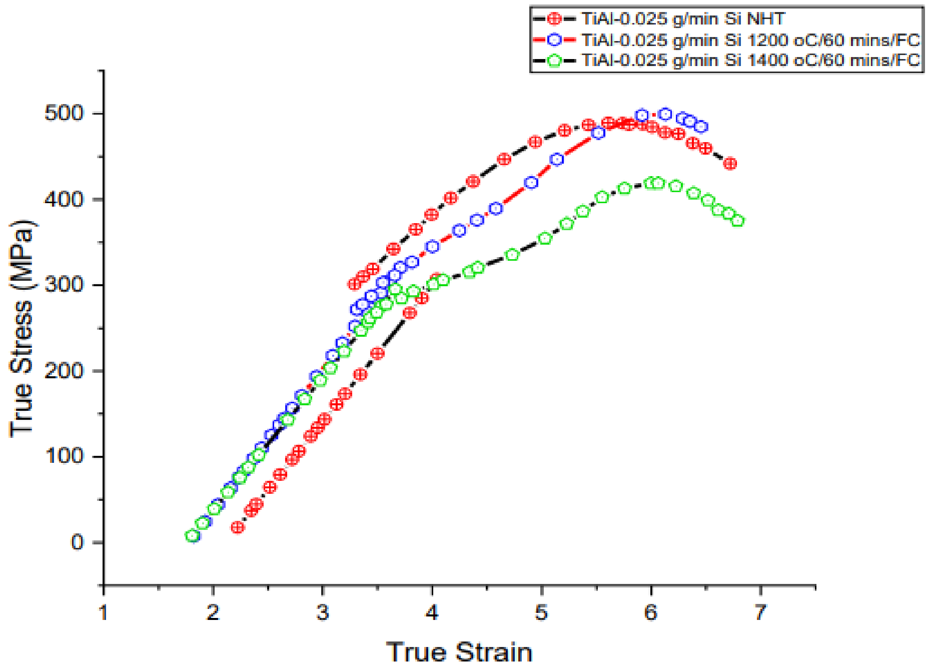

Figure 2: *True Stress-True Strain Curves of Ti-Al-0.025 g/min Si Alloy*

Wear Results

Evaluating the tribological behaviour is crucial in order to determine the longevity of TiAl-based alloy components in service. For high-temperature TiAl-based alloys to remain stable over time when other components are present that constantly rub against one another, this is a crucial feature. The wear rate and coefficient of friction (also known as μ) of the as-built and heat-treated Ti-Al-0.025 g/min Si alloy, manufactured via LENS, are displayed in Figure 3. Figure 3 shows that, on average, the CoF decreases from the as-built sample (0.428) to the 1200 ºC/60 mins/FC sample (0.193), with the lowest value of CoF being found in the 1400 ºC/60 mins/FC sample (0.137). But because the wear rate rose in the opposite direction,

it displayed an inverse proportionality to the CoF. Thus, the sample that was heat-treated for 60 minutes at 1400 degrees Celsius had the maximum wear rate value of 2.28 x 10^{-5} mm^3 /N/m. The sample that was heat-treated for 60 minutes at 1200 degrees Celsius had the second-highest wear rate value, 1.083 x 10^{-5} mm^3 /N/m, while the as-built sample had the lowest wear rate, 4.499 x 10^{-6} mm^3 /N/m.
The ternary Ti-Al-Si alloy's tribological behaviour indicates that the alloy will wear out more quickly with lower CoF. The hard ζ-Ti_5Si_3 particles and the FL microstructure of the 1400 ºC/60 mins/FC sample were found to be responsible for the elevated wear rate. More material removal from the surface as a result during the sliding test. As observed from the SEM image reported in our previous work, Raji *et al.* (2021a), the as-built sample had the maximum CoF and the lowest wear rate due to the limited number of ζ-Ti_5Si_3 particles and presumed unmelted Al. Additionally, the heat-treated 1200 ºC/60 min/FC sample's CoF was almost identical to the as-built sample's 1400 ºC/60 min/FC value, which was less than half of that of the former. However, the wear rate is less than half of the 1400 ºC/60 mins/FC sample and nearly three times that of the as-built sample. Thus, for the ternary Ti-Al-Si alloy, 1200 ºC/60 mins/FC had comparatively balanced tribological properties.
A further breakdown threshold for α_2 is provided by the need for it to delaminate into fine α_2 and γ lamellae due to the diffusion of a large number of silicon atoms following heat treatment. Furthermore, as ζ-Ti_5Si_3 particles would remove Si from α_2 lamellae, the main cause of α_2 dissolution was the common deposition of silicides in α_2 lamellae (Huang, 2013). The effort and coherent precipitation of Si to give friction-reducing qualities as a result of the refined microstructures of the in situ alloyed samples is accountable for the outstanding wear properties of the produced alloys. Notably, the non-porous and crack-free behaviour is thought to have played a direct role in the comparatively low friction coefficient that was attained, since the addition of Si particles might have altered the microstructural evolution and improved the alloy that was created (Kanyane *et al.* 2024). Because of the fast cooling caused by the LENS process, the as-built alloy has smaller grains, which helps the Ti-Al-Si alloy have less surface area in contact with the stainless-steel ball, reducing the smearing effect. Furthermore, the alloy has been strengthened more by the additional ζ-Ti_5Si_3 phase that has developed, which lowers the possibility of surface enhancement.

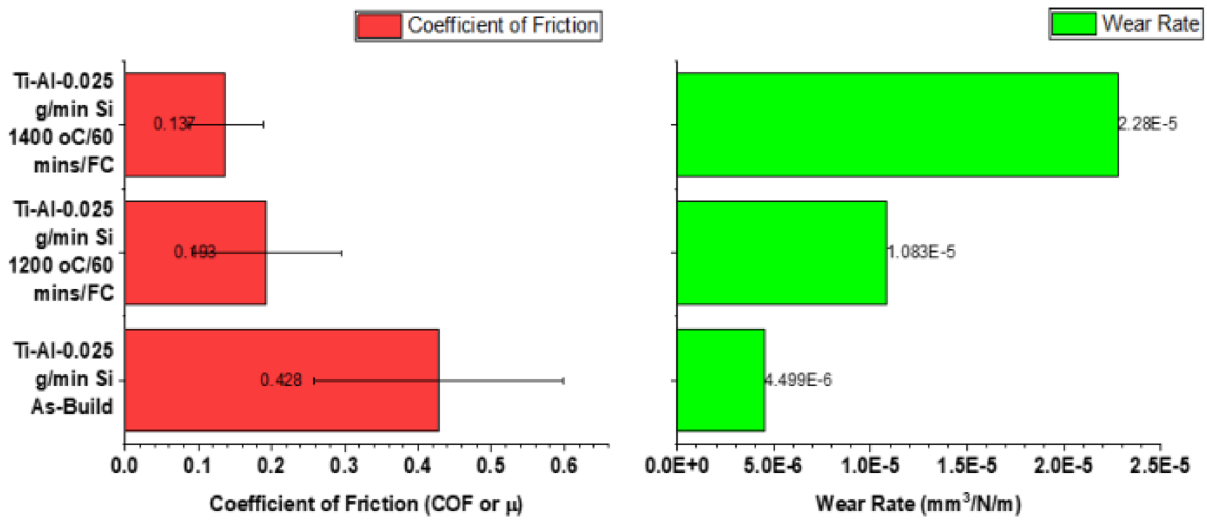

Figure 3: *Coefficient of Friction and Wear Rate of Ti-Al-0.025 g/min Si Alloy*

TGA Results

It is vital to assess the high-temperature stability in order to determine the longevity of TiAl-based alloy components in service. TiAl alloys' oxidation behaviour is a crucial component of high-temperature applications for gas turbines and engines in cutting-edge supersonic aircraft (Qu *et al.* 2018). Given that the operational temperature range of a turbocharger is between 700 and 950 degrees Celsius, this poses a serious problem for aero-engine applications. Extended stability in the presence of air is a crucial feature of high-temperature TiAl-based alloys, as the microstructure and mechanical properties must be maintained for the duration of the component's life (Huang, 2013). The Ti-Al-0.025 g/min Si alloy, as-built and heat-treated, was manufactured using LENS, and Figure 4 displays the TGA curves for it. The TGA findings display mass gain or loss in relation to the sample's initial mass per unit area as a function of temperature. It is implied that the corrosion products generated stayed adhered to the sample surfaces when the mass gain is recorded. This is dependent upon the chemical bonds (nitrogen and oxygen) that are created with air. A negative mass change is noted in cases where the solid scaling spalls or products of corrosion are flammable, indicating the loss of alloy components Kai, Chang and Bai, 2001; Mengis, Ulrich, Watermeyer, Liebscher and Galetz, 2021; Mitoraj-Królikowska and Drożdż, 2022).

It was observed that the as-built sample had a sharp drop in mass after 400 degrees Celsius, with mass loss going in the opposite direction. Up to 800 ºC, the cumulative mass loss persisted in decreasing, leading to a slight increase in the cumulative mass that indicates mass gained. The mass acquired at 800 ºC, however, was insufficient to make up for all of the material lost. Although the mass loss was also noted to be negative, indicating the loss of alloy components as a result of the development of volatile corrosion products, the heat-treated samples showed better high-temperature stability. Additionally, the heat-treated samples showed an acute loss of mass at 500 ºC and 525 ºC, respectively, for the 1200 ºC/60 mins/FC and 1400 ºC/60 mins/FC samples. The mass gain that was generally observed in all the samples between 800 and 900 degrees Celsius indicates that the oxide layers that have formed are solid and adhered to the surface samples. The findings indicated that the development of Al_2O_3 and TiO_2 oxides on the alloy surface had a higher thermodynamic probability. The produced alloys generally exhibited good oxidation behaviour at high temperatures, which qualified them for use in gas turbine applications (Kanyane *et al.* 2023). It is evident that the addition of Si and heat treatment have increased the oxidation resistance. The boost is mostly attributed to the dissolved Si's solid solution hardening action and the finer lamellar thickness (Kastenhuber *et al.* 2018).

It is determined that by adding small amounts of Si to the TiAl alloy system along with carefully thought-out heat treatment techniques, an improved alloy performance lifespan can be achieved. A developed Ti-Al-Si alloy had a microstructure made up of γ-TiAl/α_2-Ti_3Al lamellae that were distinctive, with ζ-Ti_5Si_3 particles located at the grain boundaries. The alloy showed its high-temperature oxidation kinetics at 800 and 900 degrees Celsius, as well as a higher resistance to oxidation over 700 degrees Celsius (Qu *et al.* 2018). The present study on Ti-Al-Si alloy has further discovered that the combination of heat treatment as Si in TiAl alloy has a favourable effect on the mechanical characteristics, indicating that the manufacturing method matters in terms of the alloy performance.

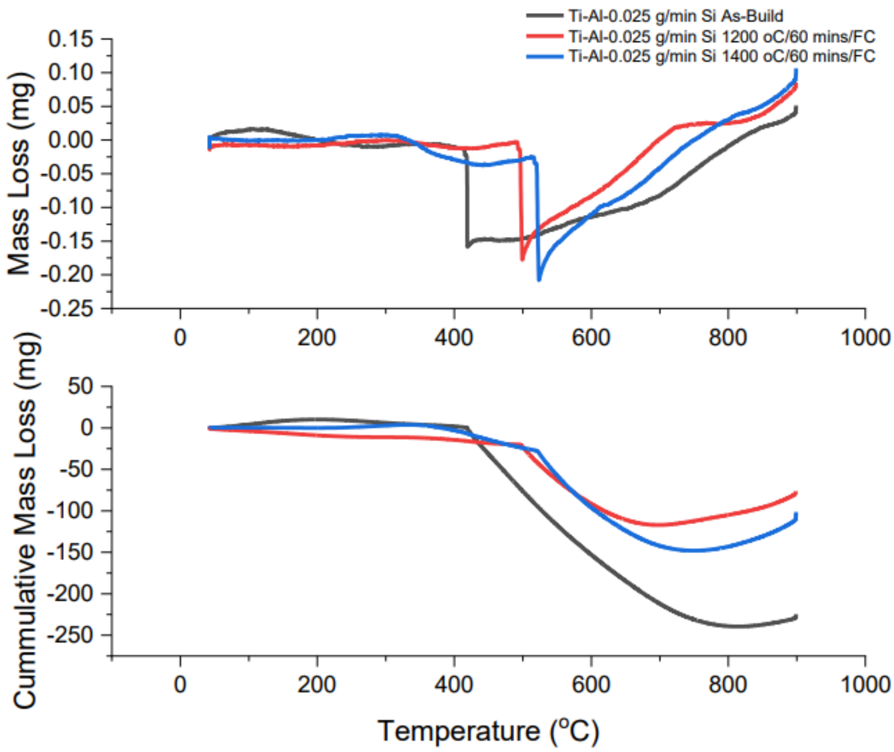

Figure 4: *TGA Curves of Ti-Al-0.025 g/min Si Alloy*

CONCLUSIONS

This study examined the effects of heat treatment on the wear, oxidation, and nanomechanical characteristics of Ti-Al-Si alloy created via LENS in-situ alloying. It was determined by this investigation that:

1. Although the ternary Ti-Al-Si alloy samples would deform plastically at lower stress levels than GE, its as-built and heat-treated (1200 ºC/60 mins/FC) sample's UTS value suggests that it has greater fracture toughness than GE alloy that is sold commercially.
2. The wear rate of the ternary Ti-Al-Si alloy heat-treated at 1200 ºC/60 mins/FC is less than half of the 1400 ºC/60 mins/FC sample and nearly a third of the as-built sample.
3. The Ti-Al-Si alloy samples exhibited mass gain between 800 ºC and 900 ºC on average. This indicates that the oxide layers generated are solid and adhere to the surface samples, boosting their resistance to oxidation at high temperatures.

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REFERENCES

Ahmadi, M., Hosseini, S.R. & Hadavi, S.M.M. 2016. Effects of Heat Treatment on Microstructural Modification of As-Cast Gamma-TiAl Alloy. *Journal of Materials Engineering and Performance*, 25:2138-2146. https://doi.org/10.1007/s11665-016-2067-7

Burtscher, M., Alfreider, M., Schmuck, K., Clemens, H., Mayer, S. & Kiener, D. 2021. In Situ Fracture Observations of Distinct Interface Types within a Fully Lamellar Intermetallic TiAl Alloy. *Journal of Materials Research*, 36:2465-2478. https://doi.org/10.1557/s43578-020-00088-z

Gong, X., Chen, R.R., Fang, H.Z., Ding, H.S., Guo, J.J., Su, Y.Q. & Fu, H.Z. 2018. Synergistic Effect of B and Y on the Isothermal Oxidation Behavior of TiAl-Nb-Cr-V Alloy. *Corrosion Science*, 131:376-385. https://doi.org/10.1016/j.corsci.2017.12.013

Huang, X.M., Zhu, L.L., Cai, G.M., Liu, H.S. & Jin, Z.P. 2017. Experimental Investigation of Phase Equilibria in the Ti–Al–Mo Ternary System. *Journal of Materials Science*, 52:2270-2284. https://doi.org/10.1007/s10853-016-0520-5

Huang, Z.W. 2013. Thermal Stability of Ti-44Al-4Nb-4Hf-0.2 Si-1B alloy. *Intermetallics*, 37:11-21. https://doi.org/10.1016/j.intermet.2013.01.011

Kahrobaee, Z. & Palm, M. 2022. Experimental Investigation of Ti–Al–Si Phase Equilibria at 800–1200°C. *Journal of Alloys and Compounds*, 924:166223. https://doi.org/10.1016/j.jallcom.2022.166223

Kai, W., Chang, M.T. & Bai, C.Y. 2001. The Corrosion of Titanium Aluminides in H2/H2S/H2O Atmospheres at 800–1000 C. *Oxidation of Metals*, 56:191-214. https://doi.org/10.1023/A:1010313726584

Kanyane, L.R., Popoola, A.P.I., Pityana, S., Raji, S.A. & Tlotleng, M. 2023. Laser In Situ Synthesis and Computational Thermal Analysis of Ti-Al-xCr Alloys: Microhardness, Electrochemical Behavior and Tribological Properties. *Journal of Materials Engineering and Performance*, 32:9838–98501. https://doi.org/10.1007/s11665-023-08257-x

Kanyane, L.R., Raji, S.A. & Tlotleng, M. 2024. Electrochemical and Tribological Performance of Ti–Al with xNb Addition Synthesized via Laser In situ Alloying. *Journal of Bio-and Tribo-Corrosion*, 10(1):8. https://doi.org/10.1007/s40735-023-00812-2

Kastenhuber, M., Klein, T., Clemens, H. & Mayer, S. 2018. Tailoring Microstructure and Chemical Composition of Advanced γ-TiAl Based Alloys for Improved Creep Resistance. *Intermetallics*, 97:27-33. https://doi.org/10.1016/j.intermet.2018.03.011

Knaislová, A., Novák, P., Linhart, J., Szurman, I., Skotnicová, K., Juřica, J. & Čegan, T. 2021. Structure and Properties of Cast Ti-Al-Si Alloys. *Materials*, 14(4):813. https://doi.org/10.3390/ma14040813

Lerch, B., Draper, S., Pereira, M. & Zhuang, W. 2003, January. Durability Assessment of Various Gamma TiAl Alloys. In: *3rd International Symposium on Gamma Titanium Aluminides*. , San Diego, CA, USA :1-7.

Mengis, L., Grimme, C. & Galetz, M.C. 2019. High-Temperature Sliding Wear Behavior of an Intermetallic γ–Based TiAl Alloy. *Wear*, 426:341-347. https://doi.org/10.1016/j.wear.2018.11.025

Mengis, L., Ulrich, A.S., Watermeyer, P., Liebscher, C.H. & Galetz, M.C. 2021. Oxidation Behaviour and Related Microstructural Changes of Two β_0–Phase Containing TiAl Alloys Between 600°C and 900°C. *Corrosion Science*, 178:109085. https://doi.org/10.1016/j.corsci.2020.109085

Mitoraj-Królikowska, M. & Drożdż, E. 2022. Some Aspects of Oxidation and Reduction Processes in Ti–Al and Ti–Al–Nb Systems. *Materials*, 15(5):1640. https://doi.org/10.3390/ma15051640

Musi, M., Graf, G., Clemens, H. & Spoerk-Erdely, P. 2023. Alloying Elements in Intermetallic γ‐TiAl Based Alloys–A Review on Their Influence on Phase Equilibria and Phase Transformations. *Advanced Engineering Materials*, :2300610. https://doi.org/10.1002/adem.202300610

Noda, T., Okabe, M., Isobe, S. & Sayashi, M. 1995. Silicide Precipitation Strengthened TiAl. *Materials Science and Engineering: A*, 192:774-779. https://doi.org/10.1016/0921-5093(94)03313-7

Oliver, W.C. & Pharr, G.M. 1992. An Improved Technique for Determining Hardness and Elastic Modulus using Load and Displacement Sensing Indentation Experiments. *Journal of Materials Research*, 7(6):1564-1583. https://doi.org/10.1557/JMR.1992.1564

Oyen, M.L. & Cook, R.F. 2009. A Practical Guide for Analysis of Nanoindentation Data. *Journal of the Mechanical Behavior of Biomedical Materials*, 2(4):396-407. https://doi.org/10.1016/j.jmbbm.2008.10.002

Raji, S.A., Popoola, A.P.I., Pityana, S.L. & Popoola, O.M. 2020. Characteristic Effects of Alloying Elements on β Solidifying Titanium Aluminides: A Review. *Heliyon*, 6(7):e04463. https://doi.org/10.1016/j.heliyon.2020.e04463

Raji, S.A., Popoola, A.P.I., Pityana, S.L., Popoola, O.M., Arthur, N.K.K. & Tlotleng, M. 2021. Modelling and Simulation of the Fatigue Usage Factor of γ-TiAl Alloy Fabricated through Laser Additive Manufacturing (LAM). *Suid-Afrikaanse Tydskrif vir Natuurwetenskap en Tegnologie*, 40(1):154-161. https://hdl.handle.net/10520/ejc-aknat_v40_n1_a46

Raji, S.A., Popoola, A.P.I., Pityana, S.L. & Tlotleng, M. 2021. Microstructure and Mechanical Properties of Heat-Treated Ti-Al-Si Alloy Produced via Laser In Situ Alloying. *Journal of Materials Engineering and Performance*, 30:3321-3332. https://doi.org/10.1007/s11665-021-05681-9

Tlotleng, M., Lengopeng, T., Seerane, M.N. and Pityana, S.L. 2017. Efects of Heat-Treatment on the Microstructure of TiAl–Nb Produced with Laser Metal Deposition Technique. In: *Materials Science & Technology 2017, David L. Lawrence Convention Center, Pittsburgh, Pennsylvania, USA*. http://hdl.handle.net/10204/9874

Qu, S.J., Tang, S.Q., Feng, A.H., Feng, C., Shen, J. & Chen, D.L. 2018. Microstructural Evolution and High-Temperature Oxidation Mechanisms of a Titanium Aluminide Based Alloy. *Acta Materialia*, 148:300-310. https://doi.org/10.1016/j.actamat.2018.02.013

Yu, W., Zhou, J., Yin, Y., Tu, Z., Feng, X., Nan, H., Lin, J. & Ding, X. 2022. Effects of Heat Treatments on Microstructures of TiAl Alloys. *International Journal of Minerals, Metallurgy and Materials*, 29(6):1225-1230. https://doi.org/10.1007/s12613-021-2252-z

INVESTIGATING THE INFLUENCE OF ERGONOMICS IN THE SOUTH AFRICAN AUTOMOTIVE INDUSTRY: GLOBAL VIEW

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ABSTRACT

The applications of ergonomics, also known as human factor (HF/E) systems techniques, are essential since they are focused on enhancing human comfort while working and raising output and product quality. Poor working conditions in the automotive and vehicle manufacturing industries are frequently linked to injuries among assembly workers, which in turn cause musculoskeletal diseases (MSDs). The Six Sigma methodology is applied to every industrial assembly line station, and it has been determined that the workers' posture is noticeably awkward while doing their tasks. Identifying issues that affect job quality and creating workable solutions to lower variability, boost flexibility, and meet customer objectives are all achievable with the help of the Six Sigma Industrial Engineering problem-solving tool. In addition, Saunders Research Onion approaches, philosophies, methodological decisions, and strategies are employed in assessing a method and process for gathering data and conducting additional data analysis. The seven examples in this paper represent engineering methods that can be used to prevent Musculoskeletal Disorders (MSDs), albeit they may not cover all possible avenues for alignment with Six Sigma. The technique can generally be used to evaluate MSD risk directly, as it would be a traditional "quality" concern, or it can be used to consider MSD risks as a contributing factor to other production challenges, such as inadequacies in quality. Productivity quality and MSD risk reduction goals are more likely to be met with a more robust understanding of ergonomics. The influence of ergonomics in the automotive industry is accurate, and it is critically important for more studies to be done. In conclusion, implementing a successful ergonomics program can help prevent most ergonomic risks.

Keywords: Ergonomics, Human factors, Automotive Industry

INTRODUCTION

The automotive industry is one of the significant industries in South Africa that has the highest economic contribution. The sector has the highest employment rate and makes a sizable contribution to the GDP. Car manufacturers have higher supply expectations for their assembly lines due to the highly competitive, rapidly expanding, and high demand in the automotive industries locally and globally. The daily production outputs set to satisfy customer demand are influenced by rising customer expectations. Employee fatigue, MSD cases, and other workplace injuries are also brought on by higher product demand. As a result, there is an evident increase in absenteeism and medical attention required by the employees, which overall impacts productivity. Many manufacturing industries have a proactive approach to implementing Ergonomics mitigation steps during the planning phase, running prototype trials, and any process planning effort before the actual Start of Production (SOP). The ergonomics evaluation is also done during the design review to eliminate human variability that may not allow the operator to perform their function because of bad design. Changes are less expensive and simpler during the early design stages of new items and production planning. Since this is the case, several automakers utilize digital human modelling tools (DHM)1 to assess physical workload and identify ergonomic concerns (Falck, et al., 2008). This is mainly done for two reasons: to ensure better product quality through an improved assembly process and to ensure the design specification matches human variability. This study attempts to draw attention to and increase understanding of the relationship between human factors and ergonomics and its impact on overall product quality and other deliverables like employee productivity and performance to offer solutions. The significance of the study is to demonstrate ergonomic interventions that can be adapted or applied in varied contexts, especially in communities with different resource availabilities and cultural backgrounds, thus embodying the Appropriate Technology principles of designing with particular consideration for the intended community's specific needs and conditions.

The study also seeks to increase productivity inside assembly lines while considering all other system components, design principles, data, and techniques to enhance individual well-being and system performance.

LITERATURE REVIEW

The influence of ergonomics on assembly might have played a significant role in the overall product quality. An effective job style involves workers in job-related tasks that forecast worker output, division productivity, and structure success (Bhatia and Arora, 2021:1). Most organizations' highest priorities are an effective and efficient movement of the manufactured product out of the production lines. In most instances, this is done without factoring in how other elements within a system interact with the humans performing the job. According to Atnafu and Balda (2018), human demand is when an instrument is valuable and safe, tasks are consistent with the area unit, and people's expectations of completing tasks are met.

Before car production becomes standard, problems like physical injuries are addressed and evaluated earlier. However, organizational characteristics, environmental factors, technology, tools, and tasks are rarely unaccounted for. Other dangers, including accidents, manufacturing mistakes (repairs), and influential movements, are frequently disregarded. Ergonomics addresses the difficulties in preventing sickness, and poor ergonomic behavior results in chronic conditions or injuries more frequently (Maksimović et al.,2022).

One of the most significant adverse impacts of bad ergonomics is the layout and design of the workstations. Additional factors, such as the type of technology employed in conjunction with the duties being carried out, cause extra health issues for people and thus impair the caliber of their output to the product. Since human reaction is influenced by environmental, physiological, and psychological variables, engineering and management strategies must be implemented in work organization to minimize exposure to harmful physical conditions and their effects on workers (Feijão et al., 2023:1). The study of ergonomics focuses on how to design products and surroundings that are compatible with people's abilities and limitations in terms of their physical, cognitive, and psychological capabilities. While doing so, it aims to protect people's health, safety, and well-being while maximizing productivity and performance (Ngcamu-Tukulula, 2023). The physique of a human cannot adjust to every circumstance. This issue is not carefully considered before hiring people for a position because people have limitations and differences (MacLeod, 1994). Musculoskeletal Disorders (MSDs) and high sick leave rates among assembly workers are frequently linked to a poor work environment in the automotive industry. In addition, numerous studies have demonstrated a direct link between assembly ergonomics and product quality, demonstrating that inefficient assembly ergonomics leads to worse product quality and higher production costs (Falck, et al., 2008).

It is vital to acquire vital information on planning this study and compiling the results, which may require several contacts at all company levels (Falck, et al., 2008). The conclusion of the evaluations demonstrates a very high correlation between bad ergonomics and the number of quality problems found, according to numerous writers who explored a related topic connected to how ergonomics affects the product. Integrating plant-wide Human Factors/Ergonomics programs into the corporate culture is the best way to reduce ergonomics risks. There is proof that having a good ergonomics program gives you an edge over others and results in a competitive advantage. People who use ergonomics must be thoroughly aware of the discipline's entire range. (Hutchings, 2020). To provide answers to workplace issues, understanding the discipline implies taking a holistic approach that takes other HF/E variables into account, such as the physical aspect, cognitive aspect, environmental aspect, social aspect, and organizational component.

Integrating Lean Six Sigma and Ergonomics

Six Sigma and Lean Management concepts are the most promising approaches to organizations' continuous improvement. While Six Sigma focuses on lowering process variability, Lean focuses on removing waste causes and aiming for a continuous process flow. It is well acknowledged that they complement one another, and businesses frequently create collaborative programs that combine Lean and Six Sigma. As a result, today, Lean Six Sigma (LSS) is the name given for the technique that combines these two principles. The LSS concept is a corporate philosophy and strategy that promotes ongoing manufacturing process improvement to increase customer happiness and profit (Nunes, 2015).

Managers frequently unintentionally limit ergonomics' scope of intervention to hazards because it is most commonly housed within the Occupational Safety and Health (OSH) department, primarily to comply with legal requirements and perform risk management. This prevents managers from using ergonomics' assistance to improve organizational effectiveness, business performance, or costs. Continuous improvement procedures should be carried out by combining ergonomic and Lean Six Sigma methodologies to improve productivity and working conditions. Integrating ergonomics and LSS must be done systematically (Nunes, 2015).

Changes to work processes and procedures are typically necessary when implementing LSS integrated with ergonomics. The success of this integration is impacted by the fact that employees frequently exhibit inertia when it comes to adopting suggestions for improvements, altering their work habits, and even learning new skills (Melton, 2005; Walder et al., 2007; Bhat et al., 2014; Bhat et al., 2016).

Six Sigma: Prevention for Musculoskeletal Disorder and Opportunities for Ergonomics

Industrial engineering's Six Sigma methodology is a data-driven, statistics-based approach to performance improvement. To maintain quality, increase organizational production, and satisfy customer expectations, Six Sigma tools can assist in identifying challenges that affect work quality, developing solutions to control process variability, and creating feedback. Because of the parallels and complementing ideas, it uses a philosophy from Total Quality

Management (TQM), which has been closely associated with Lean (Greig & Neumann, 2018).

The Six Sigma idea was first introduced in the mid-1980s at Motorola, and it has since developed and moved from manufacturing to other fields like healthcare, the automotive industry, and other manufacturing (Greig & Neumann, 2018). Six Sigma uses a broad range of tools and approaches to manage initiatives that seek to reduce quality deficiencies. These instruments could also be used to lower the risk of musculoskeletal disorders (MSDs) and enhance the standard of workplaces.

The Six Sigma approach and techniques can be an intersection point for ergonomics approaches. This position paper covers some Six Sigma tools and techniques, briefly explains them, and connects them to MSD prevention and ergonomic tools.

The focus is on seven other standard tools:

- Define, Measure, Analyze, Improve/Implement, Check (DMAIC)
- Pareto Analysis
- Process Mapping
- Data Collection Sheet
- Fishbone Diagram
- 5 Whys
- Failure Modes and Effects Analysis (FMEA)

Applying DMAIC principles for performance improvement

Define, Measure, Analyze, Improve/Implement, Check is a standard overarching improvement process associated with Six Sigma. Each phase in the process of developing process control has a specific purpose. Ergonomics Practitioners employ a similar mental model in their ergonomic evaluations as they do while following the MSD Prevention Guidelines, which use a similar investigation process flow. DMAIC provides the improvement process with a formal, structured method, which may be more recognizable to other company members.

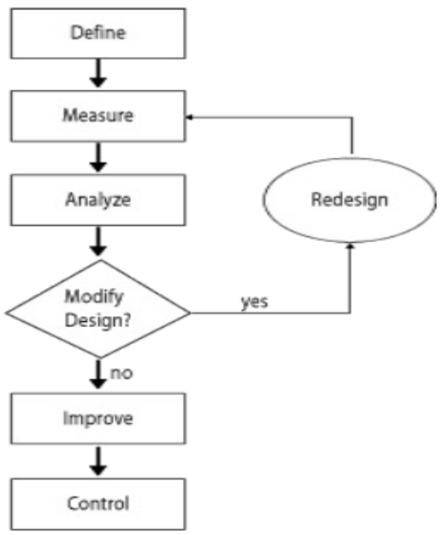

Figure 1: Five phases that make up the DMAIC process.

Figure 1 represents the five phases that make up the DMAIC process:
Define – Identify the issues that need to be resolved, assess their importance to the company or business, and set up a team for improvement. The cross-functional team will consist of the worker on the line, the line manager, an ergonomist, and process and equipment planners when identifying an issue linked to ergonomics.
The first five stages must be accomplished:

- Find the organizational values that define it.
- Find opportunities and potential
- investigate the possibilities on the list.
- Identify the projects' scope and objectives.
- Set the list of projects' priorities.

The choice of which Lean Six Sigma project to start with is made after completing these five processes.

Measure – To identify the issue and gather baseline data on how well the process or product works. Establish improvement targets and ensure a reliable measuring system is in place.

Analyze - Determine which process inputs or parameters impact the critical process outputs most.
There are two critical phases in the Analyze phase:

- Possible variations' causes
- identifying the primary reasons

Improve – The main objective of this phase is to find areas for improvement, supported by data on how these improvements advance the project's goals.
This phase consists of the subsequent actions:

- Locating the ideal solution
- Assessing the response

The objective is to create a fully functional process improvement that has undergone testing by the project team and is prepared for implementation in a natural business setting. The following factors determine the best option: Process performance as predicted, costs, implementation requirements, and risks.

Control – Implementing the selected solutions and ensuring their integration into the organizational process are the objectives of this final stage of the DMAIC methodology. Share the fixes with other interested parties that have the same problems.
The control plan contains a list of the process modifications. Each primary reason is described, along with how it is addressed by the new method of operation. The control plan also outlines how the risks associated with ergonomics will be tracked. In addition, the control plan specifies who oversees addressing any issues. The control plan also defines the intervals at which the process and any modifications are checked or audited to ensure permanent changes.

METHODOLOGY

This study's approach includes conducting in-person observations of the actions performed on the assembly line, following up with a talk with the lineside operator, and giving MB Suid-Afrika employees a comprehensive questionnaire. A qualitative research methodology was used for this examination. Nine (9) stations make up assembly line 2's boot, engine compartment, and side operations sections. Throughout the two (2) shifts out of three (3), a total of fifteen (15) operators will be chosen as a sample. Operators will be asked to respond to constructed questions about their workstations created using the system's five critical components for this study. It is frequently used to examine people's ideas, experiences, attitudes, behavior, and interactions. Qualitative research focuses on understanding a research question from a humanistic or idealistic perspective (Pathak et al., 2013). Face-to-face contact with the employees was used to conduct the research. It will also examine the extent of their job output and other influencing elements related to workstation design. This was a fantastic chance to collect the information required for additional investigation to determine the cause of the product's apparent low quality because of poor ergonomics. Nineteen (19) stations comprise the assembly line, divided into assembly lines 2A and 2B. The assembly line starts at Station 1 and runs until Station 19, whereas assembly line 2A runs from Station 1 to Station 9, the remainder being Assembly 2B. Given that the researcher oversees Assembly line 2A, conducting the study and evaluating the station was simpler, considering the process planning in place. To summarise processes in each station, the starting point was station 1 on both sides of the line, LHS & RHS. Each station process was summarised by highlighting tasks, equipment, tools, cognitive elements, and technologies. The next step was to identify each station's risk and establish an **Ergonomics Advisory Board** (EAB) status.

- **Red (high risk)** - High physical stress from work harms the body because of the high load (risk) level.
- **Yellow (medium risk)** - Medium load (risk) level entails moderate physical stress with potential adverse health effects if work is done for prolonged periods.
- **Green (low risk)** - Low physical stress and little chance of adverse physical effects from employment indicate a low load (risk) level.

ASSESSMENT EVIDENCE THROUGH STATION ANALYSIS

The risk assessment is done throughout the entire line. The Ergonomic Assessment Summary shows the station as bottlenecks and having more significant ergonomics stressors:

a. Station 1 LHS – Cockpit fitment LH
b. Station 1 RHS – Cockpit fitment RH
c. Station 3 LHS – Cockpit Connections LH
d. Station 3 RHS – Cockpit Connections RH
e. Station 4 LHS – LH Door Piping
f. Station 7 RHS – RH Door Piping
g. Station 8 LHS – LH Window bag
h. Station 8 RHS – RH Window bag
i. Station 9 LHS – LH Seatbelt
j. Station 9 RHS – RH Seatbelt

Analysing all Data and prioritization of all open risks

A list of risk factors and possibilities for risk reduction is then prioritized using all available information and insights. The fresh subjective and objective data and the already collected data are evaluated. Prioritizing these chances based on injury risk and severity is crucial for identifying significant insights and opportunities for risk mitigation.

Table 1: Summary of EAB results

STATION	PROCESS DESCRIPTION	EAB STATUS	BOTTLENECK AREA 1	POSTURE	LOAD	SHOULDER & ARM FORCES	ADDITIONAL STRAINS	UPPER LIMBS	COMMENT / STATUS DESCRIPTION
1 LHS	**Cockpit Fitment** LH	**EAB yellow**	42,10	3,20	**0,00**	37,90	1,00	0,80	Shoulder arm forces due to various push and pull forces of the manipulator (Highest measured force = 274N); Status Red - when the manipulator is challenging to align at 343N)
1 RHS	**Cockpit Fitment** RH	**EAB yellow**	**30,50**	21,30	0,00	5,20	4,00	18,50	Awkward sustained posture due to arms above shoulder (6.34%), trunk tilt (29.42%), and head rotation (23.18%) during Antenna routing.
3 LHS	**Cockpit Connection** LH	**EAB yellow**	28,90	10,70	9,10	5,10	4,00	29,10	Multiple clips (>5) using thumb/two fingers, a manual load of DC Tool (3kg), awkward sustained posture (sitting**, bend >20degrees) and** excessive reach, and hand used as a hammer on the insertion tool. Manual load of DC Tool - long extension -3kg.
3 RHS	**Cockpit Connection** RH	**EAB yellow**	**46,70**	28,20	9,10	5,40	4,00	30,70	Multiple clips (>5) using thumb/two fingers, a manual load of DC Tool (3kg), awkward sustained posture (standing**, bend forward >60 degrees) and** excessive reach, and hand used as a hammer on the insertion tool. Manual load of DC Tool - long extension -3kg.
4 LHS	**LH Front** Door Pipping	**EAB yellow**	**40,40**	15,80	**0,00**	22,60	2,00	46,50	Shoulder and arm force for door pipping installation (Ball of Thumb - 39.2N and 196.2N)
8 RHS	**RH Windowbag**	**EAB yellow**	38,70	**14,10**	**0,00**	22,60	2,00	37,00	Shoulder and arm force for door pipping installation (Ball of Thumb - 39.2N and 196.2N); Multiple Window bag clips (x9 clips at 30N) using thumb/four fingers.
8 LHS	**LH Windowbag**	**EAB yellow**	38,40	**13,80**	**0,00**	22,60	2,00	37,00	Shoulder and arm force for door pipping installation (Ball of Thumb - 39.2N and 196.2N); Multiple Window bag clips (x9 clips at 30N) using thumb/four fingers.
9 LHS	**LH Seatbelts** Front	**EAB green**	21,90	13,40	**0,00**	6,50	2,00	15,90	
9 RHS	**RH Seatbelts** Front	**EAB green**	**22,80**	13,50	0,00	7,30	2,00	25,00	

Table 1 displays the results in summary. Under "Process description," an overview of each process is provided. Other tasks are under the operator's purview; however, because they include using a manipulator for Cockpit fitment, the scope is summed up as "Cockpit fitment." An IT system called EAB is used to determine overall EAB. The Hand-Arm Vibration Calculator, RULA, REBA, and NIOSH lifting equation are all included in this system. The entire value is calculated by combining the posture kept at each station, the overall load, the shoulder and arm force, and any other extra stresses. The reasons for the general EAB status are discussed in the comments on the process description, and an answer is sought. Organizations should consider all legislative and regulatory requirements: Regulations, Acts, Standards, Codes of Practice, and Industry guidance notes. Recognizing and using scientific principles and concepts in risk management related to ergonomics is also beneficial. A comprehensive strategy that considers all pertinent HF/E components and considers complicated relationships is necessary for optimal HF/E management. Comprehend the work system and all its components, including people, tasks, tools, equipment, organizational variables, and the workspace. Understand how to measure different factors (objective and subjective measurements have value). Education and awareness of ergonomics play a critical role in the safety of employees.

CONCLUSION

A good ergonomics program involves more than just installing new equipment. It must be a continuous program with managerial direction and instruction. The mindset and cultural variety among agents are a hindrance to this accomplishment. Another way to incorporate ergonomics into current organizational procedures and problem-solving techniques is through Six Sigma. Human-friendly methods can make ergonomics improvement efforts easier to understand and more widely accepted. The seven examples in this paper illustrate engineering tools that can be utilized to prevent MSDs, although they do not exhaust all possible routes for alignment with Six Sigma. The tool can be used to either examine MSD risk directly as if it were a typical "quality" problem or to incorporate MSD risks as a contributing factor to other production issues, such as quality shortfalls. An improved understanding of ergonomics increases the possibility of improving production quality and MSD risk reduction goals. Organizations should consider all legislative and regulatory requirements: Regulations, Acts, Standards, Codes of Practice, and Industry guidance notes. Recognizing and using scientific principles and concepts in risk management related to ergonomics is also beneficial. A comprehensive strategy that considers all pertinent HF/E components and considers complicated relationships is necessary for optimal HF/E management. Comprehend the work system and all its components, including people, tasks, tools, equipment, organizational variables, and the workspace. Understand how to measure different factors (objective and subjective measurements have value). The importance of education and awareness. There are shared organizational and people responsibilities for controlling hf/e. It is vital to look at options to enhance ergonomics capability internally for more sustainable deployments of ergonomics. A multidisciplinary and participative approach to managing hf/e is necessary, involving employees and other stakeholders. The practical implication of this study is on the economy and health of community members who work in the automotive industries. Increasing productivity improves people's culture and the Appropriateness of Technology deployed in the communities focusing on ergonomics. A safety culture that supports and facilitates changes in ergonomics. The fundamental goal is to develop an ergonomics culture that is internally regulated. Future studies will create an optimized human collaboration model with machines to integrate LSS and ergonomics in manufacturing effectively.

REFERENCES

Falck, A. C., Hogberg, D. & Ortegren, R., 2008. *The influence of assembly ergonomics on product quality in car manufacturing - a cost-benefit approach.* Skovde, Department of Product and Production Development, Chalmers University of Technology, p. 2.

Falck, A., Ortengren, R. & Hogberg, D., 2008. *The influence of assembly ergonomics on product quality and productivity in car manufacturing – a cost-benefit approach,* Sweden: Department of Product and Production Development, Chalmers University of Technology.

Greig, M. & Neumann, P., 2018. *Six Sigma: Opportunities for Ergonomics & MSD Prevention,* s.l.: Centre of Research Expertise for the Prevention of Musculoskeletal Disorders.

Hutchings, J., 2020. *IMPLEMENTING AN ERGONOMICS PROGRAMME.* s.l., s.n., p. 4.

MacLeod, D., 1994. *The Ergonomics Edge: Improving Safety, Quality, and Productivity.* New York: Thompson Publishing.

Ngcamu-Tukulula, N., 2023. *Human Factors/Ergonomics Definition: Introduction to Human Factors/Ergonomics in Automotive Manufacturing Operations.* Pretoria(Gauteng): Smart Ergonomics.

Nunes, I., 2015. Integration of Ergonomics and Lean Six Sigma. A model proposal. *Science Direct,* pp. 1-2.

Ramdass, Kem, n.d.. The Implementation of Ergonomics as a Sustainable Competitive Advantage in the Clothing Industry.

Ramdass, K. & Pretorius, L., n.d.. The role of ergonomics towards performance improvement.

Melton, T., 2005. The benefits of lean manufacturing: what lean thinking offers the process industries. Chem. Eng. Res. Des. 83 (6), 662–673. https://doi.org/10.1205/cherd.04351.

Walder, J., Karlin, J., & Kerk, C. (2007). Integrated lean thinking and ergonomics: utilizing material handling assist device solutions for a productive workplace integrated lean thinking & ergonomics. Charlotte.

Bhat, S., Gijo, E.V., Jnanesh, N.A., 2016. Productivity and performance improvement in the medical records department of a hospital: an application of Lean Six Sigma. Int. J. Product. Perform. Manag. 65 (1), 98–125. https://doi.org/10.1108/IJPPM-04-2014-0063.

Bhat, S., Jnanesh, N.A., 2014. Application of Lean Six Sigma methodology to reduce the cycle time of out-patient department service in a rural hospital. Int. J. Healthc. Technol. Manag. 14 https://doi.org/10.1504/IJHTM.2014.064257.