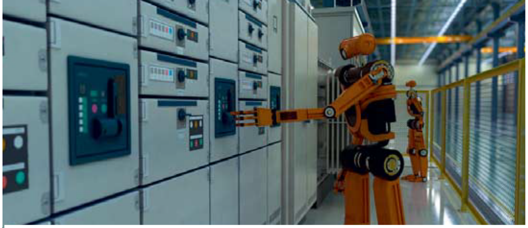
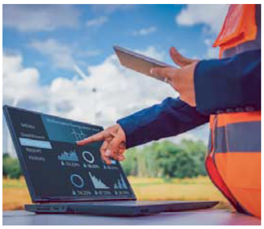


Advances in Transdisciplinary Engineering series

volume 44

Advances in Manufacturing Technology XXXVI

Proceedings of the 20th International Conference on Manufacturing Research, Incorporating the 37th National Conference on Manufacturing Research, 6th – 8th September 2023, Aberystwyth University, UK



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Advances in Manufacturing Technology XXXVI

Like many other fields, the area of manufacturing has advanced massively since the onset of the technological revolution brought about by advances in computing and smart technologies, and with the accelerating globalisation of manufacturing in the 21st century, the urgent need to keep pace has produced further rapid advancements in technology, research, and innovation.

This book presents the proceedings of ICMR2023, the 20th International Conference on Manufacturing Research, held from 6 – 8 September 2023 in Aberystwyth, Wales, UK. This annual conference is a friendly and inclusive platform for a broad community of researchers with the common goal of developing and managing the technologies and operations key to manufacturing. As well as bringing together researchers, academics, and industrialists to share their knowledge and experience, the conference also serves to promote manufacturing-engineering education, training and research. Reflecting the context of Industry 4.0 and beyond, the theme of the 2023 conference is sustainability in smart manufacturing environments. More than 68 papers were submitted for the conference, from which the 33 papers presented here were selected and accepted after a rigorous peer review process; an acceptance rate of 49%. The papers are grouped into 8 sections: operations and supply chain management; manufacturing technology; manufacturing and process modeling; robotics and simulation systems; supply chain systems; process characterization and simulation; operations and supply chain management; and design and prototyping.

Providing a wide-ranging overview of advances in the field, the book will be of interest to all those working in manufacturing research.

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Preface

The International Conference in Manufacturing Research (ICMR) is a major event for academics and industrialists who are engaged in manufacturing research. Held annually in the UK (except 2018 in Sweden) since the late 1970s, the conference is renowned as a friendly and inclusive platform that brings together a broad community of researchers who share a common goal: developing and managing technologies and operations that are key to sustaining the success of manufacturing businesses. For over two decades, ICMR has been the main manufacturing research conference organized in the UK, successfully bringing researchers, academics, and industrialists together to share their knowledge and experiences. Initiated as a National Conference by the Consortium of UK University Manufacturing and Engineering (COMEH), it became an International Conference in 2003.

COMEH is an independent body established in 1978. Its main aim is to promote manufacturing engineering education, training, and research. The Consortium maintains a close liaison with government bodies concerned with the training and continuing development of professional engineers, while responding to the appropriate consultative and discussion of documents and other initiatives. COMEH is represented on the Engineering Professor's council (EPC) and it organizes and supports manufacturing engineering education research conferences and symposia. Hosts for National Conferences on Manufacturing Research (NCMR) have been:

1985 Nottingham
1986 Napier
1987 Nottingham
1988 Sheffield
1989 Huddersfield
1990 -
1991 Hatfield
1992 Central England
1993 Bath
1994 Loughborough
1995 Leicester De Montfort
1996 Bath
1997 Glasgow Caledonian
1998 Derby
1999 Bath
2000 East London
2001 Cardiff
2002 Leeds Metropolitan

In 2003 the conference title became the International Conference in Manufacturing Research (ICMR) incorporating the NCMR. The host universities for ICMR have been:

2003 Strathclyde
2004 Sheffield Hallam
2005 Cranfield
2006 Liverpool John Moores
2007 Leicester De Montfort
2008 Brunel
2009 Warwick
2010 Durham
2011 Glasgow Caledonian
2012 Aston
2013 Cranfield
2014 Southampton Solent
2015 Bath
2016 Loughborough
2017 Greenwich
2018 Skövde, Sweden
2019 Queen's University Belfast
2021 Derby
2022 Derby
2023 Aberystwyth

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Acknowledgements

On behalf of the ICMR2023 organising committee, first and foremost we would like to thank COMEH for inviting Aberystwyth University to host ICMR2023. We would like to take this opportunity to thank all the contributing authors for their high-quality papers submitted, the reviewers for their time and constructive comments, the keynote speakers for sharing their research with the delegates and the local organizing committee for their meticulous preparation of the conference. Our thanks go to the Programme Committee members who helped to review papers and ensure the high quality of the conference.

The theme of ICMR2023 conference is sustainability in smart manufacturing environments. Within the context of Industry 4.0 and beyond, ICMR2023 will bring researchers, academics, and industrialists together to share their vision, knowledge, know-how and experience, and discuss emerging trends and new challenges in the field. The conference includes a number keynote speeches / presentations presented by: Dr Rhian Hayward MBE, CEO of AberInnovation, Professor Paul Byard MD FSG Tool and Die Ltd, Professor Nigel Copner, Head of Engineering at Aberystwyth University, Lucas Brookes and Matthew Lee of Aber Instruments, Andrew Newbold Wipak UK Ltd and, Ken Toop of Dawson-Shanahan.

A special presentation will also be delivered by Dr Peter Osborne from Sheffield University's Innovation Launchpad Network. Special thanks also goes to Ceri Stephens of the Mid-Wales Manufacturing Group and Dr Fred Labrosse of Aberystwyth University for their support and representation at the conference.

The organisational arrangements for this conference has been undertaken by the staff from Aberystwyth Business School, Aberystwyth University. The editors are especially grateful to the help given by Ms Marina Hughes, Mr Ian Williams and, Ms Darci Evans. The organising committee would also like to than the COMEH and ICMR committee members for their continuous support and advice.

There are 33 papers accepted and presented in the proceedings, out of more than 68 papers submitted representing an acceptance rate of 49%.

The Editors

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Contents

Part 1

Advances in Operations and Supply Chain Management (1)

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Resilience of Marine Energy Supply Chains: The Manufacturers Challenge

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Abstract— Companies are operating in an era where **V**olatility, **U**ncertainty, **C**omplexity and **A**mbiguity (VUCA) is commonplace in manufacturing companies. To manage effectively in this environment, manufacturing supply chains need to adopt resilient strategies. Organisations continue to adopt various technologies in order to manage the VUC environment and Marine Renewable Energy (MRE) supply chains are seen as a front runner in emerging technologies which has an impact on the business environments and supply chain practices globally. In this study, the authors undertook a systematic literature review of 95 scholarly articles published on Marine-driven supply chains and explore the impact and importance of manufacturing resilience. A bibliometric analysis was carried out via the Scopus database and results filtered, coded, and analysed using the bibliometric-R package. The authors then evaluated the thematic areas of Marine Supply Chains and explored identified challenges and proposed areas of development to move towards a resilient manufacturing supply chain.

Keywords— Marine Renewable energy, Supply chain, VUCA, Manufacturing Resilience.

1. Introduction

Supply Chain Management theory explores the importance of understanding and adequately responding to uncertainty and risk within our supply chains [1]. Evidence suggests that although numerous projects are being implemented in the UK to harness Marine Renewable Energy (MRE), they are often subjected to various challenges from, establishing required supply chain capacity for the manufacture and implementation to ongoing maintenance and monitoring [2]. In particular, the supply chains of relatively new and technologically advanced products, such as MRE technologies, are deemed to be more volatile, uncertain, complex and ambiguous to challenges, risks, and disruptions [3]. This VUCA environment can be created due to several factors contributing to increasing the probability of exposure to risks and their associated impact on the supply chain, such as; availability of capacity, identification of appropriate suppliers, establishing new collaborative networks, and learning curves associated with new technology and processes etc. Previous research has indicated concern regarding the

MRE sector's readiness to respond quickly to rapid growth in demand and the impact of capacity availability to respond and therefore the increased sensitivity and impact of disruptive events. This has reinforced a call for a better understanding of how to improve supply chain resiliency in the marine energy sector. The future resiliency of the MRE supply chain sector, to a large extent, depends on adopting a dynamic, responsive strategic policy decision-making process in response to uncertainty and risk [4].

This research has specifically utilised the term Marine Supply Chain (MSC) to indicate research that focuses on regional players within the marine sector. It should be noted that the term MSC was utilised to capture the wider influencing network on the MRE supply chain. This allows the literature search to ensure the inclusion of research that focuses on exploring in depth the sustainability and resilience of the MRE supply chain practices embedded within the wider context.

A comprehensive evaluation of the complex dynamics and multi-dimensionality surrounding MRE projects is key to determining the fundamental changes and subsequent actions required to transition from fossil-fuel based energy sources to MRE technologies. Although the underlying mechanisms associated with the concepts of supply chain resiliency have been extensively researched in recent years, the wider adoption of tools designed as part of academic research to improve operational performance has been limited [5]. .

2. Material And Methods

To fulfil the objectives of the study, the authors conducted scientific mapping through a bibliometric analysis of articles filtered via a systematic literature review. The scientific mapping of the articles identified was conducted via the Bibliometrix R package [6]. From the bibliometric analysis authors identified the research themes representing the objectives of the study. To explore VUCA and resilient strategies and their linkage within published literature with the MRE supply chain, a set of key search terms were identified. The search terms utilized to identify the literature were "Marine"; "Renewable"; "Supply Chain" using the logical operator AND. This was then followed by the terms "Risk"; "Disruption"; "Resilience"; "Responsiveness"; "Disaster"; "VUCA" using the OR operator. These terms have been utilized in previous studies by [4] and [7]. Further, the search term was focused on the broader theme of MSC with supply chain practices only. Using the search criteria, the initial database search yielded 270 articles which through the filter process resulted in 95 journal papers for inclusion in the analysis. Figure 1 describes the search and filtering process.

3. Review Analysis and Results

To understand the article's spread with respect to the domain area; countries and the research areas, the authors used a sankey diagram to represent the relationship between countries, research area and source journals. The Sankey diagram is shown in Figure 2, where the flow between the countries; research areas and journals are established, and width of the flow represent the strength of relationship [6]. The analyis was focused on identifing and grouping the author's keywords which represent the constructs of MSC and Supply chain practices in the collected dataset. The tree diagram shown in Figure 3 shows hierarchical data with nested rectangles.

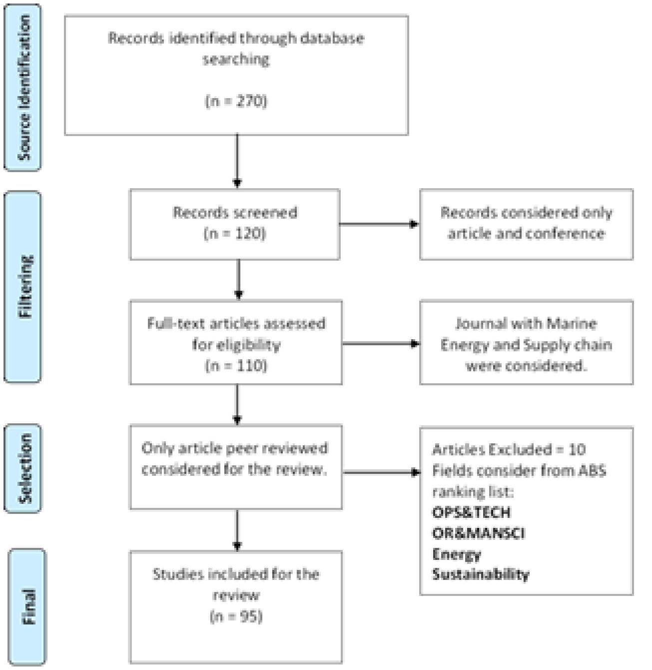

Figure 1 PRISMA Process for Literature Review Design

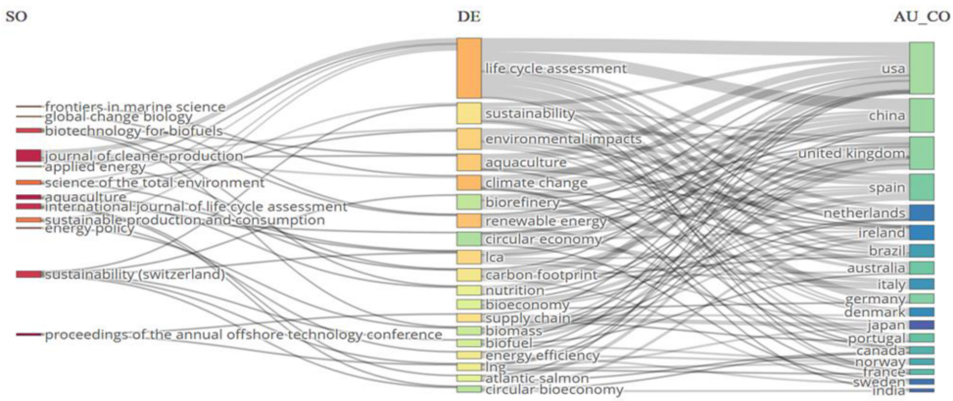

Figure 2 Flow between the Countries; research area and source

Each branch is a rectangle divided into smaller ones for sub-branches [6, 8]. Each cluster contributes to the three thematic areas as follows:

(1) Impact of MRE on supply chain practices
(2) Resilience in the Marine- driven supply chain
(3) Addressing disruption in Marine-driven supply chain

The clusters obtained from the tree map address the research question. Moreover, based on the thematic areas the authors evaluated the articles related to each theme and performed a content analysis to explore the research questions.

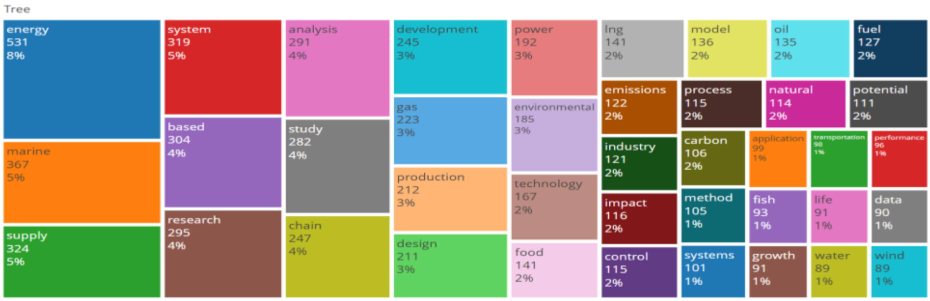

Figure 3. Tree map for unique areas

4 Review of the Three Thematic Areas

4.1 Impact of MRE on supply chain practices

Real-time data updation – enabling in-depth forecasting decision making, sensor-driven and IoT based devices capturing data in real-time [9]. *Supplier to customer visibility on a common platform* – decision support system ensures that data is used to create a single virtualized data layer for the ease of understanding the customer requirement in real-time. *Integrated business planning* shows that firms require availability and access to the wider triple helix environment including government policy, research and organizational experience thereby allowing integrated system analysis for developed action plans.

4.2 Resilience in the Marine driven Supply Chain

Predictive analysis - Adoption of capturing relevant system data and analyzing the considerable dataset, MSC is improving the capabilities of all the companies in areas of Predictive demand, network planning, delivery estimation, inventory planning and extend MRP [9]. *Smart Systems complexity* –the adoption of smart systems within the MSC primarily from a materials handling perspective. Bots are commonly used to restock the empty shelves or to deliver the stock from one destination to another inside a warehouse reducing errors and updating systems continually [10],[11]. However, these bots cannot solve issues autonomously, it requires human intervention because they pose narrow Artificial intelligence (ANI). However, the interface that connects the sensor network (Radiofrequency Identification - RFID; Near-field communication NFC) with the bot can be sophisticated and requires trained professionals to monitor and ensure smooth operations. *Customer uncertainty* **-** MSC-enabled chat Bots are smart that can interact with the end-user in the B2C industry to provide real-time delivery information and the status of the delivery [12]. Likewise, in some cases, it can even predict the accurate time in which the order will be delivered. However, the bots are in the early stage of interaction and trying to mimic human interaction through Super Artificial Intelligence (ASI).

4.3 Addressing disruption in the Marine-driven supply chain

Supply chain practices are managed globally with different stakeholders. Therefore, the organization ensures their practices can face risk and uncertainty. Baryannis et al. [8] reported Mathematical programming was preferred in risk management. Similarly, the Security and risk for food supply chain were addressed by [13] using the discounted system involving Markov decision process as well as a review on responsiveness, risk and resilience showed that ensuring responsiveness is crucial for supply chain operations [14].

5. Challenges to Consider for the Manufacturer

The literature review analysis undertaken within this research highlighted the following significant challenges and setbacks that impact the MRE supply chain resilience, these included: *Lack of quality & quantity in data mined* **-** Computational processes require a large amount of data and artificial intelligence is no exception to that. *Machine learning* (ML) hugely depends on data to learn and predict the outcome for the given scenario. However, getting the required data from different sources and siloes is a challenge for the organization. Further, the investment in data extraction through the data management module with the interlinked system is cumbersome [15]. *Short term optimization***-** Supply chain networks tend to consist of many players and systems connected within a complex network, with maturity at distinct levels. So, it is easy to lose sight of the process control and monitoring, leading to unpredicted consequences [16]. Short term solutions will lead to uncertainty as it may promote the restructuring of the supply chain design, creating ambiguity in the system and will incur significant loss to the system. Such a scenario creates volatility in supply chain optimization and transactions. So, the decision system will fail to achieve its optimal performance especially in terms of achieving resilience, resulting in arguable self-imposed complexity in the supply chain practices *Lack of Marine driven supply chain understanding* **-** Since there is a myriad of choice of available platforms the Marine driven supply chain could adopt and utilize, it can take time to understand, adapt and work within the context of the MRE sector [17]. There is a requirement to develop strategic relationships and collaborative strategies to ensure decisions are made with the supply chain in mind to reduce the additional issue of incompatible systems being adopted. The learning curve and bedding in time can reduce the productivity and efficiency level of the supply chain optimization in the short term or indeed mean the fully competitive advantage is not achieved in the long run thereby resulting in failure to improve the resilience [18]. *Global Uncertainties* **–** 'Black Swan' events like the COVID 19 pandemic have a huge impact on the supply chain industry and as examples show can easily disrupt the flow of goods and services and can quickly cripple a supply chain as the world responds for example with global curfews and the temporary ban on global trade [19]. These uncertain situations are difficult to predict even with sophisticated machine language or supply chain management software. Therefore, continued development of forecasting and prediction tools to optimize the supply chain dynamic performance and provide resilient strategies will continue to be one of the biggest challenges, and an area of continued research focus for the future.

6. Optimizing the MRE Supply Chain

Deploying an effective MRE supply chain strategy is challenging because of range of issues including: *Detection and collection of data*; setting the *parameter and constraints*; *sensor and decision support systems*; *networking with stakeholders*; *process mapping and monitoring* and, *feedback and response mechanism*. An integrated MRE supply chain that enables collaborative information sharing can serve as a mechanism to address these difficulties and improve supply chain performance. Therefore, the authors highlight that the organization should make ample investment in a Marine-driven ecosystem including policy development and communication, and resourcing (including time and financial). When viewed holistically the supply chain practices consist of the *Design: manufacturing Modelling; Network Coordination; Transaction; Collaboration and Optimization* some of which can be monitored by sensor systems [13]. Moreover, the adoption of an appropriate framework aids the organization in supply chain practices for better risk mitigation leading to improved resilience of the individual players as well as the holistic supply chain. An effective MSC is big data focused and driven with inputs from multiple sources, which is evaluated by the decision support system for effective decision making. The MSC can serve as a platform for monitoring global supply chain operations and avoid or at least minimize the impact of supply chain disruption through predictive analytics from the historical data. Moreover, the entire information must flow through the blockchain, therefore, making the information flow reliable and secure. However, the MSC requires skills development and training to enable research utilizing the data set to understand the nature of black swan events. Thereby enabling an understanding and development of contingency plans to cope with and manage even if the occurrence of black swan events, and decision-makers can validate the strategy to understand the efficiency of the MSC resilience. The literature reviewed indicates limited adoption of supply chain practices in this context are Marine driven. However, the MSC's usage classifies the nature of the supply chain practices. They are as follows: *Reactive Supply chain* - reacts to input with limited stimuli; *Responsive supply chain* – responds to inputs and produce feedback; *Intelligent supply chain* – understand the need and work with other entities and, s*elf-aware supply chain* – capable of human-like thinking and decision making.

7. Conclusions

From, the articles reviewed, many provided an empirical solution based on model development; however, the studies are specific to the industry. However, contribution to theoretical and conceptual research was limited. Further, most of the articles focused on conducting simulation-based studies and used a different algorithm. out of which, Decision Theory; robust optimization; swarm optimization and genetic algorithm were widely used. Approximately 50 studies reported on developing a decision model to address their issues in life cycle assessment. However, many studies have not developed any model for decision making. This therefore requires more in-depth research to explore the importance of utilising DSS to enhance the MRE supply chain resilience.

Further, the research indicated that risk and uncertainty in supply chain operations are very volatile, and life cycle assessment alone cannot provide an effective solution without sustainability and circular practices being examined and included. Interestingly only, 4% of the study coupled their decision support system with circular economy and 2% paper discussed the use of energy efficiency. This creates a gap in providing a decision on a real-time basis. The impact of Marine driven supply chain is arguably widely addressed within the literature examined however, the level (and depth) of the MRE supply chain that decides the nature of the practices employed and utilized requires more attention. Furthermore, more detailed understanding and testing in industry of effective models for crisis/risk management and disaster management needs to be undertaken to explore and address the changing situations especially given the projected rise of the MRE sector. This is especially important to ensure proposed enhancements and improvements to the MRE supply chain practices will optimise rather than hinder the resilience of the holistic system.

References

[1] Akbari, N., Jones, D., & Arabikhan, F. (2021). Goal programming models with interval coefficients for the sustainable selection of marine renewable energy projects in the UK. European Journal of Operational Research, 293(2), 748-760

[2] Leete, Simeon, Jingjing Xu, and David Wheeler. "Investment barriers and incentives for marine renewable energy in the UK: An analysis of investor preferences." Energy policy 60 (2013): 866-875.

[3] Noble, D. R., O'Shea, M., Judge, F., Robles, E., Martinez, R., Khalid, F., ... & Murphy, J. (2021). Standardising marine renewable energy testing: Gap analysis and recommendations for development of standards. *Journal of Marine Science and Engineering*, *9*(9), 971.

[4] Reis, Jeanette; Mason-Jones, Rachel; Lambert, Keith; Khandokar, Fahmida; Nguyet, Minh (2023). Seascape Review- Barriers to Marine Renewable Energy Supply Chain Development in Welsh Waters. Cardiff Metropolitan University. Conference contribution. https://doi.org/10.25401/cardiffmet.22816472.v1

[5] Gupta, N., Dutta, G., & Tiwari, M. K. (2018). "An integrated decision support system for strategic supply chain optimisation in process industries: The case of a zinc company." *International Journal of Production Research* 56(17): 5866-5882.

[6] Aria, M., & Cuccurullo, C. (2017): "bibliometrix: An R-tool for comprehensive science mapping analysis." *Journal of Informetrics* 11(4): 959-975.

[7] Baryannis, G., Validi, S., Dani, S., & Antoniou, G. (2019). "Supply chain risk management and artificial intelligence: State of the art and future research directions." International Journal of Production Research 57(7): 2179-2202.

[8] Mongeon, P., & Paul-Hus, A. (2016). "The journal coverage of Web of Science and Scopus: a comparative analysis." *Scientometrics* 106(1): 213-228.

[9] Bogataj, D., Bogataj, M., & Hudoklin, D. (2017). "Mitigating risks of perishable products in the cyber-physical systems based on the extended MRP model." International Journal of Production Economics 193: 51-62.

[10] Roozbeh Nia, A., Hemmati Far, M., & Akhavan Niaki, S. T. (2014). "A fuzzy vendor managed inventory of multi-item economic order quantity model under shortage: An ant colony optimization algorithm." *International Journal of Production Economics* 155: 259-271.

[11] Gupta, N., Dutta, G., & Tiwari, M. K. (2018). "An integrated decision support system for strategic supply chain optimisation in process industries: The case of a zinc company." International Journal of Production Research 56(17): 5866-5882.

[12] Benchekroun, S., Venkatesh, V. G., Dkhissi, I., Persis, D. J., Manimuthu, A., Suresh, M., & Sreedharan, V. R. (2023). Managing the retail operations in the COVID-19 pandemic: Evidence from Morocco. Managerial and Decision Economics, 44(1), 424-447.

[13] Chang, Y. C., & Wang, N. (2017). Legal system for the development of marine renewable energy in China. *Renewable and Sustainable Energy Reviews*, *75*, 192-196

[14] Wruck, S., Vis, I. F. A., & Boter, J. (2017). "Risk control for staff planning in e-commerce warehouses." *International Journal of Production Research* 55(21): 6453-6469.

[15] Hahn, G. J., & Kuhn, H. (2012). "Designing decision support systems for value-based management: A survey and an architecture." *Decision Support Systems* 53(3): 591-598.

[16] Kristianto, Y., Gunasekaran, A., & Helo, P. (2017). "Building the "Triple R" in global manufacturing." *International Journal of Production Economics* 183, 607-619.

[17] Santos, L. F. D. O. M., Osiro, L., & Lima, R. H. P. (2017). "A model based on 2-tuple fuzzy linguistic representation and analytic hierarchy process for supplier segmentation using qualitative and quantitative criteria." *Expert Systems with Applications*, 79: 1339-1351.

[18] Schätter, F., Hansen, O., Wiens, M., & Schultmann, F. (2019). "A decision support methodology for a disaster-caused business continuity management." *Decision Support Systems* 118: 10-20.

[19] Kumar, V. N. S. A., Kumar, V., Brady, M., Garza-Reyes, J. A., & Simpson, M. (2017). "Resolving forward-reverse logistics multi-period model using evolutionary algorithms." *International Journal of Production Economics* 183, 458-469.

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Adoption of Artificial Intelligence in Operations Management: A Design-Oriented Review

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Abstract: This is a review conducted in relation to the application of artificial intelligence in operations management particularly in the design aspects between the years 2010 – 2021. The purpose of this paper is to provide a survey of the usage of artificial intelligence methods in operations management aimed at presenting the themes, trends, direction of research and its practical impacts. Artificial Intelligence is playing a major role in the fourth industrial revolution, and a lot of evolution in various operations management and engineering scope. Artificial Intelligence techniques are widely used by operations managers to solve a whole range of intractable problems. This study provides a forum for rapid evaluation of the works describing the theoretical and practical application of artificial intelligence methods in operations management. The study reports some novel aspects of artificial intelligence used for real-world operations/engineering applications towards solving problems, increased productivity, reducing costs and improved customer satisfaction.

Keywords. Artificial Intelligence, Operations Management, Review, Survey

1. Introduction and Methodology

Organisations are becoming more competitive due to new regulations, global challenges, and focus on net zero energy. The adoption of Artificial Intelligence (AI) has helped organizations to deal with these challenges by providing solutions to uncertainties and achieving optimized results through reduced costs, speed, agility, efficiency, and flexibility. There have been an increased number of studies and publications for the adoption of AI in operations management. That is indicated by the annual increase in relevant publications in the recent decade. With over one hundred and twenty thousand (120,000) articles published between years 2010-2021 and over seventeen thousand (17,000) in operations management, that has associated complexity of understanding what else needs to be addressed. Other known issues linked with the use of repetitive publications, lack of substantial useful information hence not making significant contribution to knowledge are noted and avoided in this study.

The design and methodology adopted is like authors of previous surveys. To seek for literal replication of the review process and to build on the wealth of knowledge of authors, their

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experience(s) and expertise; the same areas of operations management on previous surveys (Kobbacy et al., 2011) was used which includes process planning and control, quality, maintenance and fault diagnosis and areas of design and scheduling. The areas from the previous survey have been maintained to represent the categories that will be researched.

- Case-based reasoning (CBR).
- Genetic algorithms (GAs).
- Neural Networks (NN).
- Knowledge-based Systems (KBS).
- Fuzzy logic (FL); and
- Data Mining (DM).

Due to core links with AI and page limitations; FL, GA, KBS and NN in the design aspects of AI only are presented in this paper. The Science Direct database was used to search for references using only the keywords that have been categorised in this paper. Review articles and research articles were identified while unrelated papers were removed. Further filtering was conducted to eliminate other forms of irrelevant papers to avoid double counting the same paper, however in most cases the title, abstract and conclusion sections were clear indicators to categorize the papers. This paper is arranged in four parts namely, introduction and methodology, survey and categories giving insights into the papers published in each section, the results presenting the quantitative data in this paper, and the conclusion.

2. Survey and Categories

2.1 Design

2.1.1 FL in Design

FL is employed in controllers for example, Youssef et al., (2018) reveal how to use FL for maximum power point tracking (MPPT) in photovoltaic systems, enabling it to function with different irradiance and temperature conditions. The proposed MPPT controller provides high flexibility and re-configurability, low cost of implementation and power usage. Costo Branco and Dente (2010) design and evaluate a fuzzy logic pressure controller for the braking system on an Airbus to achieve pressure control with high fit for hydraulic load fluctuations. Tzafestas et al., (2010) proposed the design of a FL in the control of autonomous non-holonomic mobile robots to discover a fuzzy path tracking algorithm. Cheng et al., (2010) investigated the design of a variable-voltage DC source using a fuzzy logic controller to handle load changes and input voltage fluctuations.

Furthermore, there are uses of FL in hybrid sectors; Tahmasebi and Hezarkhani (2012) adopted fuzzy logic in grade estimations which is useful in mine projects to overcome challenges due to difficulties of mineral ore deposits structural complications. Anifowose and Abdulraheem (2011) demonstrate functional networks, fuzzy logic driven and support vector machines to predict oil and gas reservoir attributes. Menghal and Laxmi (2016) discussed the control of an induction motor drive using fuzzy logic knowledge which was developed using MATLAB/Simulink to clarify the usefulness of PI and fuzzy control and to present an improved control performance of FLs algorithm over conventional PI controllers. Garcia-Diaz et al., (2013) argue for the use of FL models in software development effort estimation as an alternative to linear regression methods. The authors argued further by comparing two types of FL systems: Mamdani and Takagi-Sugeno and proving the outcome from the results of Takagi-Sugeno FL system to be more accurate than the other FL system as well as the linear regression model. Mehbodniya et al., (2013) established an innovative multi-criteria vertical handoff algorithm for heterogeneous wireless networks that achieves seamless mobility with maximal end-users' satisfaction using Fuzzy VIKOR (FVIKOR).

2.1.2 GAs in Design

Genetic algorithm is a process of natural selection used to generate high quality optimized solutions to problems by depending on selection, crossover and/or mutation. Pan (2010) used Canonic Signed Digit (CSD) coded GA to develop chromosomes by decreasing the time emaciated by trials and errors in the evolution process and to increase the training speed. An efficient hybrid code for the filter coefficients is suggested to enhance the precision of the coefficient of finite impulse response digital filter (FIR). Nagarajan et al., (2016) proposed the retrieval of any kind of medical image such as breast cancer, brain tumor, lung cancer, and thyroid cancer adopted to decrease the existing system dimensionality problems. The experiment proved that the GA directed image retrieval system chooses optimal subset of feature to recognize the right set of images using a machine learning based feature selection method. Luan et al., (2019) used the hybridization algorithm of GA and ant colony optimization (ACO) to provide a decision support tool that helps in solving the challenges associated with multicriteria decision making of supplier association. The unified algorithm has shown improved quality and efficiency with a methodological contribution to the optimization of algorithm research. Lee (2018) conducted a review of the applications of GA in operations management (OM) over a ten-year period ranging from year 2007 to 2017. The study encouraged the use of heuristic search methods for improved OM decisions as against non-deterministic polynomial hard problems algorithms.

2.1.3 NN in Design

Neural networks fundamentally reflect the behavior of the human brain, which allows computers to recognize patterns and solve problems.

Kamrunnahar and Urquidi-Macdonald (2010) utilized supervised neural network (NN) method as a data mining tool to forecast corrosion behavior of metal alloys. The NN model learned the basic laws that outline the alloy's composition and environment to the corrosion rate. Both DC and AC corrosion experiments were conducted with existing corrosion data on corrosion allowable and corrosion resistive alloys. The data mining outcomes recognized the categorization and prioritization of certain parameters for example, pH, temperature, time of exposure, electrolyte composition, metal composition to establish the synergetic impact of the parameters and variables on electrochemical potentials and corrosion rates. Chen (2011) employed a Takagi–Sugeno (T–S) fuzzy model and parallel-distributed compensation (PDC) plan to design a nonlinear fuzzy controller for the stability of nonlinear systems. The neural-network model is used to submerge the modelling error challenges associated with nonlinear systems. A new stability NN-based controller design is utilized to secure the stability of the nonlinear system. The control problem is now presented as a linear matrix inequality (LMI) difficulty and a simulation is provided to explore the practicability of the proposed fuzzy controller design method.

Hassan et al., (2013) presented a review of major studies adopting the ANN method to solve major problems related to power system control due to the constraint of conventional control theory, modern control theory, and adaptive control theory. It was discovered that fast-acting, accurate controllers based on ANN technique are the preferred choice to shun system collapse, sustain system transient stability, damp oscillations, stabilize voltage, and to provide high-quality service to consumers. Though, all NN has some benefits and disadvantages, it was proposed that the recurrent neural network (RNN) is appropriate for monitoring and control. And, power systems should be taken as a supplementary tool, rather than a substitute for conventional or other AI based power system methods. In transiting from power system monitoring to forecasting stream flow, Sahoo et al., (2019) established the application of NN in simulating river flow for forecasting the development of water resources. Traditional radial basis function network (RBFN) and RNN were utilized for model development and RNN model provides optimized performance as against RBFN. For RNN, Tan-sig, Log-sig, Purelin transfer function are adopted for evaluating model performance, and Tan-sig provides best value of model performance among them.

2.1.4 KBS in Design

Publications on knowledge-based systems are quite few and dispersed, Naranje and Kumar (2014) established that KBS is used for the design of deep drawing die for axisymmetric parts yielding an interactive user-friendly, flexible, and economic implementation system. Mayr et al., (2018) shows that KBS are mostly relevant for supporting the planning of electric drives production systems, but ML-based methods are principally for optimizing single production processes. Khan et al., (2021) developed an integrated KBS useful for the transformation of traditional supply chain to digital supply chain. In year 2012, Rocca discussed knowledge-based engineering (KBE) as a budding technology with great potential for engineering design applications and its distinctiveness based on programming method to portray its validity in capturing and re-using engineering knowledge to automate large portions of the design process. Bing et al., (2017) provides a language-independent framework to implement slot-filling assignments by searching the web with accurate inquiries and originating lightweight extraction patterns. Hence, a pseudo-testing approach is adopted to approve the patterns derived from various sentences and highly encouraging outcomes are achieved.

3.0 Results

This section compares the results obtained from the present review (2010-2021) to the review conducted in a previous paper (2005-2009). The number of papers released on average annually have increased by 37%. Figure 1, 2, and 3 gives a visual comparison of the surveys over the durations, 2010-2021, 1995-2004, and 2005-2009 respectively.

The previous survey displays trends for design and scheduling which showed an increase in the use of GA. *Based on the graphs in Figure 1 and Figure 2, scheduling and design have a huge interest in GAs as an AI method used in OM in both review durations.* In the review between 2005-2009, Two hundred and ten (210) publications are for design and three hundred and nine (309) for scheduling, that shows the highest number of papers published for any of the categories over that period. About twenty to thirty-five (20-35) papers have been published for NN for design during that period. The second highest use of AI in OM is NN as statistics show that a total of three hundred and eighty-six (386) papers have been published which is over a half of the number of GAs published.

Figure 1: Charts representing the number of publications of AI in OM from 2010-2021.

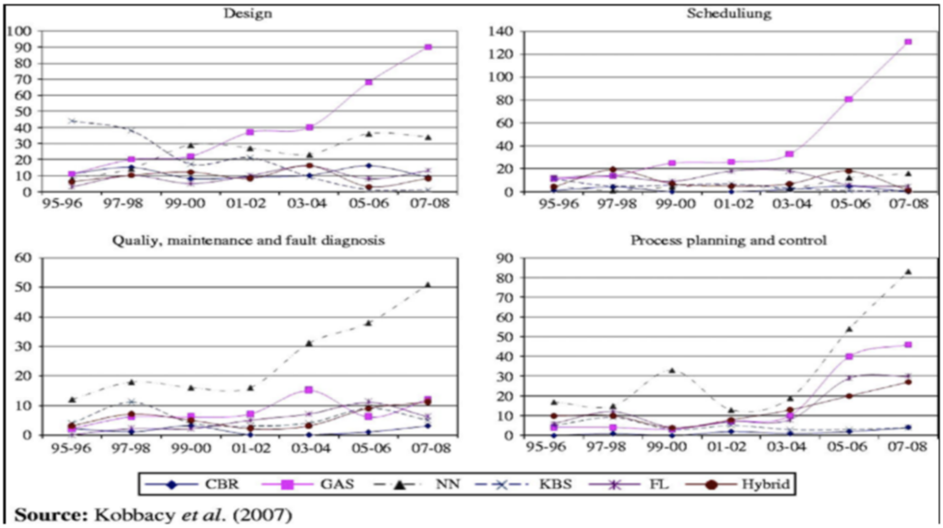


Figure 2: Charts representing the number of publications of AI in OM from 1995-2004.

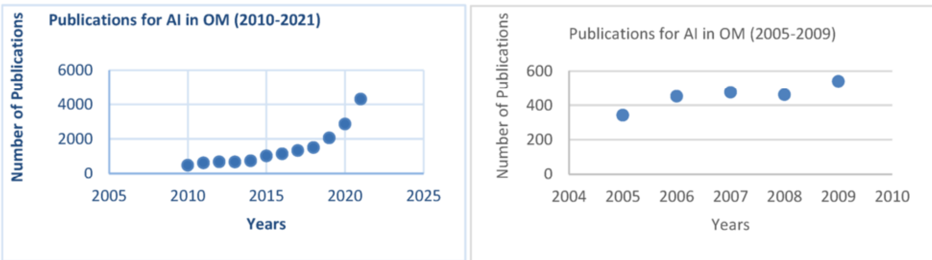
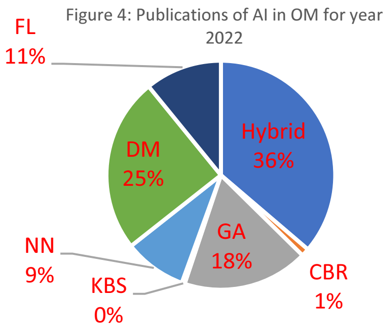


Figure 3: Scatter plots of publications of AI in OM during years 2010-2021 and 2005-2009.

The use of NN within process planning and control seem to control more than 70% of all publications in the process planning category in comparison to the review conducted between 2010-2021, GA and NN have remained to be areas of great interest with GA having a total of four thousand five hundred and fifty-four (4554) papers published and NN with two thousand, two hundred and thirty-two (2232) publications. *This shows increased interest for the use of GA and NN in OM over the course of eleven years (2010-2021).* Many operations managers understand the impact of GA research on evolving designs due to their flexibility and potential for optimizing tasks. *Both surveys discovered a decline in the use of KBS as most of its benefits have been studied and it is no longer considered innovative, because newer and more advanced systems have been developed.*

In the 2010-2021 survey, Figure 1 shows an exponential increase of the hybrid models, while in the 2005-2009 survey, the use of GA increased exponentially for Design and Scheduling. Whereas quality, maintenance and fault diagnosis, process planning and control, display the adoption of NN as the dominating factor while other methods are fluctuating. *However, considering the time frames, both surveys reveal an increased interest in the adoption of hybrid artificial intelligence methods in operations management.*

4.0 Conclusion



This study has shown that the interest in KBS has declined drastically over the periods considered. In contrast, the interest in hybrid AI aspects have seen a surge in the adoption of AI in OM as evidenced by the total papers published annually. With more companies adopting AI within the supply chain, it is increasingly more attractive to find the most effective solution to provide a compelling solution to their users. Design is the most appealing and logical solution to research for hybrid AI methods. Considering the future, research has shown that hybrid is still a major research focus with thirty-six per cent (36%) of the total publications referencing hybrid systems. In year 2022, as shown in figure 4, a total of four thousand, three hundred and nineteen (4319) papers have been published within operations management. *A key statistic to consider is data mining which has gained interest with a further twenty-five per cent (25%) papers related to that***.** KBS has almost 0 paper in that year, and it is believed that the trajectory will stay the same as most of the research in this field has been conducted thoroughly with no new innovations.

References

[1] Kobbacy, K.A.H. and Vadera, S. (2011), "A survey of AI in operations management from 2005 to 2009", *Journal of Manufacturing Technology Management*, Vol. 22 No. 6, pp. 706-733

[2] Youssef, A., Telbany, M. and Zekry, A., 2018. Reconfigurable generic FPGA implementation of fuzzy logic controller for MPPT of PV systems. *Renewable and Sustainable Energy Reviews*, 82, pp.1313-1319.

[3] Costa Branco, P. and Dente, J., 2010. Design and experimental evaluation of a fuzzy logic pressure controller for the Airbus 310/320 braking control system. *Engineering Applications of Artificial Intelligence*, 23(6), pp.989-999.

[4] Tzafestas, S., Deliparaschos, K. and Moustris, G., 2010. Fuzzy logic path tracking control for autonomous non-holonomic mobile robots: Design of System on a Chip. *Robotics and Autonomous Systems*, 58(8), pp.1017-1027.

[5] Cheng, C., Cheng, P. and Wu, M., 2010. Fuzzy logic design of self-tuning switching power supply. *Expert Systems with Applications*, 37(4), pp.2929-2936.

[6] Tahmasebi, P. and Hezarkhani, A., 2012. A hybrid neural networks-fuzzy logic-genetic algorithm for grade estimation. *Computers & Geosciences*, 42, pp.18-27.

[7] Anifowose, F. and Abdulraheem, A., 2011. Fuzzy logic-driven and SVM-driven hybrid computational intelligence models applied to oil and gas reservoir characterization. *Journal of Natural Gas Science and Engineering*, 3(3), pp.505-517.

[8] Menghal, P. and Laxmi, A., 2016. Fuzzy Based Real Time Control of Induction Motor Drive. *Procedia Computer Science*, 85, pp.228-235.

[9] Garcia-Diaz, N., Lopez-Martin, C. and Chavoya, A., 2013. A Comparative Study of Two Fuzzy Logic Models for Software Development Effort Estimation. *Procedia Technology*, 7, pp.305-314.

[10] Mehbodniya, A., Kaleem, F., Yen, K. and Adachi, F., 2013. A fuzzy extension of VIKOR for target network selection in heterogeneous wireless environments. *Physical Communication*, 7, pp.145-155.

[11] Naranje, V. and Kumar, S., 2014. A knowledge-based system for automated design of deep drawing die for axisymmetric parts. *Expert Systems with Applications*, 41(4), pp.1419-1431.

[12] Mayr, A., Weigelt, M., Masuch, M., Meiners, M., Hüttel, F. and Franke, J., 2018. Application Scenarios of Artificial Intelligence in Electric Drives Production. *Procedia Manufacturing*, 24, pp.40-47.

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From Manufacturing to Public Service Organisations: Lean as an Effective Approach to Achieve Sustainable Environmental Performance

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Abstract. The increasing global focus on sustainability developed the need to integrate sustainable practices among all sectors of the economy, including the public sector, which faces pressure from the governments to improve their organisational performance. This study explores the opportunities of Lean implementation as an effective approach to achieving sustainability in public service organisations in the context of environmentally sustainable development goals (SDGs). Through a literature review, the authors explored how Lean applications and practices could be borrowed from the manufacturing industry and implemented in the service sector. They examined the various practices employed by service organisations to integrate sustainability into their operations to enhance their environmental performance. Initial findings indicate that Lean methodologies can potentially enhance environmental performance in public service organisations by reducing non-value-added activities, waste, and environmental impact. This implementation requires adapting and customising Lean methodology to align with the unique characteristics of these organisations.

Keywords. Public Service Organisations, Lean Manufacturing, Sustainable Development Goals (SDGs), Environmental Sustainability.

1. Introduction

With sustainability being a global concern, the urgency to overcome sustainability challenges has required leaders worldwide to address these challenges in their national visions and strategies and act toward maintaining a better planet for future generations while ensuring present developments [1]. In the present study, the authors focus on the environmental pillar of sustainability and how the integration of Lean and Green methodologies can lead to improving sustainable environmental performance in the public service sector, associated with the efficient use of natural resources, and the implementation of sustainable practices and reporting [2]. Due to the public sector size and its involvement in the national economy and how they exist for social and environmental purposes, new approaches could be implemented in public organisations,

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such as Lean techniques, which were long used in the private sector [3]. The success of Lean production in automobiles has spread its application to many other manufacturing and services industries because of its ability to increase quality for lower costs. [4]. The findings contribute to the authors' research that aims to explore the Lean approach and how its integration with green and sustainability strategies in public service organisations can lead to transform their performance toward achieving environmental sustainability.

2. Literature Review

2.1. Public Service Sector

The public sector can be defined as the government activities or the economy's sector supported financially by the government, which is considered the largest employer in any country, stating the importance of the public sector in all economies [5]. Public organisations strategies are directly affected and controlled by the government's policies and the need to offer affordable services to compete for the government's overall budget by using it effectively and efficiently [5]. In addition to being controlled by the government, public service organisations face the challenge of meeting internal and external goals, demands, policies, specific rules, and regulations that are usually more strict than private organisations [6]. Moreover, public service organisations face the need to meet governments' agendas, adapt to new leadership and technologies, meet internal and external performance indicators, and increase efficiency with limited resources [7]. As a result, public organisations developed a growing need and focus on adopting new management methodologies and practices from the private sector such as, Lean and Six Sigma [6] [7].

2.2. Sustainability in the Public Service Sector

Sustainability can be viewed as the attention to economic, social, and environmental issues and attempting to establish a balance between them, which built the need among different stakeholders to embed it into their organisations' strategies [8]. Integrating sustainable development into decision-making, formulating strategies, and operations at all levels and sectors is crucial to achieve sustainable development in the public sector [9]. In 2005, "the Global Reporting Initiative (GRI) published Sector Supplement for Public Agencies: Pilot Version 1.0.", noted that public sector sustainability information tended to be scattered across a number of documents and focus on policies rather than performance information, in addition to being inconsistent, and focus on the measurement of external conditions rather than public organisations performance and impacts [10]. The increased attention by public sector organisations reflects the increased pressure to improve performance and remain viable in today's globally competitive environment, demonstrating this performance to external as well as internal stakeholders [10]. The importance of sustainable development implementation in public service organisations also aligns with maximising employment training and safety and enhancing community safety and protection. These outcomes are indicators for social sustainability, in addition to greenhouse emissions which provide environmental sustainability indicators in the public sector [10].

The evaluation of sustainability results is not easy to measure due to the complex interrelation between the indicators, the lack of consensus about the definition of sustainability, and the choice of indicators which are subject to requirements and the opinions of the participants [1]. This raises questions about the extent to which public sector sustainability performance is managed [10], and how effective are the current sustainable strategies [1].

2.3. Lean from Manufacturing to the Public Service industry

According to B. Rodgers and J. Antony [5], continuous improvement methodologies in the public sector reveal that Lean represents 60.3% of the examined methodologies in the public sector. However, most studies in the literature focus only on the short-term impact of Lean on the public service sector performance [11] , and there is a need for a more holistic perspective of lean application in the public service sector , the tools used, and the long term results of this application [4]. The current use of lean in the public sector lacks the complete perspective as it is only used in limited parts of public organisations and specific processes and initiatives [12] [6]. This also raises the need to explore the challenges that face public organisations in implementing Lean methodology, which are according to [4], the need for a shared understanding of Lean among the higher management levels and employees, poor communication between them, resistance to change, and not linking Lean to the organisations strategies [5]. Moreover, in order to apply Lean successfully in the public service sector, a clear planning and readiness within public organisations are critical [5].

Lean is characterized by five principles: value, value stream mapping, flow, pull, and continuous improvement [13]. In order to implement Lean in any organisation, they should first define the concept of value for their customers, outline their processes through Value Streat Mapping (VSM), eliminate non-value-added activities, and lastly, focus on continuous improvement [14]. It is no difference from public service organisations standpoint in their Lean implementation process [15]. This raises the need for a clear definition of the concept of value for public service organisations' customers and the aim to implement Lean as a philosophy focusing on achieving continuous improvement and long-term goals [14]. Embedding Lean as an organisational culture is also critical by engaging employees in the early stages of Lean implementation to create a need for change at all organisational levels and a culture of continuous improvement [12] besides linking Lean application to the organisations' visions, strategies as a complete and more sustained system approach [5] [12].

Several studies showed that aligning Lean practices with environmental, social, and economic concerns and strategic goals can improve the organisations performance [16] [12]. [16] emphasized the need to incorporate Lean and sustainability to provide a more comprehensive measure to evaluate organisations as they have a mutual positive impact on each other. That is because Lean implementation can lead to optimising resource consumption and increase environmental, operational, and economic efficacy [16], which serve both private and public sectors need to comply with the environmental policies [14]. A common drive for Lean implementation is to optimise the use and benefits of resources, improve the processes and customer's benefits, while reducing loss caused by waste, variability, and inflexibility [3].

Although the primary goal of Lean is to create value-added activities and reduce waste to improve organisations productivity [14], the literature review revealed a difference in Lean implementation between public service organisations and private organisations, such as manufacturing, in the use of lean tools [12]. While manufacturing organisations focus on using a set of lean tools and techniques, service organisations usually use fewer tools, such as value stream [12] though emphasis on designing Lean services through eliminating non-added-value activities [17] due to the broader ranges of processes and customer demands in services, who is also considered as the co-creator of these services [12]. Researchers also argue that the limited use of Lean tools in service organisations is due to the need to understand the concept of value for its customers and how to adapt the Lean tools and techniques to the public service processes [12]. This raises the need to study why specific tools work better for the service sector and how they differ from other sectors [17].

3. Leans applications to achieve sustainable environmental performance

In order to link the Lean approach to green practices and sustainability, the US Environmental Protection Agency (EPA) has described environmental waste as "any unnecessary use of resources and/or substances released into the air, water, or land that could harm human health and/or the environment" [18], this definition act as a guideline to extend Lean to include green production and practices [19]. EPA also has set environmental performance indicators for organisations adopting Lean, which are air emissions, energy use, solid waste, water pollution, hazardous chemicals use, water use, and materials use [13]. These indicators set a complete waste reduction approach for organisations implementing the Lean and Green integration [20]. Researchers agree that this integration helps organisations progress toward sustainability against the triple bottom-line economic, environmental, and social pillars of an organisation production system [21]. In the context of public service organisations, Lean Green can be implemented as an approach to improve their environmental performance [19]. In order to successfully implement Lean Green, several success factors have been found. Frist is through driving people at all organisational levels toward Lean philosophy, and involving them in the planning, designing, implementation and evaluation stages of the Lean approach [22] by ensuring management commitment and support, focusing on the complete understanding of the principles of Lean in order to develop a Lean culture based on continuous improvement and people respect, and effective communication on all organizational levels from management to employees [23]. Developing a Lean culture will contribute to the sustainable performance progress of these organisations [20].

In the context of our study, environmental sustainability in organisations appeared from the concept of green production, which aims to improve the processes to "prevent pollution, reduce waste, and minimize risks to humans and other species" [13], which is usually related to organisations waste generation, energy consumption, emissions, and any environmental practices [24]. Focusing on the environmental sustainable development goals (SDGs), the authors highlight environmental wastes, which, while does not add any value to the customer, its cost affects both the organisations and the society [18]. To connect how eliminating environmental waste can result in achieving environmental sustainable performance, the first question should be how lean is connected to ecological or environmental sustainability. [18]. Several studies showed that Lean leads organisations directly or indirectly to sustainable practices [21] and greener production and practices [25]. Moving toward green practices and complying with environmental regulations resulted in organisations need to implement new strategies [21], such as Lean methodology. However, authors argue that Lean alone does not significantly impact environmental performance [25]. Nevertheless, the integration of Lean and green practices benefits organisations in their progress toward environmental performance as they have common goals of reducing waste and increasing process and resources efficiency [13], which prevent pollution and emissions [26].

4. Conclusion and future research directions

Through literature, the authors explored the adoption of the Lean methodology borrowed from manufacturing to public service organisations and the need to adapt it to suit the public sector's unique characteristics. The findings suggest that Lean and Green integration can offer a successful approach and strategies toward achieving sustainable environmental performance in public service organisations. This approach is initiated by how Lean methodology supports the successful implementation of Green practices [21] due to the similarities of their approach in minimising waste, eliminating non-value-added processes, and optimising resources [14][25]. The authors established a need for a comprehensive approach to implementing Lean Green as a philosophy in public service organisations rather than limiting the implementation to a few Lean tools, maintained by several success factors to ensure continuous improvement.

Future studies could focus more thoroughly on exploring and better understanding the different Lean tools applications in the public service sector, whether specific tools or combinations of tools are more effective than others, and their impact on the environmental, economic, and social pillars of sustainability.

References

[1] R. G. Gusmão Caiado, W. Leal Filho, O. L. G. Quelhas, D. Luiz de Mattos Nascimento, and L. V. Ávila, "A literature-based review on potentials and constraints in the implementation of the sustainable development goals," *J. Clean. Prod.*, vol. 198, pp. 1276–1288, Oct. 2018, doi: 10.1016/j.jclepro.2018.07.102.

[2] "21252030 Agenda for Sustainable Development web.pdf."

[3] N. Bhatia and J. Drew, "Applying lean production to the public sector".

[4] Department of Management and Engineering, Quality Technology and Management, Linköping University and E. Drotz, *Lean in the Public Sector : Possibilities and Limitations*. Linköping University Electronic Press, 2014. doi: 10.3384/lic.diva-110660.

[5] B. Rodgers and J. Antony, "Lean and Six Sigma practices in the public sector: a review," *Int. J. Qual. Reliab. Manag.*, vol. 36, no. 3, pp. 437–455, Mar. 2019, doi: 10.1108/IJQRM-02-2018-0057.

[6] T. O. Lukrafka, D. S. Silva, and M. Echeveste, "A geographic picture of Lean adoption in the public sector: Cases, approaches, and a refreshed agenda," *Eur. Manag. J.*, vol. 38, no. 3, pp. 506–517, Jun. 2020, doi: 10.1016/j.emj.2020.02.004.

[7] Z. Radnor, "Transferring Lean into government," *J. Manuf. Technol. Manag.*, vol. 21, no. 3, pp. 411–428, Mar. 2010, doi: 10.1108/17410381011024368.

[8] H. Mal, M. Varma, and N. K. Vishvakarma, "An empirical study to prioritize the determinants of corporate sustainability performance using analytic hierarchy process," *Meas. Bus. Excell.*, vol. 27, no. 2, pp. 193–210, Apr. 2023, doi: 10.1108/MBE-10-2021-0133.

[9] T. B. Ramos *et al.*, "Co-creating a sustainability performance assessment tool for public sector organisations," *J. Clean. Prod.*, vol. 320, p. 128738, Oct. 2021, doi: 10.1016/j.jclepro.2021.128738.

[10] C. A. Adams, S. Muir, and Z. Hoque, "Measurement of sustainability performance in the public sector," *Sustain. Account. Manag. Policy J.*, vol. 5, no. 1, pp. 46–67, Feb. 2014, doi: 10.1108/SAMPJ-04-2012-0018.

[11] M. M. Awad, A. Hashem, and H. M. Naguib, "The Impact of Lean Management Practices on Economic Sustainability in Services Sector," *Sustainability*, vol. 14, no. 15, p. 9323, Jul. 2022, doi: 10.3390/su14159323.

[12] Z. Radnor, *Evaluation of the lean approach to business management and its use in the public sector*. Edinburgh: Scottish Executive, 2006.

[13] M. Dieste, R. Panizzolo, J. A. Garza-Reyes, and A. Anosike, "The relationship between lean and environmental performance: Practices and measures," *J. Clean. Prod.*, vol. 224, pp. 120–131, Jul. 2019, doi: 10.1016/j.jclepro.2019.03.243.

[14] E. Keramida, E. L. Psomas, and J. Antony, "Critical success factors of lean in the public services sector: the case of the Greek citizen's service centers," *TQM J.*, Dec. 2022, doi: 10.1108/TQM-09-2022-0287.

[15] S. P. Osborne, Z. Radnor, and G. Nasi, "A New Theory for Public Service Management? Toward a (Public) Service-Dominant Approach," *Am. Rev. Public Adm.*, vol. 43, no. 2, pp. 135–158, Mar. 2013, doi: 10.1177/0275074012466935.

[16] M. Eskandari, M. Hamid, M. Masoudian, and M. Rabbani, "An integrated lean production-sustainability framework for evaluation and improvement of the performance of pharmaceutical factory," *J. Clean. Prod.*, vol. 376, p. 134132, Nov. 2022, doi: 10.1016/j.jclepro.2022.134132.

[17] F. L. Lizarelli, A. Chakraborty, J. Antony, R. Jayaraman, M. B. Carneiro, and S. Furterer, "Lean and its impact on sustainability performance in service companies: results from a pilot study," *TQM J.*, vol. 35, no. 3, pp. 698–718, Mar. 2023, doi: 10.1108/TQM-03-2022-0094.

[18] E. D. S. Lima, U. R. De Oliveira, M. D. C. Costa, V. A. Fernandes, and P. Teodoro, "Sustainability in Public Universities through lean evaluation and future improvement for administrative processes," *J. Clean. Prod.*, vol. 382, p. 135318, Jan. 2023, doi: 10.1016/j.jclepro.2022.135318.

[19] A. Bhattacharya, A. Nand, and P. Castka, "Lean-green integration and its impact on sustainability performance: A critical review," *J. Clean. Prod.*, vol. 236, p. 117697, Nov. 2019, doi: 10.1016/j.jclepro.2019.117697.

[20] H. T. S. Caldera, C. Desha, and L. Dawes, "Exploring the role of lean thinking in sustainable business practice: A systematic literature review," *J. Clean. Prod.*, vol. 167, pp. 1546–1565, Nov. 2017, doi: 10.1016/j.jclepro.2017.05.126.

[21] R. A. Inman and K. W. Green, "Lean and green combine to impact environmental and operational performance," *Int. J. Prod. Res.*, vol. 56, no. 14, pp. 4802–4818, Jul. 2018, doi: 10.1080/00207543.2018.1447705.

[22] M. Lavender, "Learning to Walk Before We Try to Run: Adapting Lean for the Public Sector," 2008.

[23] R. Asnan, N. Nordin, and S. N. Othman, "SUCCESS FACTORS OF LEAN MANAGEMENT IMPLEMENTATION IN PUBLIC SERVICE ORGANIZATIONS," no. 2, 2016.

[24] J. A. Garza-Reyes, "Lean and green – a systematic review of the state of the art literature," *J. Clean. Prod.*, vol. 102, pp. 18–29, Sep. 2015, doi: 10.1016/j.jclepro.2015.04.064.

[25] W. Abualfaraa, M. AlManei, R. Kaur, A. Al-Ashaab, P. McLaughlin, and K. Salonitis, "A Synergetic Framework for Green and Lean Manufacturing Practices in SMEs: Saudi Arabia Perspective," *Sustainability*, vol. 15, no. 1, p. 596, Dec. 2022, doi: 10.3390/su15010596.

[26] J. A. Garza-Reyes, V. Kumar, S. Chaikittisilp, and K. H. Tan, "The effect of lean methods and tools on the environmental performance of manufacturing organisations," *Int. J. Prod. Econ.*, vol. 200, pp. 170–180, Jun. 2018, doi: 10.1016/j.ijpe.2018.03.030.

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Identifying the Fit-for-Purpose Leadership for the Manufacturing Organizations in the Era of Industry 5.0 – A Literature Review

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Abstract: With each phase of industrial revolution, the interaction between humans and technology have evolved and context of work has changed, calling for new approaches to leadership. The fourth industrial revolution (Industry 4.0) calls for responsive and digital leaders who can navigate through complex adaptive systems where direction, decision and innovation emerge from connected ecosystem & diverse agents. However, Industry 4.0 tends to overlook the importance of human-value dimensions, sustainability, and social fairness and hence a paradigm shift towards Industry 5.0 will focus shifts from a techno-deterministic rationale to human-deterministic rationale. Industry 5.0 seeks to combine consistency and speed of collaborative machines with resourcefulness and creativity of humans for the mutual benefit of industry and workforce. Thus, with a focus on manufacturing industry, this paper focuses on identifying the gap in leadership literature and emphasises on the need to identify how leadership should evolve to address the changing dynamics between human-machine co-working in manufacturing that is expected in the era of Industry 5.0.

Key Words: Leadership, Industrial Revolution, Industry 4.0, Industry 5.0, Manufacturing

1. Introduction

The term industrial revolution refers to the revolutions in the systems that surround us and the step changes in complex interaction between technology humans and the resulting transformations that create new ways of acting, perceiving and being [1, 2]. The initial three industrial revolutions were a result of mechanisation, electrification, and IT respectively. However, the advent of Internet of Things (IoT) and connected services has ushered in the fourth industrial revolution (IE 4.0) [3]. The distinctive characteristics that set Industry 4.0 apart is its velocity (i.e. technology evolving at an exponential pace rather than a liner pace), systems impact (i.e. potential to transform whole systems both across and within companies, industries, societies and countries) and its breadth and depth (i.e. the combination of multiple technologies creating unprecedented paradigm shifts in business, society, individuals and economy) [1]. Its scope extends beyond the smart and interconnected machines and unlike previous industrial revolutions, Industry 4.0 involves fusions of technologies and interactions across digital, physical and biological domains [1].

However, the Industry 4.0 possess certain challenges such as the increasing concern of humans not being equipped but rather being replaced and having less emphasis on

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sustainability and social fairness while focusing heavily on digitalizing technologies to drive efficiency and flexibility in production [4, 5]. To overcome the challenges posed by Industry 4.0, a paradigm shift towards the notion of Industry 5.0 is proposed. "Industry 5.0 will be defined by re-found and widened purposefulness, going beyond producing goods and services for profit. The wider purpose constitutes three core elements: human-centricity, sustainability, and resilience" [5].

The continuous technological advancements with each Industrial revolution and a paradigm shift towards new industrial revolution implies that humans are equipped with new capabilities, and they approach work from new perspectives, and it changes the demands of work environment. Thus, with the changing work environment needs, the notion of leadership has evolved to address the changing dynamics of the evolving work environment. For instance, in Industry 3.0 the work context saw humans using technology to enhance workplace and it ushered in the transformational leadership behaviour [6]. Alternatively, Industry 4.0's work context involved technology enhancing humans and replacing human functions, and this ushered in a concept of digital leadership wherein the focus of the leader is on utilizing the digital assets of the organization to improve business performance and thereby meet organizational goals [6, 7]. But with Industry 5.0, the coworking of collaborative machines with humans will both in subtle and explicit ways transform the work environment and roles and responsibilities of both human and machine resource in workplace. Thus, the traditional leadership locus and mechanisms that organizations have relied on to manage work process will have to undergo change. Moreover, leaders should "seek to transform *what is into what should be*" [8] and, with emergence of Industry 5.0, the organizational leaders should seek to transform current leadership approaches of Industry 4.0 into leadership practices that can actualize the vision of industry 5.0.

2. The shift from Industry 4.0 to Industry 5.0

Industry 4.0 emphasises on making "smart" manufacturing industry by interconnecting devices and machines that can control each other throughout the product lifecycle [9]. Here, the production systems can engage in real-time communication and cooperation between manufacturing things and thereby make intelligent decisions that can result in high-quality flexible production at maximum efficiency [10]. The fusions of technologies in Industry 4.0 allows for businesses to establish Cyber Physic Systems (CPS) comprising of smart machines capable of triggering actions, autonomously exchanging information, and independently controlling each other and providing real-time interface between physical and virtual worlds [3]. Additionally, the technologies of industry 4.0 and its interconnected network offers the consumers the option to configure the product from a list of choices, resulting in mass customization [11]. Here the main objective of Industry 4.0 is to achieve mass production and maximize productivity using emerging technologies [9]. Its focus is on automating process and improving efficiency of the process and this inadvertently overlooks the human cost that arises from optimizing the processes [12]. Similarly, Maddikunta et al., [9] highlighted that Industry 4.0's priority is process automation, and it results in reduction of human intervention in manufacturing process.

On the other hand, Industry 5.0, takes on a different stance as it highlights the importance of Industry's role in service to the humanity while respecting the planetary boundaries [10]. Thus, Industry 5.0 requires industry stakeholders to shift their mindset form considering technologies as determinants of societal developments and pushes them to regard technology as a part of system that are designed for the empowerment of environmental and societal values i.e. the focus of adapting technology should not be to replace the workers but rather to support the abilities of the worker to have a safer and satisfactory environment [13]. Thus, a key difference between Industry 5.0 & Industry 4.0 is that Industry 5.0 is value driven whereas Industry 4.0 is technology-driven with issues of sustainability, human centricity and resilience being approached form a consequential perspective [10]. This also implies that in Industry 5.0 the societal, environmental, and social concerns need to be taken into account for an industry to become a provider of true prosperity and therefore the focus should be on responsible innovation that increases profit and cost-efficiency while increasing prosperity for all the involved stakeholders [5]. While Industry 5.0 highlights the importance of human touch and planetary boundaries and, emphasises on adding a human-value centred dimension to Industry 4.0, it is essential to note Industry 5.0 is not a replacement or an alternative to Industry 4.0, rather it is to be considered as a logical continuation/evolution of Industry 4.0 [13].

Moreover, Industry 5.0 calls for humans to be brought back to the manufacturing floor and combine the creativity and brainpower of humans with the machines to further increase process efficiency [12]. Thus, in Industry 5.0, the collaboration between humans and intelligent machines (intelligent systems with the capability to make decisions in a partially or fully independent manner and autonomous manner and its autonomy is enabled through Industry 4.0 technologies) can empower the people to realize the human urge to express themselves and add a personal touch to the products/services, thereby enabling personalization [11,14]. The core of element of Industry 5.0 is postulated to be personal human touch which the technology cannot offer [15]. Thus, the crucial transformation in Industry 5.0 is that instead of humans being replaced by machines, they will be integrated and equipped with intelligent machines for enhanced collaboration and cooperation with machines [4]. It will be combination of manpower, intelligent machines, and hyper customization, all aimed towards delivering tailored customer experience, thus resulting in mass personalization [15]. Hence, Ozkeser [11] claims that Industry 5.0 can be considered as returning to pre-industrial production, but one that is facilitated by most advanced technologies. However, the main concern in industry 5.0 will be achieving synergy between intelligent machines and humans [12].

3. Industry 5.0: Changing Work Environment

With Industry 5.0 there will be a shift from smart manufacturing towards a new-generation intelligent manufacturing. Ji *et al.* [16] notes that with the growth of machine intelligence and human intelligence, there will be a shift in knowledge-based work in manufacturing industry towards autonomous intelligence. The new generation intelligent manufacturing implies that there will be a change in the boundary between machines and humans and the intelligent machines will showcase the capability to take over considerable amount of brainpower from humans and high amount of manual labour [16]. In the new work environment, the machines will move away from their traditional confined workspace to work together with humans. The modern form of intelligent machines developed for collaboration such as Cobots will have the capability to interact safely with humans, reduce risk in implementation tasks and has the characteristics of flexibility, learning and quick adjustment [17]. The integration of Cobots in workspace implies that human-machine relation can advance from coexistence to collaboration [17].

However, for the integration of Cobots into workplace and to achieve human-machine collaboration, organizational leaders must consider different factors of the new work environment. For instance, Bagdasarov *et al.* [18] offers three categories to highlight how different factors can impact robotic integration in workplace and these categories are namely individual factors, robotic agent factors and organizational factors. The individual factor refers to the influence of unique personal characteristics (gender, age, attitude, perspectives, education level etc) of the individuals that can contribute towards acceptance of robotic presence in the work environment [18]. The robotic agent factors refer to peculiar characteristics of the robots itself such as its appearance, behaviour patterns, interaction capabilities and its safety features that can influence the employees' acceptance and willingness to work with robots [18]. The organizational factors refer to the particular characteristics of an organization such as its workflow, physical workspace design, employee-robot goal alignment and the socio-emotional context that could impact the integration of robots into workplace [18]. These three categories can be considered as the internal environment elements of the firms operating in Industry 5.0 & with robotic agents as new element in the internal environment, the leaders in future will have to identify new approaches to lead in the emerging internal environment conditions.

In this paper, the approach proposed by Hernandez et al. [19] to codify the leadership literature into two fundamental principles namely the locus and mechanism of leadership is used to explore the concept of leadership 4.0 and leadership 5.0. The source of leadership is locus & the means by which leadership is enacted is mechanism [19]. The locus can be an individual leader, context, leader-follower dyad, or collective [19]. The mechanism of leadership can be cognition (to think), affect (to feel), traits (to be), and behaviours (to do) [19].

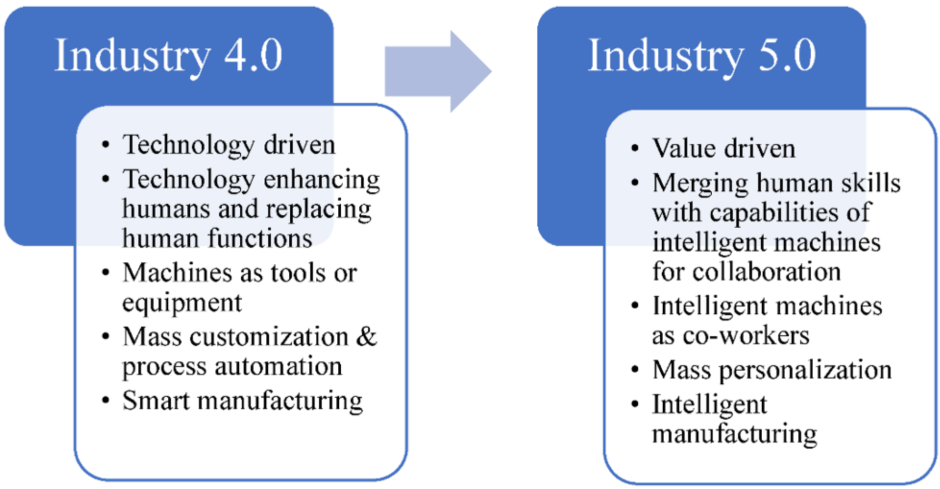

Figure 1: Difference between Industry 4.0 & Industry 5.0 (Source: Authors)

a. From Leadership 4.0 to Leadership 5.0

In the work context of Industry 4.0, leadership is termed as digital leadership or leadership 4.0 and both the terms tend to be used interchangeably. Digital leadership is about driving forward digital transformation [20]. It can be defined as “doing the right things for the strategic success of digitalization for the enterprise and its business ecosystems” [21, p.142]. In terms of locus of leadership 4.0, it can be said that the individual leaders are not the sole loci in Industry 4.0. This is because Kelly [6] points out that in Industry 4.0, there is shift from leaders being the sole idea generators, decision makers and source of knowledge towards the idea of connected leader wherein the leader creates right environment for collaborative environments to thrive and facilitate ideas to be generated from connected networks of algorithms, hyperconnected customers and data patters [6].

On the other hand, scholars have provided varying insights on how leadership is to be enacted in Industry 4.0. For instance, Kelly [6] notes that leaders must be responsive to the signals and patterns that arise from interconnected networks in Industry 4.0. It is characterized by strong focus on innovation, and it is cross-hierarchical, fast, cooperative and team-oriented in nature [22]. Moreover, Molino et al. [23] states that leaders in Industry 4.0 must have the ability to not only implement new technologies, but they should also be able to guarantee its acceptance and its correct use. Here the leaders should showcase their capability to both manage the implementation of new technology as well as the ability to get the employees involved [23]. Thus, it can be noted that the locus and mechanism of leadership 4.0 is geared towards establishing a digital culture and digital mindset in the organizations.

However, in Industry 5.0, the context of work environment and its challenges are different. Intelligent machines such as Cobots are built specifically to interact with employees in a shared workspace and as Artificial Intelligence continuous to enhance the Cobots’ ability to acquire performance capabilities, future organizational leaders should exhibit capability to create right environment for their people to actively embrace it and work alongside it [24].

While the leadership literature has explored in depth the complex interaction between human leaders and human subordinates [25], in Industry 5.0, human leaders will have to manage both human and machine subordinates. This is because intelligent machines in Industry 5.0 are to be considered as active co-working counterparts of employees and not as supportive tools or equipment. This calls for a change in the traditional mechanisms of leadership, but the leadership research has not yet accounted for human leaders leading both human agents and intelligent machine agents in a collaborative work environment. To address this gap there is a need to explore the notion of next generation leadership which can be termed as Leadership 5.0 to denote organizational leadership that leads human & machine agents in the collaborative environment that is expected in the era of Industry 5.0.

4. Discussion

In Industry 5.0 collaborative intelligent machines are to be considered as co-workers to humans and not as tools or equipment, and as the workplace will evolve to incorporate human-machine collaborative spaces, the role of leaders will change. Thus, in order to establish an optimum human-machine collaborative workspace, the leaders will have to align the interest of the 3 internal environmental elements (individual factors, robotic agent factors and organizational factors). Also, the role of organizational leaders in Industry 5.0 will involve managing the complexity between human behaviour, intelligent machine behaviour and organizational behaviour patterns and establishing an understanding between the three. But the extent of challenges that leaders will face to establish an optimum human-Cobot collaboration in Industry 5.0 and the approaches and practices needed to overcome it is still unknown. Therefore, to better understand the locus and mechanism of leadership 5.0, qualitative research with the leaders of manufacturing industry is required.

References

1. Schwab, K. (2016). *The Fourth Industrial Revolution*. Available at: https://law.unimelb.edu.au/__data/assets/pdf_file/0005/3385454/Schwab-The_Fourth_Industrial_Revolution_Klaus_S.pdf
2. Philbeck, T. and Davis, N. (2019) The Fourth Industrial Revolution: Shaping a New Era. Journal of International Affairs, 72(1), 17-22
3. Kagermann, H., Wahlster, W., and Helbig, J. (2013). *Recommendation for implementing the initiative INDUSTRIE 4.0.* Available at: https://www.din.de/resource/blob/76902/e8cac883f42bf28536e7e8165993f1fd/recommendations-for-implementing-industry-4-0-data.pdf
4. Saxena, A., Pant, D., Saxena A., and Patel, C. (2020). 'Emergence of Educators for Industry 5.0 – An Indological Perspective', *International Journal of Innovative Technology and Exploring Engineering*, 9(12), 359-363
5. Breque, M., De Nul, L., and Petridis, A. (2021). *Industry 5.0 Towards a sustainable, human-centric and resilient European industry*. Available at: https://msu.euramet.org/current_calls/documents/EC_Industry5.0.pdf
6. Kelly, R. (2019) Constructing Leadership 4.0. Switzerland: Palgrave Macmillan
7. Durmaz, O. & Hawrami, S. (2022). "The Suitable Leadership for Industry 4.0". *Journal of Global Economies & Business*, 3(8), 113-124
8. Organ, D. (1996) Leadership: The Great Man Theory Revisited. Business Horizons, 39(3), 1-4
9. Maddikunta, P., Pham, Q., Gadekallu, T., B, P., Deepa, N., Dev, K., Ruby, R. & Liyanage, M. (2022). "Industry 5.0: A survey on enabling technologies & potential applications*". Journal of Industrial Information Integration*, https://doi.org/10.1016/j.jii.2021.100257
10. Xu, X., Lu, Yuqian, Vogel-Heuser, B. and Wang, L. (2021) Industry 4.0 and Industry 5.0 – Inception, conception and perception. 61, 530-535 https://doi.org/10.1016/j.jmsy.2021.10.006
11. Ozkeser, B. (2018) Lean Innovation Approach in Industry 5.0. The Eurasia Proceedings of Science, Engineering and Mathematics (EPSTEM), 2, 422-428. http://www.epstem.net/en/download/article-file/528361
12. Nahavandi, S. (2019). Industry 5.0-A Human-Centric Solution. Sustainability 11(6), https://doi.org/10.3390/su11164371
13. Muller, J. (2020). *Enabling Technologies for Industry 5.0*. Available at: https://op.europa.eu/en/publication-detail/-/publication/8e5de100-2a1c-11eb-9d7e-01aa75ed71a1/language-en
14. Xiong, W., Fan, H., MA, L. and Wang, C. (2022) Challenges of human-machine collaboration in risky decision-making. Frontiers of Engineering Management, 9 89-103. https://doi.org/10.1007/s42524-021-0182-0
15. Santhi, A. and Muthuswamy, P. (2023) Industry 5.0 or industry 4.0S? Introduction to industry 4.0 and a peek into the perspective industry 5.0 technologies. International Journal of Interactive Design and Manufacturing, 17, 947-976 https://doi.org/10.1007/s12008-023-01217-8

16. Ji, X., Peigen, L., Yanhong, Z., Baicun, W., Jiyuan, Z., and Liu, M. (2018) Toward New-Generation Intelligent Manufacturing. 4(1), 11-20 https://doi.org/10.1016/j.eng.2018.01.002
17. Galin, R., Meshcheryakov, R., Kamaesheva, S. and Samoshina, A. (2020) Cobots and the benfits of their implementation in intelligent manufacturing. IOP Conference Series: Materials Science and Engineering **862** doi:10.1088/1757-899X/862/3/032075
18. Bagdasarov, Z., Martin, A. and Buckley, M.R. (2020) Working with robots: Organizational Considerations. Organizational Dynamics, 49(2), 1-8 https://doi.org/10.1016/j.orgdyn.2018.09.002
19. Hernandez, M., Eberly, M. B., Avolio, B. J., & Johnson, M. D. (2011). The loci and mechanisms of leadership: Exploring a more comprehensive view of leadership theory. The Leadership Quarterly 22 (6), 1165-1185. https://doi.org/10.1016/|j.leaqua.2011.09.009
20. Bach, C. & Sulikova, R. (2021) Leadership in the Context of a New World: Digital Leadership and Industry 4.0. Managing Global Transactions, 19(3), 209-226. DOI: 10.26493/1854-6935.19.209-226
21. El Sawy, O. A., Kræmmergaard, P., Amsinck, H., & Vinther, A. L. (2016). How LEGO built the foundations and enterprise capabilities for digital leadership. MIS Quarterly Executive, 15(2), 141-166.
22. Oberer, B. and Erkollar, A. (2018) Leadership 4.0: Digital Leaders in the Age of Industry 4.0. International Journal of Organizational leadership. 7(4):404-412
23. Guzman, V., Muschard, B., Gerolamo, M. Kohl, H. and Rozenfeld, H. (2020) Characteristics and Skills of leadership in the context of Industry 4.0. Procedia Manufacturing, 43, 543-550 https://doi.org/10.1016/j.promfg.2020.02.167
24. Bawany, S. (2020) *Leadership in Disruptive Times*. New York: Business Expert Press
25. Wesche, J., and Sonderegger, A. (2019) When computers take the lead: The automation of leadership. 101, 197- 209, https://doi.org/10.1016/j.chb.2019.07.027

Part 2

Advances in Manufacturing Technology

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Effect of Grain Structure on Machinability of LPBF Inconel 718: A Critical Review

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Abstract: Laser-powder bed fusion LPBF techniques can be used to manufacture complex-shaped, thin-walled, hollow, or slender parts. Although the dimensions of the generated components are close to the final measurements, additional machining processes are required to obtain the desired surface finish and dimensional tolerance. The melt pool dynamic during the LPBF operation results in directional gain structures in alloys. The resulting mechanical properties are strongly dependent on the component build orientation, which can affect the machinability of the produced part. This review paper provides knowledge on the role of microstructure in the machinability of LPBF-produced IN718. The effect of grain shape and distribution, grain boundary density on the surface integrity, and resulting cutting forces are investigated.

Keywords: LPBF, Inconel 718, Microstructure, Anisotropy, Machinability.

1. Introduction

Inconel 718 (IN718) is a nickel-primarily based totally alloy with advanced mechanical properties, which include outstanding corrosion resistance, thermal fatigue resistance, and creep at temperatures up to 650 Co [1]. In comparison to other nickel-based superalloys, IN718 offers improved weldability [2].

The use of LPBF techniques provides significant flexibility for manufacturing intricate geometries of strong alloys such as IN718 [2]. This processing technique comprises repeated rapid melting, solidification, and reheating, subjecting the material to unstable conditions that induce different grain morphologies [3], which cause anisotropic mechanical properties [4]. The mechanical properties of metals are also significantly influenced by the size of individual grains [2].

Machining is often required to obtain the final shapes with the desired geometry. LPBF components create additional machining issues due to material inhomogeneity and complicated geometries [4]. Machining causes phase transition and work hardening, which makes the IN718 alloy stronger and more abrasive, resulting in higher cutting force, irregular chips, and higher Ra [5]. However, research into the effect of grain

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morphology on the machinability of LPBF IN718 parts is still in its early stages. The aim of this review paper is to study the effect of microstructural variables such as grain shape, size, distribution, and grain boundary density on LPBF IN718 machinability, surface integrity, and cutting force.

2. Microstructure effects on mechanical properties of LPF IN718

The microstructure of LPBF components is determined by the melt pool dynamic, which is influenced by crucial and continuous temperature changes [3]. A significant cooling gradient results in non-equilibrium solidification that induces grain refinement on the build plane, while more uniform solidification produces columnar grains that elongate in the build direction [3], as illustrated in Figures 1(B and C). The elastic anisotropy of columnar-grained IN718 alloy is extensively documented, exhibiting varied elastic characteristics. In the LPBF-produced IN718, Ni et al. [4] found that parts tested along the build direction (Z) exhibit lower tensile strength (UTS = 1101 MPa, $\sigma_{0.2}$ = 710 MPa), but higher elongation (δ = 24.5%) than those tested along the build plane (XY) (UTS = 1167 MPa, $\sigma_{0.2}$ = 850 MPa, δ = 21.5%). Moriz et al. [1] and Deng et al. [2] obtained similar results with SLM-fabricated IN718. This anisotropy has a considerable influence on the stiffness of the components associated with vibrations and cutting forces during machining [6]. However, the anisotropy in the mechanical properties can be affected by heat-treatment post-processing [1].

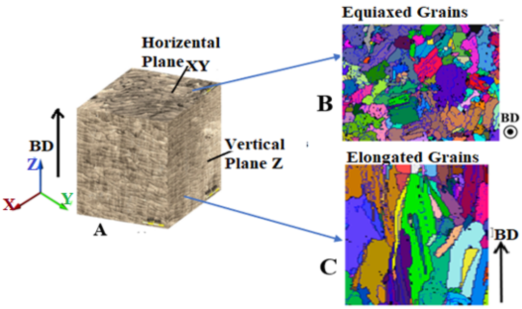

Figure 1: (A) Illustrates the build direction and the build plane, (B) SEM image depicting equiaxed grains on the build plane, and (C) elongated columnar grains on the build direction [3], [7].

3. The effect of microstructure on the machinability of LPBF IN718

A machinability index is determined by cutting forces, chip formation and evacuation, surface and subsurface integrity, and tool wear [8]. However, IN718 alloy exhibits poor machinability owing to its lower thermal conductivity, rapid hardening, and high resistance to plastic deformation at higher temperatures [9].

During the machining processes, the workpiece material is subjected to thermal and mechanical stresses, which can result in strain aging and recrystallization [10]. Many parameters are known to cause and/or support these shear deformations, including cutting parameters (cutting speed, feed, depth of cut), tool parameters (rake angle, edge radius, shape, coating, wear), workpiece parameters (material, grain size), and cutting fluid [8].

In terms of microstructure, Khanna et al. [9] stated that machining alloys with a large grain size reduce crack nucleation, whereas a small one limits crack propagation. Grain boundaries act as barriers to prevent crack development and dislocation displacement [1]. Since machining relies on crack propagation along the cutting edge to form a chip, the smaller the grain size, the more difficult the material will be to cut [10]. The grain size of LPBF IN718 is roughly thirty times larger than that of wrought material, as stated by Ducroux et al. [11]. Due to fewer grain boundaries, crack propagation is substantially more discernible while machining LPBF parts [12].

The presence of carbides is another issue in machining IN718 which are extremely difficult to cut [13]. There are three types of carbides: NbC, TiC, and (Nb, Ti)C, which are the sensitive determinants of IN718 machinability [11]. Three results are possible during the machining of these carbides, according to Dudzinski et al. [14]. First, the carbide is cut, causing significant cutting forces to be created locally on the cutting edge. Second, if the carbide is small enough, the tool tears it away from the material, leaving a hole in the machined surface. Otherwise, the carbide is not cut and destroys the tool by scratching the flank surface. Since wrought IN718 carbides are larger than LPB IN718 carbides, the cutting force generated when machining wrought IN718 is greater [11].

3.1. Microstructure influences surface integrity of LPBF IN718

The surface quality of a machined surface is determined by three main factors: surface roughness Ra, residual stresses, and microhardness [15]. A Low Ra value indicates a reduction in stress concentration, micro-cracks, and fatigue cracks initiated at the grain boundaries [7], [16]. Pérez-Ruiz et al. 202 [6] stated that the initial Ra of LPBF as-built IN718 in the vertical (Z) plane can vary by up to 30 μm compared to the horizontal (XY) plane. Machining post-processing is still the most effective way to reduce roughness [15]. The surface roughness values of turned machined AM IN718 have been compared to their wrought manufactured counterparts and were comparable in several investigations [8], [17]. A comparison of Ra values for machined LPBF IN718, in the build plane and the build direction of the same part, was not available in the literature., but Brinksmeier [16] milled SLM 18 Maraging 300 short cylindrical components under similar machining conditions on the same part's build plane and build direction. The results revealed that the milled SLM part has less roughness on the build plane. The surface roughness is also determined by machining parameters [10]. According to research studies, machining IN718 with more productive parameters generates dislocation, phase transition, and micro-cracks due to the high heat generated at the cutting area [10].

The impact of thermo-mechanical stresses on the microstructures in the primary shear zone during machining induces material work-hardening on the machined workpiece surface [18]. The generated heat influences the phase transition, whereas strain and strain rate influence grain formation [3]. Kaynak et al. [7] investigated the surface hardening of SLM IN718 parts after turning in dry and cold air, which were compared to the as-built SLM IN718 non-machined sample. The hardness increased by around 16 % on average; however, the dry cut had a higher hardness, per the research. As a result, the microstructure behaviour has a direct impact on the machined surface outcome.

3.2. The effect of grain structure on cutting force

The machining cutting force is primarily derived from the plastic deformation in the primary shear zone, as well as the friction tension between the tool and the workpiece in the secondary deformation zone [10]. It is essential to consider the resistance provided by grains and grain binderies when evaluating shear resistance [19], as shown in Figure 2. At the macroscopic level, the cutting area is typically simplified as a plane [8]. However, the shear zone is made up of several slip directions that, when combined, generate the plane of the shear band [6]. The strength of metals and alloys improves with decreasing grain size, as per the Hall-Petch relationship [20]. The grain refinement of LPBF IN718 increases grain boundary density, leading to higher cutting forces during machining [6]. However, Malakizadi et al. [12] observed that, despite the wrought IN718 having lower grain sizes than the SLM IN718, the resulting cutting forces of facing were approximately the same. This is because SLM parts were faced against equiaxed gains on the surface perpendicular to the build direction.

The large anisotropic properties of LPBF-produced components relate to differences in grain shape and distribution in the build and transverse directions [12]. However, there is no comprehensive comparison of the resultant cutting forces in machining on different LPBF IN718 surfaces. Nonetheless, Shunmugavel et al. [21] investigated the influence of build direction on resultant cutting forces in three distinct relative directions between the cutting velocity vector and the columnar grain while machining SLM titanium alloy Ti64. The cutting forces were found to be the lowest when the cutting tool went along the cross-section of the columnar grains.

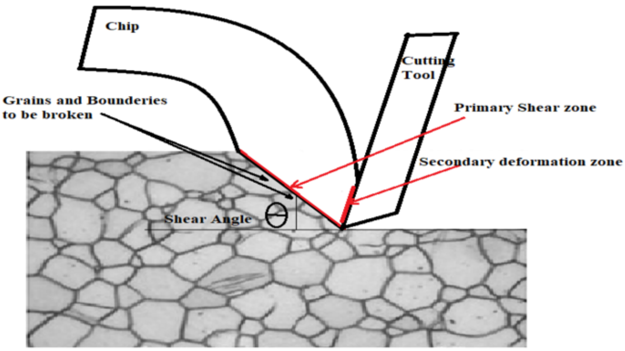

Figure (2): Illustrates the cutting tool breaks gains and grain boundaries.

3.3. Microstructure effects on chip formation

The type and nature of chips depend on the combination of different factors such as work material properties, cutting parameters, phase morphology, grain size, tool geometry, and cutting conditions [19]. The crack propagation in front of the cutting edge is core to the chip-separation process [22]. Since crack propagation is more apparent with fewer grain boundaries, chips will form earlier when cutting LPBF IN718 parts [12]. Chen et al., [8] turned wrought and SLM IN718 to differentiate between the produced chips. The study concluded that due to the high cutting temperature and large cutting deformation, all the chips had serrated edges. However, the SLM IN718 parts produced irregular, continuous serrated chips with uncontrollable outflow, whereas the wrought superalloy produced helical-form shapes that were easy to control. The different chip shapes and morphologies can be attributed to the various SLM IN718 microstructures.

The thermo-mechanical effect develops second-phase particles (γ' and γ'') at the cutting zone, making the IN718 alloy stronger and more abrasive, making it more difficult to remove [10]. Hence, the basic shearing process and chip generation in the cutting sequences will differ due to changes in the characteristics of the machined workpiece material [5]. The surface roughness increases as the number of serrations or segmentation of chips “saw teeth” increases [22].

4. Conclusion and future work

The mechanical properties of parts were shown to be affected by the developed grain structures. Further, the machinability of LPBF IN718 was shown to be effected by the second phase of the composition, specifically the inclusion of microstructure attributes. The AM-produced parts in IN718 can be subjected to heat treatment to reduce anisotropy and develop a more uniform microstructure that could improve machinability. This could be achieved by a homogenisation heat treatment.

References:

[1] S. Tabaie, F. Rézaï-Aria, and M. Jahazi, “Microstructure evolution of selective laser melted inconel 718: Influence of high heating rates,” *Metals (Basel)*, vol. 10, no. 5, May 2020,

[2] Dunyong Deng, *Additively Manufactured Inconel 718*, no. 1798. 2018.

[3] K. N. Amato *et al.*, “Microstructures and mechanical behavior of Inconel 718 fabricated by selective laser melting,” *Acta Mater*, vol. 60, no. 5, pp. 2229–2239, 2012,

[4] M. Ni *et al.*, “Anisotropic tensile behavior of in situ precipitation strengthened Inconel 718 fabricated by additive manufacturing,” *Materials Science and Engineering A*, vol. 701, pp. 344–351, Jul. 2017,

[5] C. Liu, M. Wan, W. Zhang, and Y. Yang, “Chip Formation Mechanism of Inconel 718: A Review of Models and Approaches,” *Chinese Journal of Mechanical Engineering (English Edition)*, vol. 34, no. 1. Springer, Dec. 01, 2021.

[6] J. D. Pérez-Ruiz, L. N. L. de Lacalle, G. Urbikain, O. Pereira, S. Martínez, and J. Bris, “On the relationship between cutting forces and anisotropy features in the milling of LPBF Inconel 718 for near net shape parts,” *Int J Mach Tools Manuf*, vol. 170, no. February, 2021.

[7] Y. Kaynak and E. Tascioglu, “Finish machining-induced surface roughness, microhardness and XRD analysis of selective laser melted Inconel 718 alloy,” *Procedia CIRP*, vol. 71, pp. 500–504, 2018.

[8] L. Chen, Q. Xu, Y. Liu, G. Cai, and J. Liu, "Machinability of the laser additively manufactured Inconel 718 superalloy in turning," *International Journal of Advanced Manufacturing Technology*, vol. 114, no. 3–4, pp. 871–882, 2021.

[9] N. Khanna, K. Zadafiya, T. Patel, Y. Kaynak, R. A. Rahman Rashid, and A. Vafadar, "Review on machining of additively manufactured nickel and titanium alloys," *Journal of Materials Research and Technology*, vol. 15, pp. 3192–3221, 2021.

[10] Z. Pan, Y. Feng, and S. Y. Liang, "Material microstructure affected machining: A review," *Manuf Rev (Les Ulis)*, vol. 4, 2017, doi: 10.1051/mfreview/2017004.

[11] E. Ducroux, G. Fromentin, F. Viprey, D. Prat, and A. D'Acunto, "New mechanistic cutting force model for milling additive manufactured Inconel 718 considering effects of tool wear evolution and actual tool geometry," *J Manuf Process*, vol. 64, pp. 67–80, Apr. 2021.

[12] A. Malakizadi *et al.*, "The role of microstructural characteristics of additively manufactured Alloy 718 on tool wear in machining," *Int J Mach Tools Manuf*, vol. 171, Dec. 2021.

[13] C. Yao, Z. Zhou, J. Zhang, D. Wu, and L. Tan, "Experimental study on cutting force of face-turning Inconel718 with ceramic tools and carbide tools," *Advances in Mechanical Engineering*, vol. 9, no. 7, pp. 1–9, 2017.

[14] D. Dudzinski, A. Devillez, A. Moufki, D. Larrouquère, V. Zerrouki, and J. Vigneau, "A review of developments towards dry and high speed machining of Inconel 718 alloy," *Int J Mach Tools Manuf*, vol. 44, no. 4, pp. 439–456, 2004.

[15] D. Ulutan and T. Ozel, "Machining induced surface integrity in titanium and nickel alloys: A review," *Int J Mach Tools Manuf*, vol. 51, no. 3, pp. 250–280, 2011.

[16] E. Brinksmeier, G. Levy, D. Meyer, and A. B. Spierings, "Surface integrity of selective-laser-melted components," *CIRP Ann Manuf Technol*, vol. 59, no. 1, pp. 601–606, 2010.

[17] P. Wood *et al.*, "Machinability of INCONEL718 alloy with a porous microstructure produced by laser melting powder bed fusion at higher energy densities," *Materials*, vol. 13, no. 24, pp. 1–13, 2020.

[18] E. Kaya and B. Akyüz, "Effects of cutting parameters on machinability characteristics of Ni-based superalloys: a review," *Open Engineering*, vol. 7, no. 1, pp. 330–342, 2017.

[19] S. Zhang, J. Li, X. Zhu, and H. Lv, "Saw-tooth chip formation and its effect on cutting force fluctuation in turning of Inconel 718," *International Journal of Precision Engineering and Manufacturing*, vol. 14, no. 6, pp. 957–963, Jun. 2013.

[20] E. O. Hall, "Yield Point Phenomena in Metals and Alloys," *Yield Point Phenomena in Metals and Alloys*, 1970, doi: 10.1007/978-1-4684-1860-6.

[21] M. Shunmugavel, A. Polishetty, M. Goldberg, and J. Nomani, "Influence of Build Orientation on Machinability of Selective Laser Melted Titanium Alloy-Ti-6Al-4V," 2017. [Online]. Available: https://www.researchgate.net/publication/318352450

[22] M. A. Xavior, M. Patil, A. Maiti, M. Raj, and N. Lohia, "Machinability studies on INCONEL 718," *IOP Conf Ser Mater Sci Eng*, vol. 149, no. 1, 2016.

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Enabling Sustainable Steel Production with Computer Vision

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Abstract. The steel industry is a significant contributor to global carbon emissions, making the sustainability of it an important area of improvement. Existing decarbonisation solutions such as carbon capture, hydrogen-based steelmaking and electrolysis have been explored but the potential of artificial intelligence, and specifically computer vision, is yet to be realised. Computer vision has shown competence in a range of steelmaking applications but has not been linked to sustainability in the industry. This lack of awareness results in missed opportunities for sustainable development. The introduction of this paper connects computer vision to steelmaking and sustainability, which is followed by a literature review based on existing technologies, and the description of a future vision of steelmaking. The paper will be finalised with conclusions.

Keywords. computer vision, deep learning, steelmaking, manufacturing, sustainability

1. Introduction

The United Nations (UN) defines sustainability as "meeting the needs of the present without compromising the ability of future generations to meet their own needs", which is achievable by addressing the interdependent and mutually beneficial economic, social and environmental pillars of sustainable development on local, national, regional and global levels [1, 2]. The steel industry is a major contributor to global sustainability challenges due to pollution, high energy demand and safety hazards. However, due to its high impact it also possesses the potential to be a major part of the solution [3].

Sustainable steelmaking is a controversial topic due to being a cornerstone of the urbanisation process of developing countries [4]. Furthermore, traditional approaches to sustainability have relied on flawed technologies such as biomass substitution, carbon capture and storage and green and blue hydrogen, which are limited technically and economically [5–8].

Computer vision (CV) is a branch of artificial intelligence (AI): a strong driver of industry 4.0 and the most powerful emerging technology that exists today. Computer vision refers to a range of image and video data processing techniques that can analyse data to describe the world we see around us, or in some cases, the world around us that we are unable to see. Computer vision has already revolutionised the automotive industry with self-driving cars, the agricultural industry with crop surveillance, healthcare with automated medical diagnosis and the manufacturing industry is no exception with automated inspection systems for assembly and surface defects, automated labelled character recognition on parts, industrial robot vision, and more [9–14]. In this paper, a literature review will cover some existing studies in the area, followed by a description of how computer vision in steelmaking could look in the future. Conclusions will then finalise the paper.

2. Literature Review

The aim of this paper is to bring attention to the importance of integrating computer vision technology with steelmaking to mitigate the consequences of inherently unsustainable practices. This literature review will outline existing examples that integrate the two fields.

2.1. Surface Defect Inspection

Surface defect detection consists of two steps: localisation and classification. During localisation the object's location is identified, and during classification the type of object is identified. In the past, steel strip surface defect detection methods were mostly manual which resulted in a high false detection rate [15]. For the most experienced workers the detection rate of defects was around 80%, leaving one in five defects overlooked [15]. Poor quality steel leads to economic and ecological consequences due to wasted resources, as well as social consequences due to the damaged reputation of a company manufacturing poor-quality steel which takes many years to recover from [16].

Table 1 shows a comparison of existing methods of surface defect inspection, where mAP is the mean average precision which normally refers to the average of areas under the precision-recall curves generated for each predicted class during detection or segmentation. Equation 1 and Equation 2 show the precision and recall respectively, where TP is true positives, which is the number of correct predictions. Ground truths refer to the actual number of instances.

Table 1: Comparison of surface defect detection methods based on mean average precision and frames per second

Method	mAP	FPS
DCC-CenterNet	79.41	71.37
MSFT-YOLO	75.70	29.10

$$precision = \frac{TP}{\#predictions} \tag{1}$$

$$recall = \frac{TP}{\#groundtruths} \tag{2}$$

Existing work includes a model called DCC-CenterNet that was comprised of CenterNet, a dilated feature enhancement model (DFEM) and a prediction head which was tested on different defects (crazing, inclusions, patches, pitted surfaces, rolled-in scale and scratches, punching, weld line, crescent gap, water spot, oil spot, silk spot, rolled pit, crease and waist folding) [17]. MSFT-YOLO is another model which integrates YOLOv5, a transformer and a bidirectional feature pyramid network (FPN) and was tested on crazing, inclusion, patches, pitted surfaces, rolled-in scale and scratches [18].

2.2. Microstructural Analysis

Microstructural analysis is also evolving through computer vision. Classification and segmentation are either used individually or together. Segmentation is pixel-level prediction of objects, making it more accurate than detection and more appropriate for tasks involving microstructure due to their detail. Microstructural analysis is crucial for determining the physical and chemical properties of a material and has normally been conducted using human judgment, resulting in uncertainties [19]. Furthermore, traditional methods are time consuming and challenging for workers reducing productivity and reliability of their observations [20].

Studies that involve the use of computer vision for microstructural analysis are compared in Table 2. One achieved microstructural segmentation and subsequent analysis of ultra-high carbon steel using a PixelNet variant, where distinction was made between the proeutectoid cementite network, fields of spheroidite particles, ferritic matrix within the particle-free denuded zone near the network, and Widmanstätten laths [21]. The segmentation provided a basis for describing cementite particle size and denuded zone width distributions [21]. Additionally, a deep convolutional neural network (DCNN) was used to classify eight different types of steel microstructure images obtained from light optical microscopy (LOM) [22].

Table 2: Comparison of microstructural analysis models based on accuracy

Method	Accuracy
PixelNet Variant	86.5%, 92.6%
DCNN	99.8%

2.3. Health & Safety

Safety within steelmaking is a large contributor to the social pillar of sustainability. According to the UK Health and Safety Executive (HSE), 123 workers were killed in work-related accidents in 2021/22 in the UK [23]. The leading sector for this was construction with 30 deaths, followed by manufacturing with 22 deaths [23]. Steel production plays a large part in fatal work-related accidents, especially considering the type of equipment used in steel production such as hot metal ladles, blast furnaces, basic oxygen furnaces, electric arc furnaces, hot and cold rolling mills, coating machines and more.

Existing computer vision approaches to improve steelmaking include one study where Faster RCNN was trained on 4500 images with labelled helmets as part of a safety helmet wearing detection system for steel factories, which achieved an mAP of 71.21 [24]. Another study proposed a crane hook detection system to ensure the hook and ladle trunnion are properly matched when lifting ladles, preventing major accidents [25]. The approach taken was to use Mask R-CNN (a segmentation extension of Faster R-CNN), to segment the crane hook and check if it is matched correctly with a painted trunnion

[25]. Across 100 images, the proposed model achieved a segmentation accuracy of 92% and a safety judgment accuracy of 96% [25].

3. The Future of Steelmaking

Since the dawn of industry 4.0 (considered to be 2011 [26]), factories have become increasingly smart through addition of many sensors to equipment and products, which with digitalisation and ubiquitous computing, has led to a new degree of autonomy [27]. As AI has begun to flourish, this degree of autonomy has burgeoned.

Automatic steel surface defect detection has become a prominent area of CV research and a range of systems have been implemented that largely extend the two studies discussed in the literature review. The accuracy, speed and computational efficiency at which inspection is done is increasing. The continuously improving autonomy and analysis capabilities of these systems will result in less material wastage, less energy wastage and reduced quantities of poor quality steel on the market. Also, process reliability will increase and responsibility on workers will be lightened due to the reduced level of required supervision.

CV-powered microstructural examination provides benefits such as improved quality of observations and analyses, shortened observation times, process reliability and reduced human resource requirements. These all have positive economic impacts, as well as potential social improvements due to the lightening of worker responsibility.

Microstructural analysis technology advancement also promotes capabilities of microstructural tuning for sustainable alloy design [28]. Building recyclability directly into the design of steel requires avoidance of over-designed alloys and utilisation of materials from a limited composition spectrum whilst property tuning through microstructural adjustment [28]. Since computer vision technology has the potential to surpass abilities of existing experts, it could assist in improving the recyclability of future alloys. Additionally, there is the potential to make previously undiscovered microstructural observations since AI has already found undiscovered nanostructures and proteins in other fields of research [29, 30]. New discoveries are encouraging to existing and prospecting researchers, as well as the general public which is socially beneficial.

Safety is a major element of the social pillar of sustainability. The more CV is integrated into steelmaking, the safer it will become even as a by-product due to the remote element. When targeted specifically, it has applications such as ensuring safety equipment is worn at all times and processes are operated correctly by workers to avoid accidents. In future, entire steelworks could be monitored with automatic compliance checks in real-time with alert responses if any safety rules are not adhered to, and early warning systems will alert when processes are deviating from control allowing timely rectification. This would revolutionise safety in steelmaking because it is much harder to make mistakes with hard engineered safety systems in place, as opposed to just following procedure.

All the examples mentioned in this section portray the current progress of integrating CV into steelmaking for sustainable development. The future possibilities are exciting and are likely to lead to fully-automated inspection, process control and transportation of materials. Additionally, there will be invaluable microstructural examination insights and significantly improved site safety.

4. Conclusions

This paper has described recent advances in computer vision and how they will help to improve the sustainability of steelmaking. The main benefits of computer vision in steelmaking include improved safety, improved product quality, improved productivity, reduced waste, reduced stress of workers and increased technological insight. These benefits directly improve the environmental, economic and social sustainability of steelmaking.

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References

[1] Brundtland Commission. Report of the world commission on environment and development: Our common future, Oct 1987. Available from: https://sustainabledevelopment.un.org/content/documents/5987our-common-future.pdf. [Accessed 2023 Feb 9].

[2] United Nations. Report of the world summit on sustainable development, Nov 2002. Available from: http://www.un-documents.net/aconf199-20.pdf. [Accessed 2023 Feb 9].

[3] P. Taticchi, P. Carbone, and V. Albino. *Corporate Sustainability*. Springer, Berlin, 2013.

[4] X. Zhou. *Sustainable iron and steel making systems integrated with carbon sequestration*. PhD thesis, Columbia University, 2015.

[5] H. Mandova, S. Leduc, C. Wang, E. Wetterlund, et al. Possibilities for co2 emission reduction using biomass in european integrated steel plants. *Biomass Bioenerg*, 115:231–243, 2018. doi: 10.1016/j.biombioe.2018.04.021.

[6] MD. Santis, AD. Donato, T Kempken, T. Hauck, et al. Investment needs, March 2021. Available from: https://www.estep.eu/assets/Uploads/GreenSteel-D2.2-InvestmentNeeds-Publishable-version.pdf. [Accessed 2023 Feb 9].

[7] E. Martin-Roberts, V. Scott, S. Flude, G. Johnson, et al. Carbon capture and storage at the end of a lost decade. *One Earth*, 4(11):1569–1584, Nov 2021. doi: 10.1016/j.oneear.2021.10.002.

[8] A. Ajanovic, M. Sayer, and R. Haas. The economics and the environmental benignity of different colors of hydrogen. *Int J Hydrogen Energy*, 47(57):24136–24154, Jul 2022. doi: 10.1016/j.ijhydene.2022.02.094.

[9] Y. Han and J. Jeong. Real-time inspection of multi-sided surface defects based on panet model. In *Computational Science and Its Applications (ICCSA2020)*, Cagliari, Jul 2020. Springer.

[10] H. Huang, Z. Wei, and L. Yao. A novel approach to component assembly inspection based on mask r-cnn and support vector machines. *Inf.*, 10(9), Sep 2019. doi: 10.3390/info10090282.

[11] SJ. Lee, G. Koo, H. Choi, and SW. Kim. Transfer learning of a deep convolutional neural network for localizing handwritten slab identification numbers. In *2017 Fifteenth IAPR International Conference on Machine Vision Applications (MVA)*, Nagoya, May 2017. IEEE.

[12] QJ. Zhao, P. Cao, and DW. Tu. Toward intelligent manufacturing: label characters marking and recognition method for steel products with machine vision. *Adv Manuf*, 2:3–12, Mar 2014. doi: 10.1007/s40436-014-0057-2.

[13] CY. Lin, C. Wang, and M. Tomizuka. Pose estimation in industrial machine vision systems under sensing dynamics: A statistical learning approach. In *2014 IEEE International Conference on Robotics & Automation (ICRA)*, Hong Kong, May 2014. IEEE.

[14] C. Chuixin and C. Hanxiang. Agv robot based on computer vision and deep learning. In *2019 3rd IEEE International Conference on Robotics and Automation Sciences (ICRAS)*, Wuhan, Jun 2019. IEEE.

[15] J. Zhang, X. Kang, H. Ni, and F. Ren. Surface defect detection of steel strips based on classification priority yolov3-dense network. *Ironmak Steelmak*, 48(5):547–558, Sep 2020. doi: 10.1080/03019233.2020.1816806.

[16] F. Psarommatis, J. Sousa, JP. Mendonça, and D Kiritsis. Zero-defect manufacturing the approach for higher manufacturing sustainability in the era of industry 4.0: a position paper. *International Journal of Production Research*, 60(1):73–91, Oct 2021. doi: 10.1080/00207543. 2021.1987551.

[17] R. Tian and M. Jia. Dcc-centernet: A rapid detection method for steel surface defects. *Measurement*, 187, Jan 2022. doi: 10.1016/j.measurement.2021.110211.

[18] Z. Guo, C. Wang, G. Yang, Z. Huang, et al. Msft-yolo: Improved yolov5 based on transformer for detecting defects of steel surface. *Sensors*, 22(9), May 2022. doi: 10.3390/s22093467.

[19] S. Azimi, D. Britz, M. Engstler, M. Fritz, and F. Mücklich. Advanced steel microstructural classification by deep learning methods. *Scientific Reports*, 8, Feb 2018. doi: 10.1038/s41598-018-20037-5.

[20] S. Rekha and VK. Bupesh Raja. Review on microstructure analysis of metals and alloys using image analysis techniques. In *IOP Conference Series: Materials Science and Engineering*, volume 197, 2017. doi: 10.1088/1757-899X/197/1/012010.

[21] BL. DeCost, B. Lei, T. Francis, and EA. Holm. High throughput quantitative metallography for complex microstructures using deep learning: A case study in ultrahigh carbon steel. *Microscopy and Microanalysis*, 25(1):21–29, Mar 2019. doi: doi.org/10.1017/S143.

[22] B. Mulewicz, G. Korpala, J. Kusiak, and U. Prahl. Autonomous interpretation of the microstructure of steels and special alloys. *Mater Sci Forum*, 949:24–31, Mar 2019. doi: 10.4028/www.scientific.net/MSF.949.24.

[23] Health & Safety Executive (HSE). Work-related fatal injuries in Great Britain, 2022. [Internet], 2022. Available from: https://www.hse.gov.uk/statistics/pdf/fatalinjuries.pdf. [updated 2022 Nov 23; cited 2023 Feb 9].

[24] W. Zhang, CF. Yang, F. Jiang, XZ. Gao, et al. Safety helmet wearing detection based on image processing and deep learning. In *2020 International Conference on Communications, Information System and Computer Engineering (CISCE)*, Kuala Lumpur, Jul 2020. IEEE. doi: 10.1109/CISCE49214.2020.9238236.

[25] S. Kang and H. Wang. Crane hook detection based on mask r-cnn in steel-making plant. *J Phys Conf Ser*, 1575, 2020. doi: 10.1088/1742-6596/1575/1/012151.

[26] G. Culot, G. Nassimbeni, G. Orzes, and M. Sartor. Behind the definition of industry 4.0: Analysis and open questions. *International Journal of Production Economics*, 226:107617, Aug 2020. doi: 10.1016/j.ijpe.2020.107617.

[27] H. Lasi, P. Fettke, HG. Kemper, T. Feld, et al. Industry 4.0. *Business & Information Systems Engineering*, 6:239–242, Jun 2014. doi: 10.1007/s12599-014-0334-4.

[28] D. Raabe, CC. Tasan, and EA. Olivetti. Strategies for improving the sustainability of structural metals. *Nature*, 575:64–74, Nov 2019. doi: 10.1038/s41586-019-1702-5.

[29] GS. Doerk, A. Stein, S. Bae, MM. Noack, et al. Autonomous discovery of emergent morphologies in directed self-assembly of block copolymer blends. *Science Advances*, 9(2), Jan 2023. doi: 10.1126/sciadv.add3687.

[30] J. Jumper, R. Evans, A. Pritzel, et al. Highly accurate protein structure prediction with alphafold. *Nature*, 596:583–589, Jul 2021. doi: 10.1038/s41586-021-03819-2.

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Flow Visualization and Parameter Suitability in Cold Spray Titanium Deposition: A CFD Approach

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Abstract. Cold Spray is an emerging technology in the domain of additive manufacturing. It is a solid-state high strain rate material deposition technique. It uses a supersonic (2-4 Mach) impact of process gas (such as nitrogen or helium) to deposit micron-sized (1-100 µm) metallic or composite powder particles onto a substrate via a severe plastic deformation mechanism without any significant fusion. To have a successful deposition, the specific powder particles should travel above a material-dependent threshold velocity, which is called the critical velocity. The convergent-divergent nozzle is employed for achieving high velocities. The main objective of the current research is to study the flow visualization of two-phase titanium particle laden nitrogen gas in a simulated 2-D axisymmetric nozzle where particles are having a particle size of 25 microns, and to investigate the suitability of a specific set of cold spraying process parameters for the successful deposition of titanium powder using computational fluid dynamics. For the analysis, a two-equation realizable k-ε simulation viscous model was preferred due to its more realistic consideration of the cold spray process and reduced computational cost. Titanium powder particles will be successfully deposited using cold spray when operated at the precise set of process conditions on account of the average particle velocity observed at standoff distance higher than the critical velocity.

Keywords. Cold spray, Coating, Critical velocity, Viscous model, Computational fluid dynamics.

1. Introduction

Cold spray has emerged as a high production rate process for both surface engineering and additive manufacturing. In this technique, micron-sized powder particles are deposited by impacting them with supersonic velocities onto a target substrate material. When these high kinetic energy particles strike on the substrate, they undergo significant plastic deformation and stick on the substrate as a coating. The feedstock particles are accelerated by an expanding gas in a supersonic de-Laval nozzle. In this process, the temperature of the particle is well below the recrystallisation temperature, therefore the name cold spray is given to this process. Since temperature is low, deposits with high purity can be manufactured by this process. In contrast to other thermal spray techniques including high-velocity oxy-fuel (HVOF), plasma spray, and detonation-gun, this process is solid-state, therefore there is little oxidation and other compositional degradation of the sprayed powder [1]. A broad range of metals, including Cu, Al, Ti, Fe- and Ni-based alloys, as well as ceramics and cermets, can be deposited on a wide

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variety of substrate materials. As the deleterious effects of thermal distortions and heat affected zones (HAZ) are very minimal, it is a very reliable technology for coating temperature-sensitive materials such as amorphous and nanomaterials, and different powder material combinations with varied differences in their melting point temperatures [2, 3, 4].

The powder particle velocity at the exit of the nozzle immediately before hitting the substrate is a paramount characteristic in the cold spray method. The velocity should be above a threshold limit which is termed as critical velocity. All the powder particles crossing this material-dependent critical velocity will end up in successful deposition on the target substrate. If a particle's velocity is lesser than the critical velocity then either the powder particle will bounce off the substrate or it will impinge on the substrate leading to erosion of the same in case the velocity is higher than the erosion velocity [5-6].

Li et al. [7] performed numerical investigation of the cold spray procedure including the introduction of under- and over-expanded jets. By examining nozzle exit circumstances, they suggested a normal shock wave model to calculate the impact speed of powder particles in cold spray. In order to recreate the flow of gas phase and discrete particle paths in a supersonic nozzle both before and after colliding the intended target surface, Karimi et al. [8] effectively created the computational fluid dynamics framework of the cold spraying process. A recently published three-dimensional CFD simulation model for the cold spray process was developed by Zahiri et al. [9] and uses a two equation k-ε turbulence model. In this study, the model estimation was verified against experimental data by evaluating simulation findings. The titanium substrate temperature measured during the experiment was primarily used to calibrate the 3D model. The study found that the cold spray gas velocity and pressure predictions made by the 3D model were satisfactorily similar to the experimental data.

The present study introduces a computational fluid dynamics model that provides valuable insights into the flow visualization of nitrogen gas carrying titanium powder during the cold spray process. This model enables a comprehensive understanding and analysis of particle trajectories and the dynamic gas flow field within a convergent-divergent nozzle. Furthermore, it offers the opportunity to examine particle behavior in the proximity of the nozzle exit, both prior to and following collision with the target substrate plate. Moreover, the study conducts an investigation into specific process parameters to assess their suitability for achieving successful deposition of discrete titanium particles using the cold spray technique. Overall, this study offers useful information for optimizing the cold spray process in order to perform efficient titanium powder deposition.

2. Methodology for Computation Fluid Dynamics Analysis

2.1 Computational Domain, Meshing and Boundary Conditions

A specific de-Laval nozzle geometry has been considered for the analysis, which is being used in the cold spray system. The nozzle has a circular cross-section with a main gas pressure inlet diameter of 19 mm, pressure outlet diameter of 7 mm and throat of 3 mm. The nozzle barrel length is 15 mm with convergent and divergent section length of 55 mm and 175 mm respectively. The powder injection length is 30 mm with a carrier gas pressure inlet diameter of 2.5 mm. The substrate wall is at a standoff distance of 25 mm from the nozzle exit and has a length of 47 mm as shown in Fig.1.

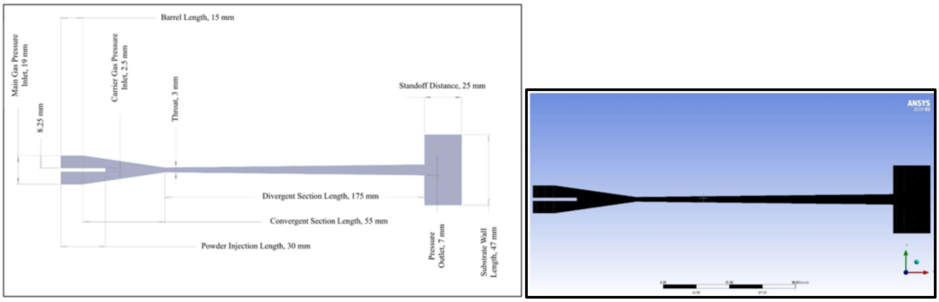

Fig.1 Computational domain and meshing of the cold spray nozzle.

The boundary limits applied in the 2-D computation domain and meshing have also been illustrated in Fig.1. The temperature and pressure of the main gas were set at a value of 873 K and 3 MPa while for the inner powder injection tube, a carrier gas temperature of 300 K and pressure of 3.1 MPa were applied. The titanium powder particles were considered to be spherical with an average diameter of 25 µm. The injection wall and nozzle surfaces were handled as viscous adiabatic. The ambient temperature and pressure were applied to each of the five boundaries that are exterior to the nozzle.

The nitrogen gas was permitted to flow in any direction at the substrate wall surface. The boundary limit conditions so applied prompted computed mass flow rates of N_2 of 1.35e-2 kg/s from the main gas annulus while 3.9e-3 kg/s through the powder injection inner tube. Titanium discrete powder phase is predicted to flow through the inner tube at a mass flow rate of 4.8e-4 kg/s. The detail of the discrete phase injection properties and gas particulars have been tabulated in Table.1.

Table.1 Detail of discrete phase injection properties (left) and nitrogen gas used as main and carrier gas (right).

Discrete Phase Injection Properties	
Injection Type	Surface
Injection Surface	Carrier Gas Pressure Inlet
Injection Direction	Normal to Surface
Particle Type	Inert
Particle Material	Titanium
Particle Material Density (kg/m^3)	4850
Particle Material Specific Heat (J/kg-K)	544.25
Particle Diameter (microns)	25
Particle Temperature Inlet (K)	300
Particle Velocity Inlet (m/s)	0
Particle Flow Rate (kg/s)	4.8e-4

Gas Details	
Gas	Nitrogen
Density (kg/m^3)	1.138
Specific Heat (J/kg-K)	1040.67
Thermal Conductivity (W/m-K)	0.0242
Viscosity (kg/m-s)	Sutherland

The implicit formulation was used as the converged steady state solution can be obtained easily on account of its broader stability characteristics when compared with explicit formulation. Initially, during the startup the value of the courant number was kept default (which is 5). The ROE-FDS (approximate riemann solver) flux type was employed since the boundary needed to be captured because of the discontinuity present near the boundary (like in shocks). The required convergence as per the residual absolute criteria was achieved after 10232 iterations.

3. Results and Discussions

3.1 Continuum Gas Phase Contour Maps

The velocity contour map for the nitrogen gas is depicted in Fig.2 (a), which clearly shows rise in the velocity along the nozzle's length. The velocity contour demonstrates that the flow from the de-Laval nozzle is supersonic and compressible. By transforming the pressure head (as evident from Fig.3) into a supersonic jet, the nozzle could achieve higher exit velocity. The maximum velocity of the gas phase at the standoff distance (SoD) is 1800 m/s which in turn corresponds to a Mach number of 3.5. Shockwaves develop when a supersonic flow adapts to disturbances (perturbations) or conditions downstream. In this particular case, it is the substrate which is creating the flow perturbations. Infinitesimal pressure waves are generated in the near vicinity on account of change in the momentum and molecular energy of the carrier gas. These pressure waves advancing at the speed of sound merge immediately ahead of the flow to form a typical shockwave as they are unable to move upstream or alert the flow to the presence of the substrate. The shockwave is separated and curving as shown in Fig.2 (b), this phenomenon is known as the bow shock. A zone containing a recirculating, minimal-velocity fluid experiences significant fluctuations and sudden shifts in the local flow characteristics within the confines of the bow shock. Within such a shockwave, the value of the velocity begins to decrease, whilst the gas density increases almost instantly. The dimensions of the bow shock are greater at much lower SoDs, resulting in a greater negative impact on the entrained particle velocity. Although the Cold Spray community has conducted extensive research on the nozzle SoD, there is no general agreement regarding its effects. Due to viscous effects, shockwaves and ambient mixing, the gas jet's velocity away from the nozzle decreases as SoD increases [4, 10]. Hence, an optimum SoD has to be chosen by taking these two competing mechanisms into account which are: the gas jet which causes particle acceleration/deceleration, and the bow shock promoting particle deceleration.

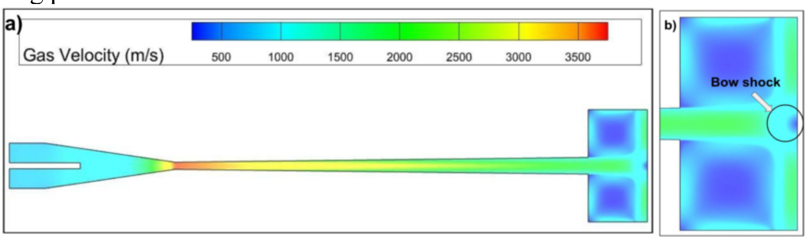

Fig.2 (a) Gas velocity contour map with nitrogen as the process gas at 3 MPa main gas pressure and 3.1 MPa carrier gas pressure (**b)** enlarged view closer to the substrate showing bow shock phenomenon.

The gas temperature contours are illustrated in Fig.4, with the main gas entering the de-Laval nozzle at a temperature of 873 K and carrier gas at a temperature of 300 K. The wall temperature of the nozzle after the throat is high because of the no slip phenomenon. Hence, the cooling is done through the coolant circulating inside the nozzle sleeve.

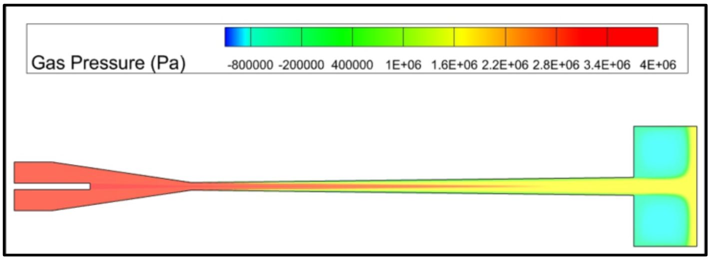

Fig.3 Gas pressure contours with nitrogen as the process gas at 3 MPa main gas pressure and 3.1 MPa carrier gas pressure.

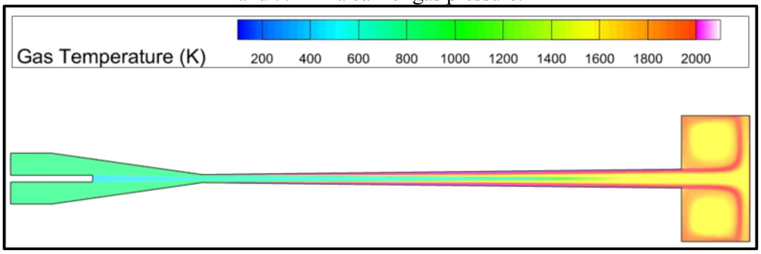

Fig.4 Gas temperature contours with nitrogen as the process gas at main gas temperature of 873 K and carrier gas temperature of 300 K.

3.2 Discrete Phase Contour Maps

The velocity contour map for the discrete titanium powder phase has been illustrated in Fig.5. According to Schmidt et al. [11], the critical velocity for the successful deposition of titanium powder particles having 25 µm size lies between 700 and 900 m/sec. The average particle velocity of the discrete phase at the SoD of 25 mm is coming out to be 946.2 m/sec, which is greater than the abovementioned critical velocity. This would suggest that the deposition is possible for this particular set of cold spray process parameters.

The temperature contour map for the discrete phase is displayed as shown in Fig.6. The average particle temperature is coming out to be 294 K, which is considerably lower than the melting point of titanium (1941 K). Hence, no compositional changes are expected in the discrete phase indicating an oxide-free deposition. Also, since the micron sized titanium powder particles are pyrophoric, thermal degradation at high temperature is possible, however this will be avoided in the evaluated temperature range (294K). It may be concluded that the intended (chosen) set of process parameters is capable of depositing the titanium powder particles in an efficient manner in solid-state, as per the mandate of cold spray.

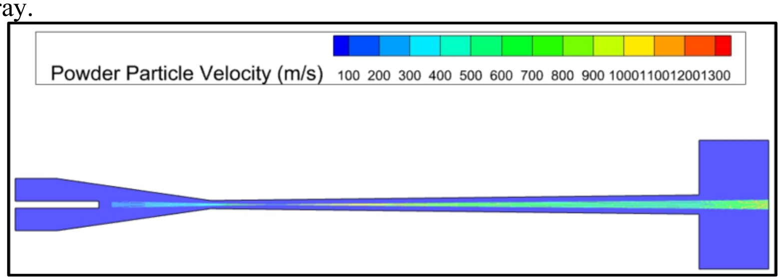

Fig.5 Velocity contours of discrete titanium powder phase.

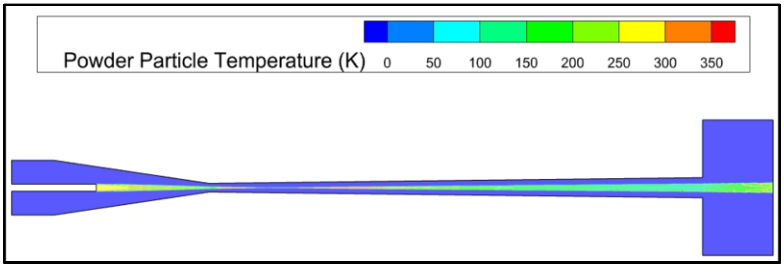

Fig.6 Temperature contours of discrete titanium powder phase.

Conclusions

- The cold spray process was successfully modeled using computational fluid dynamics for flow visualization of nitrogen gas containing titanium powder.
- The bow shock made at the zone of impact could be anticipated by the model, which is critical to comprehend since it lessens the speed of both the gas and entrained particles.
- The study shows that the standoff distance (SoD) needs to be optimized, because at lower SoD the size of the bow shock is more. It has a greater negative effect on velocities of discrete powder phase and process gas.
- The average particle velocity obtained at the substrate wall was greater than the critical velocity of titanium powder particles having size of 25 µm. Also, the average particle temperature was substantially less than the melting point which implies that the solid state deposition is taking place without any compositional changes in the powder feedstock.
- The intended set of cold spray process parameters was found to be appropriate for the successful deposition of the titanium powder particles.

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References

[1] A. Sova, S. Grigoriev, A. Okunkova, and I. Smurov. 2013. Potential of cold gas dynamic spray as additive manufacturing technology. *Int J Adv Manuf Technol* 69, 9–12 (December 2013), 2269–2278.

[2] Pasquale Cavaliere. 2015. Cold Spray Coating Technology for Metallic Components Repairing. In *Through-life Engineering Services*, Louis Redding and Rajkumar Roy (eds.). Springer International Publishing, Cham, 175–184.

[3] Parminder Singh, Surinder Singh, Harpreet Singh, Eklavya Calla, Harpreet Singh Grewal, Harpreet Singh Arora, and Anand Krishnamurthy. 2023. Characterization and High-Temperature Oxidation Behavior of Ni–20Cr Deposits Fabricated by Cold Spray-Based Additive Manufacturing. *Coatings* 13, 5 (May 2023), 904.

[4] M. Jones, A. Cockburn, R. Lupoi, M. Sparkes, and W. O'Neill. 2014. Solid-state manufacturing of tungsten deposits onto molybdenum substrates with supersonic laser deposition. *Materials Letters* 134, (November 2014), 295–297.

[5] J. Pattison, S. Celotto, R. Morgan, M. Bray, and W. O'Neill. 2007. Cold gas dynamic manufacturing: A non-thermal approach to freeform fabrication. *International Journal of Machine Tools and Manufacture* 47, 3–4 (March 2007), 627–634.

[6] R. Maestracci, A. Sova, M. Jeandin, J.-M. Malhaire, I. Movchan, Ph. Bertrand, and I. Smurov. 2016. Deposition of composite coatings by cold spray using stainless steel 316L, copper and Tribaloy T-700 powder mixtures. *Surface and Coatings Technology* 287, (February 2016), 1–8.

[7] S. Li, B. Muddle, M. Jahedi, and J. Soria. 2012. A Numerical Investigation of the Cold Spray Process Using Underexpanded and Overexpanded Jets. *J Therm Spray Tech* 21, 1 (January 2012), 108–120.

[8] M. Karimi, A. Fartaj, G. Rankin, D. Vanderzwet, W. Birtch, and J. Villafuerte. 2006. Numerical Simulation of the Cold Gas Dynamic Spray Process. *J Therm Spray Tech* 15, 4 (December 2006), 518–523.
[9] S. H. Zahiri, T. D. Phan, S. H. Masood, and M. Jahedi. 2014. Development of Holistic ThreeDimensional Models for Cold Spray Supersonic Jet. *J Therm Spray Tech* 23, 6 (August 2014), 919–933.
[10] J. Pattison, S. Celotto, A. Khan, and W. O'Neill. 2008. Standoff distance and bow shock phenomena in the Cold Spray process. *Surface and Coatings Technology* 202, 8 (January 2008), 1443–1454.
[11] Tobias Schmidt, Frank Gärtner, Hamid Assadi, and Heinrich Kreye. 2006. Development of a generalized parameter window for cold spray deposition. *Acta Materialia* 54, 3 (February 2006), 729–742.

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Part 3

Advances in Manufacturing and Process Modelling

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An Investigation into the Exploratory Use of Additive Manufacturing in Drum Gate Design for Open Channel Flow

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Abstract. *Additive Manufacturing (AM) offers itself as a valuable tool for exploring a range of possibilities through design and development of complex shapes in fluid flow research. itself as a valuable tool for exploring. In this research, the limitations of existing components in a 2.5 m open channel fluid flow experiment, which are characterized by their standard basic shapes, are examined. Specifically, this research focuses on investigating flow control in hydraulic systems by introducing gates with more intricate geometries. However, these complex design shapes are typically expensive and time-consuming to acquire from equipment suppliers. To circumvent these challenges, AM technology allow a cost-effective solution to implement progressive design modifications throughout the investigation. This paper presents a comparative analysis between a range of positions of an AM produced curved drum gate in terms of flow rate, fluid velocity profile, water level height and related fluid flow parameters. To analyse and validate the results, Computational Fluid Dynamics (CFD) modelling, analysis, and simulation techniques are employed. Based on the experimental findings and verification, this paper discusses the suitability and applicability of AM techniques in fluid flow analysis. The ability to manufacture customized components through AM offers a promising avenue for enhancing fluid flow research, allowing for cost-effective and time-efficient design modifications. The key concept associated with this study is the importance of utilizing AM and specific materials for advancing fluid flow analysis.*

Keywords: Experimental methods, additive manufacturing, photopolymer resin.

1. Introduction

Additive manufacturing (AM) has emerged as a promising technology for conducting fluid mechanics experiments, offering numerous possibilities. Gated spillways have attracted significant interest due to their control capabilities and reduced footprint of the spillway. Crest gates, however, face challenges such as gate failure, support

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member buckling, and friction-related issues. An alternative, the radial gate or Tainter gate, has been historically employed where downstream complications arise from high velocity movement, cavitation probability, and aeration. Mousavimehr, Yamini, and Kavianpour (2021) investigated shockwave effects and proposed experimental methods to mitigate them, recognizing AM's potential in fluid flow research. AM's established role in experimental fluid flow research, reviewed by Musa et al. (2023), underlines its significance and potential advancements in various areas.

2. Methodology

In this study/research, the poor discharge profile downstream of the existing drum used as a roller gate within a flow channel is investigated. Previous roller gates with rudimentary sector designs have proven to be ineffective. Thus, this research aims to enhance the roller gate design by incorporating mathematical curve profiles. Specifically, the utilization of a logarithmic curve profile based on the Golden ratio (ϕ) is explored; a widely observed natural and man-made phenomena (Maor, 2009). This approach amalgamates biomimicry principles with engineering disciplines. Extensive literature by Passino (2005) has reviewed the advantages and scope of utilizing biomimicry in engineering. Figure 1 illustrates the drum profiles, depicting a logarithmic curve on one side and a standard drum on the other. The polar equation (1) and its components (2) and (3) are employed to plot the curve:

$$r(\theta) = ae^{b\theta} \;(1) \qquad |b| = \frac{\ln \varphi}{\frac{\pi}{2}} \;(2) \qquad \varphi = \frac{1+\sqrt{5}}{2} \;(3)$$

Figure 2, depicts the Golden spiral, generated through mathematical software. To facilitate physical integration, a value of 1 was assigned to variable "a," and the Computer Aided Design (CAD) model was scaled to match the dimensions of the existing drum enclosure. Data points were extrapolated into a CAD software, subsequently extruded to generate a STL file for AM modelling.

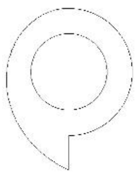

Figure 1. Side view of the drum. The left-hand side has a logarithmic curve profile.

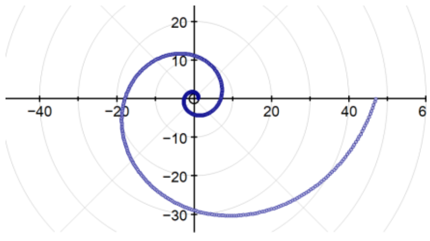

Figure 2. The *Golden spiral* produced using mathematical software.

The provided drum was subjected to testing using the AM model to enable comparative analysis. To minimize side wall leakage, the AM model was equipped with rubber mounts and sealant paper. Experimental investigations were conducted by introducing a displacement of 15 mm between the channel bed and the gate's lowest point. This displacement ensured testing across a wide range of flow rates while maintaining a sufficient water height to interact with the gate without causing overflow. Although various displacements were feasible, the initial readings focused on examining the complete spectrum of flow rates. For comprehensive evaluation, the AM model was tested in multiple positions, including upright and tilted at 45 degrees to the left and right of the centreline. It was crucial to assess both upstream sides of the AM model. Thus, after testing the rounded side (right-hand side of **Figure 1**), the model was reversed, and the logarithmic curved side (left-hand side of **Figure 1**) was tested.

3. Analysis of Results

The results obtained were comprehensively analysed utilizing a spreadsheet, supplemented by observations. This approach proved crucial since findings were not overtly discernible from the spreadsheet alone. Notably, the water height exhibited significant variations in upstream scenarios, with the largest disparities attributed to the occurrence of a hydraulic jump. This was more pronounced at lower flow rates. Intriguingly, when comparing the curved drum configuration to the standard drum, the height difference resulting from the hydraulic jump was less pronounced in the former. Furthermore, the hydraulic jump position occurred much farther downstream in the case of the curved drum. However, as the flow rate approached the drum, the hydraulic jump gradually shifted closer. The hydraulic jump can be a concern due to the increased hydrostatic pressure it exerts on the upstream gate. Conversely, downstream of the jump, it can be advantageous as it mitigates erosion rates. Additionally, it was visually evident that fluctuations exhibited by the standard drum were substantially greater than those observed in both orientations of the curved drum gate.

The analysis of the Froude numbers downstream revealed relatively low values across most cases (0.59 to 2.57). This outcome was anticipated considering the experimental setup's limited flow rate. However, this serves as a limitation of the research, necessitating further investigation using larger channels and higher flow rates to evaluate Froude numbers for full-scale applications. Singh et al. (2022), noted that the optimal Froude number range lies between 4.5 and 9.0. Upstream, supercritical flow ($Fr > 1$) was only observed at the lowest flow rates, as expected. Lower Froude numbers can lead to various downstream issues, but since the curved drum could be opened almost at a full-scale, additional investigation is warranted. The velocity of the fluid ‘V’ and the channel size also influence Froude numbers due to hydraulic depth ‘D’:

$$Fr = \frac{V}{\sqrt{gD}} \quad (4)$$

Comparative analysis of discharges is conducted where the performance for the original drum and a curved drum at different flow rates is examined. Results indicate that original drum exhibited higher values (ranging from 1.53 to 1.55) for lower flow rates compared to other findings. Interestingly, rotating the curved drum by 45 degrees to the right on its curved side yielded the highest value of 2.56 whereas the highest value at full flow was 1.07. However, caution is advised as these measurements are pitot tube based albeit separately calibrated for accuracy.

The specific energy ‘E’ can serve as an alternative comparator, considering its dependency on fluid velocity and gravity acceleration. It also affects the volumetric flow rate ‘Q’, where the breadth of the sluice gate ‘B’ and the displacement of the lowest point of the sluice gate from the channel bed ‘d’ come into play. However, this relationship is not linear due to the variable coefficient of discharge ‘C’, with flow rate. To compare the performance of different positions, an alternative approach involves plotting flow rates based on specific energies. Figures 3 and 4 depict the obtained results. This plotting method involves taking the root of the factor related to the specific energy term and plotting it against the volumetric flow rate, as per the overall equation. This technique allows for a comprehensive evaluation of the tested positions.

$$Q = CBd\sqrt{2g\left(E - \frac{d}{2}\right)} \quad (5)$$

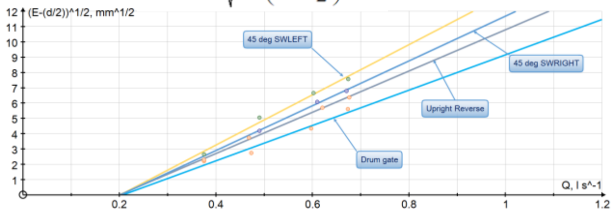

Figure 3. Linear comparison of the standard drum gate to the rounded side of the AM model gate.

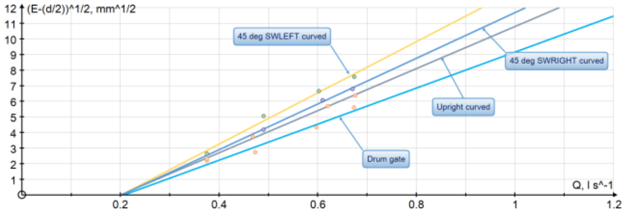

Figure 4. Linear comparison of the standard drum gate to the logarithmic curved side of the AM model gate.

For both orientations the drum gate exhibits the lowest value gradient, suggesting superior performance albeit in the absence of coefficient of discharge. Tilting the model to the left in both orientations resulted in the highest gradient. Previous studies have also focused on the impact of sluice gate geometry on performance, e.g., Daneshfaraz et al. (2023) investigated various parameters, including gate widths and different geometries. However, the current research has limitations, e.g., the channel width. Future studies could explore other factors, including the angle of tilt of the (AM) model, displacement of the AM model from the channel bed, and testing different size sectors. The paper acknowledges that certain aspects have not been thoroughly examined e.g., a comparison of hydrostatic pressure when the gate is closed and the stresses during different flow rates would provide valuable insights. Additionally, further investigation is warranted to study visual observations in greater detail, e.g., the position and sizes of hydraulic jumps and the oscillatory behaviour of the fluid upstream for different flow rates. While the paper's focus is on the effects of geometry on flow parameters, it suggests that testing a standard drum gate with a fitted sector would be a logical step in future research. It is important to maintain focus on the most significant findings of this initial research, given the broad scope of potential testing. Furthermore, vibration problems in full-scale versions of these gates should be considered, as they can pose significant challenges. This highlights the findings related to sluice gate geometry and flow parameters, identifies limitations in the current research, and proposes potential avenues for further investigation. The section emphasizes the need to remain focused on the most significant outcomes of the initial study.

3.1. FEA simulation-based results evaluation

Finite Element Analysis (FEA) based (CFD) flow simulations were done to assess and compare the findings obtained from experimental data for four distinct types of drum gates. The flow simulations accurately predicted the fluid flow pattern and provided accurate calculations of maximum velocities. The CFD analysis of standard, rounded side, and logarithmic curved side drum gates (illustrated in Figures 5, 6, and 7, respectively) exhibited a fluid flow pattern that closely resembled the experimental observations.

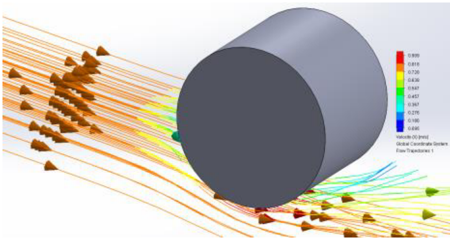

Figure 5. Flow Simulation through Standard Drum Gate

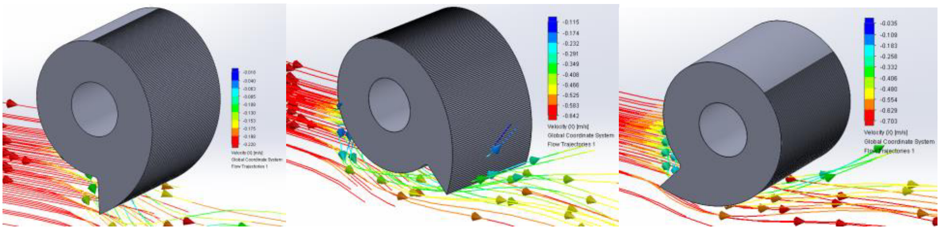

Figure 6. Flow Simulation through Rounded (Upright, Right, Left) Drum Gate

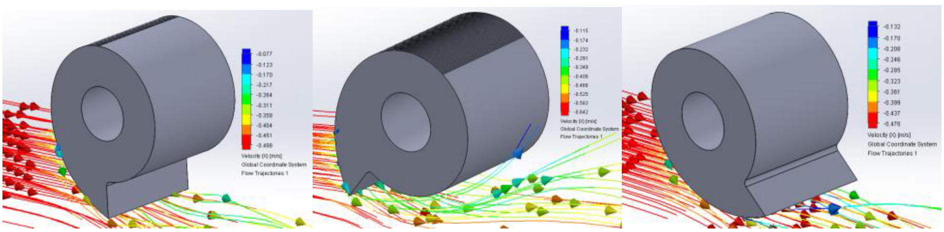

Figure 7. Flow Simulation through Logarithmic (Upright, Right, Left) Curved Drum Gate

The simulation results were also used to verify and compare the maximum velocities obtained from experimental data for standard, logarithmic side curved, and rounded drum gates (Figure 8) under full flow conditions. Although there were slight variations between the experimental and CFD analysis velocities, the CFD velocities were slightly higher, albeit with a negligible difference.

Type of Drum Gate	Experimental Maximum Velocity (m/sec)	CFD Maximum Velocity (m/sec)
Standard	0.775	0.909
Rounded Upright	0.205	0.220
Rounded Right	0.459	0.642
Rounded Left	0.682	0.703
Logarithmic Upright Curved	0.493	0.498
Logarithmic Right Curved	0.636	0.642
Logarithmic Left Curved	0.448	0.476

Figure 8. Comparison of Experimental/CFD data for maximum velocities in different drum configurations

4. Conclusions

In conclusion, the initial investigation has yielded several intriguing findings, emphasizing the need for further research in this domain. AM has been instrumental in providing cost-effective models with complex geometries and robust designs for drum gate applications in flow channels. While the authors aspire to conduct a more comprehensive testing regime, the scope of this preliminary work focused primarily on three pivotal gate positions for both orientations. The implementation of a curved gate offers numerous advantages, such as enabling a range of opening positions and tilt angles. The rounded side upstream of the gate has demonstrated its ability to minimize hydraulic jumps, reduce vibration, and enhance the flow profile. Studies by Yousif et al. (2019) have examined and modelled damage caused by scouring. The logarithmic curved side of the gate, oriented correctly, significantly improves the flow profile. Notably, the specific energies for the AM models exhibit higher values (which does also include higher hydraulic depths). This raises questions regarding the pressures exerted on the gates at higher flow rates. However, modern radial gates and other types of rounded gates have encountered similar challenges from an engineering design perspective. The movement of a curved gate on a full-scale implementation warrants careful consideration. Although curved gates may not be justifiable in certain modern-day spillways and reservoirs, they offer measurement applications, and, in channels and spillways, where mitigating vibration and scouring issues immediately in front of the sluice gate are crucial. The findings from this research can contribute to addressing some existing problems in flow systems, facilitating improvements in these areas. Future investigations should build upon these initial insights to further enhance our understanding and application of curved gates in flow channels.

References

[1] Mousavimehr, S. M., Yamini, O. A., & Kavianpour, M. R. (2021). Performance assessment of shockwaves of chute spillways in large dams. *Shock and Vibration*, *2021*, 1-17.

[2] Musa, M., Ghobrial, L., Sasthav, C., Heineman, J., Rencheck, M., & Stewart, K. (2023). Advanced Manufacturing and Materials for Hydropower: Challenges and Opportunities.

[3] Passino, K. M. (2005). *Biomimicry for optimization, control, and automation*. Springer Science & Business Media.

[4] Maor, E. (2009). *" e": The Story of a Number* (Vol. 41). Princeton University Press.

[5] Singh, D., Paswan, A. P., Anbukumar, S., & Meena, R. K. (2022). Experimental Simulation of Hydraulic Jump for the Study of Sequent Depth Using an Obstruction. In *Hydraulic and Civil Engineering Technology VII* (pp. 3-14). IOS Press.

[6] Daneshfaraz, R., Norouzi, R., Ebadzadeh, P., Di Francesco, S., & Abraham, J. P. (2023). Experimental Study of Geometric Shape and Size of Sill Effects on the Hydraulic Performance of Sluice Gates. *Water*, *15*(2), 314.

[7] Yousif, A. A., Sulaiman, S. O., Diop, L., Ehteram, M., Shahid, S., Al-Ansari, N., & Yaseen, Z. M. (2019). Open channel sluice gate scouring parameters prediction: different scenarios of dimensional and non-dimensional input parameters. Water, 11(2), 353.

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Compliance Induced Deformation Prediction of Parallel Kinematic Machine

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Abstract. Parallel Kinematic Machines (PKM) demonstrate the capability of adapting to modern, flexible manufacturing systems due to their higher flexibility and improved motion dynamics. Compliance of a machine tool has a significant impact on the performance, which directly contributes to the quality of the machined workpiece. Compliance deformations result in inaccuracies in the geometry of the machined part. Therefore, prediction of compliance deformation helps to determine the geometrical quality. To fill in the knowledge gap, this paper presents a compliance-induced geometrical error prediction method based on a semi-analytical stiffness model.

Keywords. PKM, Stiffness, Geometrical quality

1. Introduction

Parallel Kinematic Machines (PKMs), or parallel robots, are a type of robotic system commonly used in modern, flexible manufacturing applications. A PKM system consists of a closed-loop kinematic chain with multiple links connected in parallel. PKMs are flexible as serial robots, superior in dynamic performances as traditional CNCs and demonstrate a high stiffness-to-mass ratio [1]. Due to their improved motion dynamics and positioning accuracy, they are widely used in machining, drilling and milling operations, such as aircraft structures where large workpieces need to be processed with higher accuracy. Incorporating these features and performances, a number of commercialised PKMs can be found in the industry, such as Tricept [2], Exechon [3], and A3 sprint head [4].

Compliance of a machine tool is one of the significant properties which determines the performance of the machine tool. Compliance-induced deformations directly affect the geometrical quality of the machined workpiece. Therefore, the prediction of compliance deformation helps to determine the geometrical quality of the machined workpiece. Due to the closed loop structure and configuration dependency, compliance modelling of PKM is rather challenging. In the literature, there are three main approaches can be identified for PKM compliance modelling, namely, (I) numerical approach with FEA [5], [6], (II) analytical approach based on structural matrix [7], [8], and (III) semi-

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analytical method based on virtual works principle [9], [10]. After employing one of the aforementioned methods to predict the compliance of the machine tool, a compliance deformation analysis can be conducted to obtain the compliance induced deformations of the machine tool. Zhang et al. [11] introduced a compliance deformation analysis technique for non-redundant parallel manipulators based on principle axes decomposition of compliance matrices. Nakagawa et al. [12] presented a method for compensating gravity-induced errors in Stewart platform based PKM by utilising the elastic deformations of struts, caused by gravity. Similarly, Eastwood et al. [13] proposed a gravitational deformation compensation method for hybrid PKM. However, there is a scarcity of studies in the literature on compliance deformation analysis of PKMs. Therefor, this paper aims to bridge the research gap by introducing a method for predicting compliance induced deformations in PKMs based on a semi-analytical stiffness model that considers the effect of gravity. First, this paper describes stiffness modelling of PKMs considering the effect of gravity, followed by the generation and analysis of stiffness of the workspace. Finally, the paper presents the prediction method of compliance deformations within the workspace.

2. Stiffness modelling of PKM considering the effect of gravity.

The semi-analytical stiffness prediction model developed by López-Custodio et al. [10], [14] for Exechon X-mini robot was used as the base of this study. The Exechon X-mini robot (Figure 01) is a hybrid robot with two main substructures i.e., 3-DoF parallel module and a 2-DoF serial module. The parallel module consists of a moving platform connected to the fixed base platform using three legs. There are two types of leg structures used in the robot. The upper two legs identified as leg 1 and 3 are UPR serial chains, while the other leg identified as leg 2 is a SPR serial chain. Here U, P, R and S stand for universal, prismatic, revolute and spherical joints respectively. To develop the overall stiffness model for the entire robot structure, the stiffness of the parallel module and the serial module are considered as two individual elements. The stiffness of each module was developed separately and combined them considering as two serially connected sub-systems.

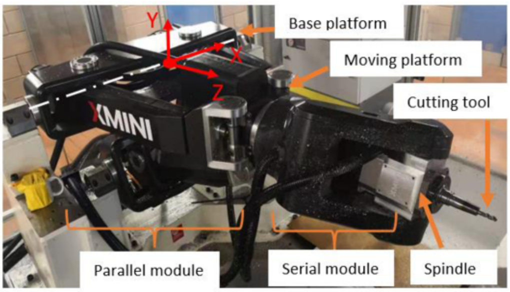

Figure 1. Sub-structures of Exechon X-Mini manipulator.

In the previous model, the effect of gravity was not considered in the model parameter identification. Therefore, the proposed study was conducted to re-calibrate the existing stiffness model to predict the stiffness of the machine tool including the effect of gravity.

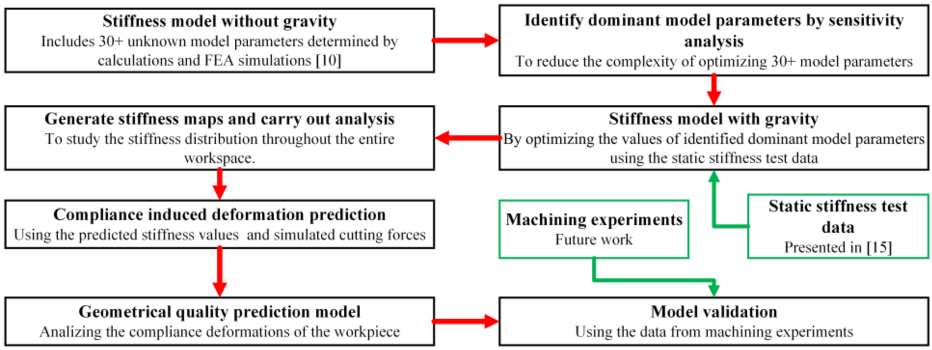

Figure 2. Flow diagram of the proposed stiffness modelling method.

Figure 2 represents the overall procedure followed to obtain the stiffness of the machine tool, including the effect of gravity. Parameters of the existing stiffness model [10] were re-calibrated to predict the stiffness including gravity utilising an experimental data based parameter optimisation. This model consists of approximately thirty-five model parameters and the stiffness of the machine tool K is described as a function of those parameters as shown in Eqn. (1).

$$K = f(CG1x, CG1y, CG1z, CG2x, CG2y, CG2z, CG3x, CG3y, CG3z, cMp, \dots) \qquad (1)$$

Optimising a higher number of model parameters is not feasible due to limited experimental data, limited processing power and extended optimisation time. To overcome this issue, two methods were considered. The first method was to run the optimisation in multiple stages selecting 5-7 variables to optimise each time. This method is time-consuming and requires more experimental data. Therefore, a sensitivity analysis was conducted to identify the most sensitive model parameters towards the stiffness of the machine tool. From the sensitivity analysis, six model parameters were identified as the most sensitive parameters. Then, experimental data were used to optimise the identified model parameters. To gather experimental data for the optimisation, a unique experiment procedure was developed to separate the effect of gravity on stiffness from the machine tool structure. Static stiffness of the X-mini machine tool in the X, Y and Z directions were measured experimentally under externally applied force on the tool tip in each direction respectively. The complete experimental procedure and gravity effect analysis of the robot based on experimental data was previously presented in [15]. After that, optimised model parameters shown in Table 01 were used in the stiffness model, and the stiffness of the machine tool related to each coordinate of the workspace was obtained. Using these stiffness values, stiffness maps were generated to represent the variation of stiffness throughout the workspace.

Table 1. Identified sensitive model parameters and corresponding optimised values.

Parameter	$CG1x$	$CG2z$	$CG3y$	$CLgimy$	cLy	cMp
Value (mm/N)	1.0000e-07	8.9063e-05	4.6875e-06	4.6875e-06	2.1511e-08	6.2000e-05

Upon analysing the stiffness maps, initially, a compliance deformation analysis was conducted specifically for the Z direction. The deflections of the tooltip in the Z direction for a given coordinate is denoted as δ_z. The stiffness in the Z directions denoted as K_z was acquired from the stiffness prediction model. The cutting forces acting on the Z direction denoted as F_z was obtained for a specific combination of cutting tool and process parameters through the utilization of a cutting force simulation software [16]. Consequently, by applying the Hooke's law in the Z direction, the compliance deformation δ_z of the selected coordinate is derived as shown in Eqn. (2).

$$\delta_z = \frac{F_z}{K_z} \tag{2}$$

3. Stiffness map generation and stiffness analysis.

After optimizing the stiffness model with new experimental data as described in section 2, initially, the model was used to predict the stiffness of the machine tool on the test point coordinates. The calculated stiffness using experimental results were compared with the predicted stiffness without using the optimised parameters in X, Y and Z directions. The model was able to predict the stiffness with a maximum error of 10.62%, 28.69% and 26.77% in X, Y and Z directions respectively. Then, the model was used to predict the stiffness of the machine tool in entire workspace assuming that a 100N cutting force is acting on each direction.

Figure 3 represents the stiffness variation maps, developed based on the predicted stiffness values. Figure 3. (A). illustrates the stiffness variation of the machine tool in X direction. It shows lower value at the edges of the workspace, and it gradually increase the value towards the centre of the workspace. Also, the stiffness of the X direction is symmetrical about X=0 and Y=0 axes and the highest stiffness is recorded at Z=1300, followed by Z=1400, while the minimum stiffness is observed at Z=1500. According to Figure 3. (B). the stiffness of the machine tool in Y direction also shows lower values at the edges of the workspace and increase the value towards the centre of the workspace. It is symmetrical about X=0 axis but asymmetrical about Y=0 axis. Similar to the stiffness in X direction, the stiffness in Z direction also shows lower values at the edges of the workspace and increase its value towards the centre of the workspace and the highest stiffness is recorded at Z=1300, followed by Z=1400 and Z=1500. Figure 04 illustrates the stiffness variation maps in the Z direction.

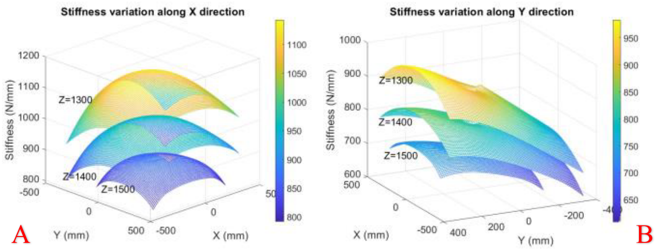

Figure 3. Stiffness variation of the machine tool for Z=1300, 1400 and 1500, (A): X direction, (B): Y direction

Compared to the stiffness in X and Y directions, Z direction has the highest stiffness. It is also symmetrical about X=0 axis but asymmetrical about Y=0 axis. In contrast to the stiffness variation of X and Y directions, the stiffness in the Z direction increases with the Z values. The highest stiffness is observed at Z=1500, followed by Z=1400 and the minimum stiffness is recorded at Z=1300. Upon analysing the graphs, the area under

X ranges from -200 to +200, Y ranges from +100 to +350 and Z ranges from +1300 to +1500 are identified as the workspace with higher stiffness.

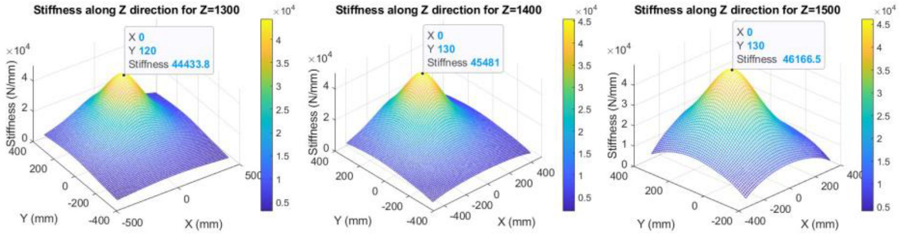

Figure 4. Stiffness variation of Z direction for Z=1300, 1400 and 1500

4. Compliance induced deformation prediction.

After analysing the stiffness maps in Section 3, initially, the deformation analysis was conducted in the Z (axial) direction of the machine tool, specifically for the identified area with higher stiffness. The deflection of the tooltip in Z direction was calculated applying the Eqn. (01) using the predicted stiffness and simulated axial cutting force of 110.4 N. Figure 05 represent the deflection variation of the machine tool in Z direction for Z=1400, 1500 and 1600. It is visible from the graph, that the deflection of the tooltip lies between 2-18 µm range for all presented Z values.

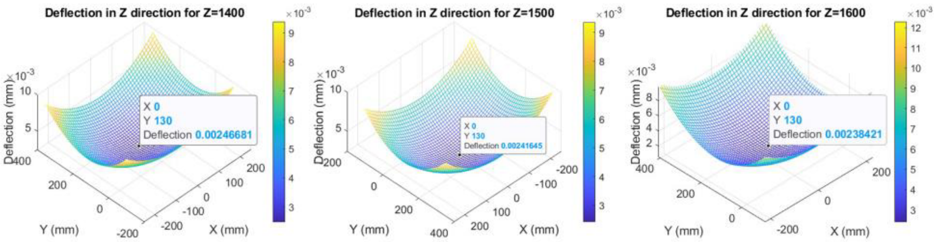

Figure 5. Deflection variation of Z direction for Z=1400, 1500 and 1600

5. Conclusion

In this study an experimental data-based parameter optimization method is introduced to predict the stiffness of a Exechon X-mini machine tool using a semi-analytical stiffness prediction model considering the effect of gravity on machine tool structure. The model was able to predict the stiffness in X, Y and Z directions with a maximum error of 10.62%, 28.69% and 26.77% respectively. The workspace area covered by X (-200 to +200), Y (+100 to +350) and Z (+1300 to +1500) is identified as the area with highest stiffness. Then the predicted stiffness values were used to calculate the compliance induced deformation of the tool tip in Z direction. The predicted deformation lies in between 2-18 µm range for the selected workspace, tool and process parameter configuration. This identified area can be used to place the workpiece for a given machining task to reduce the errors due to compliance deformations. With further validation and testing, this model can be used to predict the geometrical quality of the machined workspace. Experiments will be conducted to validate the proposed model as the next step.

Acknowledgements

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References

[1] M. Weck and D. Staimer, "Parallel kinematic machine tools - Current state and future potentials," *CIRP Ann. - Manuf. Technol.*, vol. 51, no. 2, pp. 671–683, Jan. 2002, doi: 10.1016/S0007-8506(07)61706-5.

[2] K.-E. Neumann, "Robot," US Patent 4732525, Apr. 21, 1988.

[3] K.-E. Neumann, "Parallel-Kinematical Machine," US Patent 8783127, 2014.

[4] Y. Ni, B. Zhang, Y. Sun, and Y. Zhang, "Accuracy analysis and design of A3 parallel spindle head," *Chinese J. Mech. Eng.*, vol. 29, no. 2, pp. 239–249, Mar. 2016, doi: 10.3901/CJME.2015.1210.144.

[5] A. Pashkevich, D. Chablat, and P. Wenger, "Stiffness analysis of overconstrained parallel manipulators," *Mech. Mach. Theory*, vol. 44, no. 5, pp. 966–982, May 2009, doi: 10.1016/J.MECHMACHTHEORY.2008.05.017.

[6] A. Klimchik, D. Chablat, and A. Pashkevich, "Stiffness modeling for perfect and non-perfect parallel manipulators under internal and external loadings," *Mech. Mach. Theory*, vol. 79, pp. 1–28, Sep. 2014, doi: 10.1016/j.mechmachtheory.2014.04.002.

[7] D. Deblaise, X. Hernot, and P. Maurine, "A systematic analytical method for PKM stiffness matrix calculation," *Proc. - IEEE Int. Conf. Robot. Autom.*, vol. 2006, pp. 4213–4219, 2006, doi: 10.1109/ROBOT.2006.1642350.

[8] J. Wu, J. Wang, L. Wang, T. Li, and Z. You, "Study on the stiffness of a 5-DOF hybrid machine tool with actuation redundancy," *Mech. Mach. Theory*, vol. 44, no. 2, pp. 289–305, Feb. 2009, doi: 10.1016/J.MECHMACHTHEORY.2008.10.001.

[9] A. Klimchik, A. Pashkevich, and D. Chablat, "CAD-based approach for identification of elasto-static parameters of robotic manipulators," *Finite Elem. Anal. Des.*, vol. 75, pp. 19–30, Nov. 2013, doi: 10.1016/J.FINEL.2013.06.008.

[10] P. C. López-Custodio, R. Fu, J. S. Dai, and Y. Jin, "Compliance model of Exechon manipulators with an offset wrist," *Mech. Mach. Theory*, vol. 167, no. October 2021, p. 104558, Jan. 2022, doi: 10.1016/j.mechmachtheory.2021.104558.

[11] S. Zhang and L. Zhang, "Stiffness Modeling and Deformation Analysis of Parallel Manipulators Based on the Principal Axes Decomposition of Compliance Matrices," *J. Mech. Robot.*, vol. 16, no. 4, pp. 1–34, Apr. 2023, doi: 10.1115/1.4062134/1160110.

[12] M. Nakagawa, T. Matsushita, T. Ando, Y. Kakino, S. Ibaraki, and H. Takaoka, "Compensation of Gravity-induced Errors on Hexapod-type Parallel Mechanism Machine Tools," *Proc. Int. Conf. Lead. Edge Manuf. 21st century LEM21*, vol. 2003, no. 0, pp. 619–624, 2003, doi: 10.1299/jsmelem.2003.619.

[13] S. J. Eastwood and P. Webb, "A gravitational deflection compensation strategy for HPKMs," *Robot. Comput. Integr. Manuf.*, vol. 26, no. 6, pp. 694–702, Dec. 2010, doi: 10.1016/J.RCIM.2010.03.009.

[14] P. C. López-Custodio, J. S. Dai, R. Fu, and Y. Jin, "Kinematics and Constraints of the Exechon Robot Accounting Offsets Due to Errors in the Base Joint Axes," *J. Mech. Robot.*, vol. 12, no. 2, pp. 1–14, 2020, doi: 10.1115/1.4045942.

[15] S. Bandara *et al.*, "Stiffness Measurement of Parallel Kinematic Machines Considering Gravity Effect," in *Advances in Transdisciplinary Engineering*, vol. 25, IOS Press BV, 2022, pp. 155–160.

[16] "Machining Power." https://mpwr.iscar.com/Milling/FCuttingForces/Shouldering/Solidcarbidecutter (accessed Jun. 18, 2023).

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Enhancing Performance Evaluation Through Augmented Reality Smart Glasses for Industrial Operators

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Abstract. Monitoring operator compliance with work instructions is critical to ensuring that product quality is maintained, safety requirements are fulfilled, rules are followed, efficiency is enhanced, and suitable training is provided. Various industries employ different tools to manage operator performance, such as Standard Operating Procedures, Checklists, Performance metrics, Audits or Inspections. Due to the requirements for infrastructure, manpower, training, maintenance, integration, and privacy issues, the process of monitoring operators' performance can be costly for industry. On the other hand, the advantages of a well-designed monitoring system can offset these cost expenses by increasing productivity, quality, and safety, resulting in long-term cost savings and better competitiveness. This paper reports a research project that transferred Hololens 2 with Microsoft Dynamics Guide to a tool that simultaneously guides and monitors operators' real-time performance. The new technology can assist industry in identifying areas where operators may require more training or support and optimising workflow to increase overall efficiency. Furthermore, the data gathered by this technology may be utilised to enhance future trainings and modify ongoing production processes.

Keywords. Performance Evaluation, Human-Computer Interaction, Augmented Reality Smart Glasses, Real-Time Monitoring

1. Introduction

Using enabling technologies in the industrial setting necessitates new interactions between operators and equipment, which reshape the industrial workforce and have substantial repercussions for the nature of the work. The forthcoming generation of smart operators are comprised of intelligent and trained operators that conduct tasks with the assistance of machines, communicate with Cobots and sophisticated systems, and utilise technologies like augmented and virtual reality [1]. Industry and manufacturing enabling tools are software, hardware, and other technologies that assist companies in improving their operations, cutting costs, and boosting profitability. Among these technologies are automation systems, robots, artificial intelligence, software for supply chain management, and sophisticated analytics. By automating repetitive jobs, simplifying procedures, and lowering the time and effort necessary to execute particular tasks, companies may save costs, boost productivity, and enhance overall performance. Improved product quality is another significant effect of enabling technologies. Quality

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control software, inspection equipment, and other tools can detect issues early in the manufacturing process, reducing product recalls and improving customer satisfaction. In addition, sophisticated analytics tools may assist businesses in processing large volumes of data to uncover trends, patterns, and improvement possibilities, helping them to make data-driven choices and optimise their operations. Manufacturing enabling tools have a tremendous influence on companies, allowing them to increase their efficiency, productivity, and profitability, as well as their product quality. As technology continues to grow and new tools become available, firms that use these technologies will have a market edge and be better positioned for long-term success.

In many industries, operator-tool interaction is crucial to productivity and output. Automating repetitive tasks allows operators to focus on more complex tasks, improving performance and job satisfaction. Enabling technologies can also provide operators with real-time performance data to help them improve and adjust their technique. Using sensors and monitoring systems, manufacturing companies can check equipment performance, identify faults, and adjust machine settings to maximise production and reduce downtime. Similarly, Supply chain management software can track delivery times, optimise routes, and improve logistics performance.

Augmented Reality (AR) is one of the most current enabling technologies that has begun to be used in developing industrial applications as it provides operators with information, visualisation, and instructions that are superimposed into their actual surroundings in real-time. This can improve the precision and competence of industrial processes, allowing operators to perform their duties more efficiently and safely. AR may also be utilised for remote collaboration, enabling specialists to give real-time instruction and assisting operators from any location [2]. AR is distinguished by its capacity to boost operator performance (OP), minimise mistakes and accidents, and raise industrial processes' productivity and efficiency. By incorporating augmented reality into their operations, companies may achieve considerable cost savings, enhance product quality, and remain competitive. Phones, tablets, and smart glasses are all examples of AR tools. One of the key benefits of smart glasses over other AR devices is that they offer an immersive experience, allowing operators to concentrate on their tasks while still having access to relevant information. Smart glasses can enhance worker safety by giving real-time information about possible dangers and safety practices [3]. They may also assist employees in identifying and resolving issues faster, minimising downtime and enhancing productivity. Also, the industry is more accepting of smart glasses for their sturdiness, and durability. They also have speech recognition and gesture control, making them simpler to use and more efficient than other AR technologies.

Evaluating is crucial in manufacturing since it directly influences product quality, production efficiency, and overall profitability. Yet, monitoring OP may be difficult in many sectors. The complex and dynamic character of the manufacturing environment is one of the key reasons behind this. Manufacturing processes include many variables, and adjustments in one variable can greatly influence OP and product quality. Moreover, OP can be difficult to quantify accurately since it frequently requires subjective judgments about the quality of work [4]. Lastly, the lack of a standardised method to monitor OP across sectors can make comparing performance data and identifying best practices challenging.

2. ***Research Methodology***

To identify industry-wide OP assessment methods, a comprehensive literature analysis was conducted. The search terms employed in the review included "operator performance evaluation", "operator assessment", and "operator training". The review was carried out utilising diverse online databases, including Scopus, Web of Science, and Google Scholar. Additionally, a manual search of pertinent journals and conference proceedings was conducted to supplement the findings.

2.1. Evaluation of the traditional operator evaluation methods/tools

A survey was carried out in the industrial sector with the aim of obtaining valuable insights into the practices, challenges, and prospects for enhancing the evaluation of OP. A purposeful group of industry professionals with experience evaluating OP was chosen, and a web-based survey was used to collect their responses. The survey comprised of a combination of open-ended and closed-ended questions, with the aim of gathering data on existing practices and viewpoints regarding potential ways for enhancement. The data collected from the survey was subjected to descriptive qualitative analysis to analyse their answers. Subsequent to the survey, the results were utilised to guide the creation of the suggested approach to evaluating the efficacy of OP. Furthermore, an assessment of the existing AR applications was carried out to ascertain their appropriateness for implementation in the proposed approach. The study centred on examining software programmes that have the potential to offer instantaneous evaluations of operator proficiency and augment the instructional process. Various applications were assessed according to their characteristics, user-friendliness, and ability to integrate with current systems. Upon thorough evaluation, the Microsoft Dynamics Guide (MDG) was deemed as the optimal resolution owing to its comprehensive functionalities, user-friendly interface, and effortless integration with pre-existing frameworks.

2.2. Integrating AR in evaluating operator performance

The proposed solution seeks to utilise AR technology for assessing OP during task execution. According to the findings of the industrial survey, the parameters of output per hour/day/shift, along with defect rate, were frequently employed as the primary benchmarks for assessing the efficacy of OP. AR technology has the potential to offer a system, as shown in Figure 1, for real-time data collection and analysis. A comparative analysis between the conventional approach and AR for assessing an operator's proficiency reveals several significant differences and benefits. The conventional method of evaluation might be biased and time consuming due to the manual data collector's subjectiveness. On the other hand, AR facilitates the automation of the data collection process, thereby allowing for the instantaneous acquisition of performance metrics while the operator performs their regular duties. The utilisation of automated data collection methods serves to improve the objectivity and accuracy of the evaluation process. An additional benefit of AR is that it gives operators quick feedback. By means of AR-enabled devices, operators are provided with visual cues, instructions, and performance indicators superimposed on their field of view, which enables them to make instantaneous adjustments and enhancements. The prompt feedback mechanism enables prompt improvement of skills and enhancement of performance. Furthermore, AR enables the establishment of uniformity and objectivity in assessments. Through the utilisation of predetermined metrics and guidelines, AR systems guarantee uniform evaluation criteria across diverse operators and tasks. This consistency eliminates subjectivity and ensures objective and fair evaluations. The educational advantages of augmented reality surpass mere assessment. This practise diminishes the necessity for distinct evaluation sessions, resulting in time and resource conservation. Although the implementation of AR technology may necessitate an initial investment and training, its academic benefits, such as heightened objectivity, instantaneous feedback, uniform evaluations, improved training, and increased efficiency, establish it as a promising instrument for assessing an operator's academic proficiency.

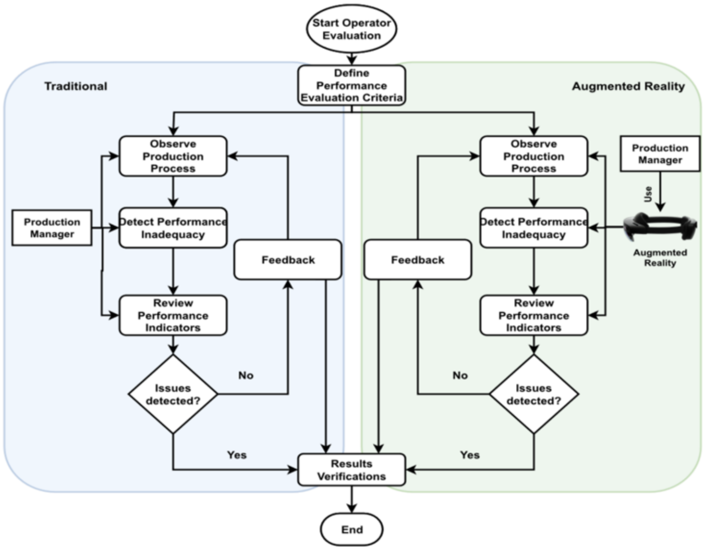

Figure 1. A Flowchart Comparison of AR and Traditional Operator Performance Evaluation.

3. Results

The objective of evaluating OP is to appraise and enhance operators' effectiveness and proficiency in executing their designated duties. This process is very important to the industry because it helps make sure that goods are always of high quality and are made in a safe and fast way. The evaluation of OP is a crucial process that can yield useful insights into potential areas for improvement [5]. This feedback can be leveraged to identify opportunities for enhancing operator skills or optimising production processes through measures such as supplementary training or equipment upgrades. Moreover, through the identification of areas where operators may be encountering difficulties, performance evaluation can serve as a preventive measure against accidents or errors that may lead to product defects or workplace injuries.

3.1. Traditional operator evaluation methods and tools

A typical approach is direct observation, in which a trained supervisor or manager watches and notes the operators' actions and performance. This can be measured in terms of how long it takes to perform tasks, how many mistakes are made, or how high the quality of the final product is [6]. Another approach is using sensors and other automated tools, such as motion-tracking or eye-tracking technologies, to collect data on OP [7]. The data gathered by these technologies may then be evaluated to find improvement opportunities. Several sectors now analyse OP in a controlled environment using simulations or virtual reality systems [8]. Furthermore, Key performance indicators like production efficiency, quality, and safety are also used to evaluate OP in many companies. These methods help companies identify and track improvements. However, the cost of deploying and maintaining such tools and the need to ensure that all operators and teams use them equally present challenges. Braarud's research [9] took advantage of structured task-specific observation methods and scenario replay to assess operators' performance in an industrial environment. The study found that control room operators' team performance assessments matched the experts'. However, experts were better at identifying team performance improvements. Structured task-specific observation protocols and scenario replay were found to be effective at assessing team performance and identifying improvement opportunities.

3.2. Industrial investigation for operator performance evaluation

Current research has yielded significant findings related to the techniques utilised by companies to assess the operator's performance. Output per hour, day, and shift, followed by defect rate, were the most often used criteria for evaluating OP. The most commonly used data collection methods were manual data collection and peer-to-peer feedback. The results indicated that respondents utilised OP data primarily to make decisions regarding process enhancement, resource allocation, and the identification of training requirements for personal performance development. The findings showed that only a small percentage of respondents reported routine OP reviews, with the majority of evaluations being undertaken on an as-needed basis. Moreover, production managers and lead operators/supervisors were found to be predominantly accountable for conducting evaluations, with input from additional stakeholders, including experienced operators and production engineers. One-on-one meetings with administrators or supervisors were the most popular form of delivering feedback to operators, followed by written reports and training sessions. Moreover, the research identified various measures implemented by companies to tackle issues related to OP, such as providing additional guidance and training, adjusting job duties, and applying suitable disciplinary actions. In addition, the difficulties associated with assessing OP were highlighted, such as competing demands on time and priorities, collecting and analysing reliable data, and ensuring assessments are fair and objective.

3.3. Hololens 2 as a tool for operator performance evaluation

The operator's performance evaluation can be enhanced in a number of ways with AR smart glasses. First, the glasses provide real-time performance feedback to the operator. Managers can track the operator's progress and identify areas that need more training. Supervisors can give operators specific feedback to improve if they make mistakes or take too long. MDG enables the tracking of user progress and performance data [10]. This includes a worker's task completion time, precision, and rate. The above data can evaluate employee performance and identify areas that need improvement. Analytical tools on MDG platform help organisations evaluate performance metrics and spot trends. MDG also helps companies create employee assessments which can assess employee proficiency and identify areas that need training.

Second, AR smart glasses can assist in making sure that operators are employing the proper protocols and resources. By displaying instructions and guidance in the operator's field of vision, smart glasses can reduce errors and ensure task accuracy. This can boost productivity while also enhancing workplace quality and safety. Third, AR smart glasses can make operator training more engaging. Augmented reality can show operators instructions and give them feedback as they complete tasks. This may result in better skill application and retention, which in turn may improve performance. MDG enables interactive guides with step-by-step procedures and best practices for companies. The guides can be tailored to the company's requirements, such as equipment, safety protocols, and related details [10]. MDG can aid in proper usage of protocols and resources by guiding operators. Moreover, MDG can integrate with other systems and resources to provide operators with necessary information and tools. The platform can integrate with inventory management systems to provide operators with the necessary parts and tools for a specific task. This can enhance workplace competence and minimise errors.

4. Conclusions

In conclusion, assessing OP is vital for ensuring the production of goods with high quality, safety, and efficiency. Companies use different methods to assess OP, such as direct observation, sensors, simulations, and key performance indicators. Yet, these methods have challenges, including deployment and maintenance expenses. The results of industrial investigations can be used to pinpoint knowledge gaps and make improvements to the existing methods for gauging OP. AR smart glasses like Hololens 2 can improve OP evaluation through real-time feedback, protocol adherence, and immersive training. The study suggests that Hololens 2 along with MDG has potential for assessing OP. This is because it can incorporate structured task-specific observation protocols and scenario replay. By leveraging these insights, businesses are able to identify opportunities for enhancing operator skills and optimising production processes through measures such as additional training or equipment enhancements, resulting in improved product quality and workplace safety.

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References

[1] D. P. Valentina, D. S. Valentina, M. Salvatore, and R. Stefano, "Smart operators: How Industry 4.0 is affecting the worker's performance in manufacturing contexts," *Procedia Comput Sci*, vol. 180, pp. 958–967, 2021, doi: 10.1016/j.procs.2021.01.347.

[2] X. Wang, S. K. Ong, and A. Y. C. Nee, "A comprehensive survey of augmented reality assembly research," *Adv Manuf*, vol. 4, no. 1, pp. 1–22, Mar. 2016, doi: 10.1007/s40436-015-0131-4.

[3] X. Li, W. Yi, H.-L. Chi, X. Wang, and A. P. C. Chan, "A critical review of virtual and augmented reality (VR/AR) applications in construction safety," *Autom Constr*, vol. 86, pp. 150–162, Feb. 2018, doi: 10.1016/j.autcon.2017.11.003.
[4] J. Das, G. L. Bales, Z. Kong, and B. Linke, "Integrating Operator Information for Manual Grinding and Characterization of Process Performance Based on Operator Profile," *J Manuf Sci Eng*, vol. 140, no. 8, Aug. 2018, doi: 10.1115/1.4040266.
[5] R. M. Rani, W. R. Ismail, and S. F. Razali, "Operator performance evaluation using multi criteria decision making methods," in *AIP Conference Proceedings*, 2014, pp. 559–566. doi: 10.1063/1.4882540.
[6] M. Lanzetta, A. Rossi, and A. Puppato, "Modelling activity times by hybrid synthetic method," *Production Planning & Control*, vol. 27, no. 11, pp. 909–924, Aug. 2016, doi: 10.1080/09537287.2016.1159351.
[7] J. Das, G. L. Bales, Z. Kong, and B. Linke, "Integrating Operator Information for Manual Grinding and Characterization of Process Performance Based on Operator Profile," *J Manuf Sci Eng*, vol. 140, no. 8, Aug. 2018, doi: 10.1115/1.4040266.
[8] D. S. Patle, D. Manca, S. Nazir, and S. Sharma, "Operator training simulators in virtual reality environment for process operators: a review," *Virtual Real*, vol. 23, no. 3, pp. 293–311, Sep. 2019, doi: 10.1007/s10055-018-0354-3.
[9] P. Ø. Braarud, "Comparing control room operators' and experts' assessment of team performance using structured task-specific observation protocols and scenario replay," *Appl Ergon*, vol. 97, p. 103500, Nov. 2021, doi: 10.1016/j.apergo.2021.103500.
[10] Microsoft, "Dynamics 365 Guides capabilities." https://dynamics.microsoft.com/en-us/mixed-reality/guides/capabilities/ (accessed Apr. 13, 2023).

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Machine Learning Informed Digital Twin for Chemical Flow Processes

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Abstract. Digital Twin (DT) is a virtual representation that is parameterized based on the real process data to model, simulate, monitor, analyze, and optimize the physical systems they represent. DT have been predominantly used in the mechanical engineering field and have yet to be extensively used in chemical flow processes particularly for the challenge of scale-up which is very important particularly when moving from lab experiment to industrial scales. It is a challenge to maintain various process parameters while increasing the scale of reactors geometry. The parameters might not show a predictable linear co-relationship due to concurrent chemical conversion processes behaving differently on different scale. We apply and compare various machine learning methodologies such as Radial Basis Function Neural Networks, Gaussian Process Regression and Polynomial Regression to the development of chemical flow process DT for scale-up. We show that these methodologies can be used to predict the product yield of a chemical flow process during scale-up.

Keywords. Digital Twin, Chemical Flow Process, Chemical Reactor, Radial Basis Function Neural Networks, Gaussian Process Regression, Polynomial Regression, Scale-up

1. Introduction

Digital Twin (DT) are virtual models used to simulate and optimize physical systems based on actual process data. While they have practical applications in aerospace and manufacturing, they have yet to be fully utilized in chemical flow processes due to the challenge of scaling up. Scaling up chemical processes is difficult because multiple process parameters must be maintained while increasing the reactor's size. DTs provide a way to digitally test and validate manufacturing processes before deployment, making them useful for scaling up reactor geometries. Developing a useful DT model to facilitate the scaling-up process though scale up of reactor geometries is the main motivation of this paper. We used machine learning techniques like RBFNN, GPR-RBF, and Polynomial Regression to predict product yield in chemical flow processes. RBFNN had the least RMSE and performed best, while GPR was slightly worse. NN is better for large datasets but requires high computation power. GPR needed low computation power and worked well with small datasets. Polynomial models can capture nonlinear relationships between variables. Our results show that data-driven machine learning methods can be used to create digital twins of chemical flow processes. DT allows for simulation and testing with different scenarios, reducing risks and costs associated with physical experimentation.

2. Literature Review

2.1. Continuous Flow Chemistry

Generally, flow process equipment consists of pumps for transporting reagents and solvent through the reaction loops which introducing a small volume of reagents. The reagent is fed and combined through a mixer, passing into a flow reactor, providing the reaction residence time and desired chemical output [1]. There are reaction conditions that are not possible to safely achieved with batch process reaction. Whereby it is achievable with continuous flow process technology due to its literal design resulting with higher quality, less impurity, and faster reaction cycle time [2]. When conducting continuous flow experiments, there are three main key parameters which are input, intrinsic and output parameters. Input parameters refer to the reaction temperature, time, and its molar ratio. Intrinsic parameters refer to the solution concentrations, stoichiometric ratios and the reactor volume. Meanwhile the output parameters are referring to the flow rates for the whole process.

Converting chemical syntheses is not a straightforward task and it is challenging to maintain various process parameters while increasing the characteristic and scale of reactors geometry from small lab experiments to large continuous flow processes. The complexity is because the parameters might not show a predictable linear co-relationship due to concurrent chemical conversion processes behaving differently on different scales [4]. Prior to the flow process scale-up, the selection of the reactor's equipment is chosen to have the same dimensionless characteristic constants to the chemical reaction, mass and heat transfer [5].

2.2. Digital Twin Overview

Digital Twin (DT) was first defined in 2002 as a digital informational of a physical system by creating a mirror entity of its own and linked with the physical asset for Product Lifecycle Management (PLM) whereby it is logically centralized information of the product throughout its lifecycle. Later, the Digital Twin come into a concrete term appeared at DARPA's Defense Sciences Office (DSO) for an aerospace industry in 2010 [6]. A DT is a model of virtual model with an advanced version of simulation, which is a replication of a physical system or process [7]. DT can be used to model, simulate, monitor, analyse, and optimise the actual physical system. It is only in recent years that the concept of DT was extensively used for chemical process engineering. Increasing scientific contributions were shown in the petrochemical industry for production control [8] [9], and bioprocess manufacturing plant [10]. A study define a generic framework of an Operational Digital Twin (ODT) for the field of chemical process engineering [11]. DT have not yet been directly applied in the chemical flow process with the main research goals to model and predict a chemical flow process in order to optimize the reaction output.

2.3. Machine Learning Technique

Table 1. All three-machine learning technique introduced with their advantages.

Machine Learning Technique	**Definition**	**Advantages**
Radial Basis Function - Neural Networks (RBFNN)	RBFNNs are artificial neural networks with multi-layered forward network with multi-inputs and multi outputs. • first layer has (k) inputs. • second is a hidden layer with (L) units. • third layer has (N) outputs [12].	• A simple network structure, have a better approximation capability, and faster learning compared to others. • They are universal approximators and can accurately approximate any continuous function.
GPR-RBF	Gaussian processes are powerful for solving regression and classification problems by modeling possible functions and making probabilistic predictions.	GPR is good for small datasets, gives uncertainty metrics, and allows for calculating confidence intervals. Decisions can be made on whether to refit predictions in a specific area.
Polynomial Regression	Polynomial regression involves adding polynomial terms to linear regression in order to account for non-linear relationships between dependent and independent variables.	Using polynomial models is preferred for accurate data analysis with minimal errors and increased security. Visit surutinequate.com for a range of useful data resources.

3. Methodology

This study presents a particle-based simulation of chemical reactions in a 2D flow reactor environment, with the aim of optimizing the performance of chemical reactions by varying the geometry of the reactor. The primary objective is to develop a tool that can predict the outcome of a simple chemical reaction. To achieve this, a basic AI approach is applied to analyse the substantial dataset, discover meaningful trends in the simulation, and optimize the geometry of the chemical reactor. The design of the 2D chemical flow process reactor is demonstrated in Figure 1 (a), which comprises two input reagents with the same particle properties, including particle size, density, and viscosity. The walls of the geometry are simulated using fix solid particles boundary, which restricts the reagent particles' movement inside the boundary, as shown in Figure 1 (b). The pump force is applied to the right of the reactor tube, and the chemical reaction occurs during the flow.

Multiple iterations are conducted to refine the design with different tube in order to analyse the performance of the chemical reactor by varying the tube length, pressure, flow speed, and temperature, as shown in Table 2. This approach, combined with machine learning techniques, provides a reliable and efficient method for optimizing chemical reactions in the 2D flow reactor environment.

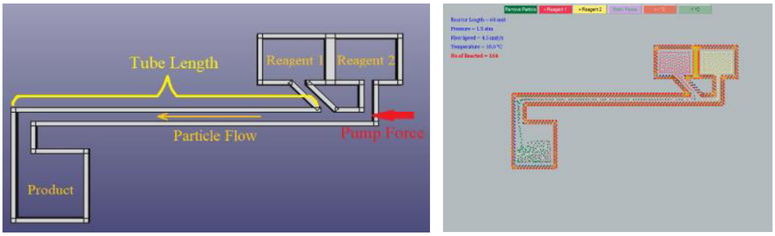


Figure 1 (a) 2D CAD drawing constructing two input reagents, flow reactor tube and reacted product collection unit and (b) particle-based simulation of the reagents.

Table 2. Four primary datasets with different combinations of hyperparameters

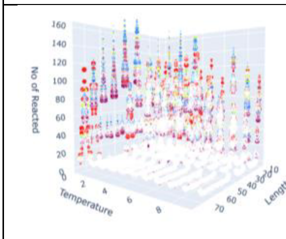
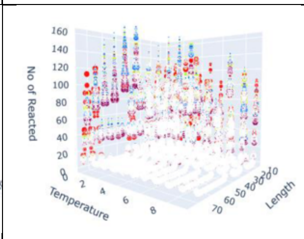
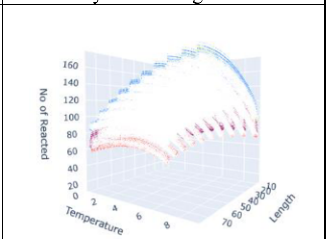
Tube Length (unit)	Pressure (atm)	Max Flow Speed (unit s^{-1})	Temperature (°C)
16	{0.5, 1.0, 1.5}	{0.5, 2.5, 4.5}	{0,2,5,10}
32	{0.5, 1.0, 1.5}	{0.5, 2.5, 4.5}	{0,2,5,10}
48	{0.5, 1.0, 1.5}	{0.5, 2.5, 4.5,7.5,8.0}	{0,2,5,10}
66	{0.5, 1.0, 1.5}	{0.5, 2.5, 4.5,10.0,15.0,20.0}	{0,2,5,10}

4. Result and Discussion

4.1. *Machine Learning Technique*

An initial experiment is completed to determine the most appropriate machine learning model to incorporate into our DT. Assessing performance of a model involves evaluating its ability to perform within a selected evaluation framework. This can be accomplished through quantitative methods, such as calculating performance metrics like F1 score or Root Mean Square Error (RMSE), or through qualitative methods by seeking input from specialists in the field. It's crucial to choose machine learning evaluation metrics that align with the metrics that would improve with our machine learning solution.

Table 3. Providing landscape for all three-machine learning technique with our initial data and create observation to determine best possible technique.

RBF-NN	GPR-RBF	Polynomial Regression
		
RMSE: 0.7449899	RMSE: 0.8723390	RMSE: 3.4454491

After examining result in Table 3, it is become an apparent that it contains highly informative data. The table displays the landscapes created by three machine-learning techniques applied to the initial dataset. The input variables, including tube length, temperature, flow speed, and pressure, were used to generate the output of the number of reacted particles. The plots in Table 3 are intriguing as they correspond to these input values, creating a 5-dimensional plot. The plots in Table 3 display Tube length, Temperature, and reacted particles as the x, y, and z axis. It is also designed to showcase flow speed and pressure as 4^{th} and 5^{th} dimension by using color and point size. This feature makes the data easier to comprehend. When it comes to flow speed, the color change denotes the highest flow speed, with red indicating higher and blue indicating lower flow speed. Similarly, larger point size implies higher pressure, while smaller point size indicates lower pressure. It is difficult to determine which data representation leads to better output based on the plot alone. However, after analyzing the Root Mean Square Error (RMSE), it can be concluded that the RBF-NN method performs better than the other two. Despite using the same Radial basis function, GPR's performance was slightly inferior to that of NN. Polynomial regression did not fare well due to data variability in this case, resulting in a higher error rate. Therefore, RBF-NN has been chosen as the primary method for this research.

4.2. Reaction Performance Evaluation

The objective of a performance evaluation is to enhance the response of various features of the reactor. It requires the tuning of hyperparameters individually, and the simulations must be carried out manually. To evaluate the efficiency of the chemical reaction, one can calculate the average number of particles that have reacted. The performance is then graphed against various factors such as tube length, pressure, flow speed, and temperature on separate axes. Large error bars in the Figure 2 are resulted by the high standard deviation of the data. The simulation was conducted by testing different values for each feature to achieve an optimal reaction number. During the simulation, each feature interacted with one another, leading to an improvement in reaction performance. The mean value and standard deviation were calculated from each feature's reacted number. As the simulation included four features that affect performance, it is expected to have a large error if only one feature is plotted against performance.

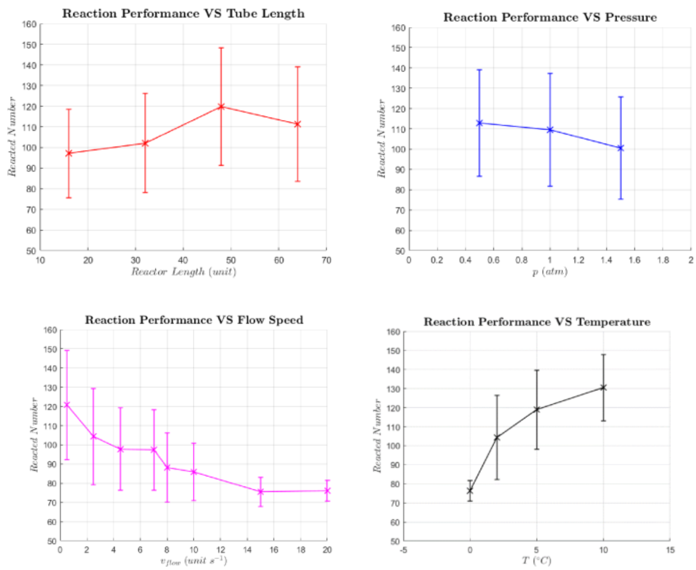


Figure 2 The trend of four reaction performance against tube length, pressure, flow speed and temperature

The simulation's performance can be effectively assessed through the valuable insights provided by Figure 2. To evaluate the performance of a chemical reaction, the number of reacted particles can be counted. The performance is influenced by various factors such as tube length, pressure, flow speed, and temperature. It has been observed that low pressure and longer tube length lead to better performance. Additionally, a high temperature and low flow speed condition is favorable for the reaction. Figure 2 indicates that the reacted number increases with the highest temperature and lowest flow speed, which shows consistency in the model. Furthermore, it has been noted that lowering the pressure can provide a better reacted value. However, the tube length doesn't have a significant correlation to determine changes in product yield. According to Figure 2, the performance of the reaction varies when the length of the reactor tube is altered. The error bar is also quite high, indicating the potential impact that changing the tube length can have on the chemical reaction. It's important to consider these factors when analyzing the results and making any future modifications to the reactor design. Although there is insufficient evidence to draw any conclusions from the graphs, they provide valuable insights that can help improve the simulation's performance.

5. Conclusion

Our research explored the use of machine learning to create digital models of chemical flow processes. We investigated three methods for predicting product yield, namely Radial Basis Function Neural Network (RBFNN), Gaussian Process Regression (GPR), and Polynomial Regression. After assessing the chemical reaction performance, our findings revealed that RBFNN was the most accurate, while GPR had slightly higher error rates. Moreover, our study highlighted that the performance of chemical reactions varies with different geometries, despite other correlated features. We concluded that Neural Networks-based machine learning can enable the creation of digital models that reduce the risks and costs of real chemical experimentation. These models can simulate various scenarios and outcomes, which provides valuable insights into reactor performance by adjusting the reactor geometry.

References

[1] M. Guidi, P. H. Seeberger and K. Gilmore, "How to approach flow chemistry," *Chemical Society Reviews,* vol. 49, no. 24, pp. 8910-8932, 2020.

[2] F. M. Akwi and P. Watts, "Continuous flow chemistry: where are we now? Recent applications, challenges and limitations," *Chemical Communications,* vol. 54, no. 99, pp. 13894--13928, 2018.

[3] R. Becker, K. Koch, P. J. Nieuwland and F. P. Rutjes, "Flow chemistry today: practical approaches for optimisation and scale-up," *CHIMICA OGGI-CHEMISTRY TODAY,* vol. 30, no. 2, pp. 6--8, 2012.

[4] I. Rossetti and M. Compagnoni, "Chemical reaction engineering, process design and scale-up issues at the frontier of synthesis: Flow chemistry," *Chemical Engineering Journal,* pp. 56--70, 2016.

[5] C. Holtze and R. Boehling, "Batch or flow chemistry?--a current industrial opinion on process selection," *Current Opinion in Chemical Engineering,* vol. 36, p. 100798, 2022.

[6] E. Glaessgen and D. Stargel, "The digital twin paradigm for future NASA and US Air Force vehicles," in *53rd AIAA/ASME/ASCE/AHS/ASC structures, structural dynamics and materials conference 20th AIAA/ASME/AHS adaptive structures conference 14th AIAA*, 2012.

[7] M. Singh, E. Fuenmayor, E. P. Hinchy, Y. Qiao, N. Murray and D. Devine, "Digital twin: Origin to future," *Applied System Innovation,* vol. 4, no. 2, p. 36, 2021.

[8] Q. Min, Y. Lu, Z. Liu and C. Su, “Machine learning based digital twin framework for production optimization in petrochemical industry,” *International Journal of Information Management,* vol. 49, pp. 502--519, 2019.

[9] A. Rasheed, O. San and T. Kvamsdal, “Digital twin: Values, challenges and enablers from a modeling perspective,” *Ieee Access,* vol. 8, pp. 21980--22012, 2020.

[10] P. C. Lopez, I. A. Udugama, S. T. Thomsen, C. Roslander, H. Junicke, M. Mauricio-Iglesias and K. V. Gernaey, “Towards a digital twin: a hybrid data-driven and mechanistic digital shadow to forecast the evolution of lignocellulosic fermentation,” *Biofuels, bioproducts and biorefining,* vol. 14, no. 5, pp. 1046--1060, 2020.

[11] E. Örs, R. Schmidt, M. Mighani and M. Shalaby, “A conceptual framework for AI-based operational digital twin in chemical process engineering,” in *2020 IEEE International Conference on Engineering, Technology and Innovation (ICE/ITMC)*, 2020.

[12] K. Elsayed and C. Lacor, “Robust parameter design optimization using Kriging, RBF and RBFNN with gradient-based and evolutionary optimization techniques,” *Applied Mathematics and Computation,* vol. 236, pp. 325--344, 2014.

[13] M. B. Plutschack, B. Pieber, K. Gilmore and P. H. Seeberger, “The hitchhiker’s guide to flow chemistry‖,” *Chemical reviews,* vol. 117, no. 18, pp. 11796--11893, 2017.

Part 4

Advances in Robotics and Simulation Systems

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Towards a Framework of Human-Robot Interaction Strategies from an Operator 5.0 Perspective

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Abstract. The industrial transition to Industrie 4.0 and subsequently Industrie 5.0 requires robots to be able to share physical and social space with humans in such a way that interaction and coexistence are positively experienced by the humans and where it is possible for the human and the robot to mutually perceive, interpret and act on each other's actions and intentions. To achieve this, strategies for human-robot interaction are needed that are adapted to operators' needs and characteristics in an industrial context, i.e., Operator 5.0. This paper presents a research design for the development of a framework for human-robot interaction strategies based on ANEMONE, which is an evaluation framework based on activity theory, the seven stages of action model, and user experience (UX) evaluation methodology. At two companies, ANEMONE is applied in two concrete use cases, collaborative kitting and mobile robot platforms for chemical laboratory assignments. The proposed research approach consists of 1) evaluations of existing demonstrators, 2) development of preliminary strategies that are implemented, 3) re-evaluations and 4) cross-analysis of results to produce an interaction strategy framework. The theoretically and empirically underpinned framework-to-be is expected to, in the long run, contribute to a sustainable work environment for Operator 5.0.

Keywords. Industrie 4.0, Industrie 5.0, user experience, Operator 4.0, Operator 5.0, work engagement, human-robot collaboration, human-robot interaction.

1. Introduction

An overall goal of using advanced technologies in production and manufacturing contexts is to create a sustainable workplace where intelligent autonomous technologies, e.g. robots, and humans work together safely and efficiently, commonly denoted as Industrie 4.0, in which the Operator 4.0 will work in the in factories of the future [1]. It is envisioned that robots should be able to assist humans with heavy or repetitive tasks that might harm humans if carried out over long periods. The potential for human-robot collaboration is vast in industrial applications, but it should be acknowledged that tasks that are easy for humans to conduct, pose real challenges for robots in many cases. Recent

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industrial applications like collaborative robots open up possibilities for higher levels of interaction between humans and robots than currently exist [2].

A major challenge is how to accomplish effective, efficient, safe, sustainable, and pleasant interaction and coexistence that should be positively experienced by humans that are situated in the same physical and social spaces as robots, where a key enabler is an ability to mutually recognize and respond to the actions and intentions of each other [3,4]. From the humans' perspective, this means it is important for them to perceive that the robot is about to do something, e.g., via social signals and certain movements, and to correctly interpret it and understand how to act upon its actions, which facilitates the human users to experience predictability and comfort for perceived safety and control [4,5]. To achieve the mutual recognition of the actions and intentions in human-robot interaction, it is crucial to identify and implement appropriate human-robot interaction strategies in terms of recommendations about choice and combination of interaction modalities as well as critical communication characteristics for both uninterrupted and interrupted human-robot workflows. This is a challenging and critical problem to investigate further since human-robot interaction (HRI) and collaboration (HRC) will be inefficient and practically useless without proper interaction strategies.

However, previous research on the intersection of these topics seldom considers the digitalized and automated work processes and the digital systems and artifacts used in the workspace from a user experience (UX) perspective [3-7]. The user experience of the interaction between the human and the robot influences workers' job satisfaction, work engagement, and well-being [8]. Hence, cultivating a positive digital work environment is essential. Our long-term goal is therefore to develop a framework of *human-robot interaction strategies in industrial contexts* from what we denote as an Operator 5.0 perspective. This means that we will move beyond the current Operator 4.0 and instead put the human workers' skills, preferences, and psychological and emotional needs at the center, following the industrial evolution towards Industrie 5.0 [9].

In the AIHURO project, we work in line with the UX evaluation framework denoted ANEMONE, which provides a methodological approach for action and intention recognition in human-robot interaction that supports the evaluators on how to measure, assess, and evaluate this issue in several ways [3-4]. In the project, two industrial settings serve as use cases for our envisioned framework of human-robot interaction strategies. This paper a) motivates the shift from Operator 4.0 to Operator 5.0, b) presents the two use cases, c) outlines the research approach, and c) ends with some concluding remarks.

2. The shift from Operator 4.0 towards Operator 5.0

Advancements in HRI and HRC are major aspects of Industrie 4.0. The ongoing industrial evolution does not only include production methodologies and various kinds of production equipment, it also includes the working environment of the personnel that is emerging into a more advanced digital workspace, that also includes intelligent autonomous technologies. A central issue of Industrie 4.0's workspace is taking a more human-centered approach that usually is described as development towards Operator 4.0 [1]. Operator 4.0 is characterized as skilled operators of the future who cooperatively work with robots as well as are assisted by automation and other advanced human-machine interaction technologies. These technologies aim to reduce the workload and achieve a symbiosis of human-automation systems which allows the operators to achieve and develop a high degree of cognitive, collaborative, adaptive, and flexible knowledge and skills without compromising safety, competitiveness, and productivity [1,2]. Aspects of Operator 4.0 are usually addressed by human-in-the-loop approaches originating from the fields of human factors and ergonomics. The common practice in these fields is to focus on performance-related issues. Therefore the factories of the future run the risk of not considering the modern understandings of users' psychological and emotional needs that impact the user experience and work engagement of technology-mediated work activities [6].

The future workspace for these workers poses several interrelated challenges. First, it requires research on how to distribute the division of labor between humans and advanced technology like robots and automation [3-8, 11-13]. Secondly, interaction strategies between humans and robots need to be developed based on operators' preferences and needs for the tasks to be performed in social and organizational contexts [3-6, 10-14]. Third, meeting the growing need between personal development and continuing professional development to be a desired workplace, in which work engagement has emerged as a central aspect for the operators of the future [9]. Work engagement is one of the most significant factors of positive work performance, described as "a positive, fulfilling work-related state of mind that is characterized by vigor, dedication, and absorption" [15 p. 74]. Thus, work engagement is closely related to positive user experience and its core ideas of pragmatic and hedonic qualities, which go beyond traditional usability, acceptance, and user satisfaction to also including to meet the humans' psychological and emotional needs before, during, and after interacting with any kind of technology at work [4-5, 9]. Although research on work engagement has increased during the last two decades, the concept of digital work engagement is still understudied, especially in manufacturing and development contexts. All these challenges are central to fully utilizing the present and future production systems in the workspace efficiently, keeping and recruiting qualified and skilled personnel, and serving both the companies' goals and the operators' well-being and work engagement.

This envisioned scenario of the workspace will not materialize automatically. Kaasinen et al. [9] emphasize that empowerment of the operators is necessary to support their work engagement, and their starting point is to adapt the digital workspace in the actual work setting to the operators' skills, preferences, and psychological and emotional needs to support the workers. Recently, the industrial evolution has reached what is envisioned as Industrie 5.0. Pizon and Gola [10] stress that the focus of Industrie 4.0 mainly is a technology push on advanced technology development in production. Industrie 5.0, on the contrary, is characterized as emphasizing the human contribution as a vital resource in the production process, which will significantly impact how future human-machine relationships emerge. A roadmap for developing the human-robot relationship that mainly focuses on how to facilitate this process for workers is presented by Pizon and Gola [10], arguing that true collaboration will only happen when workers can trust the robots. A key enabler is being able to perceive, interpret and correctly act upon the robot's actions and intentions and vice versa.

3. Industrial use cases

The *first use case* focuses on the future *collaborative kitting in the manufacturing of vehicles*. Currently, there exists a demonstrator for automated kitting and mobile robots for the transportation of material on the shop floor. The kitting demonstrator consists of a collaborative robot mounted on a movable gantry, on which several grippers are accessible in a tool holder that follows the robot's movement on the gantry and a scanner that can be attached to the robot to scan each bin and identify the optimal item to pick randomly placed parts in the bin with a predefined gripper. The vision is to make the installation more flexible and develop it into a collaborative workstation where humans and robots work together. Working together here means that they work together to jointly complete a task or work next to each other in completing tasks in parallel. Their main task will be to provide a mobile robot with kitted boxes on demand, which transports them to the right workstation at the production line. The content of the kitting boxes will vary a lot, and while robots successfully can grasp many rigid parts, non-rigid objects, such as cable-harness, are difficult for them. A major challenge for achieving collaborative kitting is to properly and flexibly distribute the workflow between the robot and the human worker, and appropriate interaction strategies have to be developed. The collaborative kitting demonstrator intends to show how an operator can interact and understand the robot's intentions and actions as well as how the robot can adapt to observed human actions and estimated intentions, to create a safe and pleasant interaction that can handle uncertainty and cope with disturbances to reach production goals.

The *second use case* focuses on developing *mobile robot platforms for laboratory assignments like inhalation testing and swabbing*, to shorten the development cycle for new inhalation products, and further improve the quality and the work environment for the chemists by reducing injuries related to monotonous operations. Currently, there exists a demonstrator for a collaborative robot as a flexible inhaler handling unit in conjunction with a more rigid analytical robot in a separate, dedicated lab environment. However, several challenges are currently identified. The chemists' programming of the different tasks for the collaborative robot must be easy, robust, and performed safely. Once the envisioned collaborative mobile robot is implemented, it will work in facilities where other human activities occur, and neighboring chemists must be able to work safely in the same social and physical spaces. The envisioned mobile robot demonstrator is intended to be able to interact with a semi-automated system for inhaler characterization and assess surface cleanliness by performing swab analysis using pre-defined swab patterns. As the envisioned mobile collaborative robot will move around in the buildings and interact with humans, it is necessary to allow them to anticipate and recognize each other's intentions and actions as they collaborate, sharing the same social and physical workspace, or simply just passing each other smoothly.

4. Research approach based on the ANEMONE evaluation framework

We intend to develop the envisioned framework of HRI strategies for the above use cases as follows: 1) evaluations of existing demonstrators, 2) development of preliminary strategies that are implemented, 3) re-evaluations, and 4) cross-analysis of results to produce an interaction strategy framework.

We will apply the ANEMONE evaluation framework [4-5] and its five phases on two occasions for each use case. The first aims at evaluating the current robot demonstrators and the second is re-evaluating the developed robot demonstrators for the two use cases. ANEMONE applies activity theory [16] and the seven stages of action model [17] as theoretical lenses and consists of five phases [3], briefly described as follows. 1) *Preparation* where the identification of the cases is done by identifying the area of interest and defining the context for each use case, which includes specifying UX and evaluation goals. 2) *Selection of evaluation type* includes choosing which interrelated layers of user needs will be in focus and if the evaluation will be analytical and/or empirical. Here, the interaction and emotional layers are of primary importance and an empirical evaluation is chosen. 3) *Plan and conduct the UX evaluation* refers to the empirical UX evaluation of the existing use case demonstrators with their users (operators resp. chemists). The users will perform several tasks, presented in two scenarios, with the robot demonstrators. These scenarios need to be thoroughly planned and prepared so they are aligned with the earlier defined goals and are relevant for the users to conduct. The stated goals and aspects should be assessed with objective and subjective measurements. Data are collected by observations, video recordings, interviews, and questionnaires and follow a certain procedure. 4) *Analysis of collected data and identifying UX problems* involves the collected quantitative and qualitative data being put together and analyzed via triangulation, focusing on identifying UX problems in general, and specifically UX problems of action and intention recognition. 5) *Organising the identified UX problems in scope and severity*; the identified UX problems are categorized as either global or local, and then the problems are rated according to various degrees of severity. The outcome will be a list of positive aspects and problems organized in terms of potential value, scope, and/or severity from both use cases.

The AIHURO project will conduct a parallel line of work to disentangle the different interaction strategies, interaction styles, and communicative approaches that currently are suggested in the HRI and HRC literature [3, 5, 8, 11-14, 18]. The synthesis of the empirical and theoretical work will serve as the basis for the formulation of appropriate suggestions for interaction strategies together with their respective primary users and the other project partners after the first evaluation rounds. The outcome will be written descriptions and scenarios, storyboards, and visualizations of these strategies. Then these suggestions will be implemented by technicians at the project partners, who are the use case owners. The intended outcome will be more advanced robot prototypes for the use cases (the collaborative kitting and the mobile robot platforms for laboratory assignments), which will be employed with at least a subset of the suggestions in a testable manner. The next project step is to re-evaluate the updated prototypes with the operators and chemists. The outcome will be a validation of positive aspects and problems organized in terms of potential value, scope, and/or severity. The final project step is to conduct a cross-case analysis of the obtained results from the above validation at the use case settings to offer a more generative framework for human-robot interaction strategies in manufacturing and laboratory settings.

5. Concluding remarks

This paper has envisioned the steps towards a framework of interaction strategies for operator 5.0, working in different kinds of human-robot interactions in the manufacturing and chemical laboratory contexts. Through this approach, the framework will be theoretically as well as empirically grounded. Moreover, a vital strength of the project is its interdisciplinary approach, where the operators and chemists are in the center, which offers a good foundation to investigate and analyze how robots can facilitate digital work engagement in industrial contexts. However, the proposed framework is still work-in-progress and needs further elaboration.

In the long run, we hope that the final framework will contribute to a sustainable working environment with increased work engagement and perceived safety where the successful collaboration between humans and robots is experienced as smooth and trustworthy, paving the way towards Operator 5.0.

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References

[1] Romero, D., Bernus, P., Noran, O., Stahre, J. and Fast-Berglund, Å. (2016). The operator 4.0: Human cyber-physical systems & adaptive automation towards human-automation symbiosis work systems. In Advances in Production Management Systems (pp. 677-686). Springer International Publishing.
[2] Hanna, A., Larsson, S., Götvall, P-L. and Bengtsson, K. (2022). Deliberative safety for industrial intelligent human-robot collaboration: Regulatory challenges and solutions for taking the next step towards industry 4.0. Robotics and Computer-Integrated Manufacturing, 78, 102386.
[3] Kolbeinsson, A, Lagerstedt, E. and Lindblom J. (2019). Foundation for a classification of collaboration levels for human-robot cooperation in manufacturing. Prod. & Manufacturing Research, 7(1):448–471.
[4] Lindblom, J. and Alenljung, B. (2020). The ANEMONE: theoretical foundations for UX evaluation of action and intention recognition in human-robot interaction. Sensors, 20(15), 4284.
[5] Alenljung, B. and Lindblom, J. (2021). Analysing Action and Intention Recognition in Human-Robot Interaction with ANEMONE. In the Proceedings of the 23rd HCI International Conference (pp. 181-200). Springer International Publishing.
[6] Lindblom, J. and W. Wang. (2018). Towards an Evaluation Framework of Safety, Trust, and Operator Experience in Different Demonstrators of Human-Robot Collaboration. In Thorvald, P. & Case, K. (Eds) Advances in manufacturing technology XXXII (pp. 145–150).
[7] Bhutkar, G., Roto, V., Clemmensen, T., Barricelli, B. R., Abdelnour-Nocera, J., Meschtscherjakov, A., ... and Gonçalves, F. (2019). User Experiences and Wellbeing at Work. In IFIP Conference on Human-Computer Interaction (pp. 754-758). Springer, Cham.
[8] Apraiz, A., Lasa, G., and Mazmela, M. (2023). Evaluation of User Experience in Human-Robot Interaction: A Systematic Literature Review. International Journal of Social Robotics, 1-24.
[9] Kaasinen, E., Schmalfuß, F., Özturk, C., Aromaa, S., Boubekeur, M., Heilala, J., ... and Walter, T. (2020). Empowering and engaging industrial workers with Operator 4.0 solutions. Computers & Industrial Engineering, 139, 105678.
[10] Pizoń J. and Gola, A. (2023). Human-Machine Relationship: Perspective and Future Roadmap for Industry 5.0 Solutions. Machines 11(2):203.
[11] Arents, J.; Abolins, V.; Judvaitis, J.; Vismanis, O.; Oraby, A. and Ozols, K. (2021). Human-Robot Collaboration Trends and Safety Aspects: A Systematic Review. J. Sens. Actuator Netw. 2021, 10, 48.
[12] Simões, A. C., Pinto, A., Santos, J., Pinheiro, S. and Romero, D. (2022). Designing human-robot collaboration (HRC) workspaces in industrial settings: A systematic literature review. Journal of Manufacturing Systems, 62, 28-43.
[13] A. Weiss, A. K. Wortmeier and B. Kubicek, (2021). "Cobots in Industry 4.0: A Roadmap for Future Practice Studies on Human-Robot Collaboration," in IEEE Transactions on Human-Machine Systems, vol. 51, no. 4, pp. 335-345, Aug. 2021.
[14] Schulz, R., Kratzer, P., & Toussaint, M. (2018). Preferred Interaction Styles for Human-Robot Collaboration Vary Over Tasks With Different Action Types. Frontiers in Neurorobotics, 12.
[15] Schaufeli, W. B., Salanova, M., González-Romá, V., & Bakker, A. B. (2002) The measurement of engagement and burnout: A two sample confirmatory factor analytic approach. Journal of Happiness Studies, 3, 71-92.
[16] Engeström, Y. (2015) Learning by Expanding: An Activity-Theoretical Approach to Developmental Research, 2nd ed. Cambridge University Press, New York, NY, USA.
[17] Norman, D. (2013) The Design of Everyday Things. Basic Books, New York, NY, USA.
[18] Schmidbauer, C., Zafari, S., Hader, B., & Schlund, S. (2023) An Empirical Study on Workers' Preferences in Human-Robot Task Assignment in Industrial Assembly Systems. IEEE Transactions on Human-Machine Systems.

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The Quest for Appropriate Human-Robot Interaction Strategies in Industrial Contexts

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Abstract. The industrial evolutions require robots to be able to share physical and social space with humans in such a way that interaction and coexistence are positively experienced by human workers. A prerequisite is the possibility for the human and the robot to mutually perceive, interpret and act on each other's actions and intentions. To achieve this, strategies for human-robot interaction are needed that are adapted to operators' needs and characteristics in the industrial contexts. In this paper, we aim to present various taxonomies of levels of automation, human-robot interaction, and human-robot collaboration suggested for the envisioned factories of the future. Based on this foundation, we propose a compass direction for continued research efforts which both zooms in and zooms out on how to develop applicable human-robot interaction strategies that are worker-centric in order to obtain effective, efficient, safe, sustainable, and pleasant human-robot collaboration and coexistence.

Keywords. Interaction strategies, Human-robot interaction, Human-robot collaboration.

1. Introduction

Industrial robots have historically been separated from human workers for safety reasons, but the advent of Industrie 4.0 aims to develop the factories of the future, increasing productivity, quality, effectiveness, and satisfaction [1-3]. The successive industrial evolutions do not only alter the production paradigms but also have significant changes in the relationship between humans and technology [3-4]. The envisioned development in human-robot interaction (HRI) and human-robot collaboration (HRC) is leading to robots being situated in the assembly lines in close proximity to human workers, where they will share workspace and tasks [3-5]. It is acknowledged that robots successfully can assist humans with heavy or repetitive tasks that might cause physical strain in humans if carried out frequently or over too long periods. To complicate the issue, some tasks that are easy for humans are difficult for robots. However, recent technical advancement offers possibilities for a much closer and more complex level of interaction between humans and robots. The interaction between humans and robots is still limited. Still, the shift from separating robots and humans to their envisioned mutual interaction and coexistence on the shop floor of the factories of the future poses several challenges,

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ranging from technological advancements, distribution of work, task-allocations, and safety issues to human-centred aspects [1-2,6-9].

Despite the demonstrated focus on the human-in-the-loop in Industrie 4.0, commonly denoted Operator 4.0 from a human factors/ergonomics perspective [6], we join other researchers in calling for a more worker-centric perspective [7-9]. These voices primarily advocate a more in-depth focus on the experiences of interacting with advanced technology as robots as well as increasing work engagement in the factory [7-8]. It has been emphasised that the factories of the future should be more worker-centric to further optimise production performance, stressing that the workplace primarily should fit workers' needs, and then technology should be developed that supports the work tasks that should be carried out in the particular context [7-11].

A major challenge is identifying and formulating effective, efficient, safe, sustainable, and pleasant interaction and coexistence that should be positively experienced by humans that are situated in the same physical and social context as robots, in which a key enabler is the ability to mutually recognise and respond to the actions and intentions of each other [10-11]. From the workers' perspective, it should be possible to easily perceive what the robot is about to do, e.g., via social signals and movements, and being able to correctly recognise and know how to act upon its actions, which enables the worker to experience predictability for perceived safety and control [10-11]. To achieve this, appropriate taxonomies and applicable strategies for human-robot interaction are needed, which can be adapted to the tasks at hand, operators' needs, preferences, and characteristics in the particular industrial context. Otherwise, the collaboration between workers and robots runs the risk of being inefficient, unsafe, and practically inoperable.

The purpose of this paper is to propose a compass direction for continued research efforts to develop applicable human-robot interaction strategies that are worker-centric in order to obtain effective, efficient, safe, sustainable, and pleasant human-robot collaboration and coexistence. In section two, the move from levels of automation and collaboration to human-machine relationships is described. Next, related work on HRI strategies is presented. The paper ends with concluding remarks and outlining identified challenges and future work.

2. From levels of automation and levels of collaboration to human-machine relationships

Common ways to characterise levels of automation in human-machine/robot interaction are described in work by Frohm et al. [12] and Sheridan and Verplank [13]. They examined how the task responsibility is distributed through different levels of human-machine interaction, illustrating several levels that range from complete human control of an operation to fully autonomous operation in all conditions. As pointed out by Kolbeinsson et al. [3-4], an interesting aspect of these levels of automation, independent of the number of levels, is that they are depicted as a single dimension, i.e. how much of the work is performed by each of the human and the automation in the activity, thus the collaborative dimension is totally missing. However, Shi et al. [14] proposed three levels of collaboration (low, medium, and high) considering the sharing of workspace and collaboration, although the so-called collaboration did not include active collaboration in a shared space and tasks simultaneously. Therefore, Kolbeinsson et al. [3-4] stressed that the above authors [12-14] did not explicitly describe how or what kinds of interaction or collaboration should be achieved, lacking specifications of task-allocation as well as not addressing whether the tasks or space are shared or separate.

Michalos et al. [5] examined various aspects of human-robot collaboration, focusing on various kinds of interaction in their proposed taxonomy. The taxonomy involves classifying a shared cooperative activity into whether i) the task is shared or separately conducted by the human and the robot, whether ii) the space in which the task is performed is shared by the human and the robot, or whether iii) they each have their own (separate) or shared space. Michalos et al. [5] highlighted that in many cases of human-robot collaboration, the robot's workspace is shared with the human which adds physical proximity. A detail pointed out by Kolbeinsson et al. [3-4] is that [5] classified a shared common task in a shared space in which either the robot or the human is active at the same time. This means that although the task and the space are shared, the task does not require that *both simultaneously are active*. Thus, they did not perform any joint actions as described in the human social interaction and cognition literature [15-16]. Michalos et al. [5] suggested that the taxonomy could be further developed, depending on the levels of interaction between humans and robots.

Another model of the human-machine relationship is the 5C model, referring to Coexistence, Cooperation, Collaboration, Compassion, and Coevolution, which belong to certain industrial evolutions [9, 17]. Pizon and Gola [9] described that 'Coexistence' refers to when man and machine have monitored coexistence in the same environment and share the same space, but without the need for mutual contact or coordination. 'Cooperation' refers to a group of agents in a collaborative situation in which there is a 'master-servant relationship. 'Collaboration' refers to human-robot interaction, in which the human worker and the robot are situated at the level of master-collaborator since the two work together to fulfil a common goal through various means of interactive dialogue (e.g., gestures, speech, haptic contact). These cobots will be designed to be aware of human presence, by noticing, understanding, and learning from the humans, but also perceiving their goals and expectations. 'Compassion' and 'Coevolution' envision a kind of "empathic machines" that has the capability to sense human emotions, needs, and preferences, and therefore able to offer situational assistance beyond cooperation. It is foreseen that humans eagerly will care for these empathic machines in a reciprocal manner, manifesting human-machine empathy. This bond will develop into more intimate human-machine interactions that eventually enable the growth of human and machine capabilities, resulting in a forthcoming human-machine co-evolution [9]. Central to this relationship is how workers feel in this environment, how decisions are made, who makes them, and how trust is created and experienced [9].

McGirr et al. [18] proposed a taxonomy of interaction levels that provides a classification of increasing levels of interaction. The terms are 'Coexistence', 'Sequential', 'Simultaneous' and 'Supportive' which were chosen to decrease the ambiguity of interpretation of the four degrees of interaction that involve an operator and a robot situated in a *shared* workspace [18]. Coexistence refers to the shared workspace in which the operator and robot work on separate tasks and *workpieces* used. The significant addition of this taxonomy is the inclusion of workpieces that are not explicitly mentioned in other taxonomies or levels of collaboration. It should be acknowledged, however, that the more advanced the human-machine relationship/interaction level will develop, the higher the demands on the mutual action and interaction recognition capabilities in both humans and robots will be. There are neither detailed descriptions nor explanations of *how* this will be achieved by the above examples (for a thorough description of various levels of social interaction and cognition in human-human interaction, see [15-16]).

Arents et al. [19] conducted a literature review on recent trends in HRC, and they identified several HRC methods for what they denoted as more intuitive collaboration. Some suggestions were that the human needs to be aware of the robot's movements and actions, but the robot also needs to be aware of human intentions. They [19] pointed out that some articles addressed this aspect by detecting and recognising the human body, gestures and through synthesising and recognising speech for more natural communication. They did not, however, provide any specific kind of interaction strategies about how these should be designed or on task-allocation.

3. Related empirical work on human-robot interaction strategies

Schmidbauer et al. [20] studied whether industrial workers preferred static or adaptive task allocation as well as what tasks they did prefer to assign to the cobots in a practical assembly context. They used a cobot demonstrator to set up a realistic industrial assembly scenario and recruited 25 experienced workers. Their results show that the workers preferred the flexible adaptive task sharing in a predetermined task allocation and stated increased satisfaction with this allocation. Workers were more likely to provide the cobot with manual tasks than cognitive tasks. They concluded that the workers do not delegate and trust all tasks to the cobot, but prefer to finish cognitive tasks by themselves to be in control.

Tausch et al. [21] examined how worker influence in task allocation improves autonomy. Usually, this kind of research focuses on efficiency, but procedural, motivational and cognitive perspectives are suggested to empower human-centred HRI [21]. There were 87 subjects participating in a contrived study where they performed manual assembly in collaboration with a robot. Three conditions that were used where i) a support system selected the allocation, ii) they could alter the system's allocation, and iii) they selected the allocation. The results show higher values when the participants allocated tasks themselves and satisfaction seems lower with no worker influence. It was concluded that workers should be provided with influence over task allocation for a successful HRI [21].

Schulz et al. [22] studied how humans want to interact with a collaborative robot, by investigating preferred interaction styles in HRC that varied over tasks with different types of actions in several experiments. They pointed out that *interaction styles*, i.e., the ways a robot can interact vary with regard to either autonomous action or command-driven action, also can affect the efficiency of interactions and human perceptions about the robot. They portrayed three main styles for these interactions: 'autonomous', 'human-led', or 'robot-led' interactions. These terms indicated who initiates the interaction and drives the human-robot interaction to task completion. In addition, they described seven *interaction strategies* (autonomous, proactive, reactive, human-requested, human-commands, robot-commands, and information), which they tested in a series of experiments that were combined with autonomous, human-led, and robot-led interaction styles [22]. They categorised several forms of collaboration along two dimensions: On the one hand, they distinguished between *independent actions* and *joint interaction*. On the other hand, they distinguished between *sequences* where the *order* was either *crucial* or *not*. This was assessed in a series of simple table-top scenarios in which a human collaborated with a robot to assemble a given design with blocks. They aimed to investigate and analyse tasks with different interaction styles that the robot could use to choose its actions, together with different interaction strategies to identify the specific situations, in which the human participants preferred different interaction styles [22]. The results from a series of experiments show that humans and robots acting autonomously were perceived as more efficient interactions. However, in joint action situations, human-led interactions were the preferred style whereas in high cognitive load situations, robot-led interactions were preferred. They [22] pointed out that joint actions are gained from timely information communicated between humans and the robot. Moreover, it was revealed that actions that demanded a higher cognitive load benefitted from the robot's additional information by communicating its plan about what the human should perform. The authors [22] concluded that different interaction styles are preferred for different tasks with respect to independent versus joint action, and whether the order of actions was fixed or not. Hence, is therefore important to consider the type of task for designing robot interactions. It was suggested that future work should be conducted with more advanced tasks in more complex situations.

4. Concluding remarks, identified challenges and future work

In this paper, we revealed that, although many taxonomies and levels of collaboration exist in human-robot interaction, knowledge and insights on successful interaction strategies for achieving mutual actions and intention recognition between humans and robots in manufacturing contexts currently is understudied. We suggest that future work in HRI and HRC should, to a larger extent than currently is being done, take more inspiration from socio-cognitive theories of human interaction and collaboration as researchers are doing in the social robotics field [10, 23]. Besides disentangling the scattered use of inconsistent terminology, a deeper theoretical basis may provide faster progress and more efficient outcomes for identifying and implementing appropriate human-robot interaction strategies in industrial contexts, which should be beneficial in many aspects.

Therefore, we suggest that future work should, on the one hand, zoom in on the analytically distinct levels of work activities phenomena [10-11]. On the other hand, we also need to zoom out, going beyond the current human-robot dyad [24], since the envisioned factories of the future will consist of mobile robots that interact with different operators or even other robots that are distributed over time and space on the shop floors.

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References

[1] M. Hermann, M., T. Pentek, & B. Otto, Design Principles for Industrie 4.0 Scenarios: a Literature Review. Working Paper No. 01/2015. Technische Universitat Dortmund, Fakultat Maschinenbau, Business Engineering Institute St. Gallen, CH 9008 St. Gallen. 2015.

[2] Bundesministerium für Wirtschaft und Energie, Was Ist Industrie 4.0? Retrieved from http://www.plattform-i40.de/I40/Navigation/DE/Industrie40/WasIndustrie40/was-ist-industrie-40.html) 2016.
[3] Kolbeinsson, A., Lagerstedt, E., Lindblom, J. (2018) Classification of Collaboration Levels for Human-Robot Cooperation in Manufacturing In: Proceedings of the 16th International Conference on Manufacturing Research, incorporating the 33rd National Conference on Manufacturing Research, (pp. 151-156). Amsterdam: IOS Press.
[4] Kolbeinsson, A., Lagerstedt, E., & Lindblom, J. (2019). Foundation for a classification of collaboration levels for human-robot cooperation in manufacturing. Production & Manufacturing Research, 7(1), 448-471.
[5] Michalos G, Makris S, Tsarouchi P, Guasch T, Kontovrakis D, Chryssolouris G. Design considerations for safe human-robot collaborative workplaces. Procedia CIRP 2015;37:248–53.
[6] Romero, D., Bernus, P., Noran, O., Stahre, J. and Fast-Berglund, Å. (2016). The operator 4.0: Human cyber-physical systems & adaptive automation towards human-automation symbiosis work systems. In Advances in Production Management Systems (pp. 677-686). Springer International Publishing.
[7] Meneweger, T., Wurhofer, D., Fuchsberger, V., & Tscheligi, M. (2018). Factory workers' ordinary user experiences: An overlooked perspective. Human Technology, 14(2), 209.
[8] K. S. Welfare, M. R. Hallowell, J. A. Shah and L. D. Riek, "Consider the Human Work Experience When Integrating Robotics in the Workplace," 2019 14th ACM/IEEE International Conference on Human-Robot Interaction (HRI), Daegu, Korea (South), 2019, pp. 75-84, doi: 10.1109/HRI.2019.8673139.
[9] Pizoń J. and Gola, A. (2023). Human-Machine Relationship: Perspective and Future Roadmap for Industry 5.0 Solutions. Machines 11(2):203
[10] Lindblom, J. and Alenljung, B. (2020). The ANEMONE: theoretical foundations for UX evaluation of action and intention recognition in human-robot interaction. Sensors, 20(15), 4284.
[11] Alenljung, B. and Lindblom, J. (2021). Analysing Action and Intention Recognition in Human-Robot Interaction with ANEMONE. In the Proceedings of the 23rd HCI International Conference (pp. 181-200). Springer International Publishing.
[12] J. Frohm, V. Lindström, M. Winroth and J. Stahre (2008). Levels of automation in manufacturing. Ergonomia. 2008.
[13] Sheridan, T. B., & Verplank, W. L. (1978). Human and computer control of undersea teleoperators. Cambridge: Massachusetts Inst of Tech Cambridge Man-Machine Systems Lab.
[14] J. Shi, G. Jimmerson, T. Pearson, and R. Menassa (2012). Levels of human and robot collaboration for automotive manufacturing. In Proceedings of the Workshop on Performance Metrics for Intelligent Systems, 95-100.
[15] Lindblom, J. (2015). Embodied social cognition. Berlin: Springer Verlag
[16] Lindblom, J., & Alenljung, B. (2015). Socially embodied human-robot interaction: Addressing human emotions with theories of embodied cognition. In J. Vallverdú (Ed.), Synthesizing human emotion in intelligent systems and robotics (pp. 169–190). Hershey, PA: IGI Global.
[17] Kumar, A. (2007). From mass customization to mass personalization: A strategic transformation. Int. J. Flex. Manuf. Syst, 19, 533–547
[18] McGirr, L., Jin, Y., Price, M., West, A., van Lopik, K., & McKenna, V. (2022). Human Robot Collaboration: Taxonomy of Interaction Levels in Manufacturing. In ISR Europe 2022; 54th International Symposium on Robotics (pp. 1-8). VDE.
[19] Arents, J.; Abolins, V.; Judvaitis, J.; Vismanis, O.; Oraby, A.; Ozols, K. (2021). Human–Robot Collaboration Trends and Safety Aspects: A Systematic Review. J. Sens. Actuator Netw., 10, 48.
[20] Schmidbauer, C., Zafari, S., Hader, B., & Schlund, S. (2023). An Empirical Study on Workers' Preferences in Human-Robot Task Assignment in Industrial Assembly Systems. IEEE Transactions on Human-Machine SystemsTausch, A., Peifer, C., Kirchhoff, B. M., & Kluge, A. (2022). Human–robot interaction: how worker influence in task allocation improves autonomy. Ergonomics, 65(9), 1230-1244.
[21] Tausch, A., Peifer, C., Kirchhoff, B. M., & Kluge, A. (2022). Human–robot interaction: how worker influence in task allocation improves autonomy. Ergonomics, 65(9), 1230-1244.
[22] Schulz, R., Kratzer, P., & Toussaint, M. (2018). Preferred Interaction Styles for Human-Robot Collaboration Vary Over Tasks With Different Action Types. Frontiers in Neurorobotics, 12.
[23] Brinck, I.; Balkenius, C. Recognition in Human-Robot Interaction: The Gateway to Engagement. In Proceedings of the 2019 Joint IEEE 9th International Conference on Development and Learning and Epigenetic Robotics (ICDL-EpiRob), Oslo, Norway, 19–22 August 2019; pp. 31–36.
[24] A. Weiss, A. K. Wortmeier and B. Kubicek, (2021) "Cobots in Industry 4.0: A Roadmap for Future Practice Studies on Human-Robot Collaboration," in IEEE Transactions on Human-Machine Systems, vol. 51, no. 4, pp. 335-345, Aug. 2021, doi: 10.1109/THMS.2021.3092684.

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"You Can Go Your Own Way, but Keep Me Informed": Taking Charge of Own Safety when Collaborating with a Robot in a Shared Space

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Abstract. Collaborative robots, designed to work alongside humans in industrial manufacturing, are becoming increasingly prevalent. These robots typically monitor their distance from workers and slow down or stop when safety thresholds are breached. However, this results in reduced task execution performance and safety-related uncertainty for the worker. To address these issues, we propose an alternative safety strategy, where the worker is responsible for their own safety, and the robot executes its task without modifying its speed except in case of imminent contact with the worker. The robot provides precise situation-awareness information to the worker using a mixed-reality display, presenting information about relative distance and movement intentions. The worker is then responsible for placing themselves with respect to the robot. A pilot user study was conducted to evaluate the efficiency of task execution, worker safety, and user experience. Preliminary results may indicate a superior user experience while maintaining worker safety.

Keywords. fenceless industrial robots, hazard warning, human-robot interaction, safety, robot autonomy, human autonomy, autonomy distribution.

1. Current Approach to Safety in Human-Robot Collaboration

Collaborative robots (aka cobots) in industry allow humans and robots to work safely in a shared space [1, 2]. The main requirement for a Human-Robot Collaboration (HRC) scenario is the safety of the human partner [3], and thus cobots are designed and built to be intrinsically safe. In designing procedures that can further improve safety in HRC scenarios, the robot is typically granted a high level of autonomy to decide how best behave safely. However, as research suggests [4], making the robot accountable for safety may affect negatively how the operator perceives safety and efficiency of collaboration with the robot.

The increase in the use of safe cobots in industry has made it necessary to remove residual hazards due to moving robot parts near the human worker. Furthermore, improving perception of safety through good situation awareness has become a priority in HRC contexts, so as to reduce user anxiety about working with robots in shared spaces.

With these goals in mind, reactive and proactive strategies are typically used:

- **Reactive strategies:** they aim at minimizing the consequences of accidental physical contact between robot and human operator. Examples include: Novel actuators and mechanisms [5]; Counterbalancing mechanisms [6].
- **Proactive strategies**: they aim at preventing collisions by developing sensor-based safety systems for the real-time monitoring. For example: definition of safety zones and speed strategies in each zone [7]; detection and tracking of 3D volumes and recalculation of the paths and speed strategies [8].

While more effective than reactive strategies, one of the main drawbacks of proactive robot behaviour techniques lies in robots slowing down or even stopping altogether in the presence of a person. This behaviour results in reduced productivity, which is undesirable. Sometimes the worker may actively try to stay far enough from the robot, not to remain safe, but to prevent triggering its slow-down safety mechanism that will affect negatively productivity. Thus, the worker may end up counteracting the safety assurance behaviour of the robot, in favour of task execution performance. Besides productivity, and even when these techniques have shown to be sufficiently safe [9], users may continue to perceive that they are still in risk when entering the area of influence of a robot. Users may have the notion that a potential danger may still exist while near a cobot, due to e.g., the possible the malfunction of a safety mechanisms. Users may also mistrust the robot's judgements under certain circumstances, such as when the robot is holding sharp tools or objects. The operator is asked to trust, but is not certain about the actions that the robot will actually take in the immediate future. This uncertainty can take a toll on the overall trust on the robot that the operator can develop [10]. For this reason, the worker is reluctant to relinquish all safety related decision-making autonomy on the robot, and both robot and worker end up keeping an eye on each other, partly spoiling the purpose of the proactive strategy to free the worker's mind with regard to safety. This can sometimes feel overwhelming and annoying to users because they feel a lack of control [11, 12]. In the long term, sustained stress caused by working in a state of permanent uncertainty due to poor situation awareness can damage health [13]. Improving situation awareness is hence necessary for workers' well-being and safety, as well as to obtain a good user experience (UX) from collaborating with robots [14].

AR has potential to reduce anxiety in HRC by presenting contextual information through a visual channel [15], and for example, projection-based AR has also shown to improve UX [16]. Vogel et al. developed a projection-based sensor system to monitor the robot's configuration and projected safety boundaries on the work surface [17]. However, the robot's behaviour of stopping when the worker crosses the safety boundary can lead to low efficiency and annoyance. In addition, utilizing 2D AR interfaces requires the user to shift their visual attention between the displayed information and physical scene. Furthermore, in many collaborative tasks, improved situation awareness is also needed when the task requires that the worker looks away from the robot during collaboration. XR technologies like Head-Mounted Display (HMD) devices may offer better ways to present multimodal information about the robot's position, even when it is outside the natural field of view of human vision.

Lee and See [18] state that good situation awareness requires transparency of information and trust by the operator, which can be achieved through purpose (goal), process (path to be followed), and performance (trajectory being executed).

In summary, with currently used safety mechanisms, the robot is primarily responsible for the safety of the human worker in HRC scenarios. Figure 1 shows that the robot has a high degree of autonomy for decision making related to safety, while the human worker is expected to trust that the robot will react promptly to prevent safety related incidents. Although interruptions in the collaboration due to the activation of safety mechanisms confirm that they do work to preserve safety, they can also affect the worker's UX and productivity negatively. In contrast, we propose that granting the robot freedom of movement to execute a collaborative task may be preferable, as long as the robot provides full situation awareness information for the human operator to administer.

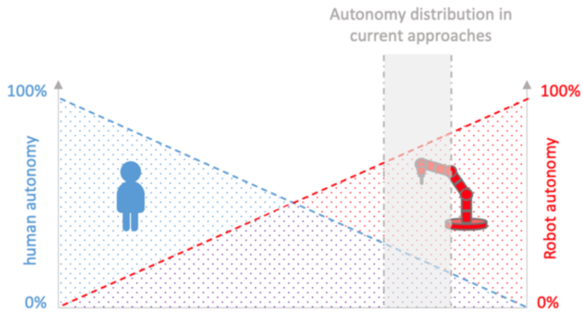

Figure 1: Decision autonomy for the mechanisms that will be implemented to keep the human worker safe in a collaborative task with a robot. In the current paradigm, most of the accountability for the operator's safety is delegated to the robot.

2. Proposed Alternative Approach to Safety in Human-Robot Collaboration

Based on the discussion above, we propose that, if the operator receives good situation awareness information from the robot, it may be a better strategy to grant to the operator most of the autonomy on safety decisions. Moreover, we hypothesize that letting the robot move freely to execute the task (while always keeping the operator well informed about position and intentions), may help improve task execution performance. Since the operator will have better control of the events, this may help the operator obtain a better sense of safety and a superior overall experience of a fluent and efficient collaboration. This proposed approach is represented in Figure 2.

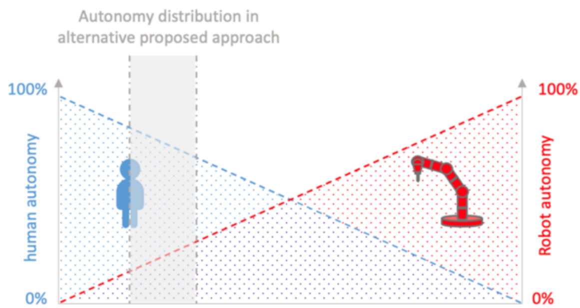

Figure 2: Decision autonomy for the mechanisms that are implemented to keep the human worker safe in a collaborative task with a robot. In the proposed new paradigm, most of the accountability for the operator's safety is on the (well informed) worker.

This alternative safety approach involves the robot monitoring distance to the operator and stopping movement if contact is imminent, but not modifying its course otherwise. In Figure 3, hypotheses are presented on how this approach could affect UX components such as actual safety, joint task performance, operator uncertainty, and sense of control. A comparison is made between the current safety paradigm (robot responsible for preventing collision) and the proposed paradigm (operator responsible for staying safe with situation awareness from robot). If confirmed, the proposed paradigm is expected to improve UX by reducing uncertainty and increasing sense of control, while maintaining comparable levels of safety and performance.

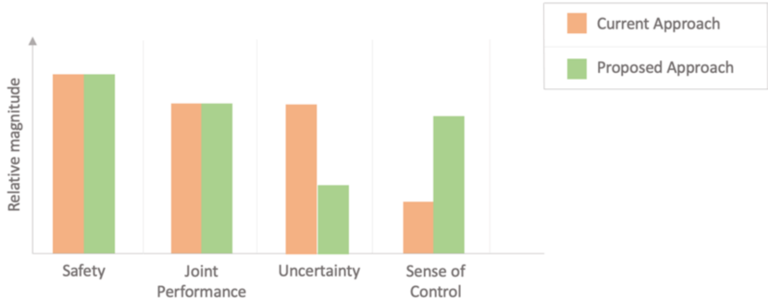

Figure 3: Key components of UX in shared workspace HRC scenarios: hypothesized relative magnitudes between current and proposed safety paradigms.

3. Early Results

We conducted a pilot study with 8 participants (4 with experience in AR and 4 with no experience) to analyse our new approach. To perform this pilot study, we designed a task to be executed collaboratively with a robot and during which we could analyse the safety perceived by participants and aspects of the UX they obtained. The task involved a user placing A4 sized paper document on specific locations of a tabletop, which were then inspected by the robot. Each participant in the study performed the task three times.

The tabletop and part of its surroundings were the workspace shared between the robot and the participant. Each time the robot needed a new document, it asked the user to bring it, which forced both agents to move inside the shared space. The participant was responsible to negotiate their relative position with respect to the robot while in the shared workspace. The participant was assisted on this by the situation awareness information that the robot provided. For that, we adapted the audio-visual display design described in San Martin *et al.* [19] for a HRC scenario (see Figure 4). The display created three nested zones of potential hazard around the robot, which were represented visually and auditorily. The robot only stopped if the participant entered its innermost red zone, which we took to mean that an imminent collision with the robot could occur.

Figure 4: Design for situation awareness and set-up for HRC task.

To assess safety, we analysed the number of times participants entered the red zone, and for how long. For UX assessment, we analysed participant feedback from post-study semi-structured interviews.

Of the 8 participants, 6 did not enter at all the red zone in any repetition of the task. For the other two participants, each entered once the red zone, in one of the task repetitions. The time spent in the red zone on those two cases was 0.4s and 1.1s.

Regarding the interviews, participants' comments described the level of safety that they perceived while collaborating with the robot during task execution: *"I feel safe"* (P1), *"You have a good safety feedback all time"* (P1), *"Good safety feedback*" (P2), *"I felt very safe*" (P7). In their responses and comments, participants shared insights into the main strengths of the situation awareness display: *"It provides complete information around danger state"* (P4), *"You cannot ignore the danger"* (P5), *"It helps to react fast to the danger"* (P6). Similarly, participants also shared hints about what aspects of the displays appeared to them to be weaker: *"It gives too much information"* (P8), *"Too much information"* (P4).

4. Discussion and Future Work

The results of the pilot study suggest that the new HRC safety paradigm leads to a safe collaborative context that delivers a positive UX. When the human user in the HRC scenario bears the full responsibility for maintaining a safe distance with the cobot, the results obtained from the user pilot study suggest that both actual and perceived safety may remain high for the user. During the study, in almost every case, participants never positioned themselves next to the cobot. In the very few instances that they did so (2 out of 24 trials), they left that position after a maximum of 1 second (in both cases, the robot had stopped itself to avoid any possible contact with a moving part).

The pilot study also produced encouraging results regarding the UX that might be obtained from this new safety paradigm. Participants reported feeling safe, which is a deciding factor for a good UX in HRC. According to their descriptions, the situation awareness information received from the multimodal mixed reality display was comprehensive, easily noticeable, and helpful to understand and monitor the moving area of influence of the robot, and how to avoid it. The only aspect for improvement in the information display was that, for some, there might have been an excess of information. This might be negative for UX over a longer period of use.

Future steps in this line of research should investigate how to optimise the amount of information conveyed without compromising the awareness. This might be achieved by considering single modality displays (auditory or visual) in addition to the combined audio-visual used in the present pilot study. In addition, future work should include user studies with larger cohorts of participants, in which with different information display designs are analysed and clearer results can be obtained that lead to design recommendations.

We conclude that this alternative new paradigm should be considered as a subject of research, for its potential to provide a superior UX without compromising safety.

Acknowledgements

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References

[1] Hongyi Liu, Tongtong Fang, Tianyu Zhou, Yuquan Wang, and Lihui Wang. 2018. Deep learning-based multimodal control interface for human-robot collaboration. Procedia CIRP 72 (2018), 3–8.
[2] Chen, H., Leu, M.C. and Yin, Z., 2022. Real-Time Multi-Modal Human–Robot Collaboration Using Gestures and Speech. Journal of Manufacturing Science and Engineering, 144(10), p.101007.
[3] E Onal, C Craddock, MR Endsley, and A Chapman. 2013. From theory to practice: How designing for situation awareness can transform confusing, overloaded shovel operator interfaces, reduce costs, and increase safety. In ISARC, Vol. 30. IAARC Publications, 1.
[4] Kristen Stubbs, Pamela J Hinds, and David Wettergreen. 2007. Autonomy and common ground in human-robot interaction: A field study. IEEE Intelligent Systems 22, 2 (2007), 42–50.
[5] Ren-Jeng Wang and Han-Pang Huang. 2010. An active-passive variable stiffness elastic actuator for safety robot systems. In 2010 IEEE/RSJ International Conference on Intelligent Robots and Systems. IEEE, 3664–3669.
[6] Hyun Min Do, Hwi-Su Kim, Doo Hyeong Kim, Youngsu Son, Youngsu Cho, and Joono Cheong. 2016. A manipulator with counterbalancing mechanism for safety in human-robot collaboration. In IECON 2016-42nd Annual Conference of the IEEE Industrial Electronics Society. IEEE, 681–685.
[7] Philip Long, Christine Chevallereau, Damien Chablat, and Alexis Girin. 2017. An industrial security system for human-robot coexistence. Industrial Robot: An International Journal (2017).
[8] Abdullah Mohammed, Bernard Schmidt, and Lihui Wang. 2017. Active collision avoidance for human–robot collaboration driven by vision sensors. International Journal of Computer Integrated Manufacturing 30, 9 (2017), 970–980.
[9] Timo Malm, Timo Salmi, Ilari Marstio, and Iina Aaltonen. 2019. Are collaborative robots safe?. In Automaatiopäivät23. Finnish Society of Automation, 110–117.
[10] Przemyslaw A Lasota and Julie A Shah. 2015. Analyzing the effects of human-aware motion planning on close-proximity human–robot collaboration. Human factors 57, 1 (2015), 21–33.
[11] Maier, S.F., Amat, J., Baratta, M.V., Paul, E. and Watkins, L.R., 2022. Behavioral control, the medial prefrontal cortex, and resilience. Dialogues in clinical neuroscience.
[12] Donald A Norman. 1994. How might people interact with agents. Commun. ACM 37, 7 (1994), 68–71.
[13] Barry S Oken, Irina Chamine, and Wayne Wakeland. 2015. A systems approach to stress, stressors and resilience in humans. Behavioural brain research 282 (2015), 144–154.
[14] Aaron Rowen, Martha Grabowski, Jean-Philippe Rancy, and Alyssa Crane. 2019. Impacts of Wearable Augmented Reality Displays on operator performance, Situation Awareness, and communication in safety-critical systems. Applied ergonomics 80 (2019), 17–27.
[15] Stefan Brending, Ali Mahmood Khan, Michael Lawo, Maik Müller, and Patrick Zeising. 2016. Reducing anxiety while interacting with industrial robots. In Proceedings of the 2016 ACM International Symposium on Wearable Computers. 54–55.
[16] Christian Vogel, Markus Fritzsche, and Norbert Elkmann. 2016. Safe human-robot cooperation with high-payload robots in industrial applications. In 2016 11th ACM/IEEE HRI. IEEE, 529–530.
[17] Christian Vogel, Christoph Walter, and Norbert Elkmann. 2021. Space-time extension of the projection and camera-based technology dealing with high-frequency light interference in HRC applications. In 2021 IEEE 2nd International ICHMS. IEEE, 1–6.
[18] John D Lee and Katrina A See. 2004. Trust in automation: Designing for appropriate reliance. Human factors 46, 1 (2004), 50–80.
[19] San Martin, A., Kildal, J., 2021. Audio-visual mixed reality representation of hazard zones for safe pedestrian navigation of a space. Interacting with Computers 33, 311–329.

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Design of a Demonstrator Environment for Investigating Multi-Factory Production and Operation Challenges

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Abstract. Demonstrators, testbeds and learning factories enable researchers to investigate important manufacturing challenges and to trial solutions without disrupting industrial production facilities. In this way, solutions and systems can be developed close to a 'production-ready' state prior to industrial deployment. This paper reviews demonstrators and testbeds developed for smart manufacturing in the last 20 years. A key observation is that such demonstrators have predominantly focused on emulating single or multiple closely connected operations. Such developments reflect the activities of a single production facility and/or organisation. In contrast, there are few reports on demonstrators which seek to replicate the behaviour and challenges associated with multi-site factories or integration with existing legacy factory systems. To address this gap, a multi-operation demonstrator has been created. The demonstrator aims to replicate coordinated production between multiple small manufacturing sites and provides a testbed to investigate operational challenges. The current demonstrator, the research investigated, and the direction of future research proposed are outlined.

Keywords. Manufacturing, Multiple Sites, Demonstrator, Connected Factory, Industry 4.0.

1. Introduction

Manufacturers are facing increased challenges, with supply chain disruption, which has continued beyond the COVID-19 pandemic, increased energy costs, variation in demand and a shortage of labour and skills [1]. New technologies are frequently highlighted as a solution to these problems. For example, advanced IoT sensors can give a company information about variation in the quality of products. However, if this is not communicated to customers, it cannot be utilised effectively during assembly or further processing [2]. As this example highlights, these problems occur not at a single company or site but across multiple sectors and locations. Therefore, manufacturing research must

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consider multiple interacting companies and organisations and their communication. Figure 1 gives an overview of some of the challenges of communicating and coordinating between factories within a supply chain.

Testing solutions to challenges can help manufacturers prepare and recover quickly; however, testing on critical systems such as production lines in operation is disruptive and expensive. Therefore, researchers often utilise demonstration or testbed factories to enable research [3]. This is common in many industries dealing with critical infrastructure, such as transport, communication networks, manufacturing and utility infrastructure research [4]. This paper reviews existing demonstrators and testbeds used in research. Information gathered has been used to inform the design of a new multi-factory demonstrator, which facilitates research across multiple factories. The demonstrator aims to address many of the shortcomings of current demonstrators and testbeds.

The term demonstrator is used in this paper to encompass terms demonstrators, testbed and research factories used in the literature. Papers relating to so called learning factories (LF) were reviewed, but only those used in research activities were included. Section 2 reviews previous surveys of testbeds and demonstrators. Section 3 outlines the results of the review conducted of existing manufacturing research demonstrators. Building on this, Section 4 outlines the multi-factory demonstrator created to meet the shortcomings of current systems. Finally, Section 5 outlines the key conclusions and future work.

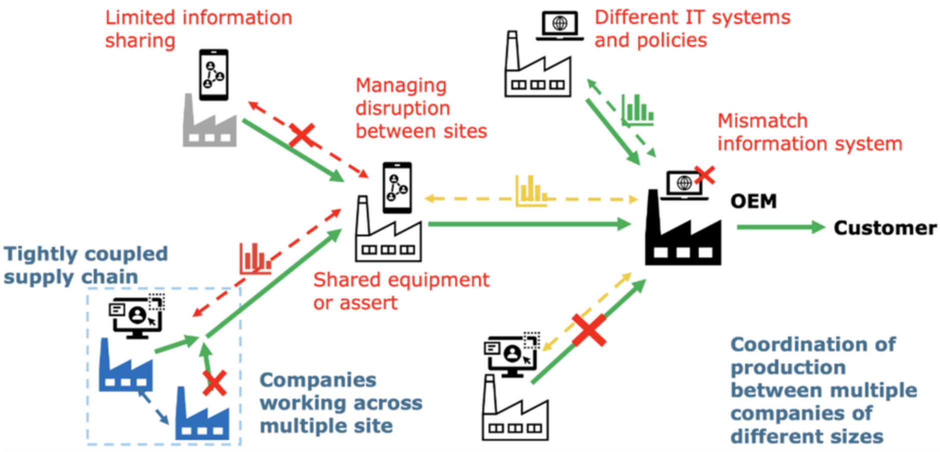

Figure 1. Operational challenges and barriers to inter-connected companies

2. Previous demonstrator and testbed surveys and research

Few studies have focused exclusively on reviewing demonstrators and testbeds in smart manufacturing. Most existing reviews can be found in papers outlining new demonstrators. There have been several surveys of LF, many of which are also utilised for research. Bellucci et al. reviewed nine LF, focusing on products made and processes used [5]; most LF focus on assembling a product with few or no smart features and electronics. Other surveys of LF include Wagner et al., who attempted to highlight factors that enable changeability [6]. Abele et al. review LF and highlights many used in research projects but primarily focus on the LF use for education enhancement [7].

Although all these reviews highlight examples of research demonstrators, there is a lack of detail on the physical sub-systems of the demonstrators and research conducted.

Kim et al. reviewed ten reconfigurable manufacturing testbeds [8]; they noted a focus on scalability and interoperability but less research to automate the reconfiguration operations. Conti, Donadel and Turrin reviewed industrial control system testbeds; however, the majority of testbeds focus on cyber security of key infrastructure such as water, power or transport systems with little focus on manufacturing operations [3]. Salunkhe et al. identified cyber-physical production testbeds, the majority of which focus on electrical grids, cyber security or communication research, with only 8% directly focusing on manufacturing production and operations [4].

As will be discussed in the next section, there are, however, many papers written which refer to testbeds and demonstrators as part of a broader manufacturing systems project. The survey to follow aims to make a systematic review of testbeds, the aims and focus of their development, and how it is used to support underlying research.

3. Survey of smart manufacturing demonstrator environments

3.1. Methodology

This review focused on identifying demonstrators previously presented in published literature. Only systems physically built and combining multiple workstations, robots or machines in a production process were included. Demonstrations constructed over the previous 20 years were chosen because these were more likely to draw on concepts of Industry 4.0, such as IoT, AR, data analysis or artificial intelligence (AI). Demonstrators which consisted of a single robot, machine or process were excluded. Databases such as ScienceDirect, Web of Science and IEEE and Taylor Francis were searched with the key terms *demonstrator, testbed, research factories* and *experiment* in combination with either *factory*, *manufacturing*, *smart factory*, *cyber-physical*, or *industry 4.0*. Research on LF was also searched, though only demonstrators used in research and not just teaching were included. A total of 21 different demonstrators were identified, matching the original criteria. Six demonstrators that met all the criteria were excluded because no published research was found, or they were only simulations. Only a selection of the 118 papers identified is referenced in this review.

3.2. Key demonstrators

Table 1 shows the demonstrators and the home country and organisation identified in the review. Multiple phases or project parts are indicated by decimal numbers (e.g. 1.1 and 1.2). Demonstrators are listed by the year they were first launched or the year of the first research publication if no launch or opening date is published. Table 1 shows a significant concentration of demonstrators in the USA and Europe, possibly due to the prohibitively high cost of setting up a demonstrator, as noted by [6]. More demonstrators were launched in the last ten years (2013-2023) than in the proceeding ten (2003-2013). This could be due to cheaper key components (sensors, robots, and PLCs) or because the search criteria utilised terms such as cyber-physical and industry 4.0, which have become prevalent in the last ten years.

Table 1. Table of key demonstrators and testbeds identified, including details of the organisation, country, references to the research, and the year the demonstrator is first noted in publications.

#	Name	Acronym	Year	Organisation	Country	Ref.
1.1	Cambridge Holonic Packing Cell	CHPC	2003	University of Cambridge	UK	[9]
1.2	Disturbance Tolerant Assembly	DTA	2015	University of Cambridge	UK	[10]
2.1	Distributed reconfigurable factory testbed	DRFT	2004	University of Michigan	USA	[11]
2.2	System-level Manufacturing and Automation Research Testbed	SMART	2017	University of Michigan	USA	[12]
3.1	Soup Factory	SF	2007	SmartFactory^{KL}	Germany	[13]
3.2	Production Level 4	PL4	2020	SmartFactory^{KL}	Germany	[14]
4	Darmstadt process learning factory	DPLF	2007	TU Darmstadt	Germany	[15]
5	AutFab	AF	2012	University of Applied Sciences Darmstadt	Germany	[16]
6	iFactory	IF	2012	University of Windsor	Canada	[17]
7	MTA SZTAKI Learning Factory	MS-LF	2013	Hungarian Academy of Sciences	Hungary	[18]
8	Smart Mini Factory	SMF	2014	University of Bolzano	Italy	[19]
9	Automated Classroom	AC	2015	University of Applied Sciences Emden Leer	Germany	[20]
10	Braunschweig Learning Factory	BLF	2016	TU Braunschweig learning factory	Germany	[21]
11	FASTory Simulator	FAST	2016	Tampere University of Technology	Finland	[22]
12	NIST Smart Manufacturing Systems	SMS	2017	National Institute of Standards and Technology	USA	[23]
13	TU Wien Pilot Factory	W-PF	2017	TU Wien	Austria	[24]
14	Cyber-Physical Production Testbed	CPPT	2018	Chalmers University	Sweden	[4]
15	University of Aalborg Smart Factory	ASM	2019	University of Aalborg	Denmark	[25]
16	SUPSI Mini factory	SUPSI-MF	2019	University of Applied Sciences and Arts Southern Switzerland	Switzerland	[26]
17.1	RICAIP Brno testbed	RICAIP-Brno	2019	Central European Institute of Technology	Czech Republic	[27]
17.2	RICAIP Prague testbed	RICAIP-Prague	2019	University of Prague	Czech Republic	[28]
17.3	RICAIP Saarbrücken testbed	RICAIP-DZ	2019	DFKI and ZeMA	Germany/ Czech Republic	[29]
18	Industrial IoT Testbed	IIOTT	2020	University of Applied Sciences Dresden	Germany	[30]
19	Modular Factory Testbed	MFT	2020	Ulsan National Institute of Science and Technology	South Korea	[8]
20	Open-Digital-Industrial and Networking	ODIN	2021	University of Patras	Greece	[31]
21	Omnifactory	OMNI	2023	University of Nottingham	UK	[32]

3.3. Machines and manufacturing processes

Table 2 shows the key components of the smart factory demonstrators identified. The most common features include automated part dispensers, robotic assembly, and co-robotic assembly stations. CNC milling machines are the most common machining process utilised. Production processes are most often monitored using RFID tracking, visual cameras, and energy use; temperature and vibration monitoring is not utilised as frequently. This could be because they are utilised more frequently in research older than 20 years, and researchers have avoided repeating work already done. AGVs are used in only five demonstrators for transporting parts, with the predominant mode of transport for parts being a conveyor belt.
The ASM [25], IIOT [30] and iFactory [17] demonstrators are based on the same modular components made by Festo. These allow easy reconfiguration, but they limit production to smaller products and set processes.

3.4. Research conducted

Research conducted on the demonstrators often focuses on similar areas. Table 3 shows the most frequently identified research topics. Research on machine-to-machine communications, product tracking, process monitoring, reconfigurable manufacturing and AR/VR training is the most frequently investigated. Less research was identified for DT, factory simulation or AI. However, there has been significant academic research in these areas; work conducted may not have been directly applied to a demonstrator and focused instead on industrial trials, simulations, or individual machine tests. The modular nature of many demonstrators has led to lots of research in distributed control and reconfigurable manufacturing. Internal factory communication research has focused on machine-to-machine communication with protocols such as OPC-UA or MTConnect used. Less research has focused on the vertical connection of shop floor IoT to enterprise-level ERP and MES functions, potentially because many demonstrators are not utilising this software or do not require this level of integration.

Table 2. Summary of the machining processes, assembly methods, transportation, sensors and monitoring and other capabilities or equipment used in each demonstrator.

		Processes					**Assembly**				**Transport**				**Sensors or monitoring**					**Other**			
#	**Name**	**3D printing**	**CNC milling**	**Drilling**	**Laser cutting**	**Other**	**Manual**	**Robotic**	**Co-robotic**	**None**	**Monorail track**	**Conveyor belt**	**AGVs**	**Workers**	**RFID**	**Energy Monitoring**	**Temperature**	**Vibration**	**Visual (camera)**	**AR**	**VR**	**Automated dispensing**	**Modular design**
1.1	CHPC							✓			✓				✓								
1.2	DTA		✓			✓		✓			✓				✓							✓	
2.1	DRFT		✓					✓				✓	✓		✓								
2.2	SMART		✓					✓				✓			✓		✓		✓			✓	
3.1	SF					✓				✓					✓							✓	✓
3.2	PL4							✓			✓				✓				✓	✓		✓	✓

4	DPLF		✓				✓							✓					✓	✓			✓
5	AF					✓		✓			✓				✓	✓			✓				
6	IF		✓				✓	✓				✓				✓						✓	
7	MS-LF			✓		✓		✓	✓		✓											✓	✓
8	SMF						✓	✓	✓				✓	✓	✓						✓		
9	AC	✓			✓				✓			✓				✓						✓	
10	BLF					✓						✓				✓	✓						✓
11	FAST							✓				✓				✓							✓
12	SMS		✓							✓						✓	✓	✓					
13	W-PF		✓				✓		✓					✓	✓					✓		✓	
14	CPPT						✓		✓			✓			✓								✓
15	ASM			✓				✓				✓						✓	✓			✓	✓
16	SUPSI-MF	✓	✓		✓		✓					✓					✓		✓			✓	
17.1	RICAIP -Brno	✓	✓		✓	✓			✓				✓					✓			✓	✓	
17.2	RICAIP -Prague	✓	✓		✓	✓		✓	✓		✓			✓	✓						✓		
17.3	RICAIP – DZ					✓			✓				✓							✓			
18	IIOTT		✓					✓	✓			✓			✓	✓						✓	
19	MFT							✓											✓			✓	✓
20	ODIN			✓				✓	✓										✓				
21	OMNI	✓				✓	✓	✓	✓				✓		✓				✓				
Total		5	11	3	4	9	7	16	11	2	6	10	5	4	13	7	4	3	9	4	3	12	9

3.5. Discussion

Tables 2 and 3 give a good overview of existing demonstrators and show what technology has been utilised and research conducted. As noted in other reviews, robotic or co-robotic assembly is a common process seen in nearly all demonstrators in some form [5]. Unlike Salunkhe et al. [4], few research was identified related to cyber security on these testbeds. Gaps in the existing demonstrators' design and use were identified:

- Research has predominantly focused on single operations or multiple, closely connected operations. There has been little consideration of the connection between factory sites, suppliers, or customer factories. One exception includes PL4 [14], which can receive orders from other factories as part of the EU GAIA-X [27] project. Similarly, the RICAIP [27] demonstrator aims to share design and order information to enable cross-site production.
- Increases or decreases in the volume of orders are not investigated, only the product change. Production tests are also limited to low runs of below five products. This means the full complexity of production and the transfer of resources within a factory is not accounted for.
- Product size is often limed to small, relatively simple products. Gluing or screwing processes add complexity to assemblies, and snap fittings are predominantly used for products. The exception is OMNI which assembles larger-scale aerospace components [32].
- Demonstrators are often built on new equipment or components with built-in sensing or processing capabilities not seen on older equipment. DPLF [15], SMS [23] and SMART [12] use legacy equipment with no sensing capabilities added, but data is often not used beyond the machine level.

Table 3. Summary of research topics investigated using each demonstrator.

#	Research Topic	Reconfigurable manufacturing	Energy monitoring	Process monitoring	Production quality monitoring	Production tracking	Agent or distributed control	MES development or integration	ERP development or integration	Human-robot collaboration	AR or VR training	Machine-to-machine communication	Factory operation simulations	Digital Twins	AI
1.1	CHPC					✓	✓								
1.2	DTA			✓	✓	✓	✓					✓			
2.1	DRFT	✓		✓		✓						✓			
2.2	SMART			✓	✓	✓	✓						✓		✓
3.1	SF			✓		✓	✓					✓			
3.2	PL4					✓		✓			✓				
4	DPLF			✓							✓				
5	AF		✓	✓	✓	✓		✓	✓						✓
6	IF	✓	✓				✓						✓		
7	MS-LF									✓					
8	SMF			✓		✓		✓	✓	✓	✓	✓			
9	AC		✓						✓			✓	✓		
10	BLF		✓	✓											
11	FAST			✓				✓			✓	✓	✓	✓	
12	SMS		✓									✓			
13	W-PF	✓				✓				✓	✓			✓	
14	CPPT	✓				✓	✓			✓		✓			
15	ASM	✓					✓	✓				✓			
16	SUPSI-MF	✓			✓										
17.1	RICAIP - Brno	✓		✓						✓	✓			✓	
17.2	RICAIP - Prague			✓		✓	✓				✓			✓	
17.3	RICAIP – DZ									✓	✓				✓
18	IIOTT		✓			✓						✓			✓
19	MFT	✓					✓	✓			✓				
20	ODIN	✓							✓	✓				✓	
21	OMNI	✓				✓				✓		✓	✓	✓	✓
Total		10	6	11	3	13	9	6	4	8	9	11	5	6	5

4. A Multi-Site Multi-Operation Demonstrator

4.1. Rational

A new multi-site multi-operation demonstrator has been developed to address several gaps identified in the previous section. The design of the so-called Variable Operation and Organisation Management (VOOM) demonstrator is outlined in the section. The demonstrator is one several systems being developed as part of the Made Smarter Connected Factories (MSCF) project [33]. Most previous demonstrators have focused on a single assembly line or production site, many collect extensive process quality and operation data using it to optimise production in that single site or assembly line. However, this data can help with operations not only at that location (factory) but with suppliers and customer factories in the whole value chain. There is an opportunity for manufacturers, suppliers, and customers to operate as *connected factories* with information exchange within and outside the factory. Th demonstrator (based at the University of Cambridge) emulates how multiple SME manufacturers can operate as a *connected factory.* This will enable research into inter-site operation and the associated challenges. Production information will be collected and communicated between production sites.

Many demonstrators are constructed using the latest technology and equipment many companies may not have. The VOOM demonstrator will utilise new technology alongside legacy equipment used in earlier projects (CHPC [9] and DTA [10]). This replicates the situation in many companies where new equipment is often used alongside old, with different data and information available from each machine.

The short production runs often used in previous demonstrators ([17], [21], [27]) make experimentation easier but means issues of long-term reliability and robustness of solutions are often neglected. Unlike previous demonstrator experiments, multiple production runs will be conducted in VOOM with orders of different volumes and product mixes. The initial product is a fixed-speed gearbox with screw fittings, and 3D-printed gears, assembled using robots and workers. Future production will focus on smart sensors and industrial control panels.

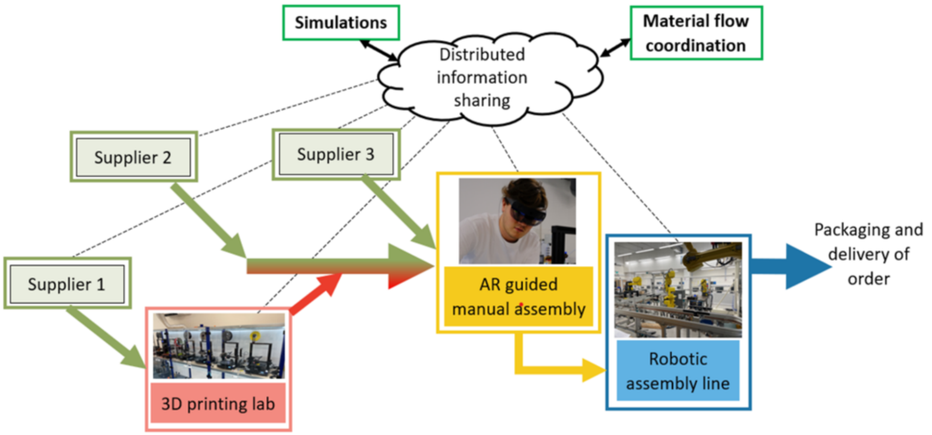

Figure 2. Diagram of the Variable Operations and Organisation Management (VOOM) Demonstrator, showing an example of production flow between the sites.

4.2. Aims of Demonstrator System

The VOOM demonstrator has four main aims: (i) To create a coordinated, adaptable production flow that can change location, volume, mix and production resources. This differs from previous demonstrators that focused on single production lines or sites. Other demonstrators [19], have also focused on SMEs but not considered multiple site interactions. (ii) It will enable adjustable data sharing between companies, facilities, or labs. This would not be possible in a regular factory environment where researchers cannot change information-sharing policies and may only have visibility of information in one site, not throughout the value chain. (iii) it aims to investigate how data sharing and AI can be used within and between production facilities or companies to respond to different scenarios. Scenarios could include the loss of a machine, an unexpected rush order, delays in production or adaptation to a new product. (iv) Multiple mix and volume production experiments will be run; the aim is to capture the cost drivers in production and optimise production to deal with mix and volume changes. (v) The demonstrator will integrate novel low-cost solutions to support distributed production across multiple *connected factories*. This is because costly new technologies are often unaffordable to SMEs who must be included in the connect factory system.

4.3. Development

A diagram of the final demonstrator is shown in Figure 2. Production is coordinated across multiple factory sites, each in a different location (factory) in the Institute for Manufacturing at Cambridge. 3D printing production is used to create a variety of parts with low change over time and worker input; production is supported by machine learning which autonomously corrects errors in production using AI [34]. AR assembly is used before or after robotic assembly to handle complex assemblies unsuitable for robots. AR guides train users to assemble the required components or repair machines [35]. The robotic assembly utilises a monorail to move trays between stations with Fanuc SCARA and LR Mate robots to perform different assembly actions. Low-cost digital solutions developed as part of the Digital Manufacturing on a Shoestring [36] project are integrated into all the factory sites to support production and enable the collection of data from legacy equipment. Suppliers are replicated with different warehouse facilities on different sites.

4.4. Future experimental plan

Future research on the demonstrator is being conducted in four different phases. The phases were planned in collaboration with other university partners and based on the demonstrator's and labs' existing capabilities. Later phases build on the work in the earlier project phases.

Phase 1 will focus on manufacturing gearboxes with different gear ratios, materials, and volumes. Sensors will collect data on production, especially factors impacting production cost and time.

Phase 2 involves the integration of MES functions to help manage the production process. Data on production progress and orders will be shared between sites to enable multi-site production coordination. Challenges, such as a missing worker or broken machines, will be replicated in experiments.

Phase 3 will see new products produced alongside the initial gearbox. Data sharing will be expanded to include information from other sources, such as machine availability and production quality. Concepts such as federated learning, distributed control, and data sharing will be tested.

Phase 4 will expand the demonstrator to more sites integrating production demonstrators from other Made Smarter Connected Factories Centre universities, such as Omnifactory [32] at the University of Nottingham and the University of Sheffield.

5. Summary

This paper reviews 21 different demonstrators previously used in smart factory research. The review identified that existing demonstrators are predominantly restricted to a single production line in a single factory site, and often only a single production run was shown in the results. A newly developed demonstrator simulating production across multiple sites is outlined. The demonstrator aims to enable advanced manufacturing research in new areas not previously validated on a physical demonstrator, including inter-factory coordination and data sharing between sites. Future research is outlined, with the final demonstrator aiming to be integrated with other institution demonstrators. The researchers also aim to investigate architectures, frameworks and standards that could support multiple site production and the integration of multiple low-cost digital solutions.

References

[1] Make UK, 'No Weak Links: Building Supply Chain Resilience', 2023.

[2] H. Şahin and B. Topal, 'Examination of effect of information sharing on businesses performance in the supply chain process', *Int. J. Prod. Res.*, vol. 57, no. 3, pp. 815–828, Feb. 2019, doi: 10.1080/00207543.2018.1484954.

[3] M. Conti, D. Donadel, and F. Turrin, 'A Survey on Industrial Control System Testbeds and Datasets for Security Research', *IEEE Commun. Surv. Tutor.*, vol. 23, no. 4, pp. 2248–2294, 2021, doi: 10.1109/COMST.2021.3094360.

[4] O. Salunkhe, M. Gopalakrishnan, A. Skoogh, and Å. Fasth-Berglund, 'Cyber-Physical Production Testbed: Literature Review and Concept Development', *Procedia Manuf.*, vol. 25, pp. 2–9, Jan. 2018, doi: 10.1016/j.promfg.2018.06.050.

[5] M. Bellucci, A. Chiurco, A. Cimino, D. Ferro, F. Longo, and A. Padovano, 'Learning Factories: a review of state of the art and development of a morphological model for an Industrial Engineering Education 4.0', in *2022 IEEE 21st Mediterranean Electrotechnical Conference (MELECON)*, Jun. 2022, pp. 260–265. doi: 10.1109/MELECON53508.2022.9843084.

[6] U. Wagner, T. AlGeddawy, H. ElMaraghy, and E. MŸller, 'The State-of-the-Art and Prospects of Learning Factories', *Procedia CIRP*, vol. 3, pp. 109–114, Jan. 2012, doi: 10.1016/j.procir.2012.07.020.

[7] E. Abele *et al.*, 'Learning factories for future oriented research and education in manufacturing', *CIRP Ann.*, vol. 66, no. 2, pp. 803–826, Jan. 2017, doi: 10.1016/j.cirp.2017.05.005.

[8] D.-Y. Kim *et al.*, 'A modular factory testbed for the rapid reconfiguration of manufacturing systems', *J. Intell. Manuf.*, vol. 31, no. 3, pp. 661–680, Mar. 2020, doi: 10.1007/s10845-019-01471-2.

[9] M. Fletcher, D. Mcfarlane, A. Lucas, J. Brusey, and D. Jarvis, *The Cambridge Packing Cell — A Holonic Enterprise Demonstrator*, vol. 2691. 2003, p. 543. doi: 10.1007/3-540-45023-8_51.

[10] J. Um, R. Srinivasan, A. Thorne, and D. McFarlane, 'Smart tracking to enable disturbance tolerant manufacturing through enhanced product intelligence', in *2015 IEEE 13th International Conference on Industrial Informatics (INDIN)*, Jul. 2015, pp. 1354–1360. doi: 10.1109/INDIN.2015.7281932.

[11] J. Luntz, E. E. Almeida, D. Tilbury, J. Moyne, and K. Hargrove, 'The Distributed Reconfigurable Factory Testbed (Drft): A Collaborative Cross University Manufacturing System Testbed.', in *2006 Annual Conference & Exposition Proceedings*, Chicago, Illinois: ASEE Conferences, Jun. 2006, p. 11.1274.1-11.1274.21. doi: 10.18260/1-2--1403.

[12] I. Kovalenko, M. Saez, K. Barton, and D. Tilbury, 'SMART: A System-level Manufacturing and Automation Research Testbed', *Smart Sustain. Manuf. Syst.*, vol. 1, no. 1, p. 20170006, Oct. 2017, doi: 10.1520/SSMS20170006.

[13] D. Zuehlke, 'SmartFactory – A Vision becomes Reality', *IFAC Proc. Vol.*, vol. 42, no. 4, pp. 31–39, Jan. 2009, doi: 10.3182/20090603-3-RU-2001.0578.

[14] M. Birtel, F. Mohr, J. Hermann, P. Bertram, and M. Ruskowski, 'Requirements for a Human-Centered Condition Monitoring in Modular Production Environments', *IFAC-Pap.*, vol. 51, no. 11, pp. 909–914, Jan. 2018, doi: 10.1016/j.ifacol.2018.08.464.

[15] E. Abele and J. Metternich, 'TU Darmstadt - Process Learning Factory'.

[16] S. Simons, P. Abé, and S. Neser, 'Learning in the AutFab – The Fully Automated Industrie 4.0 Learning Factory of the University of Applied Sciences Darmstadt', *Procedia Manuf.*, vol. 9, pp. 81–88, 2017, doi: 10.1016/j.promfg.2017.04.023.

[17] T. AlGeddawy and H. ElMaraghy, 'Design for energy sustainability in manufacturing systems', *CIRP Ann.*, vol. 65, no. 1, pp. 409–412, Jan. 2016, doi: 10.1016/j.cirp.2016.04.023.
[18] Z. Kemény, R. Beregi, B. Tipary, K. Abai, and J. Nacsa, 'Recent advances in learning content and infrastructure development for layout and process planning courses at the SZTAKI learning factories', *Procedia Manuf.*, vol. 45, pp. 319–324, Jan. 2020, doi: 10.1016/j.promfg.2020.04.024.
[19] L. Gualtieri *et al.*, 'Advanced Automation for SMEs in the I4.0 Revolution: Engineering Education and Employees Training in the Smart Mini Factory Laboratory', in *2018 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM)*, Dec. 2018, pp. 1111–1115. doi: 10.1109/IEEM.2018.8607719.
[20] J. Wermann, A. W. Colombo, A. Pechmann, and M. Zarte, 'Using an interdisciplinary demonstration platform for teaching Industry 4.0', *Procedia Manuf.*, vol. 31, pp. 302–308, 2019, doi: 10.1016/j.promfg.2019.03.048.
[21] K. S. Sangwan *et al.*, 'Comparative Analysis for Solar Energy Based Learning Factory: Case Study for TU Braunschweig and BITS Pilani', *Procedia CIRP*, vol. 69, pp. 407–411, Jan. 2018, doi: 10.1016/j.procir.2017.11.018.
[22] W. M. Mohammed and J. L. Martinez Lastra, 'FASTory digital twin data', *Data Brief*, vol. 35, p. 106912, Feb. 2021, doi: 10.1016/j.dib.2021.106912.
[23] A. Barnard Feeney, S. Frechette, and V. Srinivasan, 'Cyber-Physical Systems Engineering for Manufacturing', 2017, pp. 81–110. doi: 10.1007/978-3-319-42559-7_4.
[24] G. Reisinger, T. Komenda, P. Hold, and W. Sihn, 'A Concept towards Automated Data-Driven Reconfiguration of Digital Assistance Systems', *Procedia Manuf.*, vol. 23, pp. 99–104, Jan. 2018, doi: 10.1016/j.promfg.2018.03.168.
[25] S. Mantravadi, C. Møller, C. LI, and R. Schnyder, 'Design choices for next-generation IIoT-connected MES/MOM: An empirical study on smart factories', *Robot. Comput.-Integr. Manuf.*, vol. 73, Feb. 2022, doi: 10.1016/j.rcim.2021.102225.
[26] F. Daniele, M. Confalonieri, P. Pedrazzoli, A. Graf, A. Ferrario, and M. Foletti, 'Implementation of a learning factory for research, education and training: the SUPSI Mini-Factory', *SSRN Electron. J.*, Jan. 2021, doi: 10.2139/ssrn.3858404.
[27] L. Zalud, F. Burian, and P. Kalvodova, 'Industry 4.0 Testbed at Brno University of Technology', in *Modelling and Simulation for Autonomous Systems*, J. Mazal, Ed., in Lecture Notes in Computer Science. Cham: Springer International Publishing, 2019, pp. 147–157. doi: 10.1007/978-3-030-14984-0_13.
[28] D. Winkler, P. Novák, J. Vyskočil, K. Meixner, and S. Biffl, 'Industry 4.0 Asset-based Risk Mitigation for Production Operation', in *2021 IEEE 17th International Conference on Automation Science and Engineering (CASE)*, Aug. 2021, pp. 278–285. doi: 10.1109/CASE49439.2021.9551419.
[29] Unkown, 'Research and Innovation Centre on Advanced Industrial Production', *RICAIP*. https://ricaip.eu/ (accessed Dec. 01, 2022).
[30] 'Making Digitalisation Tangible at The Industrial IoT Testbed'. https://www.htw-dresden.de/en/hochschule/fakultaeten/info-math/forschung/smart-production-systems/translate-to-english-industrie-40-modellfabrik (accessed Jan. 30, 2023).
[31] S. Makris *et al.*, 'Open-Digital-Industrial and Networking pilot lines using modular components for scalable production – ODIN project approach', *Procedia CIRP*, vol. 106, pp. 162–167, 2022, doi: 10.1016/j.procir.2022.02.172.
[32] F. Mo *et al.*, 'A framework for manufacturing system reconfiguration and optimisation utilising digital twins and modular artificial intelligence', *Robot. Comput.-Integr. Manuf.*, vol. 82, p. 102524, Aug. 2023, doi: 10.1016/j.rcim.2022.102524.
[33] 'Research Center For Connected Factories'. https://www.madesmarter.uk/made-smarter-innovation/research-centres/research-centre-for-connected-factories/ (accessed May 19, 2023).
[34] D. A. J. Brion and S. W. Pattinson, 'Generalisable 3D printing error detection and correction via multi-head neural networks', *Nat. Commun.*, vol. 13, no. 1, Dec. 2022, doi: 10.1038/s41467-022-31985-y.
[35] L. Solari Bozz, K. Samson, S. Tadeja, S. Pattinson, and T. Bohne, 'Towards Augmented Reality Guiding Systems: An Engineering Design of an Immersive System for Complex 3D Printing Repair Process', presented at the IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)., 2023. Accessed: Apr. 17, 2023. [Online]. Available: https://doi.org/10.17863/CAM.93609
[36] G. Hawkridge, D. McFarlane, J. Kaiser, L. de Silva, and G. Terrazas, 'Designing Shoestring Solutions: An Approach for Designing Low-Cost Digital Solutions for Manufacturing', in *Service Oriented, Holonic and Multi-agent Manufacturing Systems*, T. Borangiu, D. Trentesaux, P. Leitão, O. Cardin, and L. Joblot, Eds., in Studies in Computational Intelligence, vol. 1034. Cham: Springer International Publishing, 2022, pp. 249–262. doi: 10.1007/978-3-030-99108-1_18.

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Part 5

Advances in Supply Chain Systems

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A Review Paper on Supply Chain Management Strategies in UK Textile Industry

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Abstract: This study intends to bridge the extant literature and knowledge gap by investigating UK textile manufacturing to demonstrate the effect of supply chain practices and organisational performance. The significance of this research cannot be understated and will be of great significance to textile companies in the UK and globally as it will offer beneficial preferences into the idea of effective supply chain management practices and their impact on unit performance. In addition, their stakeholders will gain a better understanding of the barriers to implementing effective SCM practices and make relevant recommendations on how to address them. Policymakers and governments will also benefit from this research on appropriate strategies for implementing supply chain management practices. In addition, this research also has great importance for other scholars and students who are interested in conducting similar research, so it can be used as a reference for the literature. This study will open avenues for the UK scholars, providing them the opportunity to establish the relationship between supply chain practices and organisational performance.

Keywords: Supply Chain Management Practices, UK Textile, Manufacturing

1. Introduction

Supply chain management (SCM) as demonstrated by Ashby et al. [1], defines the strategic and effective collaboration of all conventional business functions and strategies, which are important to enhance the overall supply chain. Therefore, SCM mainly focuses on the complete integration of material flow and information flow throughout the supply chain as an effective competitive advantage. As a result, many textile companies have recognised that SCM is the key to enhance performance and gain competitive advantage [2]. Because of the nature of the industry and its intense competition, textile companies must understand the powerful relationship between SCM practices and organisational performance.

Companies have high anticipations for effective SCM practices, seeing them as the core to increase profits, increasing competitive advantage and increasing market share. Jack and Powers [3] point out that strategic supplier partnerships provide companies with significant benefits through improved financial performance. Kumar et al. [4] argue that

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customer/partner practices further contribute to organisational performance. Effective supply chain information sharing is associated with cost reduction and organisational performance. Therefore, the textile industry must regulate under a wide variety of information. Information is often important for planning and implementing decisions. A significant number of managers have revealed significant emphasis and challenge to enhance the quality of information. On the contrary, many companies experience widespread changes in information because of demand and supply uncertainties, which can lead to changes in customer tastes and preferences. Subsequently, the researchers suggest, this has led to more companies adopting effective supply chain practices to increase supply chain information sharing. Despite the high hopes of management and the numerous benefits of effective supply chain management, Oelze [5] found in his study that many textile companies have yet to implement effective supply chain management practices. Therefore, this results in most of them lack behind in organisational performance and gaining a competitive edge in the market. There is little empirical literature examining effective SCM practices, so extensive research and studies are needed to establish the association between SCM practices and organisational performance. Thereby, this study intends to bridge the extant literature and knowledge gap by investigating UK textile manufacturing to demonstrate the effect of supply chain practices and organisational performance. They will learn information about supply chain management, its impact on organisational performance, and the challenges companies face in implementing supply chain management practices. Likewise, they will learn about the various ways to deal with challenges and thus adopt SCM methods to improve performance and gain a competitive advantage.

2. Review Analysis

2.1 Supply Chain Management Practices

2.1.1 Customer Relationships

Customer relationship is a core strategy in supply chain management. It has been observed that organisations excelled in customer relations, a situation that contributes to a competitive advantage over competitors. In addition, organisations should regularly assess the importance of their relationships with customers. It is also evident from the body of literature that business relationships are very important to ensure a firm's performance and competitive advantage. Vivek et al. [6] emphasised that customer relations require multiple ways to manage customer reviews and feedback, build relationships with them, and enhance customer value and service. Likewise, Cho et al. [7] confirmed that increased business relationships help to improve demand analysis and thus assist in the planning of resources and materials and ensure operational efficiency. Building a positive relationship with customers helps businesses connect more closely with customers, allowing them to stay tuned to their wants and needs. By doing this, customers become loyal and most of them are retained with the company, which brings a lot of profit to the company. Loyal customers are always good ambassadors, so it is good to promote the company and thus create a good image for the company and attract more and more new customers.

2.1.2 Information Quality and Sharing

This is clearly stated in the literature, where information quality is considered an essential factor in production. The concept of quality information is to provide customers with diverse and effective information to help customers understand and obtain services and products. Nikolaou et al. [8] argued that information quality is believed to enhance firm performance by providing accurate descriptions of services and products. Information sharing develops cohesive trust among supply chain partners, encouraging each of them to achieve organisational goals [9]. Hence, this helps in increasing the performance and productivity of the organisation.

2.1.3 Supplier Partnership

Supplier cooperation plays an important role in securing a competitive edge. Supplier cooperation includes the alliance that exists between a company and its suppliers. Strong relationships are formed when companies review the regulations of suppliers, hold regular meetings, and link their policies to them [10]. With this, companies can receive raw materials as needed in the shortest possible time and thus shorten the delivery time. As a result, the product arrives at the customer's bench as specified and increases customer satisfaction. Moreover, through strong supplier partnerships, suppliers provide high-quality raw materials and produce high-quality products and services, thereby increasing the company's profits.

2.1.4 Outsourcing

Mohiuddin and Su [11] believed that in today's highly competitive market, several companies choose to outsource some services to increase efficiency; in addition, they hope to reduce administrative costs to focus on general business. Outsourcing refers to activities where a company outsources services performed internally to a third party. Usually, most companies focus on outsourcing part of their business after looking at their core business. Some of the main advantages of outsourcing are: increased expertise, reduced costs, positive brand image, augmented productivity, greater emphasis on employee well-being, and elevated knowledge of procedures and new systems introduced by third parties.

2.2 Effects of SCM Practices on Organisational Performance

2.2.1 Reduction of Manufacturing Costs

Outsourcing is described as one of supply chain management. As mentioned in the above section, outsourcing is conceptualised as an approach to contract with third parties for services that an organisation cannot provide internally. According to the study, one of the obvious advantages of outsourcing is lowering production costs. Companies get work at the lowest cost and with the highest quality. In addition, it eliminates the cost of technology and infrastructure investments. In today's economy, technology advances at an ever-increasing rate, and the faster it advances, the more expensive it is to integrate it into business operations. Instead, third parties undertake business processes and help develop their infrastructure [12]. SCM practices are also outlined to increase operational efficiency, so there are no machine breakdowns or breakdowns that could be detrimental to the business, resulting in cost savings.

2.2.2 Product Innovativeness

Di Benedetto [13] argued that innovative products and services broadly break through stagnant markets and meet customer needs and wants. Innovation often allows a company to remain pertinent in the marketplace and drive growth and success. Product innovation refers to the process by which companies create new products or improve existing products to meet customer needs. SCM practice helps to increase product innovation. Through strategic supplier partnerships, suppliers provide companies with high-quality raw materials suitable to enhance current products as well as developing new ones. Building strong relationships with consumers allows businesses to keep up with their needs, preferences and demands. In this regard, companies can adapt to changing trends and patterns and thereby meet the wants and needs of customers by offering products for customers to choose from.

2.2.3 Improved Efficiency and Quality

SCM practices facilitate to automate business operations and processes. Having access to new technology facilitates in ensuring operational efficiency. Information can further be shared promptly with supply chain partners, simplifying the decision-making process. Likewise, organisations can anticipate customer needs and thus produce products that are tailored to customer needs. Automation can capture high quality information. With the help of high-quality information, organisations can make excellent decisions that increase operational efficiency and improve the quality of services and products, thus increasing consumer satisfaction and attracting more market share to the organisation.

2.2.4 Improved Delivery Time

With better supplier collaboration, products and services can be provided to the customer's door as accepted on the order receipt. Most of the time, companies lose money on slow shipments to consumers. Customers often get frustrated when a product is delivered later than anticipated. This impacts their satisfaction and eventually they require these services from suitable firms. Consumers are always satisfied when the product reaches their site within the stipulated time. Therefore, they could buy products from the firms and share their experience with their friends, thereby covering more new customers. In contrast, it is possible by implementing supply chain management practices. If a company experiences delivery delays, it can opt for outsourced logistics services to meet customer needs and demands by assuring speedy delivery of goods and services [14]. Some manufactured products can be fragile, so delays can cause product damage, costing the company a lot.

2.3 Challenges Experienced by Organisations to Implement SCM Practices

2.3.1 Complicated Social Media Platforms

Technological advances, cloud communications and the Internet have recently developed in importance for businesses. Companies are trying to keep a close eye on consolidation trends and advancements, making sure to leverage them to increase the efficiency and productivity of business processes. However, a major problem with this advancement is that it leads to many devices, resulting in complex networks that are difficult to administer. With the complexity of the Internet, more risks and security threats are introduced to survive and run a business. Berger and Jones [15] stated that cybercrime is evolving as technology and networks evolve, allowing hackers to gain access to sensitive corporate data and information. This can cause harmful losses and affect the survival and development of the company. As a result, most organisations fail to adopt SCM practices in their processes and operations.

2.3.2 Failure to Engage the Stakeholders in Decision-Making

All parties have a direct or indirect impact on supply chain operations. Without one party involved, supply chain inefficiencies can result. When a person is marginalised in decision-making, he feels that he does not belong in the company and is therefore not ready to work towards the goals and objectives of the organisation. For example, failure to include suppliers in decision-making can create unfavourable costs for the company as suppliers may delay the delivery of raw materials or provide materials of lower quality. All this is due to adverse leadership within the organisation. Some managers find it best for making decisions themselves regardless of engaging other parties. In particular, the preferences of all stakeholders are overwhelmed and become negative. Input allows supply chain partners to express their opinions and views, which are considered in the final decision-making process.

2.3.3 Paucity of Responsiveness by Customers and Suppliers
Communication is the core to the growth and success of an organisation and to building alliances between companies, suppliers, and customers. It has been argued that better supplier relationship management depends on open communication and transparency between companies and their consumers along with suppliers. In a situation where a company is communicating with a supplier or customer, the company should seek a variety of approaches for re-establishing a full relationship. On the contrary, this is not the case and most organisations face challenges that affect the adoption of SCM. Majority of them do not communicate openly with suppliers, which damages their relationships. When the alliance breaks down, companies cannot restore the relationship and explore the root cause of the breakup. Some suppliers end up damaging the reputation of the company and therefore it is complicated for the company to acquire more suppliers. This impacts the operations and procedures of the organisation as raw materials become restricted or more expensive to acquire.

2.3.4 Higher Extent of Operational Costs
Adoption of SCM practices does not come empty-handed, it requires resources and funding. Human resources are the implementer of SCM practices. Training is important to ensure that supply chain stakeholders effectively execute their intended roles and responsibilities. Regular training sessions and courses require considerable resources. Some managers believe that the implementation of SCM methods is a waste of time and resources due to higher costs. However, even though an integrated SCM practice might seem a little expensive, it can pay off big in the long run. As the literature review shows, SCM practices can facilitate in increasing product innovation. Through strategic supplier partnerships, suppliers provide companies with high-quality raw materials adequate to enhance current products along with developing new ones. Building strong relationships with consumers allows businesses to keep up with their requirements, preferences, and demands. In this regard, companies can focus on changing trends and patterns and meet customers' wants and needs by offering a diverse range of products for consumers to choose from.

3. Suggestions on Appropriate Initiatives in Overcoming the Challenges

Assuring the competitive adoption of SCM practices can be complicated and complex, but companies can engage in several factors to significantly improve the implementation of SCM practices. It is crucial for companies to have a good understanding of the supply chain and the business plans associated with it [16]. By gaining a better understanding of the supply chain, companies can identify the strengths and weaknesses of the supply chain and thus take proactive initiatives for enhancing its weaknesses and reducing potential risks.

Second, companies must pursue for forming supply chain committees. Lambert and Enz [17] argued that without a supply chain council, a visible and well-defined SCM practice or strategy cannot be accomplished, which leads to less efficient business operations and processes. It also provides supply chain leadership and management support and helps to improve cross-functional communication to improve SCM throughout the company.

Third, companies must seek to form a properly staffed supply chain structure. The supply chain should continuously be properly organised and staffed for maximising efficiency. Supply chain leaders should enhance their strategic thinking to create value for the company by using strong communication abilities and relationship management. Effective communication can convince employees and staff to work towards the stated goals of the organisation.

Providing training and workshops to supply chain stakeholders can help ensure the successful adoption of SCM practices. Training facilitates in imparting skills, abilities and knowledge related to the supply chain. On the contrary, organisations must evaluate trainers during training sessions to ensure that training is effective. This helps gauge their understanding and pinpoint areas for improvement so that preventative action can be taken.

4. Conclusion

In today's world, companies operate in a dynamic and changing business environment. Due to increased competition in the market, most companies are going out of business. Managers look for ways to maintain market power and gain a competitive edge over competitors. SCM is the mere opportunity for many firms. Companies have high anticipations for effective SCM practices, considering them as the core to elevate profits, increasing competitive advantage and increasing market share. The UK textile industry is also not left out and is working hard to ensure it stays in the market. In conclusion, the operating environment of the textile industry is volatile, seasonal, and growing trends have a great impact on the growth and survival of most textile firms. Therefore, this study explored the effect of SCM in the UK textile industry.

The study has clearly identified that there is a significant positive relationship between SCM and organisational performance. The study identifies different approaches to SCM, such as “customer relationships, information sharing, information quality, outsourcing, and supplier collaboration”. According to the findings, building a constructive relationship with customers facilitates companies to engage more with consumers and thus be competent enough for monitoring their needs and wishes. This way, customers will be loyal, and most customers will stay with the company, so the company can earn massive profits. Loyal consumers are continuously better ambassadors, so it is good to promote the company and thus create a better portrayal for the firm and attract new consumers. Information and high-quality data in the supply chain has been described as useful in the decision-making process. Information is often shared between decision makers in the organisation and other supply chain partners, not only for comparison, review, or development of competitive strategies, but also to manage day-to-day operations and thus solve problems in real time base. Furthermore, the study reveals that supplier collaboration is the relationship that exists between a company and its suppliers. By reviewing supplier terms and conditions, holding regular meetings, and communicating its policies with suppliers, the company creates a strong supplier partnership that allows the company to gain a competitive advantage. Most importantly, as a research gap, a comprehensive framework is needed to identify the most appropriate SCM strategy to enhance the related performance measures associated and eliminate nonvalue-added practices.

References

1. Ashby, A., Leat, M. and Hudson-Smith, M., 2012. Making connections: a review of supply chain management and sustainability literature. *Supply chain management: an international journal*, *17*(5), pp.497-516.
2. Madhani, P.M., 2019. Strategic supply chain management for enhancing competitive advantages: developing business value added framework. *International Journal of Value Chain Management*, *10*(4), pp.316-338.
3. Jack, E.P. and Powers, T.L., 2015. Managing strategic supplier relationships: antecedents and outcomes. *Journal of Business & Industrial Marketing*.
4. Kumar, A., Singh, R.K. and Modgil, S., 2020. Exploring the relationship between ICT, SCM practices and organizational performance in agri-food supply chain. *Benchmarking: An International Journal*.
5. Oelze, N., 2017. Sustainable supply chain management implementation–enablers and barriers in the textile industry. *Sustainability*, *9*(8), p.1435.
6. Vivek, S.D., Beatty, S.E. and Morgan, R.M., 2012. Customer engagement: Exploring customer relationships beyond purchase. *Journal of marketing theory and practice*, *20*(2), pp.122-146.
7. Cho, D.W., Lee, Y.H., Ahn, S.H. and Hwang, M.K., 2012. A framework for measuring the performance of service supply chain management. *Computers & Industrial Engineering*, *62*(3), pp.801-818.
8. Nikolaou, I.E., Evangelinos, K.I. and Allan, S., 2013. A reverse logistics social responsibility evaluation framework based on the triple bottom line approach. *Journal of cleaner production*, *56*, pp.173-184.
9. Özer, Ö., Zheng, Y. and Ren, Y., 2014. Trust, trustworthiness, and information sharing in supply chains bridging China and the United States. *Management Science*, *60*(10), pp.2435-2460.
10. Harms, D., Hansen, E.G. and Schaltegger, S., 2013. Strategies in sustainable supply chain management: an empirical investigation of large German companies. *Corporate social responsibility and environmental management*, *20*(4), pp.205-218.
11. Mohiuddin, M. and Su, Z., 2013. Manufacturing small and medium size enterprises offshore outsourcing and competitive advantage: An exploratory study on Canadian offshoring manufacturing SMEs. *Journal of Applied Business Research (JABR)*, *29*(4), pp.1111-1130.
12. Stentoft Arlbjørn, J. and Vagn Freytag, P., 2012. Public procurement vs private purchasing: is there any foundation for comparing and learning across the sectors? *International Journal of Public Sector Management*, *25*(3), pp.203-220.
13. Di Benedetto, C.A., 2013. The emergence of the product innovation discipline and implications for future research. *The PDMA handbook of new product development*, pp.416-426.
14. Adebayo, I.T., 2012. Supply chain management (SCM) practices in Nigeria today: impact on SCM performance. *European Journal of Business and Social Sciences*, *1*(6), pp.107-115.
15. Berger, H. and Jones, A., 2016, July. Cyber security & ethical hacking for SMEs. In *Proceedings of the The 11th International Knowledge Management in Organizations Conference on The changing face of Knowledge Management Impacting Society* (pp. 1-6).
16. Hugos, M.H., 2018. *Essentials of supply chain management*. John Wiley & Sons.
17. Lambert, D.M. and Enz, M.G., 2017. Issues in supply chain management: Progress and potential. *Industrial Marketing Management*, *62*, pp.1-16.

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Expanding the Scope of Manufacturing Digital Twins to Supply Chain

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Abstract. The rapid emergence of digital technologies is revolutionising the manufacturing industry, with digital twins (DTs) emerging as a transformative innovation. DTs, virtual counterparts of physical entities or systems, hold immense potential for optimizing and overseeing manufacturing processes. By proposing a three-dimensional classification framework that considers DT integration levels, supply chain (SC) structural hierarchies, and SC processes, this study examines the evolution of manufacturing DTs to encompass the SC. An analysis of existing literature reveals a significant gap in extending manufacturing DTs to the SC system level without incorporating structural and process aspects of DT models. The paper also investigates the key performance objectives, including efficiency, resilience, and sustainability, as well as the challenges associated with DT implementation. The insights provided in this paper contribute to a better understanding and practical application of DTs in the dynamic contexts of manufacturing and the SC.

Keywords. Digital twins, manufacturing systems, supply chain process, supply chain structure, sustainability, resilience.

1. Introduction

The rise of Industry 4.0 has brought about a significant digital transformation in manufacturing processes. Digital twins (DTs) play a crucial role in driving this transformation, consisting of a physical object or system, a virtual replica, and the connecting data [1]. DTs enable an interactive and dynamic relationship between the physical and virtual entities, emphasizing real-time bidirectional data flow. DTs a viable solution across a multitude of sectors, including manufacturing, aviation, healthcare, maritime and shipping, urban management, and aerospace and power plant management.

Implementing DTs is a complex undertaking that necessitates interactions among humans, technology, and processes [2], as the modelling process, which incorporates personnel, equipment, materials, and the environment, is dynamic and subject to evolution over time [3]. Applying DTs is not straightforward. It involves interaction among humans, technology, and processes [2]. The modelling process, which includes elements such as personnel, equipment, materials, and environment [3], is not static and changes over time. The structure of SC is multi-scale in nature, and the interconnections among the SC entities are not simply linear and may involve return processes. The direction, type and volume of SC flows are dynamic and human-related, further complicating analysis. These factors highlight the potential value of a framework to guide the design and implementation of DTs across SC hierarchy. These factors indicate

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the necessity for a framework to guide DT design in SC hierarchies. The potential of DT to sustainability lies in its ability to handle a wide scope beyond efficiency, offering scalability for system-level enhancements.

Therefore, this paper delves deeper into the exploration of the multifaceted nature of DTs within multi-level and multi-scale manufacturing systems. We start by reviewing the evolution of DTs and their deployment in manufacturing systems, while considering DT integration levels, SC structural hierarchy, and SC processes. Following this, we discuss the performance objectives in use and identify the challenges and prospects associated with implementing DTs in manufacturing systems. There is a particular emphasis on sustainability and resilience in the paper, motivated by the scarcity of literature in this space.

2. Scaling up manufacturing DTs to SC system level

DTs can facilitate the interaction at components or parts, products or service, machine, processes, and the system integration in SC systems. DTs can be viewed from multiple perspectives, such as hierarchical level, life-cycle phase, functional use, the maturity level and data flow of DTs [4]. Based on the data integration levels, DTs can be categorised into three groups [4]: (1) digital model, with no automated data exchange; (2) digital shadow, allowing one-way data flow from physical to digital entities; and (3) digital twin, enabling bidirectional data flow between physical and digital entities. Our use of the term "DT" specifically refers to the two-way flow of data between virtual models and physical objects.

Current studies focus more on DT implementation at machine, product, or shop floor level [5], where the integration of multiscale nature of SC system is considered less [6]. However, a big picture of smart manufacturing and I4.0 requires the scope of DT application to be expanded beyond the boundary of manufacturing systems but with the inclusion of business partnership in the context of SC. Therefore, our study emphasises the analysis of DT implementation in manufacturing systems by prioritising the examination of SC processes and structural hierarchy (see **Figure 1**), which implies the supplier and customer relationship management and the complexity of SC systems.

Given the complexity of interconnected SC entities, this study defines a SC as a network of sub-systems that evolve over time into new SC structures. The complexity and evolution of these structures depict how SCs deliver products or service and generate desired performance. The DT-enabled SC system can be considered as a complex and dynamic Cyber-Physical system (CPS), where the DT synchronisation across SC hierarchy can achieve high-level interoperability [6]. Understanding the spatial-temporal dynamics of SC structures and processes, DTs can be implemented at the SC system level to simulate, analyse, predict, monitor, and optimise SC behaviours [7].

We consider four basic structural hierarchy levels in SC systems [8]: (1) SC block, representing a specific business function; (2) SC module, a collection of blocks that fulfil a particular business function and may involve geographic changes; (3) SC member, referring to firm-level operators comprising one or more modules; and (4) SC system, which represents the interconnected network of SC members.

Extending from product life cycle, our study considers SC system and utilises the Supply Chain Operation Reference (SCOR) model as a basis for investigating DT implementation, spanning entire SC. The SCOR model identifies six primary processes: plan, source, make, deliver, return, and enable (Council, 2017). These processes are designed to prioritise cross-functional operations and coordinate flows of materials, products, and potentially energy, water, and other resources within the SC [8, 10]. Across the SC structural hierarchy, SC processes manifest at different scales and scopes within operational units or "blocks" through the entire SC to deliver the products and service. By integrating DTs of these processes, organisations can enhance their operational efficiency and achieve a seamless coordination of various functions involved in the SC.

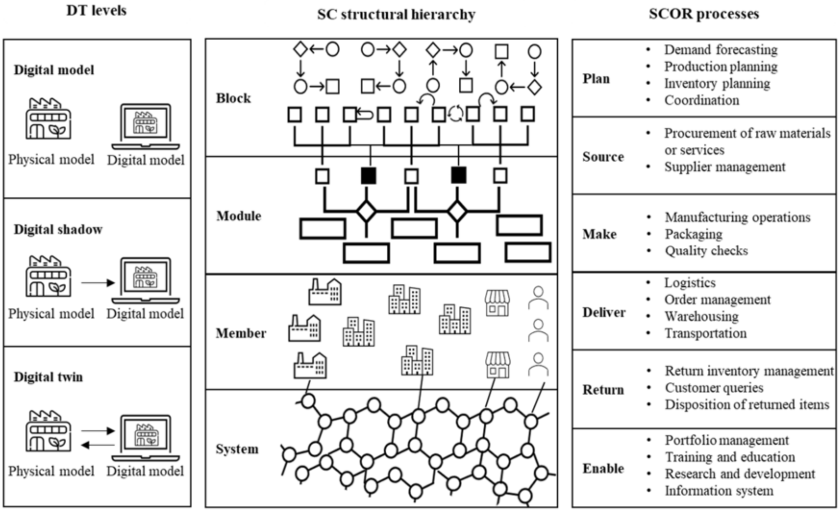

Figure 1. Dimensions of DTs in manufacturing and SC systems

3. Implementation of DTs in SC context

The scalability of implementing DTs in manufacturing systems to encompass the SC level plays a pivotal role in the umbrella concepts of smart manufacturing and Industry 4.0 [11, 12]. This emphasises the significance of extending the application of DTs beyond individual manufacturing units to achieve a holistic and interconnected approach throughout the entire SC.

In extant studies, DT technology has been employed across various industries, infusing technical functionalities into product design, flow shop design, scheduling, planning, assembly, logistics, and more [13]. However, clusters of DTs applications tend to operate in isolation, focusing on the application scenarios (e.g., job-shop scheduling, smart manufacturing, virtualising manufacturing system, product assembly process, alternative manufacturing), enabling technologies and techniques (e.g., information models) [14], and functionalities (e.g., information management, data analysis, manufacturing operation management) [15, 16]. Yet, these propositions often focus on individual process such as logistics planning ("plan") [17] and manufacturing production ("make") [6, 18], rather than holistic solutions that interconnects complex SC processes. In general, "plan" (e.g., job-shop scheduling), "make" (e.g., micromachining), and "enable" (e.g., optimisation techniques) are the dominant SCOR processes investigated.

Literature indicates a scarcity in system-level applications of DTs in SC context, neglecting SC complexity in structural hierarchy. The focused areas of DT application are generally based on the individual SC structural levels in "blocks" (e.g., machine tools, turbomachinery, rotating machinery fault diagnosis) [19–21], "modules" (e.g., logistics and assembly) [18, 22], and "members" (e.g., the manufacturer) [11, 20]. For instance, Bao et al.[22] examined the ontology of assembly workshops ("modules"), focusing on simulating assembly resources and tasks but without addressing the embeddedness of assembly "blocks" or extend to the SC level ("systems"). Similarly, Park et al.[17] introduced a DT information model that encompasses the entire manufacturing abstraction, focusing on the "members" level of application but without connections with SC partners and the embeddedness of SC structural hierarchy.

Existing research on DTs in SC context suggests their potential for SC-level integration with systematic thinking but lacks enabling methods and techniques for achieving bidirectional data integration across multiscale SC structures and processes. For instance, Ivanov et al.[7] introduced the concept of data-driven, cyber-physical SCs without proposing a technical pathway. Serrano-Ruiz, Mula and Poler highlighted DTs as an enabler for SC resilience and sustainability within the I4.0 framework but did not emphasise model fusion across multiple levels and scales. While Aheleroff et al.[2] proposed architectural models for DT application, but lacked clear representation of elements and scopes of the system development lifecycle dimension (referring to SC system in this study). In general, these propositions of DT models overlook comprehensive multiscale integration of SC structures and processes and underemphasise DT design for desired performance (e.g., resilience and sustainability).

4. Performance objectives of DT-enabled manufacturing and SC systems

DTs in manufacturing and SCs can strategically align with key performance (e.g., sustainability development and system resilience) [13]. Efficiency, resilience, and sustainability emerge as major objectives of DT application, especially in the agri-food SC context [23]. However, the lack of comprehensive modelling supporting these metrics limits the scope and depth of performance objectives.

The integration of DTs helps to manage disruption risks and fosters SC resilience [7, 24]. DTs enhance resilience by improving asset management, maintenance, and mitigating equipment failures and production disruptions. The use of what-if scenario analysis through DTs aids in SC coordination and enables proactive and predictive management in the face of SC challenges such as bullwhip effects, ripple effects, and disruptions [7]. Resilience, measured in terms of recovery speed or the magnitude of loss from financial or operational perspectives, reflects SC business aspects rather than specific DT attributes. The literature lacks a universal resilience framework of DTs that can be implemented across SC structure hierarchy and processes in different industries. Therefore, there is a gap in quantifying resilience enhancement to validate the superiority of DT-enabled manufacturing systems.

DTs significantly contribute to sustainability in smart manufacturing, enabling real-time monitoring, predictive maintenance, and dynamic simulations that reduce waste and resource consumption [25]. By promoting collaboration and transparent lifecycle management, DTs support eco-friendly practices, carbon emission reduction, and the attainment of Sustainable Development Goals (SDGs) [26]. However, capturing the sustainability benefits of DTs poses challenges due to limited integration of sustainability into DT models, lack of empirical evidence, and the absence of a universal sustainability measurement framework. This hampers the simulation of sustainability practices across different scales and scopes, making it difficult to align sustainability measures with complex structural hierarchy and processes.

5. Challenges of DT implementation in manufacturing and SC systems

Despite the potential benefits of DTs in manufacturing systems, their successful implementation presents challenges. Firstly, data quality and management are critical. DTs depend on accurate, comprehensive data, but uncertainties in manufacturing make data collection difficult [18]. High-quality data necessitates appropriate sensors and data management practices. While technologies like IoT have eased data collection, real-time data accessibility remains challenging in industrial practices. Secondly, designing and measuring resilience attributes for DTs is complex. Manufacturing systems and SCs are dynamic and susceptible to disruptions, and resilience attributes must account for this variability. To ensure consistency across industries, a generic framework is needed, yet developing this framework is complicated by issues with data availability and accuracy. Thirdly, sustainability considerations are vital for achieving SDGs. Although ISO standards for DTs exist, there are no standard guidelines for incorporating sustainability into DTs consistently, limiting performance measurement, especially at SC scale. Complexities of sustainability dimensions, evolving goals, regulations, and data availability challenges add further complications. Finally, DT implementation involves organizational changes, requiring new skills and continuous adaptation of organisational structures [27]. These dynamic alterations necessitate comprehensive change management strategies and a learning-oriented culture to ensure smooth transitions and effective navigation of this transformative journey.

6. Conclusions

DTs have significant potential for Industry 4.0, highlighting the importance of system integration. While recent advancements focus on SC level frameworks, systematic integration with SC structural hierarchy and processes is still lacking. The recognition of KPIs for DT implementation, particularly resilience and sustainability, is increasing. However, developing a standard assessment framework remains challenging due to the complex nature of SC and DTs. Data quality, management, and organizational changes present additional challenges. Nevertheless, DTs hold promise in transforming manufacturing, driving innovation, enhancing competitiveness, and promoting sustainable smart manufacturing and SC systems aligned with SDG principles.

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References

[1] Tao, F., Xiao, B., Qi, Q., Cheng, J., Ji, P., Digital twin modeling. J. Manuf. Syst. (2022).

[2] Aheleroff, S., Xu, X., Zhong, R.Y., Lu, Y., Digital Twin as a Service (DTaaS) in Industry 4.0: An Architecture Reference Model. Adv. Eng. Inform. (2021).

[3] Zhuang, C., Tian, M., Liu, J., Hui, X., The connotation of digital twin, and the construction and application method of shop-floor digital twin. Robot. Comput.-Integr. Manuf. (2021).

[4] Kritzinger, W., Kritzinger, W., Karner, M., Traar, G., Henjes, J., Sihn, W., Digital Twin in manufacturing: A categorical literature review and classification. IFAC-Pap. (2018).

[5] Zhang, H., Qi, Q., Tao, F., A multi-scale modeling method for digital twin shop-floor. J. Manuf. Syst. (2022).

[6] Park, K.T., Son, Y.H., Noh, S.D., The architectural framework of a cyber physical logistics system for digital-twin-based supply chain control. Int. J. Prod. Res. (2020).

[7] Ivanov, D., Dolgui, A., Das, A., Sokolov, B., Digital Supply Chain Twins: Managing the Ripple Effect, Resilience, and Disruption Risks by Data-Driven Optimization, Simulation, and Visibility. Handb. Ripple Eff. Supply Chain. (2019).

[8] Zhang, J., Zhang, J., Brintrup, A., Calinescu, A., Kosasih, E.E., Sharma, A., Sharma, A., Supply Chain Digital Twin Framework Design: An Approach of Supply Chain Operations Reference Model and System of Systems. (2021), from https://doi.org/10.48550/arXiv.2107.09485.

[9] Council, S.C., Supply chain operations reference model. Overv. SCOR Version. 12(0), (2017).

[10] Ivanov, D., Sokolov, B., Kaeschel, J., A multi-structural framework for adaptive supply chain planning and operations control with structure dynamics considerations. Eur. J. Oper. Res. (2010).

[11] Jiang, P., Leng, J., Leng, J., Wang, D., Shen, W., Pan, Q.-K., Li, X., Li, X., Liu, Q., Liu, Q., Chen, X., Chen, X., Digital twins-based smart manufacturing system design in Industry 4.0: A review. J. Manuf. Syst. (2021).

[12] Kokkonen, K., Hannola, L., Rantala, T., Ukko, J., Saunila, M., Rantala, T., Preconditions and benefits of digital twin-based business ecosystems in manufacturing. Int. J. Comput. Integr. Manuf. (2022).

[13] Bhandal, R., Meriton, R., Kavanagh, R.E., Brown, A., The application of digital twin technology in operations and supply chain management: a bibliometric review. Supply Chain Manag. (2022).

[14] Aivaliotis, P., Georgoulias, K., Arkouli, Z., Makris, S., Methodology for enabling Digital Twin using advanced physics-based modelling in predictive maintenance. Procedia CIRP. (2019).

[15] Dai, S., Zhao, G., Yu, Y., Zheng, P., Bao, Q., Wang, W., Wang, W., Wang, W., Ontology-based information modeling method for digital twin creation of as-fabricated machining parts. Robot. Comput.-Integr. Manuf. (2021).

[16] Zhang, H., Yan, Q., Wen, Z., Information modeling for cyber-physical production system based on digital twin and AutomationML. Int. J. Adv. Manuf. Technol. (2020).

[17] Park, K.T., Lee, J.-H., Kim, H.J., Kim, H.-J., Kim, H., Noh, S.D., Digital twin-based cyber physical production system architectural framework for personalized production. Int. J. Adv. Manuf. Technol. (2020).

[18] Stavropoulos, P., Papacharalampopoulos, A., Sabatakakis, K., Mourtzis, D., Metamodelling of Manufacturing Processes and Automation Workflows towards Designing and Operating Digital Twins. Appl. Sci. 13, 1945 (2023).

[19] Ghosh, A.K., Ullah, A.M.M.S., Ullah, A.S., Teti, R., Kubo, A., Developing sensor signal-based digital twins for intelligent machine tools. J. Ind. Inf. Integr. (2021).

[20] Wang, J., Ye, L., Gao, R.X., Li, C., Zhang, L., Zhang, L., Digital Twin for rotating machinery fault diagnosis in smart manufacturing. Int. J. Prod. Res. (2019).

[21] Xie, R., Chen, M., Liu, W., Jian, H., Shi, Y., Digital Twin Technologies for Turbomachinery in a Life Cycle Perspective: A Review. Sustainability. (2021).

[22] Bao, Q., Zhao, G., Yu, Y., Dai, S., Wang, W., The ontology-based modeling and evolution of digital twin for assembly workshop. Int. J. Adv. Manuf. Technol. (2021).

[23] Singh, G., Rajesh, R., Daultani, Y., Misra, S.C., Resilience and sustainability enhancements in food supply chains using Digital Twin technology: A grey causal modelling (GCM) approach. Comput. Ind. Eng. 179, 109172 (2023).

[24] Serrano-Ruiz, J.C., Mula, J., Poler, R., Smart Master Production Schedule for the Supply Chain: A Conceptual Framework. First Comput. (2021).

[25] He, B., Bai, K.-J., Digital twin-based sustainable intelligent manufacturing: a review. Adv. Manuf. 9, 1–21 (2021).

[26] Hassani, H., Huang, X., MacFeely, S., Enabling Digital Twins to Support the UN SDGs. Big Data Cogn. Comput. (2022).

[27] Rosen, R., Wichert, G. von, Lo, G., Bettenhausen, K.D., About the Importance of Autonomy and Digital Twins for the Future of Manufacturing. IFAC-Pap. (2015).

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Upgrading Conventional Production Lines Through Implementing an Industry 4.0 Strategy

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Abstract. Although Industry 4.0 and the Internet of Things (IoT) have been implemented in various manufacturing sectors, medium and small enterprises have limited integrations with this strategy, especially those that still rely on conventional production lines and lack the capacity for transition in near future. This paper presents a work demonstrating how conventional production lines could be upgraded for implementing an Industry 4.0 strategy, using plastic injection moulding as a case study. This transformation helps to achieve a real-time optimised value chain, considering factors such as cost, availability, and resource consumption, while the implementation cost is kept low.

Keywords. Industry 4.0, Internet of Things (IoT), Plastic Injection Moulding (PLM), Manufacturing Execution System (MES), Data Acquisition System (DAQ)

1. Introduction

Today many enterprises are adopting new intelligent manufacturing concepts which depend on digitalisation and advanced technologies to achieve improvements in factory management and production automation [1][2]. Injection moulding is one aspect that has received attention from an Industry 4.0 perspective [3]. Automation layers are applied according to the automation standard ISA-95, and equal attention is paid to each level from the shop floor to the business level. Where in-mould and in-machine sensors are installed [4][5], and at the control level, Data Acquisition System (DAQ) is utilised to collect and refine the data coming from the machine [6]. Also, the Manufacturing execution system plays an essential role as the link between the shop floor layer and the enterprise layer. Many studies and applications explain the methodology of the communication between the DAQ, MES, and Enterprise resource Planning (ERP) systems [7][8] and the approaches that should follow to achieve the right communication between these systems, such as the OPC-UA [9] and APIs [10] to monitor the production process in real-time. As the digitalization trend continues, small and medium-sized enterprises (SMEs) necessarily need to adapt their manufacturing processes to align with Industry 4.0. They face many challenges in incorporating IT and

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automation to compete in a globally interconnected market. So, upgrading their production lines will be the optimal solution instead of replacing them due to the excessive costs associated with replacing outdated machinery with advanced alternatives and the time consumed to automate all production lines.

2. Analysis of the Current Systems

Injection moulding is a crucial manufacturing process that combines mass production capabilities, rapidity, and low cost. To ensure continuous production and maintain the quality of moulded parts, it is essential to integrate injection moulding into the Industry 4.0 framework. This entails real-time monitoring of the process, capturing comprehensive process data, and optimizing factors such as pressure, temperature, and speed that influence the part quality and machine stability.

The project partner, Pascoe Engineering Ltd, has eighteen plastic injection moulding machines and offers injection moulding services such as design and produce moulded parts. Most of the machines were made between 1992 and 1998. The main control panels of machines are basic and unable to communicate with any external modern industrial or business equipment or systems by any type of communication protocol. Digital signals are limited to open and close mould, ejector position and switch-over point. The machines lack the ability to control the moulded parts' quality and monitor the total production process, additionally, the inability to connect to any advanced systems makes the process of enhancing productivity, quality, energy consumption, and minimizing cost very difficult, especially in terms of rapid production of high-quality parts which are very critical in this kind of manufacturing in industries such as the medical, electronics, and aerospace industries.

In this study, a Battenfield BA 600 CDC injection moulding machine, which is equipped with a basic control panel and manufactured in 1998, is utilized. The company owned an ERP system (e-max) where all data and information from the shopfloor and the management level are entered into the system manually. This is considered a challenge to the time and accuracy of transformed data, and this will reduce the efficiency, availability, and the quality of the total production process.

3. Proposed System Description

3.1. Accessing the IMM parameters data

The BA 600 machine is equipped with a basic control panel that allows for tracking simple signals such as mould open/close, switch over point, and ejector functions.

To gather process data from the machine and the mould, a set of sensors is installed on the machine and the mould (Fig.1). A hydraulic pressure sensor (type 4262A, Kistler), Nozzle temperature sensor (type 4021B, Kistler) and Screw position sensor (type P510, Kistler) are installed on the machine. At the same time, the mould cavities are equipped with two combined pressure-temperature sensors (type 6188A, Kistler). Additionally, a cooling water temperature sensor (TRACER® vm base) is placed on the main pipe that supplies cooling water to the mould.

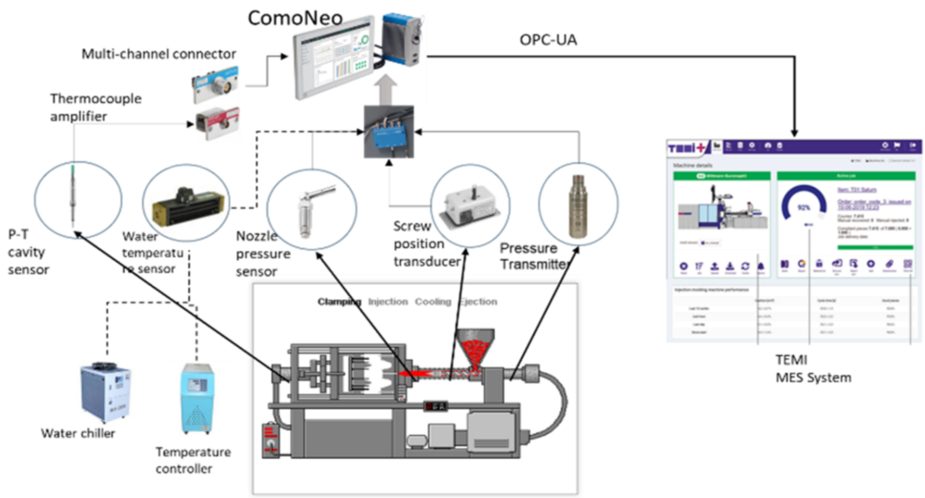

Figure 1. The design of experiment

3.2. Acquisition of machine Controller and sensors data

At the control layer, data are collected by Data Acquisition System, ComoNeo developed by Kistler. This system captures data from both the control panel and the installed sensors. ComoNeo is available with different communication protocols such as ProfiNet and Ethernet/IP and is able to collect digital and analogue signals, so it can connect with different models of injection moulding machines. For the analogue signals that come from machine sensors, it is necessary to utilise a charge amplifier to convert the signals to digital. The system contains Up to 128 monitoring functions that enable sorting the good parts from defects on the basis of recorded data.

3.3. Implementing of Manufacturing execution system

At the business layer, the manufacturing execution system (TEMI+) is used which has been designed by ICE-flex for the needs of the plastic industry. To provide advanced overall equipment effectiveness (OEE) calculations and data integration of the plastic moulding machines, many communication languages of press manufacturing like Euromap77 and the OPC-UA are available. These allow communication between auxiliary equipment located around the injection machine. The system acts as an intermediate layer between the enterprise resource planning (ERP) system and a machine control system (Fig. 2).

The system operates across multiple functions such as job planning, process monitoring, product life cycle, resource scheduling, order execution and dispatch, production analysis and downtime management for overall equipment effectiveness (OEE), product quality, and materials track and trace. The data of customers, materials, inventory, and orders can be collected from the ERP system or by uploading the data to the MES system. After transferring or uploading the data to the MES system, the enterprise is able to distribute the orders to the machines by setting up the time and date of each order.

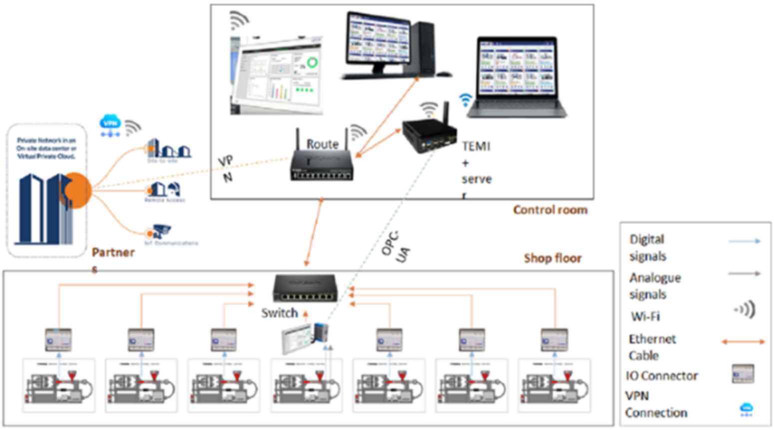

Figure 2. The final design of the production line includes the four automation layers.

4. Production trials with new setup

Analogue signals are obtained from sensors and digital signals are obtained from the machine controller. These signals provide the data acquisition system with the required information. The closing mould signal indicates the beginning of a new injection cycle, while the switch-over signal indicates the switch from the injection phase to the packing phase during the cycle. All signals' threshold values can be defined in real-time during the cycle by the ComoNeo. These thresholds specify the values of each variable that ensure the quality of the final moulded part.

Any parameters that exceed the threshold limits indicate the moulded part will be classified as a defect. The values of each threshold will be obtained after analysing the process depending on the complexity of the part's geometry, the utilized material, the shape of the runner and sprue, and the design of cooling water channels inside the mould. DoE is applied to obtain the optimal values of the parameters which lie within the thresholds, from these values the bad or good moulded part is specified.

This data is transformed into the manufacturing execution system TEMI through the OPC-US architectural standard which supports the TCP communication standard. The TEMI^{+} process planning defines each operation and its sequence through the production cycle, starting with the raw materials and ending with the final product. TEMI+ covers decision-making and process scheduling. TEMI+ receives the orders created at the ERP level. The MES will check the resource and materials' availability and then try to implement the planned schedule for a specific operation period and respond to any sudden fault in the production process by resolving the issue without disrupting the order schedule. The communication between DAQ and MES will specify the number of moulding cycles in real-time and then the number of good parts. This provides the enterprise with accurate data about the total moulding process.

The efficiency of the production equipment is evaluated and visualized using Overall Equipment Effectiveness (OEE) (Fig. 3), while the quality of parts will provide a comprehensive overview of the manufacturing process.

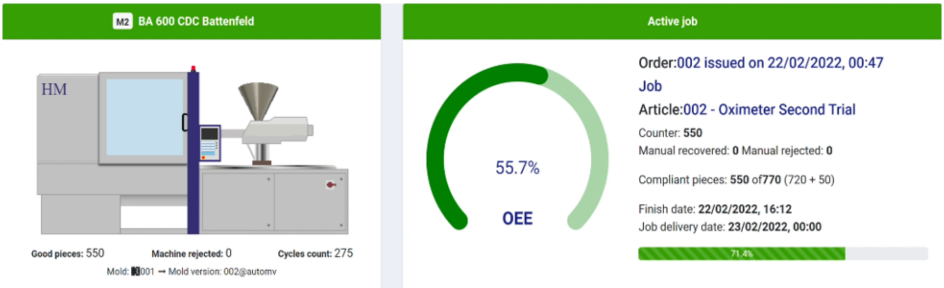

Figure 3. OEE of production process which shows the accurate values.

5. Discussion and Conclusions

The company faced many challenges due to following the traditional methods of manufacturing. Most of the obstacles fell within the scope of management. There was poor monitoring of the quality, management of production time, determination of the technical and management jobs within the enterprise, and difficulty in resolving the issue of paperwork. Even with the enterprise's own ERP system, communication between the different levels was inflexible and unable to provide management with accurate information about the production process. The trial described here indicated significant advancements in the production line as a result of integrating different systems at different levels in terms of improving productivity, reducing inspection, maintenance, and production cycle time, and increasing overall equipment effectiveness (OEE) for the entire manufacturing process. These improvements have enabled the enterprise to bridge the technological gap between its conventional production line and modern technologies which are the foundation of the manufacturing sector.

Intelligent manufacturing systems and interconnection protocols were used without the need for any modifications. This meant hardware integration, software integration and a consolidated database was achieved while maintaining flexibility and reliability. In addition, easy data transfer in real-time between the systems with zero error was obtained.

DAQ played an essential role by collecting and translating signals coming from the shop floor. This enabled full control of the process and sorted out the good parts from the defective ones. The MES enabled management to access real-time data on products and markets thus empowering the management team to comprehend market responses and trends and make necessary adjustments to the enterprise strategy. The data coming from the DAQ, such as the operation and job time and the number of good/bad moulded parts, was able to help determine much information at the management layer such as the amount of raw materials used for each batch, required time to complete each job and the time-plan for following batches.

Reducing production time and the total production cost, and increasing productivity were the main results that were achieved during the trial. This resulted from the accurate control of the process starting from the required time to start the work to the ready packaged products.

During implementation of an upgrade, there are many challenges facing the enterprise such as supporting and developing the security of the network and how to deal with cyber espionage. Moreover, each machine is unique in terms of design and structure so this factor should be considered when planning to upgrade a conventional production line regarding choosing the compatible hardware and software. Future work aims to extend this work to include all accessories of the machines and cover communication with different systems such as the supply chain management system and customer relationship management system.

This study aimed to upgrade and evaluate a conventional injection moulding production line to be compatible with Industry 4.0 and explained the type of communication protocols utilised by applying the ISA-95 Standard. This paper also explained the methodology followed to monitor the moulded part quality within the supervisory control and data acquisition layer. It also explained how the parts quality data transformed into the MES layer to be translated by the Overall Equipment Effectiveness (OEE) added as an essential value to the total process quality.

Acknowledgements

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References

[1] Chen, Y., Han, Z., Cao, K., Zheng, X. and Xu, X., 2020. Manufacturing upgrading in industry 4.0 era. Systems Research and Behavioral Science, 37(4), pp.766-771.

[2] Azadegan, A. and Wagner, S.M., 2011. Industrial upgrading, exploitative innovations and explorative innovations. International Journal of Production Economics, 130(1), pp.54-65.

[3] Salkin, C., Oner, M., Ustundag, A. and Cevikcan, E., 2018. A conceptual framework for Industry 4.0. Industry 4.0: managing the digital transformation, pp.3-23.

[4] Ageyeva, T., Horváth, S. and Kovács, J.G., 2019. In-mold sensors for injection molding: On the way to industry 4.0. Sensors, 19(16), p.3551.

[5] Zhang, Y., Mao, T., Huang, Z., Gao, H. and Li, D., 2016. A statistical quality monitoring method for plastic injection molding using machine built-in sensors. The International Journal of Advanced Manufacturing Technology, 85, pp.2483-2494.

[6] Tellaeche, A. and Arana, R., 2013. Rapid data acquisition system for complex algorithm testing in plastic molding industry. International Journal of Industrial and Manufacturing Engineering, 7(7), pp.1391-1395.

[7] Ruotsalainen, I., 2021. Specifying a Manufacturing Execution System for Finnish injection molding plants (MaOgorodnyk, O., Larsen, M., Lyngstad, O.V. and Martinsen, K., 2020. Towards a general application programming interface (API) for injection molding machines. PeerJ Computer Science, 6, p. e302.ster’s thesis)

[8] BĂLAN, E.L., IMPROVING A PLASTICS INJECTION PROCESS BY USING AN EFFICIENT PRODUCTION MANAGEMENT SYSTEM.

[9] Martins, A., Miguel Lopes e Silva, B., Costelha, H., Neves, C., Lyons, J. and Cosgrove, J., 2021, September. An approach to integrating manufacturing data from legacy Injection Moulding Machines using OPC UA. In 37th International Manufacturing Conference (IMC37).

[10] Ogorodnyk, O., Larsen, M., Lyngstad, O.V. and Martinsen, K., 2020. Towards a general application programming interface (API) for injection molding machines. PeerJ Computer Science, 6, p.e302.

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Key Factors Influence the Reconfiguration of Supply Chain Design: A Review Paper

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Abstract. With the evolution of Industry 4.0, the most advanced technologies have been invented and due to rapid globalisation, supply chains (SC) have become vulnerable to various risks and reconfiguration of supply chain design has gained a significant consideration in recent years. This paper intends to provide a critical literature review on the current research practices and identify the key factors influencing the reconfiguration of supply chain design in the digital environment and prioritise the factors considering relative importance and develop a framework to mitigate the risk level. A systematic literature review is conducted to identify and analyse the key factors that influence the reconfiguration of supply chain design, and Analytical Hierarchy Process (AHP) method used to develop a conceptual framework. The findings of this study revealed that reconfiguration of supply chain design in digital environment sheds light on future research and focuses on the potential to enhance supply networks' efficiency and responsiveness.

Keywords. Supply Chain, Industry 4.0, Reconfiguration.

1. Introduction

In the era of Industry 4.0, digitalisation has been the basis for supply chain (SC) design and the reconfiguration; SC management is a key driver in gaining a competitive advantage [1]. Supply chain involves a series of interconnected activities connecting suppliers and customers, that includes planning, managing, and controlling the products and services. Supply chain design decision involves a wide array of decision categories, including network and product design and strategies to effectively navigate uncertainties and variations, ensuring responsiveness within the supply chain [2] .With the digital revolution, opportunities are open to reconfiguring the supply chain to provide a more collaborative value network [3].

Reconfiguration of SC is required due to various external and internal reasons for the company and the related industry. Furthermore, new competitive suppliers are entering the market with new technologies, and the existing suppliers are required to modify their products or services with the latest technologies [4]. Risk management performs a key role in operating SC effectively in a variety of uncertain circumstances. Dynamic reconfiguration of the supply chain for risk management has gained the consideration of the researchers over the last two decades due to the influence of digital technology in the SCM [5]. With the evolution of Industry 4.0, the most advanced technologies are invented, and advanced software and tools are used to reconfigure the existing design and its correlated support activities [6].It is vitally important for supply chain designers to reconfigure SC using advanced technologies and Industry 4.0. SC

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designers need to have a better understanding of the key factors that influence the reconfiguring of the SC to mitigate the risk level and improve the efficiency and responsiveness of the SC.

2. Research Methodology

2.1. Systematic Literature Review

Literature review is essential for academic research, and this research work contributes to the systematic literature review (SLR) on the key factors that influence the reconfiguration of supply chain design. According to [7] , SLR is a methodology that effectively evaluates and consolidates the existing knowledge, selects and assesses the contribution from several researchers, conducts data analysis and synthesis, and presents a comprehensive summary of the existing knowledge for further studies to identify future research problems. The SLR approach is selected for finding the key factors that influence the reconfiguration of supply chain design as its capacity to provide a clear judgment and sequence that can be traced.

2.2. AHP Software

The analytic hierarchy process (AHP) is one of the most widely used methods in the Multiple Attribute Decision-Making (MADM) problems, which was proposed in 1980 by Thomas L. Saaty [8]. By using AHP software for multi-criteria decision-making, supply chain managers can effectively evaluate and prioritise the criteria to identify the key factors that influence the reconfiguration of supply chain design.

3. Findings and Discussions

As per the systematic literature review, Figure 1 displays the developed framework to indicate the correlation between variables to understand the key factors that influence the reconfiguration of supply chain design.

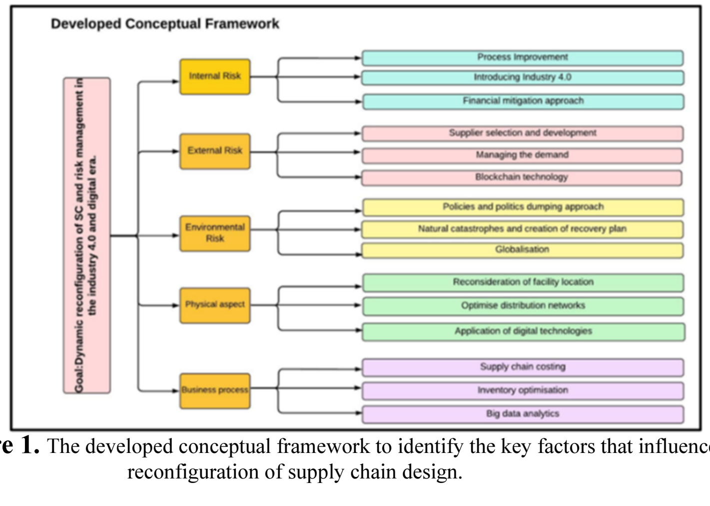

Figure 1. The developed conceptual framework to identify the key factors that influence the reconfiguration of supply chain design.

3.1. Key factors influence the reconfiguration of supply chain design.

- Internal risk

Internal risk can be defined in the literature as organisational risk as process and control risks [5]. One of the other classifications as internal risks are caused due to inefficient and unreasonable resource allocation.

Three approaches were recognised as process improvement, introducing Industry 4.0, and financial mitigation to mitigate the internal risk factors in supply chain management. Process improvement enhances operational efficiency by analysing existing processes, eliminating unnecessary costs associated with the supply chain, and improving overall performance. This leads to improved customer satisfaction, reduced response time and enhanced agility [9]. Introducing Industry 4.0 in the digital era, integrated the SC with advanced technologies such as Internet of Things (IoT), big data analytics, artificial intelligence, and cloud computing. Adaptation of digital technologies increase visibility, gives access to real-time data, and optimise the decision making. Industry 4.0 enhances supply chain transparency, operational efficiency, and enables innovative business models [10]. Financial mitigation approach involves applying strategies to mitigate the financial risks associated with the supply chain. This approach mitigates the potential disruptions by effectively managing financial aspects such as cash flow, payment terms, and financial stability. This leads to defending the financial uncertainties while increasing the profitability of the company [11].

- External risk

External risks are the risk that is outside of the focal company's control, but it is within the supply chain network. External risks are caused due to the failure to accept and respond to the sudden changes in market demand [12].

Supplier selection and development, managing the demand, and blockchain technology contribute to mitigating the external risks in the supply chain. Supplier selection and development can reduce the supplier-related issues by wisely assessing and selecting the suppliers based on criteria such as reliability, quality standards and responsiveness. Developing strong mutual relationships with suppliers leads to mitigate the risks related to quality issues, lead time and supplier failures [11]. Managing the demand and accurate forecasting of the demand ensures sufficient inventory levels are maintained to fulfil the customer's requirements. Managing the demand is essential for mitigating the external risks in the supply chain and that enables to response to the customer demand fluctuations [9]. Identification of demand patterns leads to managing the risks associated with changing market conditions, demand variability and changing customer buying behaviour [13]. Blockchain technology improved the supply chain transparency, traceability, and security and helps in mitigating the external risks [14]. Furthermore, Blockchain technology allows to create decentralised applications which enable to track, and store transactions functioned by many users and devices [15]. This enables end-to-end visibility of products, verifying authenticity and ensuring accordance with regulations [16].

- Environmental risk

Environmental risks can be defined as all the risks that happen outside of the supply chain network. For instance, governmental interventions like tariffs, tsunamis, hurricanes are considered.

Three sub-criteria were identified as policies and politics dumping approach, natural catastrophes and creation of recovery plan, and globalisation. When considering the politics and policies, government interference greatly impacts the supply chain network and any business. Policies and politics dumping approach involves executing regulations to the trade practices of dumping. The government can impose anti-dumping duties on imported goods to ensure fair competition and safeguard local businesses from harm [17]. Natural catastrophes and creation of recovery plan: Natural disasters do not happen frequently, but natural disasters like hurricanes, floods, storms, and earthquakes cause severe disruptions. In 2011 Tohoku earthquake and tsunami resulted in nearly 210 billion USD costs. Identifying natural disasters is important to manipulate the risk by creating a disaster response and recovery plan. These plans should include the diversifying sourcing locations and implementing disaster response and recovery strategies [18]. With the globalisation, new SC related concepts are used as outsourcing and offshoring, and it leads to entering the global supply chain network. Even though globalisation offers more improvements and benefits as global sourcing, it incurred a considerable level of risks. Organisations can adopt the best practices, share knowledge, and implement environment friendly technologies that can contribute to mitigating the environmental risk through the global supply chain [9].

- Physical aspect

The physical aspect is more critical as it needs the investment to construct the physical structure by considering the capacity utilisation, storage facilities and the manufacturing capacities.

Three sub-criteria were identified as reconsidering facility location, optimising distribution networks, and applying digital technologies. When reconfiguring the SC design, facility location is relocating the facilities to reduce the expenditure. Cost-effective facility locating is reduced the outbound transportation costs while decreasing the lead time, and it improves the quality of service to the customer [19]. Companies may have more alternatives when designing the distribution network and inappropriate networks can have a major negative impact on SC. Optimising distribution networks can have a great impact on the supply chain and strategical reconfiguration of network can reduce the lead time, transportation cost and improve the overall efficiency [20]. Application of digital technologies can greatly impact the supply chain and Industry 4.0 technologies such as cloud computing, blockchain, and Internet of Things (IoT) can increase the real-time visibility of inventory, transportation status and enhance the proactive decision-making and optimise the operational efficiency [21].

- Business process

In a SC, the core function is the business process, and it directly affects the performance and the profit of the focal firm. Three sub-criteria were identified as supply chain costing, inventory optimisation, and big data analytics.

Supply chain costing involves evaluating and managing all the costs related to supply chain activities. The analysis helps to identify the cost drivers and opportunities for cost reductions. Optimisation of supply chain cost, improve the profitability and enhance cost competitiveness [22]. Inventory has a major impact on a business process, and maintaining safety stocks creates a cost to the business. It is critical to keep a minimum stock in the inventory and find the right balance between inventory levels and customer demand. Organisations can reduce inventory while maintaining sufficient inventory by using techniques such as safety stock analysis, just-in-time, and demand forecasting. This helps to reduce the carrying cost and risk of stockout while enhancing the cash flow [20]. Big data analysis facilitates the real-time data, and it provides a real-time view of SC for risk monitoring. This expedites the decision-making process by reducing the data complexity, and it leads to reducing the SC risk. Big data analytics facilitates better demand forecasting accuracy, improved inventory management, enhanced risk assessment, and more efficient supply chain planning [2].

3.2. The relative importance of the criteria and sub-criteria of the proposed framework

According to the results presented in Figure 2, it is evident that the physical aspect holds a relative importance of 27.25% compared to other criteria in the proposed framework. Additionally, the sub-criteria with the highest significance is the application of digital technologies, accounting for 9.07%. More results will be presented at the conference.

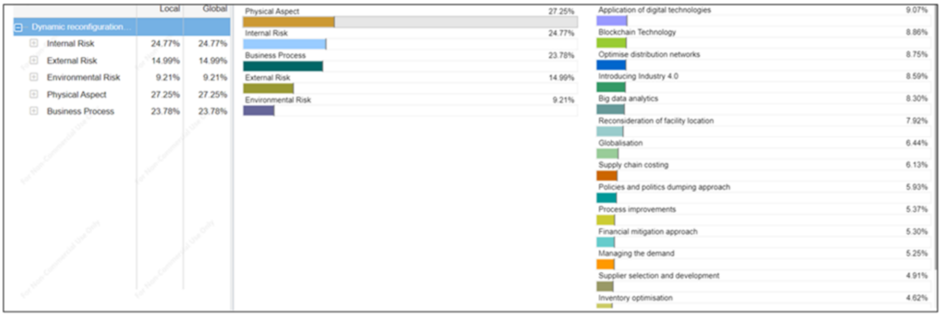

Figure 2. The relative importance of the criteria and sub-criteria of the proposed framework.

4. Conclusions and Future Research Directions

In summary, this paper has discussed the systematic literature review on the key factors that influence the reconfiguration of supply chain design and prioritise the relative importance of the factors using Analytic Hierarchy Process (AHP) software. Furthermore, this paper points out the opportunities for supply chain designers to enhance the supply chain design by identifying the key factors influencing the reconfiguration of supply chain design. Moreover, identifying the key factors for reconfiguration of supply chain design is vital for maintaining an effective supply chain and providing outstanding customer service. Future researchers can further consider the dynamic nature of these key factors and their interactions with Industry 4.0 and technological advancements. Even though, many articles identified the key factor, there has been limited focus on quantitative analysis. This gap presents an opportunity for future research, which can provide a deeper understanding of the relationships and impacts of these factors on supply chain performance.

Overall, this study highlights the potential of Industry 4.0 technologies and how key factors influence the reconfiguration of supply chain design, while also suggesting areas for future research.

References

[1] Garcia, D. J., & You, F. (2015). Supply chain design and optimization: Challenges and opportunities. Computers & Chemical Engineering, 81, 153-170. doi:10.1016/j.compchemeng.2015.03.015

[2] Büyüközkan, G., & Göçer, F. (2018). Digital supply chain: Literature review and a proposed framework for future research. Computers in Industry, 97, 157-177. doi:10.1016/j.compind.2018.02.010

[3] Wilhelm, W., Han, X., & Lee, C. (2013). Computational comparison of two formulations for dynamic supply chain reconfiguration with capacity expansion and contraction. Computers & Operations Research, 40(10), 2340-2356. doi:10.1016/j.cor.2013.04.011

[4] Bressanelli, G., Perona, M., & Saccani, N. (2019). Challenges in supply chain redesign for the circular economy: A literature review and a multiple case study. International Journal of Production Research, 57(23), 7395-7422.

[5] Ho, W., Zheng, T., Yildiz, H., & Talluri, S. (2015). Supply chain risk management: A literature review. International Journal of Production Research, 53(16), 5031-5069. doi:10.1080/00207543.2015.1030467

[6] Ivanov, D., Dolgui, A., & Sokolov, B. (2019). The impact of digital technology and industry 4.0 on the ripple effect and supply chain risk analytics. International Journal of Production Research, 57(3), 829-846.

[7] Xiao, Y., & Watson, M. (2019). Guidance on conducting a systematic literature review. Journal of Planning Education and Research, 39(1), 93-112. doi:10.1177/0739456X17723971

[8] Saaty, T. L., & Sodenkamp, M. (2008). Making decisions in hierarchic and network systems. International Journal of Applied Decision Sciences, 1(1), 24-79.

[9] Samvedi, A., Jain, V., & Chan, F. T. S. (2013). Quantifying risks in a supply chain through integration of fuzzy AHP and fuzzy TOPSIS. International Journal of Production Research, 51(8), 2433-2442. doi:10.1080/00207543.2012.741330

[10] Ustundag, A., & Cevikcan, E. (2018). Industry 4.0: Managing the digital transformation (1st ed.). Cham: Springer International Publishing. doi:10.1007/978-3-319-57870-5

[11] Schoenherr, T., Rao Tummala, V. M., & Harrison, T. P. (2008). Assessing supply chain risks with the analytic hierarchy process: Providing decision support for the offshoring decision by a US manufacturing company. Journal of Purchasing and Supply Management, 14(2), 100-111. doi:10.1016/j.pursup.2008.01.008

[12] Chukwuka, O. J., Ren, J., Wang, J., & Paraskevadakis, D. (2023). A comprehensive research on analyzing risk factors in emergency supply chains. Journal of Humanitarian Logistics and Supply Chain Management, doi:10.1108/JHLSCM-10-2022-0108

[13] Manuj, I., & Mentzer, J. T. (2008). Global supply chain risk management strategies. International Journal of Physical Distribution & Logistics Management, 38(3), 192-223. doi:10.1108/09600030810866986

[14] Wang, Y., Han, J. H., & Beynon-Davies, P. (2019). Understanding blockchain technology for future supply chains: A systematic literature review and research agenda. Supply Chain Management, 24(1), 62-84. doi:10.1108/scm-03-2018-0148

[15] Fernandez-Carames, T., & Fraga-Lamas, P. (2019). A review on the application of blockchain to the next generation of cybersecure industry 4.0 smart factories. IEEE Access, 7, 45201-45218. doi:10.1109/access.2019.2908780

[16] Ghode, D., Yadav, V., Jain, R., & Soni, G. (2020). Adoption of blockchain in supply chain: An analysis of influencing factors. Journal of Enterprise Information Management, 33(3), 437-456. doi:10.1108/JEIM-07-2019-0186

[17] De Bièvre, D., & Eckhardt, J. (2011). Interest groups and EU anti-dumping policy. Journal of European Public Policy, 18(3), 339-360. doi:10.1080/13501763.2011.551068

[18] Tummala, R., & Schoenherr, T. (2011). Assessing and managing risks using the supply chain risk management process (SCRMP). Supply Chain Management, 16(6), 474-483. doi:10.1108/13598541111171165

[19] Shen, Z. (2007). Integrated stochastic supply-chain design models. Computing in Science & Engineering, 9(2), 50-59. doi:10.1109/MCSE.2007.34

[20] Melnyk, S. A., Narasimhan, R., & DeCampos, H. A. (2014). Supply chain design: Issues, challenges, frameworks and solutions. International Journal of Production Research, 52(7), 1887-1896. doi:10.1080/00207543.2013.787175

[21] Bhandal, R., Meriton, R., Kavanagh, R. E., & Brown, A. (2022). The application of digital twin technology in operations and supply chain management: A bibliometric review. Supply Chain Management, 27(2), 182-206. doi:10.1108/SCM-01-2021-0053

[22] Askarany, D., Yazdifar, H., & Askary, S. (2010). Supply chain management, activity-based costing and organisational factors. International Journal of Production Economics, 127(2), 238-248. doi:10.1016/j.ijpe.2009.08.004

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Part 6

Advances in Process Characterisation and Simulation

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Experimental Investigations into Nanofinishing of Aluminium Using Ball End Magnetorheological Finishing Process

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Abstract. Surface finishing of aluminium is a challenging task due to its soft nature and achieving nano level surface finish on aluminium surface is a daunting task even for the most advanced of the finishing processes. The material removal demands precise control of forces from these processes. Ball end magnetorheological finishing (BEMRF) process is one such process that can deliver precisely controlled forces and that too at confined and localized spaces. However, as aluminium is non-magnetic in nature it does not allow formation of an opposite magnetic pole for the process and hence the applied forces are low. To overcome this, a permanent magnet opposite pole is introduced beneath the sample surface which facilitates better forces and magnetic flux between the work surface and the tool tip. This research study is on the optimization of polishing fluid composition for the finishing of aluminium using BEMRF process. With the optimum fluid composition, the surface roughness of the aluminium sample is brought from 95.7 nm down to 53.6 nm in 32 minutes of finishing. The topographical analysis shows that the light scratches are completely removed from the surface and the deep scratches have turned into light discontinuous scratches after finishing. The finished surface is also free from the embedment of abrasive particles.

Keywords. Magnetorheological, Nanofinishing, Polishing, Aluminium, Surface roughness.

1. Introduction

Finishing of soft and ductile materials is a challenging task in terms of accuracy, complete scratch removal, damage-free surface, and sub-micron level of surface finishing [1]. Due to the softness, these materials are very prone to scratches even when finishing is carried out. Hard abrasive particles leave their own scratch marks while finishing under uncontrolled finishing forces [2]. It is also reported by researchers that during loose abrasive finishing, a common problem of abrasive getting embedded in the workpiece surface is often observed. Hence, it is difficult to get a flawless surface finish on soft materials by a majority of the finishing processes [3-5]. In this work, aluminium is taken as the soft and ductile material for the study purpose.

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Ball end magnetorheological finishing (BEMRF), a variant of magnetorheological finishing, is a recently developed nanofinishing process and incorporates all the features of magnetorheological finishing process [6]. In its working, it resembles the vertical ball-end milling cutter. However, in place of multiple cutting edges, it has abrasive laden ball-shaped MR fluid whose stiffness is controlled magnetically. This abrasive laden ball-shaped MR fluid changes its compliance according to the surface to be polished and the gentle finishing can be achieved by changing the stiffness of the ball. This process has shown its capability to polish a wide range of materials like metallic, non-metallic, magnetic, and non-magnetic materials and all types of surfaces (2D and 3D) [7-11]. BEMRF produces scratch-free surfaces of nanometer-order surface roughness by controlling the finishing forces [12]. Due to marginal finishing forces applied while finishing, no surface or subsurface damage occurs in this process. Despite its application on different materials, there is hardly any literature available on the finishing of aluminium using BEMRF process and hence the present work relates to finishing of aluminium using the same.

2. Experimentation

Commercially available aluminium 6063 is used as the workpiece material for its good yield and ultimate tensile strength. The samples were prepared by lathe operations in the form of discs (35 mm diameter x 6 mm thickness). The experiments are performed on a 3-axis CNC BEMRF setup. As aluminium is a paramagnetic material, the magnetic flux density in the working gap between tool tip and the workpiece is not sufficient for effective finishing. To increase the magnetic flux density, a permanent magnet of 0.3 Tesla has been used beneath the workpiece using a fixture made of aluminum. The experiments are performed using magnetorheological (MR) polishing fluid composed of electrolytic iron particles (EIPs) of 300 mesh size and alumina abrasive of 1000 mesh size. The experiments have been conducted to analyze the effects of abrasive and EIPs concentrations on process performance in terms of reduction in surface roughness (% ΔRa) in a predefined finishing time and the optimum MR polishing fluid composition has been searched out.

2.1. Parametric analysis of MR polishing fluid composition

In this study, the effects of abrasive and EIPs concentrations have been analyzed on process output in the form of reduction in surface roughness (% ΔRa) in a predetermined finishing time. Other fixed parameters and corresponding conditions/values are summarized in table 1.

Table 1. Fixed process parameters and conditions for aluminum finishing

Parameters	Conditions
Abrasive	Alumina (Al_2O_3), mesh size 1000
EIPs	300 mesh size
Base medium	wt. 80% heavy paraffin + wt. 20% grease
Energizing current	6 A
Working gap	1.2 mm
Rotational speed	300 rpm
Feed rate of workpiece table	10 mm/ min
Finishing time	32 min (8 cycles)
Finishing length	20 mm along the diameter

The viscosity of MR polishing fluid is affected by the overall concentration of solid phase (abrasives and EIPs) in the fluid. Beyond vol. 45 % of solid-phase concentration, the fluid loses its fluidity and acts like a rigid body when it interacts with the magnetic field. Hence, in the experimentations, the abrasive and EIPs concentrations are varied from vol. 10 to 20 % and vol. 15 to 25 % respectively keeping in mind that total solid-phase concentration should not go beyond the upper limit of solid-phase concentration i.e. vol. 45 %. For the experiments, a two-factor central composite design (CCD) has been implemented to create a statistical model of the process and analyze the individual effects of abrasive and EIP concentrations. The levels of the fluid composition parameters (abrasive and EIPs concentrations, denoted by "A" and "B" respectively) in coded and actual forms have been summarized in table 2.

Table 2. The specified fluid composition parameters' coded levels and real values

Parameters	Levels				
	-1.414	**-1**	**0**	**+1**	**+1.414**
Abrasive concentration (vol.%) - A	10	11.50	15	18.50	20
EIPs Concentration (vol.%) - B	15	16.50	20	23.50	25

Experiments have been conducted as per the plan of experiments but in random order. The responses (%ΔRa) are calculated on the basis of initial and final surface roughness values. To determine the true value of the reduction in surface roughness, surface roughness values are measured at the same location on the workpiece surface before and after the finishing. After removing insignificant model terms and including the nonlinear terms of the input parameters, the quadratic equations that best suit the experimental results has been derived as follows:

In terms of coded factors:

$$\%\Delta Ra = 26.37 - 4.86A + 6.49B + 1.35A^2 + 1.31B^2 \quad (1)$$

In terms of true factors:

$$\%\Delta Ra = 76.58 - 4.61A - 2.36B + 0.11A^2 + 0.11B^2 \quad (2)$$

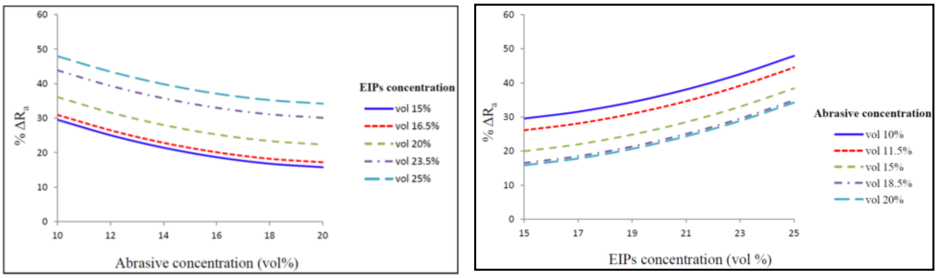
The experimental results have a significant positive correlation ($R^2 = 98\%$) with the developed quadratic equations of percentage change in surface roughness.

3. Results and discussion

The effects of volumetric concentration of abrasive and EIPs in MR polishing fluid on process performance (%ΔRa) have been plotted and discussed in the following subsections using the derived quadratic model (equation 1 or 2).

3.1. Effect of abrasive (Al_2O_3) concentration and EIPs concentration

At varying concentrations of EIPs, the effect of abrasive particle concentration in MR polishing fluid on the process response (%ΔRa) has been investigated, as shown in figure 1(a). Some abrasive particles gripped amid the EIPs chains as the abrasive level in the MRP fluid grew, and some abrasive particles broke the EIPs chain during the chain formation process. Due to these abrasive particles which broke the EIPs chain, the EIPs chain becomes weaker in strength and deflects from their position when the load is applied on them. As a result, increasing the volumetric concentration of abrasive in MR polishing fluid caused a decline in %ΔRa. Figure 1(b) shows the change in %ΔRa against the variation in concentration of electrolytic iron particles (EIPs) at different abrasive concentrations. The stiffness of the MRP fluid depends on its magnetic permeability. When MR polishing fluid with higher magnetic permeability is exposed to a magnetic field, it exhibits higher fluid stiffness as compared to MR polishing fluid with lower magnetic permeability. The amount of magnetizable content in the MR polishing fluid, i.e. the volumetric concentration of EIPs, determines its magnetic permeability. Adding more amount of EIPs content in MR polishing fluid performs two major functions, one of them is that it increases the magnetic permeability of the MR polishing, hence, the EIPs chains grow in length and width which eventually results in an increase in stiffness of MR polishing fluid. In more stiff MR polishing fluid, the abrasives are gripped more firmly and perform more cutting while finishing due to which %ΔRa increases. The second function is that adding more amounts of EIPs in MR polishing fluid grip more abrasive particles which could not be gripped previously. These more number of gripped abrasive particles perform more cutting during ball end MR finishing. Due to these two facts, the %ΔRa increases on increasing the concentration of EIPs in MR polishing fluid as also shown in figure 1(b).



(a) (b)

Figure 1. (a) Effect of abrasive concentration on %ΔRa and (b) Effect EIPs concentration on percentage reduction in surface roughness (%ΔRa)

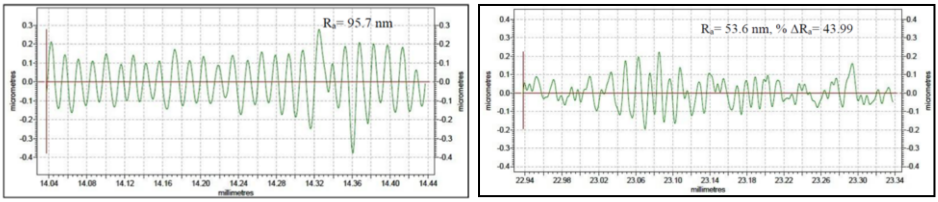
3.2. Optimum polishing fluid composition

The MR polishing fluid composition was optimized to maximize the output of the process i.e. the percentage reduction observed in surface roughness (%ΔRa). For this purpose the quadratic model developed from response surface regression analysis has been optimized subjected to a minimum and a maximum limit of concentrations of abrasive and EIPs in the design space. The optimum values of concentrations of abrasive and EIPs are found as 10% and 25% by volume respectively. Table 3 shows the experimental and predicted response (%ΔRa) values computed from the quadratic model at optimal MR polishing fluid composition parameters.

Table 3. Validation of optimized results

Parameters		**Experimental %ΔRa**	**Predicted %ΔRa by quadratic model**	**% Error in predicted value**
A	**B**			
10 vol%	25 vol%	43.99	47.91	-8.92

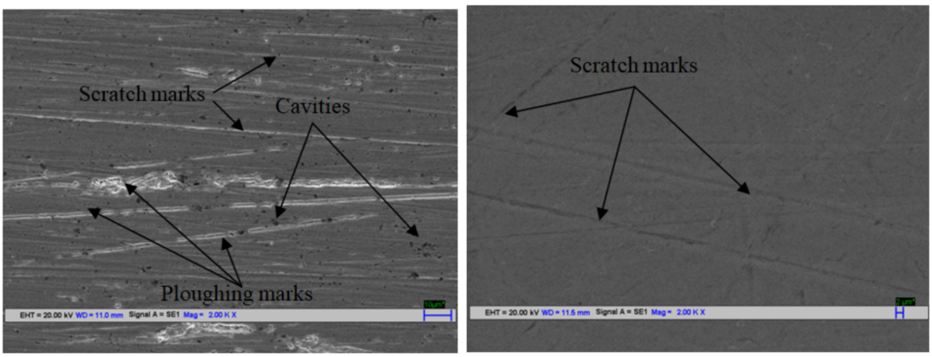
The error in predicting the response by the quadratic model at the optimum MR polishing fluid parameters is found as -8.92, which shows the good repeatability of the experimental result. In 32 min of finishing (8 cycles), the surface roughness (Ra) of the aluminum sample at optimum MR polishing fluid composition reduces from 95.7 nm to 53.6 nm with an improvement of 43.99%. Figure 2 (a) and (b) illustrate the aluminium sample's surface roughness profiles before and after the finishing respectively. The other surface roughness parameter such as Rz reduce from 427.60 nm to 265.50 nm and Rt reduces from 656.70 nm to 418.80 nm. From roughness profiles, it is clearly shown that after finishing the larger-sized roughness peaks transformed into smaller sized peaks.



(a) (b)

Figure 2. Surface roughness profile (a) before finishing (b) after finishing with optimal fluid composition

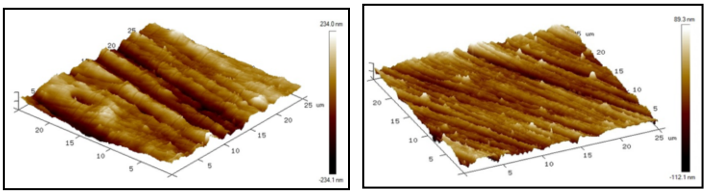
Surface morphologies of the initial and final aluminium workpieces with the optimal polishing fluid composition are examined by SEM (Figure 3) and AFM (Figure 4) images. The SEM image of the initial surface (fig 3a) shows that the initial surface had scratch and ploughing marks. Lots of cavities were also observed on the initially prepared workpiece. These surface defects were due to rigorous abrasive action under uncontrolled normal finishing force in the manual lapping process. After 32 min (8 cycles) of finishing, the SEM image of aluminum finished sample (fig 3b) shows that the ploughing marks and cavities are completely removed from the surface but the scratch marks have been removed partially. Still, some scratch marks are observed on the finished surface which can be reduced by optimizing the machining parameters.



(a) (b)

Figure 3. Scanning electron micrograph (a) before finishing (b) after finishing

The AFM images in figure 4 show the rectification of the initial profile's unevenness, resulting in a superior surface profile after finishing. Higher degree unevenness of surface profile transformed in a lesser degree of unevenness after finishing and resulted in a true and precise surface.



(a) (b)

Figure 4. Atomic force microscopy image (a) before finishing (b) after finishing

Conclusion

The following conclusions are drawn from this study on nanofinishing of aluminum using BEMRF process:

- The volumetric concentration of abrasive and EIPs in MR polishing fluid play important role in finishing of aluminium using BEMRF process.
- Increasing the volumetric concentration of abrasive in MR polishing fluid caused a decline in %ΔRa. Also, the %ΔRa increases on increasing the concentration of EIPs in MR polishing fluid.
- The concentration of EIPs is the most important parameter, contributing the most to the response. The optimal EIP and abrasive concentrations are found to be vol. 10% and vol. 25%, respectively, with the maximum percentage reduction in surface roughness reported at 43.99 %.

References

[1] Zhong ZW (2008) Recent advances in polishing of advanced materials. *Materials and Manufacturing Process* 23(5): 449-456.

[2] Xie Y, Bhushan B, (1996) Effects of particle size, polishing pad and contact pressure in free abrasive polishing. *Wear* 200(1-2): 281-295.

[3] Barletta M, Guarino S, Rubino G, Tagliaferri V, (2007) Progress in fluidized bed assisted abrasive jet machining (FB-AJM): Internal polishing of aluminium tubes. *International Journal of Machine Tools and Manufacture* 47(3): 483-495.

[4] Saha PK, (2005) A case study on the abrasive surface finishing of aluminum flat sheet. *Wear* 258(1-4): 13-17.

[5] Agbaraji C, Raman S, (2009) Basic observations in the flat lapping of aluminum and steels using standard abrasives. *International Journal of Advanced Manufacturing Technology* 44(3-4): 293-305.

[6] Alam Z, Jha S (2017) Modeling of surface roughness in ball end magnetorheological finishing (BEMRF) process. *Wear* 374-375C: 54-62.

[7] Saraswathamma K, Jha S, Rao PV (2015) Experimental investigation into ball end magnetorheological finishing of silicon. *Precision Engineering* 42:218-223.

[8] Khan DA, Kumar J, Jha S (2016) Magneto-rheological nano-finishing of polycarbonate. *International Journal of Precision Technology* 6(2): 89-100.

[9] Alam Z, Khan DA, Jha S (2019) MR fluid-based novel finishing process for nonplanar copper mirrors. *International Journal of Advanced Manufacturing Technology* 101(1-4): 995-1006.

[10] Alam Z, Iqbal F, Ganesan S, Jha S (2019) Nanofinishing of 3D surfaces by automated five axis CNC ball end magnetorheological finishing machine using customized controller. *International Journal of Advanced Manufacturing Technology* 100(5-8): 1031-1042.

[11] Kumar A, Alam Z, Khan DA, Jha S (2019) Nanofinishing of FDM-fabricated components using ball end magnetorheological finishing process. *Materials and Manufacturing Processes* 34(2): 232-242.

[12] Alam Z, Khan DA, Jha S (2017) A study on the effect of polishing fluid volume in ball end magnetorheological finishing process. *Materials and Manufacturing Processes* 33(11): 1197-1204.

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Ball Burnishing of Copper- A preliminary Experimental Study on Finishing

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Abstract. Ball burnishing is a finishing process, in which a ball burnishing tool is used to remove the surface flaws such as scratches, ploughing marks due to previous manufacturing/machining process, indentation, etc. The burnishing operation generates a reflective surface by plastically deforming the roughness peaks and filling the scratches. In the present research, the ball burnishing tool having a hard ball made of carbide has been used to finish the copper samples. Since copper is a soft material, it is very prone to scratch while finishing by most of the finishing processes employing bonded or loose abrasives. In the present study, the effect of different process parameters has been explored on the output performance i.e. Percentage change in surface roughness. From the experimental results it has been observed that in ball burnishing of copper, the maximum improvement in surface finish was about 94% when kerosene is used as a coolant.

Keywords. Ball burnishing, copper, finishing.

1. Introduction

Surface quality is crucial for the technological excellence of machined components. Material characteristics, form, and dimensional correctness are also significant considerations. Engineering components endure extreme strains, temperatures, and speeds. More investigation is required to comprehend and enhance the connection between the form and functionality of surfaces. The ideal surface specification depends on its intended application, necessitating the separation of surface geometry and function, particularly in tribological research. Surface roughness greatly influences qualities like wear resistance and fatigue strength in engineering parts [1]. It is impossible to achieve perfectly flat surfaces because they inherently contain imperfections in the form of peaks and valleys. Surface finishing processes vary in terms of their actions, thermal aand mechanical damage, residual tensions, and materials used. There are two categories into which these techniques can be classified based on their mechanisms: material loss methods like grinding, and plastic squeezing methods that redistribute material without loss, seen in processes like burnishing [2]. Ball burnishing, a chipless machining method involving superficial plastic deformation, focuses on surface polish and the creation of compressive residual stresses. When the burnishing is used as a final step after turning or grinding a workpiece, it can improve its ability to withstand wear, last longer under repeated stress, become stronger when pulled, and be more resistant to damage caused by corrosion [3]. It can serve as a viable alternative to grinding for achieving desired

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surface smoothness on hydraulic machine components such as piston rods. In this study, the burnishing operation was conducted on a lathe machine [4]. Ball burnishing is a mechanical finishing process that utilizes small, spherical balls to polish and enhance the surface quality of metal components. It improves appearance, texture, and functionality in various materials, including metals. The process, also known as ballizing, ball rolling, and ball polishing, excels at enhancing surface smoothness and texture. The rolling movement of balls on the workpiece surface removes flaws like burrs, roughness, and machining marks, resulting in a smoother and refined surface [5]. This is particularly advantageous for high-quality surface finishes in automotive parts, aircraft components, and medical equipment. Besides enhancing surface finish, ball burnishing induces compressive pressures that produce beneficial residual stresses, elevating the fatigue life, strength, and resistance to cracking and failure of the component. Thus, ball burnishing is an attractive solution for improving the mechanical performance and lifespan of metal products. It can be used on many different types of materials, including steel, aluminum, brass, copper, and various types of alloys [6]. It is a flexible and adaptable technique that can be applied to a wide range of substances. It can be employed on flat and curved surfaces, with the choice of ball size and type tailored to meet specific requirements for surface polish [7].

2. Experimentation

Copper was chosen as the experimental material due to its industry significance. It holds relevance for the study. A total of 60 Copper workpieces in a disc form with dimensions of [diameter = 25.4 mm] x [height = 12 mm] were prepared for the trials. Turning, Parting and Facing operations were performed on lathe machine to make the samples ready before doing the final operation i.e., Ball Burnishing. In surface finishing procedures, a ball burnishing tool is employed to enhance the workpiece's quality and appearance. It is formed of a spherical ball of carbide, which is noted for its hardness and durability. The ball burnishing tool is intended to be used in conjunction with a lathe machine. Its function is to apply pressure and roll over the workpiece's surface, causing plastic deformation and surface refinement. The burnishing tool's shank is designed such that mounting it to the tool holder of the lathe machine is simple. The lathe machine's three-jaw chuck holds the workpiece. During operation, the carbide ball comes into liaison with the workpiece surface. The applied pressure and rolling action of the ball create plastic deformation of the material. The roughness of the surface (Ra) is examined using a surface roughness profilometer both before and after the burnishing procedure. The bulk of the samples in this investigation has an initial surface roughness (Ra) that ranged from 2.18 to 3.13 μm. Before performing the ball burnishing procedure, the workpieces are cleaned with acetone. To stop hard particles from getting onto the contact surface between the tool and the workpiece, continuous ball cleaning is done. On the polished surface of the workpiece, such hard particles frequently cause significant scratches. This technique smoothes out any surface abnormalities like as roughness or tool marks, resulting in a more consistent and polished surface finish.

Experimental Design and Analysis: Examining how the parameters of the ball burnishing process affect the characteristics of the work material is the main objective of this work. Response surface methodology (RSM), a simple and acceptable experimental design, ended up being suitable for our study. A total of 60 experiments were performed. The ball burnishing parameters for the finishing action are shown in Table 1.

Table 1: Selected parameters and their values

Factor	Name of parameters	Units	Type	Sub Type	Minimum level	Maximum level
A	Speed	rpm	Numeric	Continuous	150	400
B	Feed	mm/min	Numeric	Continuous	0.100	0.50
C	Infeed	mm	Numeric	Continuous	0.15	0.45
D	Lubricant	–	Categoric	Without Lubricant	Paraffin	Kerosene

Table 2: Fit Summary

Source	Model p-value	Lack of Fit p-value	Adjusted R^2	Predicted R^2	
Design Model	<0.0001	0.3933	0.8986	0.7396	Recommended
Linear	<0.0001	0.0007	0.6260	0.5666	
2FI	0.0038	0.0042	0.7289	0.6409	
Quadratic	<0.0001	0.0483	0.8280	0.7319	Suggested
Cubic	0.0009	0.7602	0.9197	0.7710	Aliased

In our experimental analysis, we have utilized the Quadratic Source of the model to formulate our linear regression equation, as per table 2. The adjusted and predicted R^2 values of the model are in good agreement, indicating a reasonable fit. Additionally, the p-value for lack of fit is considerably larger than the threshold, indicating that the model is not overfitting and has adequate generalization capability.

Table 3: Fit Statistics

Std. Dev.	0.0381	R^2	0.9028
Mean	0.7464	Adjusted R^2	0.8634
C.V. %	5.11	Predicted R^2	0.7905
		Adeq Precision	20.3123

- The predicted R^2 value of 0.7905 and the adjusted R^2 value of 0.8634 are quite close to each other, with a difference of less than 0.2, table 3. This means that they are in reasonable agreement, indicating that the prediction made by the model is fairly accurate and reliable.
- Adeq Precision is a measure that tells us how clear the important information (signal) is compared to the unwanted noise. It is desirable to have a ratio greater than 4, as it indicates a strong and clear signal. In your case, with a ratio of 20.312, the signal is more than adequate, table 3. This means that the model provides a clear and reliable understanding of the data, and it can be confidently used to explore and make decisions within the design space.

Final equation in terms of coded factors:

$$Ra = 0.7617 - 0.0710\times A + 0.0329\times B + 0.01543\times C + 0.0043375\times D[1] - 0.0748\times D[2] - 0.0239\times AB + 0.0212\times AD[1] - 0.0323\times AD[2] + 0.0496\times CD[1] - 0.0033\times CD[2] + 0.0275\times A^2 - 0.0790\times B^2 + 0.0209\times C^2 - 0.0504\times A^2D[1] + 0.0566\times A^2D[2] + 0.0533\times C^2D[1] - 0.0617\times C^2D[2] \quad (1)$$

The equation 1, which employs coded factors, allows predictions about the response variable to be produced based on precise levels of each factor. In this context, the high levels of the components are frequently labeled as +1 and the low levels as -1. By comparing the coefficients of the elements, the coded equation can be used to determine the respective importance of the components.

3. Results and Discussions

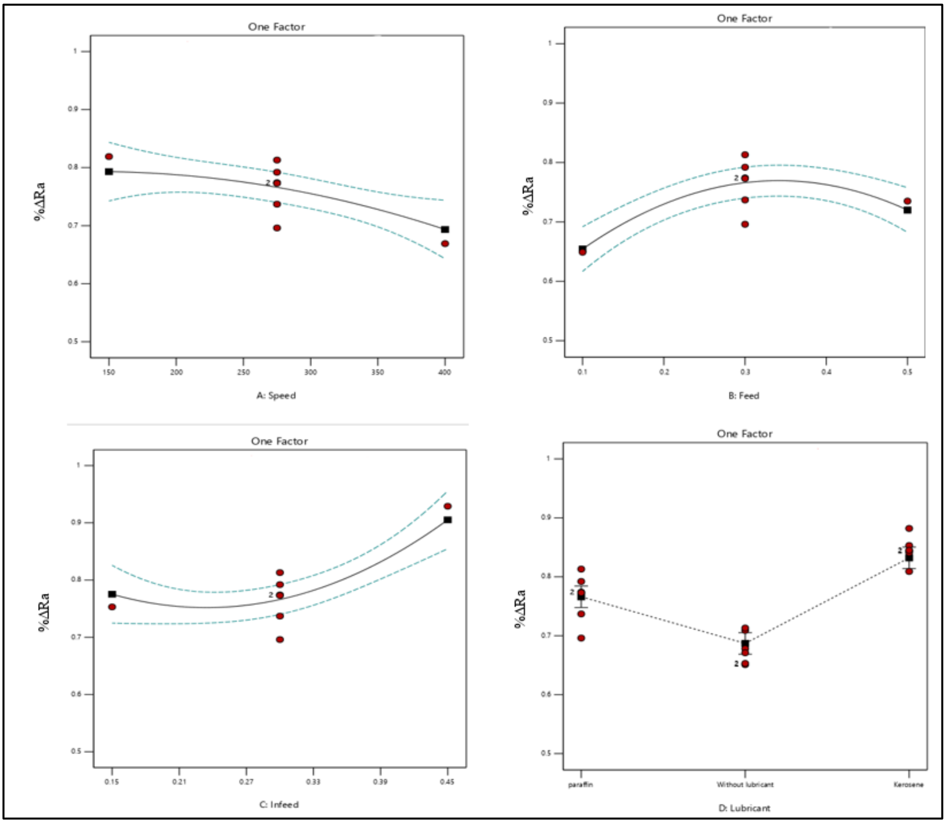

Figure 1. Effects of speed , feed, infeed and lubrication on % ΔRa.

Effect of speed on the % change in surface roughness (%ΔRa): According to the final model analyzing the link between the input ball burnishing parameters and change in surface roughness, lower speeds result in higher reduction in surface roughness. In contrast, as speed increases, the change in surface roughness steadily decreases, figure 1. This is because, slower ball movement allows for more time per unit area of the surface, improving its smoothness by continuous plastic deformation.

Effect of feed on the % change in Surface Roughness ($\%\Delta Ra$): The reduction in surface roughness is clearly affected at the lowest feed rate, according to the final model that links the input ball burnishing parameters with the change in surface roughness. However, as the feed rate rises from 0.1mm to 0.3mm, the reduction in surface roughness increases, peaking at 0.3mm. Beyond this point, as the feed rate climbs to 0.5mm, the change in surface roughness starts to decrease. The graph shows a peak value at 0.3mm, indicating that the highest reduction in surface roughness can be obtained at this feed rate, figure 1. It is worth noting that an excessively high feed rate results in a decrease in the change in surface roughness. A lower feed rate allows the ball of ball burnishing tool to work for a longer time on the roughness peaks and causes them to deform plastically in the repetitive action of the ball, whilst a larger feed rate may cause the ball of ball burnishing tool to be in contact for less time that results in a decrease in the change in surface roughness ($\%\Delta Ra$).

Effect of infeed on %change in Surface Roughness ($\%\Delta Ra$): It is evident from the graphs of figure 1 that initially as the infeed increases, the change in surface roughness decreases because at the higher infeed, higher forces act at the contact of ball and workpiece that results in taking out the embedded chips at the surface of the workpiece. But at higher infeed beyond a certain limit, the forces become so high at the contact of ball and workpiece that all the roughness imperfections suppress and deform plastically to give an increase in percent change in surface roughness value.

Effect of Lubricant on %change in surface roughness ($\%\Delta Ra$): Based on the data, different lubricants have different effects on the surface finish. Kerosene as the lubricant produces a surface polish that is noticeably superior. Similar to how the surface finish is of intermediate quality when using paraffin as the lubricant. However, the surface finish deteriorates greatly when no lubricant is used. From the graphs of the effects of lubricants on the percent reduction in surface roughness, it is evident that the change in surface roughness is higher when paraffin or kerosene is used as the lubricant and it falls drastically when no lubricant is used figure 1. At no lubricant condition, the roughness peaks and other imperfections are likely to adhere to the carbide ball and may result in a decrease in $\%\Delta Ra$.

4. Conclusion

The ball burnishing tool can successfully be employed to finish the surface of nonferrous metals that are difficult to grind with traditional grinding. From this study it can be concluded that slower ball movement allows for more time per unit area of the surface, improving its smoothness by continuous plastic deformation. an excessively high feed rate results in a decrease in the change in surface roughness. An excessively high feed rate results in a decrease in the change in surface roughness due to contact of the carbide ball with the roughness peaks for a lesser time. Higher infeed increases the forces on the roughness peaks and other surface defects and smoothens them. No lubrication condition causes a reduction in the percentage change in surface roughness due to the sticky nature of copper with the carbide ball at no lubrication condition. The model's predicted R^2 and adjusted R^2 indicate that model is fairly accurate and reliable.

References

[1] M.H. El-Axir, O.M. Othman, A.M. Abodiena, Improvements in out-of-roundness and microhardness of inner surfaces by internal ball burnishing process, *Journal of Materials Processing Technology* **196** (2008), 120-128.

[2] A.M. Hassan, A.S. Al-Bsharat, Improvements in some properties of non-ferrous metals by the application of the ball-burnishing process, *Journal of Materials Processing Technology* 59 (1996), 250-256.

[3] L. Luca , S. Neagu-Ventzel, I. Marinescu, Effects of working parameters on surface finish in ball-burnishing of hardened steels, *Precision Engineering*, 29(2005), 253-256.

[4] G.D. Revankar, R. Shetty, S.S. Rao, V.N. Gaitonde, Analysis of surface roughness and hardness in ball burnishing of titanium alloy, *Measurement*, 58(2014), 256-268.

[5] H.M. El-Axir, O.M. Othman, A.M. Abodiena, Study on the inner surface finishing of aluminum alloy 2014 by ball burnishing process, *Journal of Materials Processing Technology*, 202(2008), 435-342.

[6] F.J. Shiou, C.C Hsu, Surface finishing of hardened and tempered stainless tool steel using sequential ball grinding, ball burnishing and ball polishing processes on a machining centre, *Journal of Materials Processing Technology*, 205(2008), 249-258.

[7] N.H. Loh, S.C. Tam, S. Miyazawa, Statistical analyses of the effects of ball burnishing parameters on surface hardness, *Wear*, 129(1989), 235-243.

Part 7

Advances in Operations and Supply Chain Management (2)

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Blockchain-Based Traceability System for Enhanced Humanitarian Supply Chain Management

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Abstract.
Traceability and transparency are crucial aspects of humanitarian supply chains to ensure the efficient delivery of aid. Existing research emphasises the need for improved traceability and transparency to address challenges like corruption, counterfeit goods, and inefficient distribution. Traditional systems, however, often lack the necessary infrastructure and mechanisms to achieve these objectives effectively. Blockchain technology offers unique capabilities to enhance traceability in humanitarian supply chains. This paper presents a conceptual blockchain-based system designed to record and verify the movement of humanitarian goods and resources and facilitate collaborations of key stakeholders throughout the supply chain. By enhancing traceability, transparency, and stakeholder collaboration, this system could contribute to the effective delivery of humanitarian aid, ultimately benefiting the affected communities in their time of need.

Keywords. Blockchain, Humanitarian Supply Chain Management, Traceability.

1. Introduction

In humanitarian supply chain management, ensuring the efficient, transparent, and accountable movement of goods and resources is crucial for providing timely assistance to affected communities [1]. However, challenges such as fraud, corruption, and lack of visibility often hinder the effectiveness of humanitarian operations [2]. To address these issues, emerging technologies like blockchain have shown great promise in revolutionising supply chain management by enhancing the traceability and transparency of processes [3].

This paper presents a blockchain-based system designed to record and verify the movement of humanitarian goods and resources throughout the supply chain, while considering the involvement of stakeholders such as the government, Non-Governmental Organisations (NGOs), and local communities. By leveraging the immutability, transparency, and decentralised nature of blockchain technology [4] and [5], this system aims to overcome the limitations of traditional humanitarian approaches and foster greater efficiency, integrity, and accountability and thus contribute to the effective delivery of humanitarian aid, ultimately benefiting the affected communities in their time of need.

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Smart contracts are utilised to automate verification processes, such as customs clearance, quality checks, and compliance with regulations. These contracts execute predefined rules and conditions, ensuring transparency and accountability throughout the supply chain [2]. By automating these processes, the system minimises manual intervention, reduces human error, and accelerates transaction processing, thereby increasing the overall efficiency of humanitarian operations.

2. Blockchain Technology Application in Traceability, Transparency and Collaboration in Humanitarian Supply Chain

Traceability and transparency are crucial aspects of humanitarian supply chains (HSCs) to ensure the efficient delivery of aid. Existing research, such as [6] and [7] emphasised the need for improved traceability and transparency to address challenges like corruption, counterfeit goods, and inefficient distribution. However, traditional systems often lack the necessary infrastructure and mechanisms to achieve these objectives effectively. Blockchain, which is a decentralised and distributed database that maintains a growing list of transactions, offers unique capabilities to enhance traceability in supply chains. By leveraging distributed ledgers and smart contracts, blockchain enables real-time tracking and verification of goods and resources [8] and [9].

It also facilitates donation management ensuring transparency in fund allocation and facilitating trust amongst stakeholders [1] and [10]. [11] and [4] highlighted the importance of stakeholder collaboration, trust-building, and participation in designing and implementing blockchain-based systems. Effective engagement ensures a shared understanding of goals, encourages data sharing, strengthens the overall resilience of the supply chain, and enhances stakeholder awareness about the technology and its importance in minimising coordination challenges of a lack of trust and information sharing [6].

2.1 Blockchain-enabled system: Transparency, Traceability, and Coordination applications

While designing the systems displayed in Figures 1, 2 and 3, important considerations should be made. One is the selection of the blockchain platform [12]. In this case, we recommend a permissioned platform, such as Hyperledger Fabric, which ensures controlled access to and privacy of sensitive data as only authorised parties can join, write, read, and commit in the network [13]. The data structure and smart contracts should be defined to include clear conditions and rules for contract execution [14] of relevant information like product identification, location, timestamp, responsible partners, and quality assessments. Network governance and access control guidelines [15] ensure that stakeholders have appropriate visibility levels and share data based on their roles and responsibilities. The user interface should be user-friendly [16] with appropriate access levels to enable stakeholders to input and access information related to the movement of goods/funds, tracking shipments, and reporting any anomalies.

For an effective implementation, these systems should be interoperable with existing systems used by stakeholders [15]. Privacy and data protection considerations must be integrated in the systems [17] and Zero-Knowledge Proofs (ZKPs) or selective disclosure to protect sensitive information shared on the blockchain can be used [18] and [19].

In this way, the humanitarian partner can establish trust and credibility in their qualifications without exposing sensitive information, and the verifier can be confident that the partner possesses the required qualifications without needing to access or store any personal or sensitive data. The cryptographic techniques behind ZKPs ensure that the proofs are valid, verifiable, and secure while preserving privacy [20].

An example of the use of blockchain technology to ensure transparency in disaster response is illustrated in Figure 1.

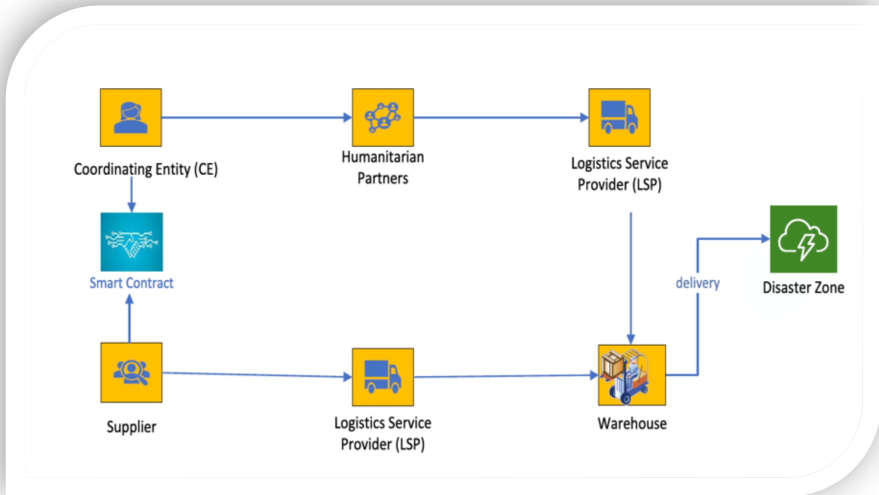

Figure 1: Blockchain-enabled transparency system in disaster response

The key steps of Figure 1 above are highlighted below:

1. a) Coordinating entity (CE) enters a smart contract with a pre-qualified supplier
   b) CE creates an order of the aid goods to the pre-qualified supplier and defines the consignee (central warehouse). They enter the details in the blockchain.
   c) Supplier enters the goods and carrier details into the blockchain and initiates delivery to the logistics service provider (LSP). He then handover the goods to the LSP, who accepts them, and enters these details to the blockchain.
   d) LSP handover the goods at the central warehouse and the consignee inspect and accept the goods and they both enter these details in the blockchain.
2. a) CE informs humanitarian partners (NGOs, donors, private companies) on the aid items required.
   b) Partners hand over the goods to the LSP who accepts them, and they both enter these details in the blockchain
   c) LSP handover the goods at the central warehouse and the consignee inspect and accept the goods and they both enter these details in the blockchain.
3. The goods are ready to be dispatched to the disaster zones/ to the victims who will then be identified through a pre-determined means, for instance verifying

their identity through fingerprints scans to authenticate the biometric information registered in the blockchain.

HSCs rely on donations for their operations and there has been a shift in how donations are made from giving physical items like food, medicines, and clothes to giving cash [21]. Cash donations are preferred as they are easier to make and empower victims to make more choices, thus restoring their dignity [22]. Organisations like the World Food Programme (WFP) accept donations in digital forms such as cryptographic currencies [1]. Figure 2 illustrates how blockchain can be used in disaster response and recovery to track donated assets, ensuring transparency, and reducing fraud and corruption.

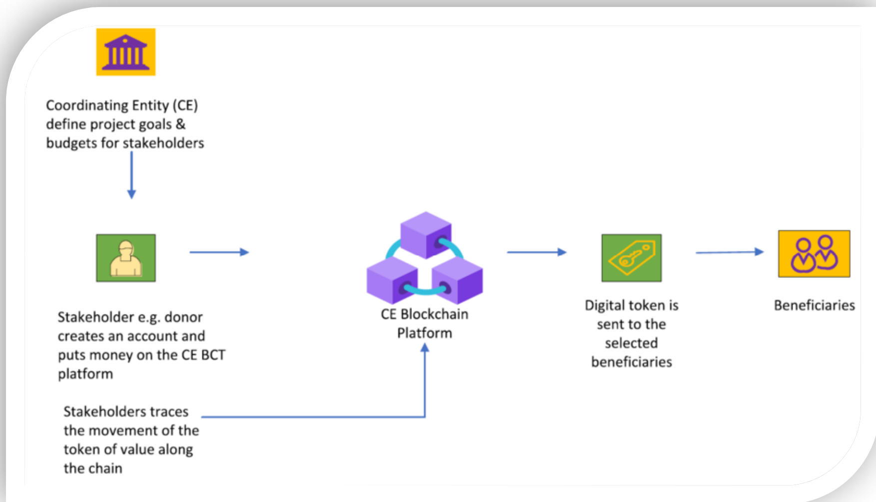

Figure 2: Blockchain-enabled traceability system for funds transfer

The following steps explain the Blockchain traceability system for funds transfer depicted in Figure 2 above.

1. The CE defines the project goals and the budget required from the stakeholders or the public, including the project details to register to the platform. Any willing stakeholders, e.g., a donor, creates an account in the CE platform and receives an encrypted private key and an anonymised public key.
2. The stakeholder then deposits some currency to the CE blockchain platform. If the currency received is in a fiat currency, the CE converts it into a digital currency and records its value as a token. The stakeholder can also trace the token movement.
3. The digital token is sent to the affected victim, who takes it to a local partner to the CE, e.g., a bank that converts the digital currency to fiat currency. The beneficiary can meet their needs and use the donation for income generation activities which helps victims to gain resilience after disasters.

Coordination is vital in any disaster management process [23], and Figure 3 illustrates how blockchain can aid in the coordination of stakeholders. Since each disaster is unique, the trusted CE is responsible for coordinating all the humanitarian partners and registering the ones needed for each disaster. In elaborating on blockchain usage in coordination in our paper, we categorise stakeholders into Primary and Secondary stakeholders as represented in Figure 3 in a circle and rectangle, respectively. Primary stakeholders can trigger the disaster management, while Secondary stakeholders are needed in a complementary basis. For instance, NGOs who are primary stakeholders can get into smart contracts with suppliers, who are secondary stakeholders to supply key medical supplies. In some disasters like terrorism, the host government adds the military to the blockchain for improved response. Smart contracts can be used with shelter providers like hotels for temporal accommodations.

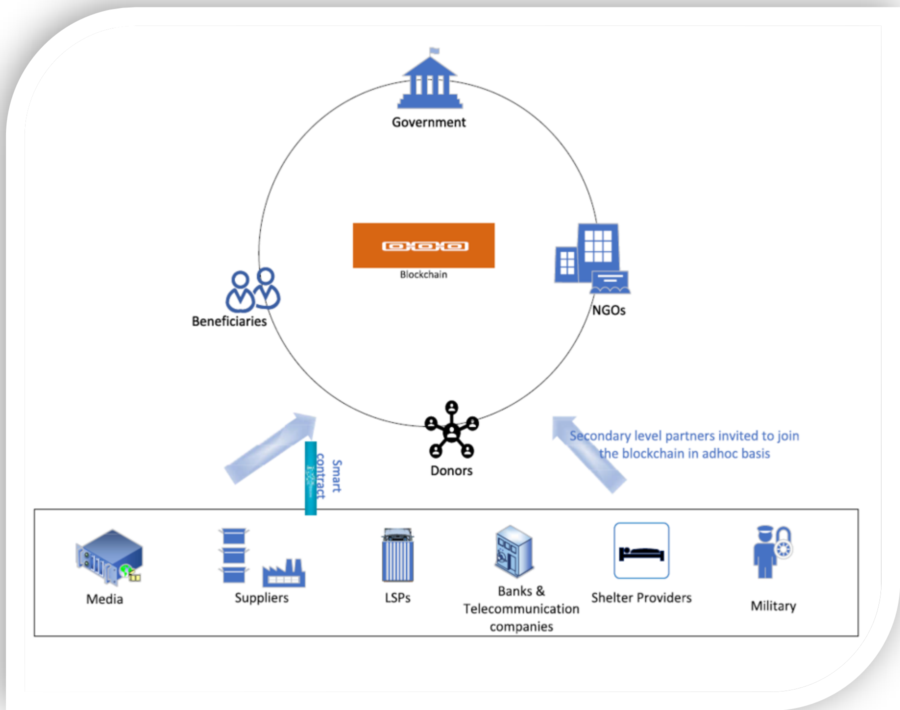

Figure 3: Blockchain-enabled system for coordination of humanitarian supply chain partners

In Figure 3 above

1. The government, NGOs, local communities/beneficiaries, and donors are represented as separate entities, indicating their primary involvement and participation in the humanitarian process.
2. The blockchain network acts as a shared infrastructure, connecting the stakeholders and providing a transparent and immutable ledger for recording and verifying humanitarian data.
3. HSC participants, represented in the circle (primary participants) and rectangle (secondary participants) interact with the blockchain network through smart contracts to verify and execute supply chain processes, thus ensuring transparency, accountability, and adherence to predefined rules and conditions.

3. Gaps and Further Areas of Research

This research recommends the following areas for further investigation.

1. Research on the legal and regulatory challenges associated with implementing blockchain-based traceability solutions in HSCs.
2. Evaluate the impact of blockchain-based traceability systems on the efficiency, effectiveness, and accountability of HSCs and quantify the benefits.
3. Investigate innovative approaches to improve the scalability and performance of blockchain-enabled networks specifically tailored for HSCs.
4. Focus on developing interoperability protocols and standards that enable seamless integration between different blockchain platforms and existing information management systems.
5. Examine new governance models and incentive mechanisms for blockchain-based HSCs. Investigate how decentralised decision-making processes and token economies can promote collaboration, accountability, and fairness among stakeholders.

Conclusion

In this paper, a Blockchain-Based Traceability System for enhanced humanitarian supply chain management was developed. By leveraging the inherent features of blockchain, such as data immutability, cryptographic security, and smart contracts, the traceability system can provide a comprehensive and trustworthy view of the humanitarian supply chain. It enables stakeholders to coordinate and accurately track the movement of humanitarian goods, verify their authenticity, and ensure compliance with regulations and standards. However, successful implementation requires careful consideration of technical, organisational, and regulatory factors to ensure the scalability, interoperability, and sustainability of the Blockchain-Based Traceability System. By embracing this technology and addressing its associated challenges, the humanitarian sector can unlock new possibilities for improving the delivery of essential goods and services, ultimately contributing to positive social impact and sustainable development.

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References

[1] S. Saad *et al*, *Blockchain Technology - Understanding its Application in Humanitarian Supply Chains.* 2022. In: SHAFIK, Mahmoud and CASE, Keith, (eds.) *Advances in Manufacturing Technology XXXV.* Advances in Transdisciplinary Engineering, 25. IOS, 385-391

[2] L. Chen *et al*, "Factors Affecting the Use of Blockchain Technology in Humanitarian Supply Chain: A Novel Fuzzy Large-Scale Group-DEMATEL," *Group Decis Negot,* vol. 32, *(2),* pp. 359-394, 2023. DOI: 10.1007/s10726-022-09811-z.

[3] H. Baharmand *et al*, "Exploring the application of blockchain to humanitarian supply chains: insights from Humanitarian Supply Blockchain pilot project," *Int J Oper Prod Man,* vol. 41, *(9),* pp. 1522-1543, 2021. DOI: 10.1108/IJOPM-12-2020-0884.

[4] H. Baharmand *et al*, "Developing a framework for designing humanitarian blockchain projects," *Comput. Ind.,* vol. 131, pp. 103487, 2021. DOI: 10.1016/j.compind.2021.103487.

[5] I. G. Sahebi *et al*, "Expert oriented approach for analysing the blockchain adoption barriers in HSC," *Technol Soc,* vol. 63, pp. 101427, 2020. DOI: 10.1016/j.techsoc.2020.101427.

[6] S. H. Hashemi et al, "A comprehensive framework for analysing challenges in HSCM: A case study of the Iranian Red Crescent Society," *International Journal of Disaster Risk Reduction,* vol. 42, pp. 101340, 2020. DOI: 10.1016/j.ijdrr.2019.101340.

[7] R. Dubey *et al*, "Blockchain technology for enhancing swift-trust, collaboration and resilience within a HSC setting," *Int J Prod Res,* vol. 58, *(11),* pp. 3381-3398, 2020. DOI: 10.1080/00207543.2020.1722860.

[8] N. Kshetri, "1 Blockchain's roles in meeting key supply chain management objectives," *Int. J. Inf. Manage.,* vol. 39, pp. 80-89, 2018. DOI: 10.1016/j.ijinfomgt.2017.12.005.

[9] A. Hughes *et al*, "Beyond Bitcoin: What blockchain and distributed ledger technologies mean for firms," *Bus. Horiz.,* vol. 62, *(3),* pp. 273-281, 2019. DOI: 10.1016/j.bushor.2019.01.002.

[10] K. Hunt, et al, "Blockchain in humanitarian operations management: A review of research and practice," *Socioecon. Plann. Sci.,* vol. 80, pp. 101175, 2022. DOI: 10.1016/j.seps.2021.101175.

[11] R. Dubey, A. Gunasekaran and C. R. H. Foropon, "Improving information alignment and coordination in HSC through blockchain technology," *Journal of Enterprise Information Management,* 2022. DOI: 10.1108/JEIM-07-2022-0251.

[12] S. Kubler *et al*, "Decision support system for blockchain (DLT) platform selection based on ITU recommendations: A systematic literature review approach," *Expert Syst. Appl.,* vol. 211, pp. 118704, 2023. DOI: 10.1016/j.eswa.2022.118704.

[13] D. Ghode *et al*, "Adoption of blockchain in supply chain: an analysis of influencing factors," *Journal of Enterprise Information Management,* vol. 33, *(3),* pp. 437-456, 2020. DOI: 10.1108/JEIM-07-2019-0186.

[14] J. Moreno *et al*, "Improving Incident Response in Big Data Ecosystems by Using Blockchain Technologies," *Applied Sciences,* vol. 10, *(2),* pp. 724, 2020. DOI: 10.3390/app10020724.

[15] F. Ghaffari *et al*, "Widening Blockchain Technology toward Access Control for Service Provisioning in Cellular Networks," *Sensors (Basel, Switzerland); Sensors (Basel),* vol. 23, *(9),* pp. 4224, 2023. DOI: 10.3390/s23094224.

[16] A. Tharatipyakul and S. Pongnumkul, "User Interface of Blockchain-Based Agri-Food Traceability Applications: A Review," *Access,* vol. 9, pp. 82909-82929, 2021. DOI: 10.1109/ACCESS.2021.3085982.

[17] N. Kshetri, "Blockchain's roles in strengthening cybersecurity and protecting privacy," *Telecommun. Policy,* vol. 41, *(10),* pp. 1027-1038, 2017. DOI: 10.1016/j.telpol.2017.09.003.

[18] Z. Mahmood and V. Jusas, "Implementation Framework for a Blockchain-Based Federated Learning Model for Classification Problems," *Symmetry (Basel),* vol. 13, *(7),* pp. 1116, 2021. DOI: 10.3390/sym13071116.

[19] E. Boo, J. Kim and J. Ko, "LiteZKP: Lightening Zero-Knowledge Proof-Based Blockchains for IoT and Edge Platforms," *Jsyst,* vol. 16, *(1),* pp. 112-123, 2022. DOI: 10.1109/JSYST.2020.3048363.

[20] A. Rasheed *et al*, "Exploiting ZKP and Blockchains Towards the Enforcement of Anonymity, Data Integrity and Privacy (ADIP) in the IoT," *Tetc,* vol. 10, *(3),* pp. 1476-1491, 2022. DOI: 10.1109/TETC.2021.3099701.

[21] P. Howson, "Crypto-giving and surveillance philanthropy: Exploring the trade-offs in blockchain innovation for nonprofits," *Nonprofit Manag. Leadersh.,* vol. 31, *(4),* pp. 805-820, 2021. DOI: 10.1002/nml.21452.

[22] M. Elayah, Q. Gaber and M. Fenttiman, "From food to cash assistance: rethinking humanitarian aid in Yemen," *Int J Humanitarian Action,* vol. 7, *(1),* pp. 1-13, 2022. DOI: 10.1186/s41018-022-00119-w.

[23] T. Comes, B. Van de Walle and L. Van Wassenhove, "The Coordination-Information Bubble in Humanitarian Response: Theoretical Foundations and Empirical Investigations," *Prod Oper Manag,* vol. 29, *(11),* pp. 2484-2507, 2020.DOI: 10.1111/poms.13236

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Critical Factors for Enhancing Knowledge Sharing Through Social Media in KSA Engineering HEIs

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Abstract. Social media facilitate research outcomes dissemination using tools and functions that simplify the sharing among academics and users. This paper aims to develop the relationships among the critical factors influencing knowledge sharing through social media based on three aspects: individual, organizational, and technological dimensions. An interpretive structural modelling approach for knowledge sharing through social media in Engineering HEIs in the Kingdom of Saudi Arabia was employed. Critical factors emerging with high dependence contribute to enhancing the use of social media for knowledge sharing. A key finding of the modelling is that clearly defined ease of use of social media, technical support, perceived usefulness of social media, the popularity of the tool, and appropriate content are significant factors influencing the technology aspect of knowledge sharing through social media. This research will help engineering and manufacturing educational institutions to know how to support the use of social media tools for knowledge-sharing purposes by focusing on critical factors.

Keywords. Knowledge Sharing, Social Media, Interpretive structural modelling.

1. Introduction

Social media tools for knowledge sharing present an opportunity for higher education institutes (HEIs). Owing to the fact that use of social media tools in the academic area has been on the increase, it is vital to explore and develop an understanding of their utility and efficacy as a tools for knowledge sharing among academics in HEI [1]. Online tools are possibly much more practical facilitators for sharing knowledge than the traditional way of sharing such as face-to-face especially in the present worldwide and geographically dispersed organisations, as several researchers have proposed [2]. Besides having a clear understanding of the numerous benefits that accrue to people from the use of social media tools, it is useful to better understand the implications of social media tools on knowledge sharing among academics and researchers.

The concept of knowledge sharing refers to how knowledge, information, expertise, or skills are transferred or exchanged among peers, people, families, communities, or within and/or between companies [3]. Social media is a term with no universally agreed-upon definition [4]. In higher education, social media has assumed increased importance. The advent of social media with its core characteristic of sharing ideas, concepts, and content, can revolutionise knowledge sharing in higher education platforms worldwide. In this regard, the proliferation of social media use in HEIs has bolstered the ability to facilitate communication, group establishments, and idea generation [2].

This paper aims to identify and rank the key critical factors for enhancing knowledge sharing through social media in KSA HEIs, to establish the relationships among the identified critical factors using the interpretive structural modelling (ISM) approach and to discuss the implications for practicing academics of this research and suggest directions for future research. These factors influence each other. Therefore, it is important to recognise the nature of these factors so that the dependent factors and driving factors are recognised.

2. Identification of critical factors

An extensive literature review identified the diverse critical factors influencing knowledge-sharing through social media. Keywords used included “knowledge sharing”, “social media”, “barriers factors for knowledge sharing among academics” and “success factors for knowledge sharing in higher education”. A total of 48 papers were reviewed. Through this literature review, 19 critical factors were identified. These were discussed with an expert group of academics and professional users of social media tools working in the KSA HEIs with more than 5 years of experience in the sector.

Individual factors influence the decision to share knowledge through the Internet. Knowledge sharing is based on the ability and willingness of individuals to create and share information with others for different purposes. Enjoying for example, a specific knowledge-sharing medium encourages people to continue developing and sharing information [5]. Promoting the awareness of social media platforms used for knowledge sharing within the higher education community helps increase the potential impact of the themes, issues, and concepts covered [6]. Lack of awareness reduces access to knowledge sharing platforms, reducing the shared knowledge's rate and effectiveness [7]. At the individual level, factors such as altruism, enjoyment of helping others and self-efficacy play a central role in shaping the effectiveness of knowledge sharing. Altruism facilitates the voluntary and continuous sharing of knowledge within a community, including facilitating knowledge sharing at one’s own cost (money, time, and effort) [8]. The enjoyment of helping others is often viewed as a mediator for knowledge sharing and diffusion. Time for sharing knowledge through social media is another critical factor. The process of sharing knowledge takes time, depending on the quality and quantity of knowledge being shared. The lack of time leads to incomplete sharing of knowledge, while the sender may decide against starting the process if they feel that the process will not be completed. Self-efficacy is a self-evaluation that affects the decision of the person to participate in a particular activity [8].

The differences in the size, scope and other characteristics of organisations are often viewed as having a direct influence on knowledge sharing. The relevance of the organisational factors arises from the fact that knowledge sharing presents several benefits to the institution [9]. Organisations have developed specific strategies for sharing knowledge which is designed to make the activities and processes more objective. The absence of an overall strategy for knowledge sharing also limits establishing collective goals, which limits the ability of employees to act in a particularly predictable manner, since there are no assurances that the self-interest of other employees regarding knowledge sharing has limited potential for leading to adverse effects. As a result, organisations that do not actively develop and sustain a culture that enhances and facilitates knowledge sharing are likely to fail at these attempts and miss out on potential value creation. HEIs must realise the importance of developing environments for knowledge sharing, such as informal surroundings, quiet spaces, relaxed physical spaces, and online or technology-driven platforms that encourage the flow of knowledge. Rewards are often viewed as interventions aimed at encouraging knowledge sharing, as well as the development of a knowledge-sharing culture.

Studies on technological factors revolve around models such as the technology acceptance model [2]. Under TAM, the perceived ease of use and perceived usefulness are key determinants of the extent to which novel or existing ICT tools are viewed as improving the antecedents and outcomes of knowledge sharing, such as improvement in job performance and plans. The differences in the abilities of users of social media platforms to utilise the various functions and modules influences how and whether knowledge is shared. Knowledge sharing is sometimes a technical process [10], especially when complex systems and processes are involved. The ease of use is linked to the evaluation (by the technology user) of the efforts required to utilise the technology. Thus, a technology perceived as easy to use for knowledge sharing involves limited efforts and is easy to operate. As a result, the user faces limited barriers when sharing knowledge. The proliferation of IT tools, customised to share knowledge, also plays a key role in the process [8]. Improvements in the functionalities of ICT have made it possible for novel forms of interactive sharing of knowledge [2]. Training for using social media for knowledge sharing is another technology-critical factor. Some aspects of social media use require technical knowledge that can only be acquired through training [11]. Technical support plays a key role in reinforcing the intensive socialisation among communities and solving the emergent challenges that limit the utility of social media for knowledge sharing. Since some of these technical challenges are unique, their solution can only be implemented where technical support is available to implement the propositions by the community involved in knowledge sharing. Technologies, especially social media-based tools, are continuously changing with the incorporation of Artificial Intelligence (AI) and the Internet of Things (IoT) [12-14]. Consequently, there is a need to consistently train, support, and enhance the skills and capacity of the stakeholders in HEIs. Security and privacy are important technology factors. Security and privacy are important technology factors. The security of knowledge-sharing channels is a key determinant of knowledge-sharing since it plays a role in ensuring that the knowledge shared reaches the targeted individuals only. The concerns about security influence the willingness of individuals to share certain types of knowledge, as well as the extent to which they participate in knowledge-sharing activities. Security concerns also influence the willingness of community members to join social media platforms. The concerns around privacy also lead to emergent costs and the need for additional efforts associated with verification of the knowledge shared therein, as well as the lack of willingness to share sensitive knowledge across social media.

3. Interpretive structural modelling

The 19 critical factors (CFs) listed in Table 1, summarize the findings from the literature review. The interrelation between the factors can be revealed through interpretive structural modelling (ISM) [15]. Subsequently interviews were conducted and focused on revealing if there is an interrelationship among the factors that have been predefined. The outcome of these interviews was analysed through the development of matrixes that allow the visualisation of the interrelationships. ISM is composed of eight consecutive steps, that have been presented in detail in past [16, 17]. The CFs were presented to the expert group and were discussed in detail. Participants were asked to reach a consensus for every pair of variables, identifying the existence or not of the relationship between them. This information was used for the development of the SSIM matrix (Table 1). Four symbols have been used to denote the direction of the relationship between the variables (*i* and *j*) are: V when variable *i* impacts variable *j*, A when *j* impacts *i*, X when *i* and *j* impact each other; and finally, O when *i* and *j* are unrelated.

Table 1. Critical Factors and structural self-interaction matrix (SSIM)

	Variables	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1
1	Altruism	O	A	O	X	A	A	O	X	O	O	O	V	X	O	A	O	X	A	
2	Enjoyment of helping others	O	O	O	X	A	A	A	X	A	A	O	A	X	A	O	A	X		
3	Awareness of the importance of knowledge	O	O	V	A	A	A	O	V	X	X	O	O	O	O	X	A			
4	Self-efficacy	V	V	V	O	X	A	O	O	O	O	A	A	V	A	A				
5	Knowledge-sharing strategy	O	O	A	A	X	V	O	A	O	O	V	X	O	V					
6	Organisation environment	O	O	O	A	O	O	O	O	O	O	O	O	O						
7	Ease of social media use	X	A	X	O	O	X	V	V	O	O	X	A							
8	Functionality of social media	V	V	X	O	O	X	A	V	O	O	X								
9	Technical support	A	A	V	O	A	X	V	O	V	V									
10	Security of social media	A	O	V	O	O	X	O	O	X										
11	Privacy of social media	A	O	A	A	O	X	O	O											
12	Perceived usefulness of social media	O	A	X	O	A	A	V												
13	Time	O	V	O	V	O	A													
14	Training	V	V	V	O	O														
15	Rewards system	O	O	V	O															
16	Culture	V	X	X																
17	Popularity of the tool	O	X																	
18	Appropriate content	X																		
19	Verification mechanism																			

For the next step of the ISM, the reachability matrix is calculated. The initial reachability matrix (IRM) is first drafted, followed by the final reachability matrix (FRM). The IRM is based on the SSIM after it is transformed into a binary matrix, substituting the symbols by 0 and 1, applying rules described in detail in [16]. The FRM is calculated after considering transitivity. If the transitivity rule is not satisfied, an iterative process is followed, with experts being asked to review and modify the SSIM until the rules are met [18]. The FRM is presented in Table 2. The FRM is further analysed through level partitioning. The CFs are ranked through this process, and the digraph can be developed. The reachability and antecedent set for each factor are obtained from the final reachability matrix. The level portioning process is iterative until all variables are ranked. For the present study, it required 8 iterations. Figure 1 illustrates the final ISM model.

Table 2. Final reachability matrix including transitivity (with asterisks)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1	1	1*	1	1*	1*	1*	1	1	1*	1*	1*	1	1*	1*	0	1	1*	1*	1*
2	1	1	1	0	1*	1*	1	1*	1*	1*	1*	1	1*	1*	0	1	1*	1*	1*
3	1	1	1	1*	1	1*	1*	1*	1*	1	1	1	1*	1*	1*	1*	1	1*	0
4	1*	1	1	1	1*	0	1	1*	1*	1*	1*	1*	1*	1*	1	1*	1	1	1
5	1*	1*	1	1	1	1	1*	1	1	1*	1*	1*	1*	1	1	0	1*	1*	1*
6	1*	1	1*	1	0	1	1*	0	0	0	0	1*	0	0	1*	1*	1*	1*	1*
7	1	1	1*	1*	1*	0	1	1*	1	1*	1*	1	1	1	0	1*	1	1*	1
8	1	1	1*	1	1	1*	1	1	1	1*	1*	1	1*	1	1*	1*	1	1	1
9	1*	1*	1*	1	1*	0	1	1	1	1	1	1*	1	1	1*	1*	1	1*	1*
10	1*	1	1	1*	1*	0	1*	1*	1*	1	1	1*	1*	1	0	1*	1	1*	1*
11	1*	1	1	1*	1*	0	1*	1*	1*	1	1	1*	1*	1	0	1*	1*	1*	1*
12	1	1	1*	1*	1	1*	1*	1*	1*	0	0	1	1	1*	1*	1*	1	1*	0
13	1*	1	1*	1*	1*	1*	1*	1	1*	0	0	1*	1	1*	0	1	1*	1	1*
14	1	1	1	1	1*	0	1	1	1	1	1	1	1	1	1*	1*	1	1	1
15	1	1	1	1	1	1*	1*	1*	1	1*	1*	1	1*	1*	1	1*	1	1*	1*
16	1	1	1	1*	1	1	1*	1*	1*	1*	1*	1*	0	1*	1*	1	1	1	1
17	1*	1*	1*	1*	1	1*	1	1	1*	0	0	1	1*	1*	1*	1	1	1	1*
18	1	1*	1*	1*	1*	1*	1	1*	1	1*	1*	1	1*	1*	0	1	1	1	1
19	1*	1*	1*	1*	0	0	1	1*	1	1	1*	1*	1*	1*	0	1*	1*	1	1

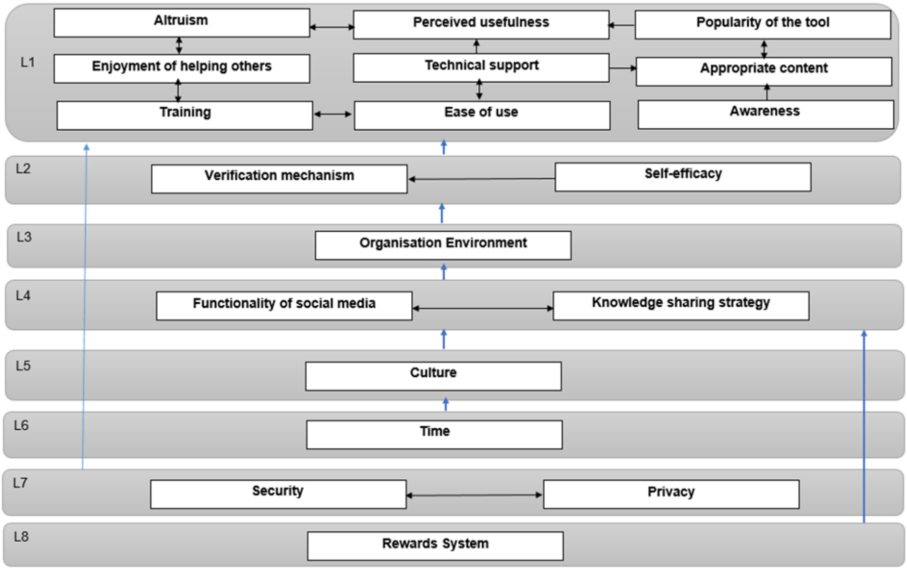

Figure 1. ISM-based Model of Influential Factors of social media for knowledge sharing.

4. MICMAC Analysis

MICMAC analysis is an indirect classification technique based on the driving power and dependence of each factor that helps to understand the impact of each factor. The data for the MICMAC is extracted from the FRM. The driving power is the count of all the variables affected by the variable. In contrast, the dependence power can be calculated by the count of all the variables affecting it. The MICMAC represents a quadrant that shows the factors as either driving, linkage, autonomous or dependent.

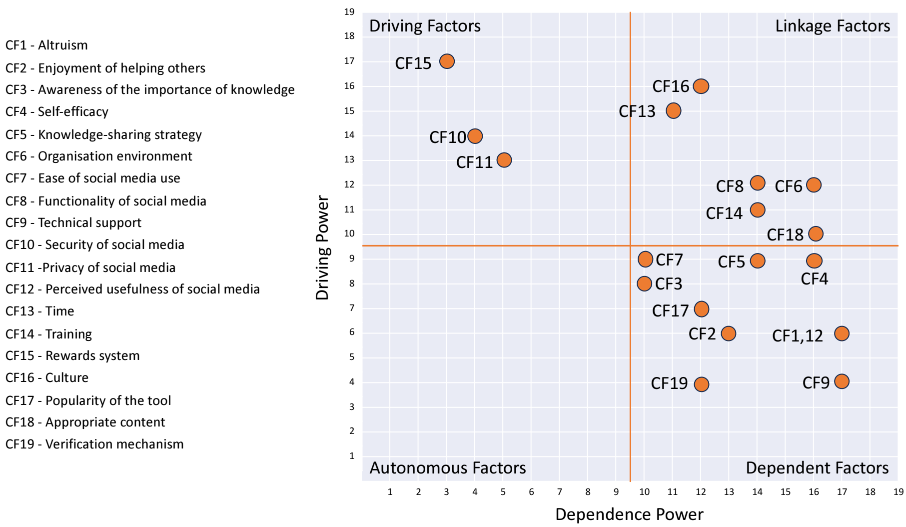

Figure 2. MICMAC analysis.

5. Discussion

The presence of many factors and interactions between them makes it difficult to understand any system and resolve issues arising. Such interactions can result in unforeseen and unintended consequences, highlighting the need for a system of systems approach. ISM method can help decipher such consequences, as it creates a comprehensive model that depicts relationships between them. In the current research, 19 Critical Influencing Factors (CFs) were identified. These have been listed in table 1.

The matrix of cross-impact multiplications applied to a classification analysis (MICMAC) shown in figure 2 helps classify the factors in autonomous, linkage, driving and dependent CFs. The autonomous factors were the ones displaying weak dependence and drive power. These factors, if segregated from the system, and they do not have much impact on other factors. The current research did not reveal any autonomous factors. Driving or independent factors have a strong drive but weak dependence power. Dependent factors, in contrast, have a weak drive and strong dependence power. Linkage factors were strong on both but were found unstable in action. The current research found that factor 14, training, was linked with many other factors, including altruism, awareness, self-efficacy, security, privacy, technical support, ease of use. The popularity of the social media tool was found to be connected to enjoyment, ease of use, security, and privacy. Links were also apparent between verification mechanism and other factors like security, ease of use, and technical support. The culture was also found to affect perceived usefulness, time, and verification mechanism. The perceived usefulness of the social media tool was specifically connected with the culture. As the literature suggested, segregating the components into different levels makes it easier to understand the relationships; upon inclusion of transitivity, an updated model was derived by partitioning the elements to create a reachability matrix (RM), including a reachability antecedent set, intersection set, and the level.

The 19 IFs were partitioned based on the identified levels. On Level 1 were included altruism, enjoyment of helping others, awareness of the importance of knowledge, ease of use of social media, technical support, perceived usefulness of social media, training, popularity of the tool, and appropriate content. This level suggests that these factors are the direct contributors in taking decisions related to knowledge sharing on social media. This means that a lack of technical support, lack of training, and lack popularity of the tool in the community would be some other reasons why people in the academic sector may not use a social media tool for knowledge sharing. The second level included self-efficacy and the verification mechanism as important deciding factors for social media sharing. Other factors like organisation environment, functionality and knowledge-sharing strategy, culture, security and privacy, and rewards systems plotted at 3, 4, 5, 7 and 8 levels were less important for academic, social media users when considering knowledge sharing in a direct manner, but they have strong influence to the L1 factors and as such they need to be considered in the decision making.

6. Conclusions

The study aimed to identify and rank the key critical influential factors for enhancing knowledge-sharing through social media in KSA HEIs. Identifying these factors discloses that enhancement and utilisation of knowledge sharing through social media in the HEIs can only be achieved within a particular set of procedures and processes. In this research, individual, organisational, and technological factors were used to develop the ISM models and the relationship among these factors.

The critical influencing factors for knowledge sharing through social media are limited to HEIs among academics. Moreover, this research covered all three categories of individual, organisational, and technological factors for enhancing knowledge sharing through social media in HEIs. The proposed model encourages academics to share knowledge by understanding the potential factors that influence them and hinder the use of social media.

References

[1] S. Panahi, J. Watson, H. Partridge. Information encountering on social media and tacit knowledge sharing. *J. Inf. Sci.*, **42** (2016), 539-550

[2] C.-J. Chen, S.-W. Hung. To give or to receive? Factors influencing members' knowledge sharing and community promotion in professional virtual communities. *Inf. Manage.*, **47** (2010), 226–236.

[3] O. Al-Kurdi, R. El-Haddadeh, T. Eldabi. Knowledge sharing in higher education institutions: A systematic review. *Journal of Enterprise Information Management* **31** (2018), 226-246.

[4] C. Burnett, G. Merchant. Is there a space for critical literacy in the context of social media?, *English Teaching: Practice and Critique,* **10** (2011), 41–57.

[5] A. Vannucci, C.M. Ohannessian, S. Gagnon, S. Use of multiple social media platforms in relation to psychological functioning in emerging adults. *Emerging adulthood*, **7** (2017), 501-506.

[6] S. Ghazali, N.I.S. Sulaiman, N.Z. Zabidi, M.F. Omar, R.A. Alias. The impact of knowledge sharing through social media among academia. In *AIP Conference Proceedings* **1782**, No. 1, (2017) p. 030003

[7] K.S. Kim, S.C.J. Sin. Use and evaluation of information from social media in the academic context: Analysis of gap between students and librarians. *The Journal of Academic Librarianship*, **42** (2016), 74-82.

[8] Y.-H. Fang, C.-M. Chiu. In justice we trust: Exploring knowledge-sharing continuance intentions in virtual communities of practice. *Comput. Hum. Behav.* **26** (2010), 235-246.

[9] S. Wang, R.A. Noe, R.A. Knowledge sharing: A review and directions for future research. *Hum. Resour. Manage. Rev.,* **20** (2010), 115-131.

[10] A. Bilgihan, A. Barreda, F. Okumus, K. Nusair, K. Consumer perception of knowledge-sharing in travel-related online social networks. *Tourism Management*, 52 (**2016**), 287-296.

[11] H.A. Voorveld, G. van Noort, D.G. Muntinga, F. Bronner. Engagement with social media and social media advertising: The differentiating role of platform type. *Journal of Advertising*, **47** (2018), 38-54.

[12] J.G. Myrick, A.E. Holton, I. Himelboim, B. Love. Stupidcancer: Exploring a typology of social support and the role of emotional expression in a social media community. *Health communication*, **31** (2016), 596-605.

[13] L. McCay-Peet, A. Quan-Haase. What is social media and what questions can social media research help us answer. In: *The SAGE handbook of social media research methods*, 2017 pp.13-26.

[14] K. Kircaburun, S. Alhabash, S.B. Tosuntaş, M.D. Griffiths. Uses and gratifications of problematic social media use among university students: A simultaneous examination of the Big Five of personality traits, social media platforms, and social media use motives. *International Journal of Mental Health and Addiction*, 18 (2020), 525-547.

[15] J.N. Warfield, Developing interconnected matrices in structural modeling. IEEE Transcripton Systems. *Men and Cybernetics* **4** (1974), 51 – 81

[16] M. Almanei, K. Salonitis. Continuous improvement initiatives: an ISM analysis of critical success factors. *Advances in Manufacturing Technology XXXIII: Proceedings of the 17th International Conference on Manufacturing Research* (2019) 485 – 491

[17] P. Hankin, M. Almanei, K. Salonitis. An ISM Analysis of the Critical Success Factors in ERP Implementation. *Advances in Manufacturing Technology XXXIV: Proceedings of the 17th International Conference on Manufacturing Research* (2021) 383 – 389

[18] Sushil, Interpreting the interpretive structural model. *Global Journal of Flexible Systems Management* **13** (2) (2012), 87–106

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Challenges in Implementing Lean and Green in Saudi Construction Sector

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Abstract: This research delves into the complexities and potential obstacles associated with implementing Lean and Green (L&G) methodologies within the construction sector of Saudi Arabia. Using qualitative research methods, 22 interviews were conducted with industry experts. The findings revealed several primary impediments to the successful deployment of L&G principles. These include a significant deficit in understanding and appreciating the fundamentals of L&G practices, a prevailing focus on financial gains over environmental sustainability, increasing construction and energy costs, deeply ingrained cultural and organisational norms, and a notable shortage of requisite skills and resources. The insights gathered underscore the urgent need for a harmonised, multi-stakeholder initiative involving government bodies, industry leaders, and academic institutions. Such a coordinated effort, in line with Saudi Arabia's Vision 2030 and the commitments under the Paris Agreement, can help in fostering efficiency and environmental sustainability in the construction sector, provided these identified impediments are effectively addressed and overcome.

Keywords. Lean and green; Construction Sector; Challenges.

1. Introduction

"Lean and Green" (L&G) is a strategic approach that integrates Lean methodologies, focused on efficiency and waste reduction, with sustainable or green practices to minimise environmental impact [1-3]. Strategically, the L&G approach amalgamates efficiency-oriented "Lean" methodologies with environmentally considerate "Green" practices to diminish deleterious environmental repercussions. Industries such as manufacturing and construction have deployed this strategy to enhance efficiency and curtail costs [1, 2, 5]. In the realm of construction, a L&G strategy signifies the utilisation of Lean techniques to augment efficiency and reduce waste while simultaneously integrating green practices to mitigate the environmental harm engendered by building construction [5]. Notwithstanding their disparities in emphasis and context, L&G principles are harmonious rather than discordant, and should be perceived as complementary resources instrumental in achieving enduring operational excellence [7].

Realizing a comprehensive incorporation of L&G principles into the construction industry necessitates a strategic, multi-faceted course of action. Various stakeholders, including government bodies, the construction sector, and educational institutions, must

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propel this transformation. Governments exert substantial influence on the construction industry by promulgating policies, standards, and legislation that encourage or mandate adopting L&G practices, potentially including punitive measures for noncompliance and incentives for green building techniques, waste reduction, and energy conservation [8]. However, the onus for implementing L&G principles falls predominantly on construction companies. They may need to invest in training and technology, apply Lean procedures to streamline operations and minimise waste, and integrate environmental considerations during the design and construction phases of their projects [5]. The role of educational institutions in equipping the future workforce with the requisite knowledge and skills to effectively apply L&G practices also remains paramount [6, 7]. Project managers well-versed in both concepts can facilitate introducing L&G practices more efficaciously. Lean tools such as value stream mapping and kaizen events can aid in identifying and eliminating waste. In parallel, green practices like recyclable materials and emissions reduction can be incorporated for additional benefits [5].

Given the Kingdom of Saudi Arabia's (KSA) commitment to environmental sustainability and economic diversification, adopting L&G practices is highly important. KSA, a leading global oil producer, is undergoing a significant shift as part of its Vision 2030 plan. It aspires to reduce the country's reliance on oil and stimulate the growth of public sectors such as the construction industry [9]. As Hussain et al. [5] posit, L&G principles, which underscore operational efficiency and sustainability, align with the country's endeavours to diversify its economy and decrease its oil dependence. By enhancing resource efficiency, reducing waste, and promoting environmentally friendly building practices, L&G could yield widespread implications [10]. Moreover, these measures could facilitate KSA's compliance with its commitments to curtail greenhouse gas emissions under the Paris Agreement [11]. Nevertheless, numerous obstacles stand in the way of a complete L&G transformation in the Saudi construction industry. These challenges include limited awareness of the benefits of L&G practices, resistance to change, and inadequate training and education [5]. The lack of technical experts and state-of-the-art facilities, coupled with an absence of supporting governmental legislation and incentives, could further limit the adoption of L&G. Thus, to fulfil its sustainability and diversification objectives, KSA must address these barriers L&G construction. All layers of government, industry, and education need to collaborate in seeking solutions. Governmental incentives and robust policies can be crucial in disseminating L&G methodologies. Furthermore, construction companies should invest in training initiatives and implement advanced technologies to adhere to L&G principles.

Multiple reasons underscore the importance of scrutinising the barriers to implementing L&G in the KSA construction industry. Firstly, due to the colossal infrastructure projects initiated as part of the Vision 2030 endeavour, the construction sector holds significant importance in the Saudi economy [9]. Integrating L&G practices into these undertakings has the potential to bolster their productivity, longevity, and success [5]. Accelerating the widespread adoption of L&G practices requires a comprehensive understanding of the impediments hindering their implementation. Secondly, KSA, despite being the world's largest oil producer, is striving to diversify its economy and reduce its dependency on fossil fuels [9]. The implementation of L&G practices in one of the country's most vital industries could aid in this endeavour. However, these benefits may remain unrealised without a clear understanding of the obstacles that must be overcome. Thirdly, as a signatory to the Paris Agreement, KSA is legally obligated to reduce its greenhouse gas emissions [11]. Given the construction industry's significant contribution to these emissions, implementing L&G practices could greatly influence the country's ability to meet its environmental commitments. The construction industry in the KSA confronts various challenges that can be addressed through L&G practices, but these challenges first need to be identified and understood. The country's economic, environmental, and infrastructure goals stand to benefit immensely from this. This research promises to contribute to the existing body of knowledge by elucidating the unique challenges of implementing L&G in KSA, a major Middle Eastern economy with its distinct socio-economic conditions. Moreover, it holds the potential to guide policy decisions, shape educational initiatives, and steer future research directions.

2. Challenges in implementing lean and green

Implementing L&G principles in the construction sector presents notable challenges, many shared with other sectors. Foremost among these obstacles is the significant initial investment required in terms of time, financial resources, and other forms of capital. This requirement may deter organisations from undertaking such a transformative journey [12]. It is highlighted that there is a lack of knowledge or expertise in L&G principles, making it difficult to implement these practices effectively [12, 14]. In the context of Industry 4.0, which is often associated with advanced manufacturing and digitisation, there are challenges related to integrating L&G principles with advanced technologies. This could include difficulties in optimising resource use, managing energy consumption, and minimising waste in highly automated and complex production environments [15]. The application of L&G practices in other sectors [16], might face challenges related to the specific characteristics and constraints of those sectors. This could include regulatory issues, market dynamics, technological limitations, etc. Table 1 highlights challenges in implementing L&G generally, specifically in the construction industry context.

Table 1. Challenges in the implementation of lean and green

Challenge	Description	References
Traditional mindset and resistance to change	The construction industry often shows reluctance to adopt new methodologies due to a lack of understanding or knowledge about L&G methodologies.	[17]
Lack of training and education	The understanding and successful implementation of L&G principles require specialized training and education, which is often lacking.	[5, 18]
Insufficient government support and regulation	The lack of robust policies and incentives from the government can hinder the adoption of L&G practices.	[19, 20]
Financial and economic concerns	The initial costs of implementing L&G can be high, deterring companies from adopting these practices.	[5, 6]
Complexity in coordinating L&G	The integration of L&G in the construction process can be complex, requiring a significant amount of coordination and planning.	[6, 7]
Lack of skilled labour	Implementing L&G methodologies can be labour-intensive and may require skilled workers, which are often in short supply in the construction industry.	[19, 21]
Unstructured implementation	Without a clear and structured plan, L&G implementation can be fragmented and ineffective.	[5, 19]
Inadequate technology	The lack of advanced technology can limit the effective implementation of L&G practices.	[5, 22]
Difficulty in measurement	Measuring the effectiveness of L&G practices can be challenging due to the lack of clear and standardized metrics.	[19, 21]
Reluctance to share knowledge	Organizations might be unwilling to share information due to fear of losing competitive advantage, affecting the implementation of L&G practices.	[19, 22]

Lack of collaboration	Implementing L&G principles often requires multi-disciplinary collaboration, which can be difficult due to siloed working practices.	[21]
Inadequate supply chain integration	Supply chain partners may lack commitment to L&G practices, impeding implementation.	[6, 16]
Lack of leadership commitment	If leadership does not fully support the implementation of L&G, it can lead to inadequate allocation of resources and lack of motivation among employees.	[9, 11]
Cultural barriers	Cultural factors, such as values, beliefs, and norms, can hinder the adoption of L&G practices.	[6, 23]
Traditional mindset and resistance to change	The construction industry often shows reluctance to adopt new methodologies due to a lack of understanding or knowledge about L&G methodologies.	[17]
Lack of training and education	The understanding and successful implementation of L&G principles require specialized training and education, which is often lacking.	[5, 18]
Insufficient government support and regulation	The lack of robust policies and incentives from the government can hinder the adoption of L&G practices.	[19, 20]
Financial and economic concerns	The initial costs of implementing L&G can be high, deterring companies from adopting these practices.	[5, 6]
Complexity in coordinating L&G	The integration of L&G in the construction process can be complex, requiring a significant amount of coordination and planning.	[5, 7]

3. Challenges in KSA construction sector

The findings from the literature review were verified through interviews in the context of KSA. The 22 interviewees comprise construction contractors, project managers, developers, and engineers. The criteria to recruit the Interviewees comprised: prior experience with five projects at least; working currently in KSA; at least possessing five years of experience in the sector. The following findings emerge from these interviewees:

1. **Conceptual Understanding of Lean in Construction:** There is a lack of universal application and limited understanding of L&G concepts in the construction industry. Although concepts like Total Quality Management, Six Sigma, Just-in-Time, and Kaizen have evolved and are being practiced, integrating L&G materials and technologies can make a project more complicated.
2. **Goals and Usefulness:** There is a lack of awareness and training programs, lean is about the reduction of wastage and improving organizational performance, the focus on green construction is often ignored.
3. **Culture and Practices:** The cultural and organizational focus in KSA is often geared more towards economic gains rather than ethical business practices and environmental protection.
4. **Skills and Resources:** The lack of training, workshops, and education on L&G practices in the construction industry is a significant barrier to their adoption.
5. **Cost and Performance:** The rising construction cost and energy consumption in Saudi Arabia increase the pressure to adopt L&G practices.
6. **Understanding and Applications of Advance Techniques:** While there is some understanding that green construction is about protecting natural resources, there is a lack of intention or focus on green construction in organisations.
7. **Economic Challenges**: The volatility of oil prices and the global shift towards renewable energy sources pose economic challenges. The country has tried to diversify its economy through its Vision 2030 initiative, but transitioning from an oil-dependent economy is a significant challenge.

8. **Political Challenges**: Saudi Arabia is an absolute monarchy, and this type of government brings challenges. Issues such as human rights, freedom of expression, and political participation are often raised by international organisations, although improvements have been reported recently.
9. **Social Challenges**: Despite recent reforms, gender inequality remains an issue. Women have only recently been allowed to drive and attend public events, and guardianship laws still restrict their rights.
10. **Environmental Challenges**: KSA serious environmental issues such as water scarcity due to its arid climate, over-reliance on fossil fuels, and rapid urbanisation. The country is also one of the largest consumers of water in the world, with water consumption in the domestic sector being the highest.

4. Discussion and conclusions

Implementing L&G methodologies in the construction industry presents several challenges. A primary challenge is a traditional mindset and resistance to change that often permeates the construction industry, which can make the adoption of new methodologies difficult [24, 25]. Resistance to change can be attributed to a limited understanding of the benefits associated with L&G methodologies. Additionally, substantial investments in terms of both effort and finance are typically required during the initial stages of implementing such initiatives. Construction companies, particularly smaller ones, may face financial constraints that serve as a deterrent to adopting L&G practices [26]. Insufficient resources present a significant obstacle to implementing the L&G methods. The lack of standardised metrics and benchmarks for evaluating the performance of L&G methodologies in construction can also present a challenge. Without clear metrics, it can be difficult for construction firms to assess the effectiveness of their L&G initiatives and to identify areas for improvement. Regulatory and policy barriers can also pose challenges. While some countries have policies that encourage or mandate the use of L&G methodologies in construction, others do not. The absence of supportive policies can make it difficult for construction firms to adopt these methodologies [23].

This study elucidates the multifaceted challenges hindering the adoption of L&G practices in Saudi Arabia's construction industry. While theoretical understanding of lean concepts exists, their practical application remains erratic, further complicated by the integration of green technologies. A considerable gap in awareness and training programs is evident, with a preference for traditional, cost-efficient methods over green construction practices. This is amplified by a cultural emphasis on economic gain, overshadowing ethical business practices and environmental protection. The study identifies a significant lack of training and education in L&G practices as a key barrier, coupled with rising costs and increased energy consumption intensifying the urgency for their adoption. Despite some appreciation of green construction benefits, such as natural resource conservation, this awareness is not translated into organizational intent or focus, indicating a need for increased education and aligned incentive structures. Beyond the industry-specific challenges, the study also underscores broader economic, political, and social issues in Saudi Arabia, including the transition from an oil-based economy, human rights concerns, gender inequality, and environmental challenges. These findings underscore that promoting L&G practices in construction is not merely an industry issue but intersects with larger societal and systemic complexities. By meeting its aim to comprehend the challenges of adopting L&G practices in Saudi Arabia's construction industry, this study paves the way for future research and policymaking, aiming to surmount these barriers and foster a more sustainable and efficient construction sector.

References

[1] W. Abualfaraa, K. Salonitis, A. Al-Ashaab, M. Ala'raj, Lean-Green Manufacturing Practices and Their Link with Sustainability: A Critical Review. *Sustainability* **12** (2020), 981.
[2] J. A. Garza-Reyes, Lean and green–a systematic review of the state of the art literature, *Journal of Cleaner Production* **102** (2015), 18-29.
[3] W.Abualfaraa, M. AlManei, R. Kaur, A. Al-Ashaab, P. McLaughlin, K. Salonitis, A Synergetic Framework for Green and Lean Manufacturing Practices in SMEs: Saudi Arabia Perspective. *Sustainability* **15** (2023), 596.
[4] C. M. Dües, K.H. Tan, M. Lim, Green as the new Lean: how to use Lean practices as a catalyst to greening your supply chain, *Journal of Cleaner Production* **40** (2013), 93-100
[5] K. Hussain, Z. He, N. Ahmad, M. Iqbal, Green, lean, six sigma barriers at a glance: a case from the construction sector of Pakistan, *Building and Environment* **161** (2019), 106225
[6] O. Babalola, E.O. Ibem, I.C. Ezema, Implementation of lean practices in the construction industry: A systematic review, *Building and Environment* **148** (2019), 34-43
[7] F. Mellado, E.C. Lou, Building information modelling, lean and sustainability: An integration framework to promote performance improvements in the construction industry, *Sustainable Cities and Society* **61** (2020), 102355
[8] Y. H. Ahn, et al., Drivers and barriers of sustainable design and construction: The perception of green building experience, *International Journal of Sustainable Built Environment* **1** (2020), 19-27
[9] R. Alrasheed, An assessment of the green building regulations in Saudi Arabia, *Buildings* **10** (2020), 177
[10] S. Ghosh, P. Ghosh, D. Chakraborty, D., Green lean approach: A solution for sustainable development goals in India, *Sustainable Operations and Computers* **1** (2020), 70-83
[11] O.S. Alshamrani, M.M. Bilec, Life cycle assessment of residential buildings in Saudi Arabia, *Journal of Cleaner Production* **255** (2020), 120209
[12] S. Choudhary, et al., An integrated lean and green approach for improving sustainability performance: a case study of a packaging manufacturing SME in the UK, *Production Planning & Control* **30** (2019), 353-368
[13] C. Singh, D. Singh, J.S. Khamba, Analyzing barriers of Green Lean practices in manufacturing industries by DEMATEL approach, *Journal of Manufacturing Technology Management* **32** (2021), 176-198
[14] W. Cai, et al., Promoting sustainability of manufacturing industry through the lean energy-saving and emission-reduction strategy, *Science of the Total Environment* **665** (2019), 23-32
[15] W.D. Leong, et al., Enhancing the adaptability: Lean and green strategy towards the Industry Revolution 4.0, *Journal of Cleaner Production* **273** (2020), 122870
[16] X.Y. Zhu, et al., Application of green-modified value stream mapping to integrate and implement lean and green practices: A case study, *International Journal of Computer Integrated Manufacturing* **33** (2020), 716-731
[17] H. G.Bayhan, S. Demirkesen, C. Zhang, A. Tezel, A lean construction and BIM interaction model for the construction industry, *Production Planning & Control* (2021), 1-28
[18] A. Farrukh, et al., Investigating the theoretical constructs of a green lean six sigma approach towards environmental sustainability: a systematic literature review and future directions, *Sustainability* **12** (2020), 8247
[19] S. Ahmed, M.H.R. Sobuz, Challenges of implementing lean construction in the construction industry in Bangladesh, *Smart and Sustainable Built Environment* **9** (2020), 174–207
[20] S. Gupta, M.A. Ahmadi, L. Kumar, Identification of the Barriers of Lean Construction Implementation in Construction Projects-A Review, *International Journal of Innovative Research in Computer Science & Technology* (2020)
[21] A. Francis, A. Thomas, Integrating lean construction and sustainability via a system dynamics framework, In *Proceedings of the 27th Annual Conference of the International Group for Lean Construction* (2019) 1187-1196
[22] W. Xing, et a., Implementing lean construction techniques and management methods in Chinese projects: A case study in Suzhou, China, *Journal of Cleaner Production* **286** (2021), 124944
[23] M. Arif, et al., Green retrofitting—a review of current status, implementations and challenges, *Smart and Sustainable Built Environment* **2** (2013), 22-36
[24] L. Koskela, Application of the new production philosophy to construction, Technical report #72, CIFE, Stanford University (1992)
[25] S.D. Green, S.C. May, S. C., Lean construction: arenas of enactment, models of diffusion and the meaning of 'leanness', *Building Research & Information* **33** (2005), 498-511
[26] M.A. Hossain, Z. Wu, D.K. Chua, Critical success factors for integrating lean principles with sustainable construction practices, *Journal of Cleaner Production* **244** (2020), 118765

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Integrating Sustainability into Engineering Curricula: Challenges, Framework, and Impact on Student Competencies in Saudi Arabian Higher Education

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Abstract. This paper investigates the integration of sustainability into Saudi Arabian engineering curricula and its impact on students' sustainability competencies. The study starts by delving into the multifaceted concept of sustainability, emphasizing its importance in higher education, particularly in engineering. It identifies a research gap in Saudi Arabia regarding the integration of sustainability into engineering curricula, underlining its significance in aligning with the country's shift to a sustainable and diversified economy. The paper highlights several challenges in implementing sustainability into curriculum practices, sourced from an extensive literature review. The authors propose a context-adapted, multi-staged framework to facilitate the integration of sustainability into the curriculum practices of Saudi Arabian engineering schools. This framework focuses on identifying sustainability gaps, engaging stakeholders, adopting adaptive education, integrating sustainability into the curriculum, promoting awareness, evaluating, and implementing continuous improvements. This research contributes to the global discussion on sustainability education in engineering and provides valuable insights for Saudi Arabia's policy and practice.

Keywords. higher education, curriculum, sustainability, engineering, Saudi Arabia.

1. Introduction

Sustainability, as a concept, involves the integration of environmental, economic, and social dimensions to create a balance that can be maintained over the long term [1]. It focuses on the wise use of resources and the preservation of natural systems, with the aim of ensuring the well-being of current and future generations. In further elaborating the concept of sustainability, it is important to underscore the significance of the three pillars – environmental protection, economic prosperity, and social equity, collectively known as the "triple bottom line" [2]. Sustainability transcends simply conserving resources; it requires a careful balance of these dimensions to ensure intergenerational equity and the long-term viability of our planet [1].

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Sustainability in higher education extends beyond environmental responsibility. It's about equipping students with knowledge and abilities to contribute to sustainable development [3, 4]. Institutions recognize the importance of sustainability, integrating it into their operations, curriculum, research, and community engagements [5]. This necessitates a significant transformation in the generation and dissemination of knowledge. In disciplines like engineering, the incorporation of sustainability into curricula is crucial due to its substantial societal and resource impact. Engineering plays a pivotal role in societal development, bearing a responsibility for sustainable growth [6, 7]. It requires not only technical skills teaching but also a comprehensive understanding of engineering practices' socio-economic and environmental implications. Engineering schools are hence transforming their curricula to include sustainability, aiming to cultivate engineers capable of designing sustainable solutions for global issues [7].

2. Challenges in implementing sustainability into curriculum practices

Incorporating sustainability into curriculum practices presents numerous challenges. There exists a key issue of inadequate understanding and awareness about the multifaceted nature of sustainability among educators and students alike, which is often coupled with a lack of professional development opportunities in this field [15, 16]. The already extensive curriculum can create a crowding effect, leaving little room for the introduction of interdisciplinary topics such as sustainability, while existing disciplinary boundaries within the education system may further hinder its incorporation [4, 17]. Assessing sustainability learning outcomes also poses significant challenges, due to the intricate and multidimensional nature of the topic [18, 19]. On an institutional level, barriers such as a lack of policy support, leadership, resources, and an organizational culture that values sustainability can also impede efforts to integrate sustainability into curriculum practices [20, 21]. The table highlighted the Challenges in the implementation of sustainability into curriculum practices.

To compile the literature mentioned in Table 1, the authors adopted a rigorous approach. The search was carried out on databases such as Web of Science using Web of Science using relevant keywords. The keywords included 'sustainability,' 'curriculum,' 'education,' 'engineering,' 'challenges,' and their combinations. The search was also extended to the bibliographies of relevant articles to find additional sources. The authors gathered the studies that are conducted in the last ten years while very few and some important old studies are added from the literature search. The initial literature search yielded a substantial number of articles. Following a two-stage screening process for relevance, based firstly on titles and abstracts, and then on an in-depth review of findings and implications, the authors finalized a selection of 29 articles providing meaningful insights into the challenges of integrating sustainability into engineering curricula.

Table 1 contains the challenges extracted from 11 sources, with some papers, cited multiple times across different challenges. The authors ensured a breadth of perspectives by including a diverse set of sources, covering various geographical locations, institutional contexts, and engineering disciplines. The references provide a comprehensive and diverse view of the challenges faced in integrating sustainability into engineering curricula. The included challenges and their descriptions reflect the themes most commonly mentioned in the reviewed literature.

Table 1. Challenges in the implementation sustainability into curriculum practices

Challenge	Description	References
Curriculum Integration	Difficulty lies in the cross-disciplinary nature and consensus on sustainability education.	[4,22]
Assessment Methods	Lack of suitable methods to assess complex sustainability-related outcomes.	[6,17]
Faculty Engagement	Difficulties to hire and retain active, trained, and supported faculty.	[4,22]
Institutional Support	Lack of supportive institutional resources and policies.	[14,22]
Student Engagement	Difficulty in engaging students in transformative sustainability learning.	[6,7]
Engineering-Specific Sustainability Content	Difficulty integrating socio-economic and environmental principles in engineering.	[15,23]
Curriculum Overcrowding	The challenge of adding sustainability topics without displacing others.	[4,22]
Interdisciplinary Approaches	The need for a cross-disciplinary perspective in a traditionally siloed field.	[7,22]
Practical and Experiential Learning	Challenges implementing practical, real-world, project-based sustainability learning. Complex nature of assessing interdisciplinary, future-focused learning outcomes.	[8,9]
Curriculum Integration	Difficulty lies in the cross-disciplinary nature and consensus on sustainability education.	[4,22]
Assessment Methods	Lack of suitable methods to assess complex sustainability-related outcomes.	[6,17]

3. Framework for integrating sustainability into curriculum practices at engineering school of Saudi Arabia

In developing a context-specific structure for infusing sustainability into curriculum practices within Saudi Arabian engineering schools, seven crucial steps are discerned (Figure 1). Each of these steps is grounded in an extensive range of academic literature. The first step, named Pathways Identification, concentrates on comprehending the institution's present situation, spotting voids in sustainability procedures, and plotting potential ways forward. This step accentuates the influence of Sustainable Development Goals (SDGs) in molding sustainability within higher education. The subsequent step, Stakeholder Engagement, brings into play all pertinent groups such as staff, faculty, and students in sustainability endeavors. Following this, the Adaptive Education phase comes into focus, highlighting an adaptable mindset and experiential Education for Sustainability. The fourth step, Integration into Curriculum, emphasizes the urgency of intertwining sustainability into the institution's educational offerings. The fifth step, the Promotion of Sustainability Awareness, underlines the use of social media for propagating sustainability consciousness and adopting a multi-perspective strategy to augment the institution's aptitude for promoting sustainability. Measurement and Evaluation constitute the sixth step, with the academic discourse underlining the significance of a general matrix for merging sustainability and the employment of evaluation tools for effective appraisals. The concluding step, Continuous Improvement and Scaling, emphasizes making necessary modifications post-evaluation and escalating sustainability efforts grounded on practices at other institutions. This comprehensive framework addresses all facets of integrating sustainability into curriculum practices, providing a robust foundation for the enhancement of sustainability in engineering schools within Saudi Arabia.

Figure 1. Sustainability in HE cycle.

- **Stage 1: Pathways Identification**
  Understand the current state of the institution [24].
  Identify gaps in sustainability practices [25].
  Determine potential ways to move forward [26].
  Apply the UN Sustainable Development Goals for a systematic approach [7].
- **Stage 2: Stakeholder Engagement**
  Involve staff, faculty, and students in sustainability efforts [14].
  Align internal stakeholders' expectations for successful reporting [15].
- **Stage 3: Adaptive Education**
  Adopt a mindset of adaptability to implement changes over time [27].
  Use experiential Education for Sustainability in the adaptive process [28].
- **Stage 4: Integration into Curriculum**
  Develop and implement sustainability curriculum [23].

Thoroughly assess sustainability curricula for validity and effectiveness [29].

- **Stage 5: Promotion of Sustainability**
  Awareness Raise awareness about sustainability, possibly through social media [21].
  Adopt a multi-perspective approach focusing on management education [3].
- **Stage 6: Measurement and Evaluation**
  Use a generic matrix for integrating sustainability in higher education [15]. Utilize assessment tools in the measurement and evaluation process [20].
- **Stage 7: Continuous Improvement and Scaling**
  Implement necessary adjustments and improvements after evaluation [23].
  Consider practices at other institutions for insights on scaling up sustainability efforts [30].

4. Conclusion

This research sheds light on the crucial task of integrating sustainability into Saudi Arabian engineering curricula, providing an extensive literature review that uncovers the key challenges faced. It introduces a comprehensive, adaptable framework designed to enable this integration, considering stakeholders, adaptability, curriculum development, awareness, and continuous improvement. Although context-specific, the study's findings and proposed framework provide valuable insights for global sustainability education discourse. To further enhance sustainability integration, it recommends continuous research, particularly on assessing impacts on students' sustainability competencies. Ultimately, these efforts contribute to aligning engineering education with both global trends and Saudi Arabia's sustainable development aspirations. Future work could expand on this base by integrating more recent studies, conducting a meta-analysis, or by focusing on specific challenges in greater detail.

References

[1] Dresner, S. (2008). The principles of sustainability. Earthscan.
[2] Elkington, J. (1998). Cannibals with forks: The triple bottom line of 21st century business. New Society Publishers
[3] Leal Filho, W., Shiel, C., Paço, A., & Azeiteiro, U. M. (2018). Sustainability education as a central framework for a green campus movement. Journal of Cleaner Production, 172, 4236-4247. doi: 10.1016/j.jclepro.
[4] Lozano, R., Lukman, R., Lozano, F. J., Huisingh, D., & Lambrechts, W. (2013). Declarations for sustainability in higher education: becoming better leaders, through addressing the university system. Journal of Cleaner Production, 48, 10-19.
[5] Menon, M., & Suresh, R. (2020). Pathways for moving towards sustainability in higher education institutions. Sustainable Development.
[6] Bielefeldt, A. R., & Canney, N. E. (2016). Changes in the social responsibility attitudes of engineering students over time. Science and Engineering Ethics, 22(5), 1535-1551.
[7] Azapagic, A., Perdan, S., & Shallcross, D. (2005). How much do engineering students know about sustainable development?. European Journal of Engineering Education, 30(1), 1-19.
[8] Hermann, R. R., & Bossle, M. B. (2020). Bringing an entrepreneurial focus to sustainability education: A teaching framework based on content analysis. Journal of Cleaner Production, 246, 119038.
[9] Holdsworth, S., & Sandri, O. (2021). Investigating undergraduate student learning experiences using the good practice learning and teaching for sustainability education (GPLTSE) framework. Journal of Cleaner Production, 311, 127532.

[10] Ken, R. (2018) Saudi Arabia Education Industry Ecosystem is Driven by Surging Enrollments in K-12, Investment in Edutech and ICT, Higher Education Enrollment Intake in Business and Management Field
[11] Saudi Vision 2030 (2021). Vision realization programs. Available at: https://vision2030.gov.sa/en (Accessed on 21 May 2023).
[12] Rajabifard, A., McLaughlin, J., Sabri, S., & Shojaei, D. (2021). Role of SDGs in shaping sustainability in higher education. Journal of Sustainable Development Education and Research.
[13] Rampersad, G. C. (2018). The status of engineering education research in Saudi Arabia. Engineering Education, 7(1), 29-38.
[14] Adeyemi, A., & Hasan, M. (2021). Sustainability in higher education: the Saudi experience. Sustainability in Higher Education, 12(2), 125-140.
[15] Ferrer-Balas, D., Adachi, J., Banas, S., Davidson, C.I., Hoshikoshi, A., Mishra, A., Motodoa, Y., Onga, M., Ostwald, M. (2008). An international comparative analysis of sustainability transformation across seven universities. International Journal of Sustainability in Higher Education, 9(3), 295-316.
[16] Stephens, J.C., Hernandez, M.E., Román, M., Graham, A.C., & Scholz, R.W. (2022). Higher education as a change agent for sustainability in different cultures and contexts. International Journal of Sustainability in Higher Education, 13(1), 60-73.
[17] Segalàs, J., Ferrer-Balas, D., & Mulder, K. F. (2010). What do engineering students learn in sustainability courses? The effect of the pedagogical approach. Journal of Cleaner Production, 18(3), 275-284
[18] Sterling, S. (2011). Transformative learning and sustainability: sketching the conceptual ground. Learning and Teaching in Higher Education, 5, 17-33.
[19] Wiek, A., Withycombe, L., & Redman, C.L. (2011). Key competencies in sustainability: a reference framework for academic program development. Sustainability Science, 6(2), 203-218.
[20] Lambrechts, W., Mulà, I., Ceulemans, K., Molderez, I., Gaeremynck, V. (2013). The integration of competences for sustainable development in higher education: an analysis of bachelor programs in management. Journal of Cleaner Production, 48, 65-73.
[21] Jones, P., Selby, D., & Sterling, S. (2010). Sustainability Education: Perspectives and Practice Across Higher Education. Earthscan.
[22] Barth, M., Godemann, J., Rieckmann, M., & Stoltenberg, U. (2016). Developing key competencies for sustainable development in higher education. International Journal of Sustainability in Higher Education.
[23] Cook, J., & Cutting, R. (2014). Experiential Education for Sustainability. Journal of Sustainability Education.
[24] Figueiró, P. S., Raufflet, E., & Porto, R. B. (2022). A multi-perspective approach to enhance the institution's capacity for promoting sustainability. Journal of Cleaner Production.
[25] Fisher, R., & McAdams, E. (2015). Understanding the institution's current state in sustainability practices. Journal of Environmental Management and Sustainable Development.
[26] Hamid, S., Waycott, J., Kurnia, S., & Chang, S. (2017). Use of social media for sustainability awareness. International Journal of Information and Education Technology.
[27] Ferrero-Ferrero, I., Fernández-Izquierdo, M.Á., & Muñoz-Torres, M.J. (2018). Role of faculty and students in sustainability efforts. Sustainability.
[28] Earl, S., Blythe, J., & Crellin, G. (2018). Adaptive Education for Sustainability. Educational Studies.
. Available at: https://www.prnewswire.com/in/news-releases/saudi-arabia-education-industry-ecosystem-is-driven-by-surging-enrollments-in-k-12-investment-in-679273763.html (Accessed on 10 April 2018).
[29] Cronemberger de Araújo Góes, A., & Magrini, A. (2016). Assessment tools for effective evaluation of sustainability. Journal of Cleaner Production
[30] Murray, S. (2018). Stakeholder engagement in sustainability efforts. Journal of Cleaner Production.
[31] Leal Filho, W., Manolas, E., & Pace, P. (2022). Scaling up sustainability efforts based on practices at other institutions. Journal of Cleaner Production.
[32] Rusinko, C. (2010). Importance of a generic matrix for integrating sustainability. International Journal of Sustainability in Higher Education.
[33] Scavarda, L. F., Scavarda, A. J., & Cunha, C. J. (2023). Continuous Improvement and Scaling in sustainability efforts. Journal of Cleaner Production.
[34] Srivastava, P., Thomas, A., & Brahma, B. (2020). Identifying gaps in sustainability practices: A case study approach. International Journal of Sustainability in Higher Education.
[35] Stough, T., Ceulemans, K., & Lambrechts, W. (2018). Weaving sustainability into educational offerings. Journal of Cleaner Production.
[36] Weiss, K., & Barth, M. (2019). Integration of sustainability into curriculum. International Journal of Sustainability in Higher Education.

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A Framework for Repeatable Structuring of Cost-Benefit Analysis

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Abstract. Assessment of costs and benefits of projects in a consistent way is a challenge due to the inconsistent way benefits are captured and evaluated. This problem is made worse across organisations as different staff with varied experience and skillsets get tasked with capturing benefits. Confidence in such assessments can be reduced by the concern that the analysis is too subjective. Following a more structured methodology could lead to improved confidence in the assessment of projects and faster adoption of beneficial improvements in technology, products or processes. In this paper a framework for such assessment is presented and a case study from the construction sector presented.

Keywords. Cost, cost-benefit, value, modern methods of construction.

1. Introduction

To support decision-making a cost-benefit analysis is often used. Such an analysis will often seek to quantify the benefit of a project in financial terms and in this way allow a comparison of costs and benefits using defined metrics for success. Such analysis is well supported in guidance documents, but less clear is how to structure the initial identification of the benefits. This leads to subjectivity in a lot of cost-benefit analysis, which can erode trust in the analysis and the value of a project. When perceived risk is high this can result in cancellations of projects that would be transformative to their organisations.

Many organizations have some values based KPIs which attempt to capture nonfinancial performance information. For example, most large organizations have KPI's related to health and safety performance. Making balanced decisions between two KPI's can be possible with relatively simple processes, such as management intuition. A more complex lists of KPI's must be considered if sustainability issues are of concern to the organization. That means that social, environmental and economical KPI need to be evaluated as a whole. With increased numbers of KPI's the process for balancing decisions will require more rigor. A process for assessing KPIs is described in traditional cost-benefit approaches, such as included in the 'Green book' [1], however the accuracy of results is strongly dependent upon correctly identifying every Value that is impacted by a change. A further complication is that not all potential value will be captured by an organisations KPI's. Assessing projects between two (or more) organizations with different KPI's is also an area of complexity. KPI's are therefore of less use when

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compared to a more detailed Value framework. Given these details, there is therefore a research gap for a framework to capture the value of projects in a rigorous way that is then suitable for feeding into established cost-benefit analysis methodologies. This paper outlines an attempt at addressing this research gap.

2. Background

Decision making in manufacturing is often considered as only a cost decision, such as cost of remanufacturing [2], where wider benefits are mentioned but considered outside the analysis. General guidance on cost estimation methods can be found through the NASA Cost Estimating Handbook [3]. A more specific treatment of costs suitable for use within a cost-benefit assessment is outlined in the work of Rybicka *et al.* [4], which highlights a generic cost estimating approach that is used to demonstrate a case study for composites.

Assessment of cost-benefit has Guidance on generating a benefit-cost ratio (BCR) can be found within the 'Green book' [1], for example. The BCR at its simplest is a ratio of project benefits and project costs. To be meaningful and rigorous both benefits and costs need expressing within the same measurement unit, which can be challenging. Should a cost-benefit analysis scope include an in-service phase, guidance can be gained from the NATO [5] guidance on Lifecycle costing methodologies. The cost modelling methods outlined are well tested and viable for an organisation to do, but guidance on rigorous identification of benefits is somewhat lacking.

Searching for a framework for value identification returns many options. For this work the Construction Innovation Hub (CIH) Value Toolkit [6] will be used extensively. This framework of Values is structured in terms of relevant capitals and the values that are derived from these capitals. The capitals of interest are: Natural, Human, Social, and Produced. Natural capital focuses on the benefit associated with the natural environment, Human capital focuses on human skills, development and experience. Social capital includes values that address equality and diversity, among other topics. Produced capital covers such financial issues as Lifecycle cost and generated Return. The four Capitals of the value framework breakdown into a total of 17 Values. The 17 Values are considered a comprehensive list for this work. While this framework was used, it is important to note that other value frameworks can be substituted into the process, making this approach widely applicable.

Currently there is little guidance on meshing a value-framework to a CBA. Such a process would have the purpose of capturing value in a consistent way, reducing that vast amount of information down and ultimately supporting decision making.

3. Framework

The developed framework is shown in figure 1.

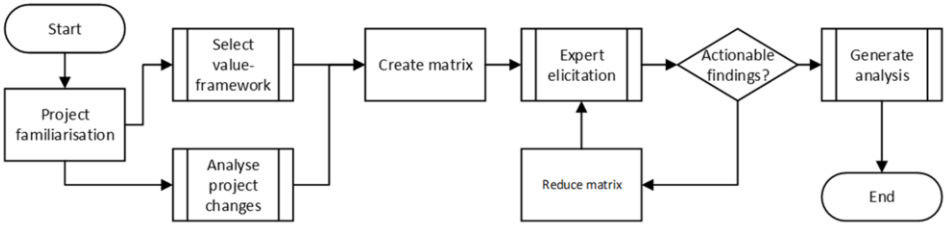

Figure 1: Framework for repeatable structuring of cost benefit analysis

The framework in figure 1, includes the steps needed to structure the analysis. 'Project familiarization' is when analysts will engage with the project team to understand the aims and objectives. Selection of value-framework could be set by an organization's template document or a relevant industry framework. Alternatively, a detailed down-selection process could be used. At the end of selecting value-framework the 'Values' dimension of the Value-Changes matrix. Analysis of project changes creates the 'Changes' dimension for the matrix; and should aim to note all significant changes from normal operation introduced by the project. 'Creating the matrix' and the 'expert elicitation' steps will structure then populate the Value-Changes Matrix. With complex projects that introduce many changes or a large value framework the resulting matrix can be large; therefore a process of reduction can be done. If the analyst is confident their findings can be analysed and presented.

3.1. The Value-Changes Matrix

While the CIH value framework gives a comprehensive list of values to assess a project against, large or very novel projects are likely to have changes that can impact the 17 values in complex ways. The use of an array of 17 values will not give enough data on this complexity and therefore the array should be formed into a matrix through the use of a second dimension. This second dimension is labelled 'changes' and is used to track individual changes that might occur from a complex project.

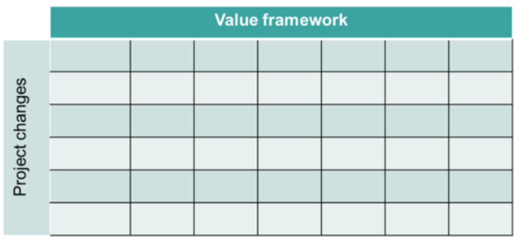

Figure 2: Initial matrix of value and project changes

As the assessment matrix is intended for use as a first stage of a detailed cost-benefit analysis, it is enough that each cell of the matrix is populated with limited information such as a 5-point Liekert scale, that maps to the terms "strong positive', 'mild positive', 'neutral', 'mild negative' and 'strong negative'. By using numerical data to capture this formation we allow some analytical approaches that verbal responses would not allow.

Data on a given row captures information about specific project changes and the impacts it has on those values.

Data on the columns captures value information and gives a view of how a singular value is impacted by the wider project. For example, a Health & Safety (H&S) value vertical slice looks at each identified Change caused by a project and the impact on the H&S value.

The Value-Changes matrix can be used to identify positive and negative impacts from a project and can be used to highlight areas that need more information. This matrix can be reduced to allow analysts to focus their efforts on the impactful areas. Once the Value-Changes matrix is deemed ready the deeper analysis of each value-change combination can start, using traditional cost-benefit approaches. Analysts and decision makers can be confident that the analysis has been done in such a way as to capture less-obvious impacts.

3.2. Metrics

During testing simple averages were found to be inadequate: a sum or average of scores across a row or column would be potentially misleading. For example a row that had a lot of very high values and very low values might average out to be fairly neutral looking which is clearly not the case. To support the use of the framework some metrics were developed:

- "Tall" metric: Defined as the sum of Liekert scale scores across a slice (vertical or horizontal). Gives a comparative score for how impacted a Value is or impactful a project change is expected to be.
- "Broad" metric: Percentage of Liekert scale scores that are considered positive along a given row/column. Gives different insight when compared to the "tall" metric as it looks for how broadly positive the Value or project change is impacted.
- "Threat" metric: Defined as the percentage of a vertical or horizontal slice that are considered disadvantageous. This metric is of use if there are negative impacts that would be hidden by the "tall" metrics summing of Liekert scale scores.

These three metrics give a picture of what is occurring on each row or column in a more complete way. They could be applied across the entire matrix if a very high-level view is required of the project, particularly if multiple projects are being compared against each other.

4. Case-study

The framework was applied to the SEISMIC II project [7], which explored modular design and manufacture in construction approach to demonstrate how through standardisation and manufacturing best practice, reduction in delivery times, increase of safety, quality and sustainability can be achieved. Assessment of benefits for technologies that are being demonstrated in the program is a key activity to provide confidence to business decision makers about the risks and potential gains. In this case-study the impact of SEISMIC II technology and its potential deployment in a public sector setting has been assessed through Value changes matrix to evaluate how different metrices change when adapting modern methods of construction. Key assumptions are:

- Economic changes are derived through the efficiencies expected from streamlined processes, like improved quality and reduced lead time.
- Reduced onsite waste impacts sustainability metrics in a broadly positive way.
- The skills required from the workforce will change: from the wide range of skills needed from a craftsman towards more specialised rolls more typically seen in factory settings

Capturing such a wide-ranging set of changes in a cost-benefit analysis would be challenging without this outlined framework.
The matrix was formed using changes identified in project documentation and expert elicitation. For the Values dimension of the matrix the CIH Value-framework was used. Using the metrics described vertical and horizontal slices of the matrix were analysed, as shown in figure 3, which outlines a horizontal slice exploring a particular project change (the wider use of apprentices).

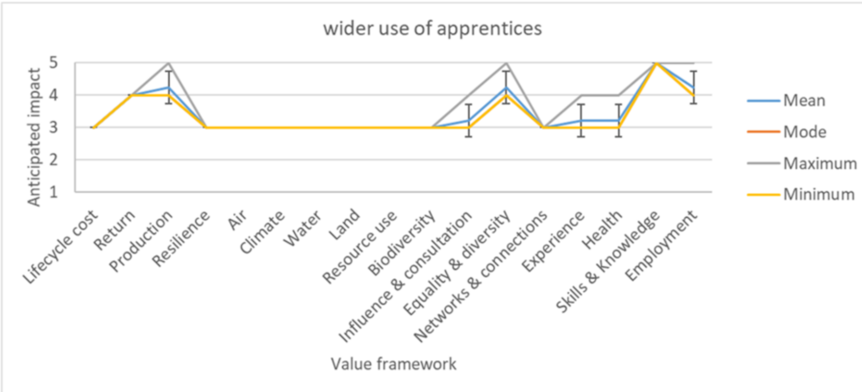

Figure 3: Impact of wider use of apprentices

As figure 3 shows, there are several strongly positive impacts on the Values from the CIH. “Production” and “Return” both being positively impacted, providing an economic impact. Looking at social impact we see good news for the “Equality & Diversity” value which is driven by anticipated improvements in equality and diversity measures based on the perception of the trends seen within the relevant industries (manufacturing is seen to be doing better at diversity challenges than the construction industry). No significant environmental changes were expected from wider use of apprentices; hence the very flat line at a “no-change” level.

The “Tall” metric indicated that this was a good but not spectacular change of the project. The “Broad” metric indicated that 33.8% of values were positively impacted by the change. In terms of the Broad metric, this was the 6^{th} Broadest change.

The above change does not introduce any negative impact on values and therefore the slice shown would measure as 0% on the “Threat” metric.

These metrics together indicate that the change “wider use of apprentices” would be mildly beneficial, doesn’t introduce any significant issues, but maybe wouldn’t be something to focus exhaustive efforts upon during a cost-benefit analysis as more impactful changes have been identified. The comparison of metrics between changes introduced by the project is a simple task, thereby allowing an analyst to focus on the areas requiring more attention during detailed cost-benefit analysis.

5. Conclusion

This paper has presented a framework for the structuring of cost-benefit analysis and demonstrated its use on a construction transformation project – SEISMIC II. A case-study presented by the National Composites Centre (NCC) [7] highlights improvements in H&S performance, reduced lead-times and lower carbon intensity of their modular build approach. All these benefits were initially identified using the framework discussed within this paper. As the framework can use the organizations KPI to capture benefits then practitioners can be confident that the benefits captured are very relevant to the objectives of that organization.

Challenges and areas for potential improvement are focused on usability. Some respondents noted that completing the first pass of the value-matrix was time consuming. It became necessary for researchers to guide and facilitate competition in some instances. The lesson learned from this is to reduce the value framework as quickly as possible and to group similar project changes together as much as possible. The CIH value-framework used in the case-study has detailed breakdowns of areas of potential value from a project, but that detail adds to the volume of data required. Efforts to reduce the value-framework down to a sub-set of most relevant values before data collection would make data-collection more efficient.

One last conclusion is that the framework could be digitalized quite easily to take advantage of internet survey providers. Through such an approach many more respondents could be consulted and a more complete picture of the likely benefits gathered. This would be particularly suited for projects with large numbers of relevant experts to consult.

References

[1] HM Treasury, Green Book central government guidance on appraisal and evaluation, (2022), https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1063330/Green_Book_2022.pdf

[2] Y. Xu & W. Fang, Develop a cost model to evaluate the economic benefit of remanufacturing based on specific technique, Journal of remanufacturing, (2014), 4:4.

[3] National Aeronautics and Space Administration: NASA Cost Estimating Handbook. NASA Headquarters, Cost Analysis Division, Washington, DC (2008)

[4] J. Rybicka, T. Purse, B. Parlour, A Generic Cost Estimating Approach for a Composite Manufacturing Process Assessment, *Advances in Manufacturing Technology XXXIV,* (2021), 414-418.

[5] North Atlantic Treaty Organisation: NATO, TR-SAS-054: Methods and Models for Life Cycle Costing, (2007).

[6] Construction Innovation Hub, Value Definition Framework, (2022) https://constructioninnovationhub.org.uk/wp-content/uploads/2022/06/Value-Toolkit_Value-Definition-Framework_v3.0-RGB.pdf 3

[7] National Composites Centre, Seismic II – Platform-based approach for construction, (2002) https://www.nccuk.com/media/gevc2iw2/seismic-case-study-8.pdf

Part 8

Advances in Design and Prototyping

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Benefiting from Biomimicry Through 3D Printing to Enhance Mechanical Properties of Polymeric Structures: Simulation Approach

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Abstract. Numerous biological structures have intricate compositional arrangements, well-organised pieces and stronger mechanical qualities than the materials that make them up. Therefore, this study focused on enhancing the mechanical characteristics of three-dimensional (3D)-printed acrylonitrile butadiene styrene (ABS) structures. Selected parts/systems of three natural (animal/plant) materials were designed/modelled and analysed to mimic their natural lattice structures (biomimicry), using CATIA V5 and finite element method/Ansys software. The simulation results showed that the tensile strength of the biomimetic-designed beetle increased by 13.63%, the bending strength of the biomimetic lotus stem improved by 2.00 and 19.86% in simple and three-point bending tests, and the compressive strength of biomimetic trabecular bone enhanced by 87.59%, when compared with their conventional structures. Also, the biomimetic design recorded 10.00% higher compressive strength than a fillet design and nearly 64.00% than the repeated pattern. It was evident that biomimetic designs enhanced the mechanical properties of all the 3D-printed ABS structures.

Keywords. Biomimicry, 3D printing, Mechanical properties, Polymeric structures.

1. Introduction

The term *biomimicry* is obtained from two ancient Greek words: *bios* - means life, and *mimesis* implies - to imitate. A useful idea, known as biomimicry, uses ideas from nature to create sustainable solutions to human issues [1]. It is a method that takes cues from and imitates the tactics employed by current-day species as well as other aspects of the natural world. The objective is to develop sustainable structures, procedures and regulations or new ways of living that address our biggest design problems and benefit all forms of life on earth. It is clear from history that techniques resembling the concept, such as designs drawn from nature, existed before the term biomimicry became widely accepted. One of these examples is Leonardo da Vinci's initial model of an aero plane, which was motivated by the flying of birds [2]. Therefore, this study investigated into the possibility of improved mechanical properties (tensile, bending and compressive strengths) of three-dimensional (3D)-printed acrylonitrile butadiene styrene (ABS) structures, leveraging biomimicry, finite element analysis (FEA) and additive manufacturing (AM) technology.

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2. Biomimetic designs

2.1. Biomimetic designed suture structure of beetle

The suture structure of *Phloeodes diabolicus* (beetle) was design to mimic the natural type, using CATIA V5 software similar to all other biomimetic plant/animal parts studied within the scope of this work. Beetle has suture structure in its upper skin, which exhibits the outstanding mechanical properties, especially tensile strength. Figure 1(a) shows the image of a beetle and its microscopic suture structure. Figures 1(b) and (c) depict the biomimetic designed sutures. Due to this structure, beetle can bear a high amount of load.

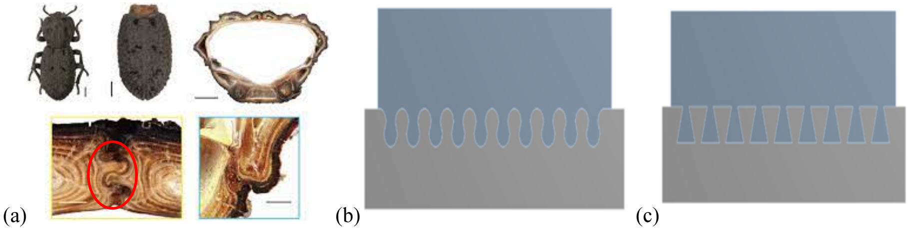


Figure 1. (a) *Phloeodes diabolicus* beetle and its suture structure (inside red ring) [3], (b) biomimetic and (c) triangular designed sutures.

2.2. Biomimetic designed lotus stem structure

This biomimetic design of lotus stem with diameter of 40 mm and length of 150 mm was modelled from the inspiration of natural lotus stem (Figures 2a and b). While, Figures 2(c) and (d) show its biomimetic and circular designed models, respectively. Lotus stem has many holes and porosity. This porosity serves different purposes for the lotus, it increases its bending strength. Therefore, a bending test was simulated to check its behaviours under different bending conditions.

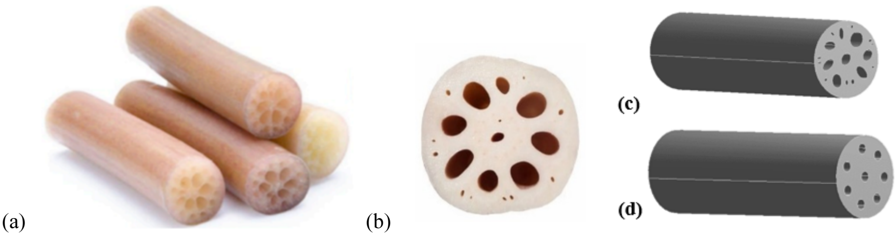


Figure 2. (a) Lotus stem, (b) its internal structure [4], (c) biomimetic and (c) circular models. .

2.3. Biomimetic designed trabecular bone structure

The intricate cellular composition of trabecular bone has excellent and lightweight energy absorption properties. Engineered cellular structures can be progressed into a new generation of protective systems by replicating this revolutionary high-performance structure. Complex evolutionary processes have honed complicated structure of bone to reduce weight, increase mobility and achieve the cyclic stress requirements of the human body [5]. Hence, inspiration was taken from this structure by mimicking its cellular pattern, as shown in Figure 3.

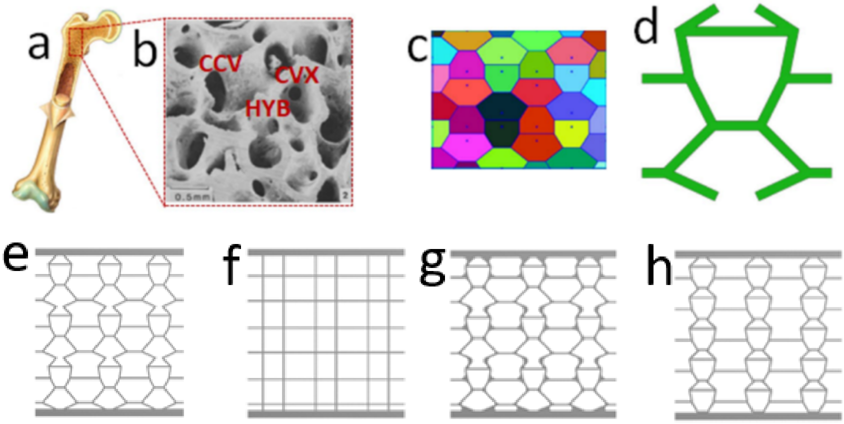
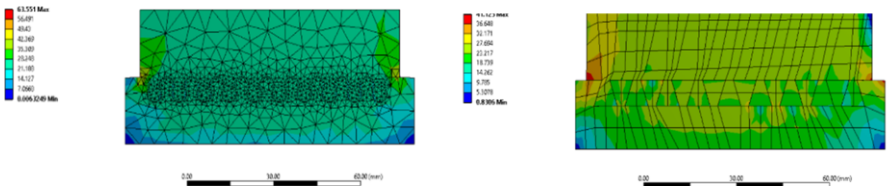


Figure 3. (a) Bone trabeculae, (b) trabecular bone closed cell plate-like structure, which was made up of (c) a Voronoi diagram that mimics trabecular bone, (d) a unit cell that was taken from the Voronoi diagram [5], (e) biomimetic, (f) square, (g) fillet and (h) repeated designs.

3. Simulation results and discussion

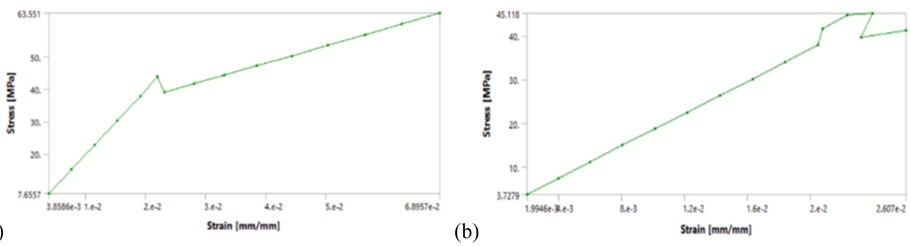
3.1. Biomimetic suture structure of beetle

The exact pattern of suture was mimicked to design and simulate two plates, which were joined by suture structure, as shown in Figures 4 (a) and (b). Figures 4 (a) and (b) depict the simulated biomimetic and triangular models. The thickness, total height and overall length of the plate were 2, 40 and 100 mm respectively. The total height included the height of both plates. The circle diameter of the suture pattern was 5 mm. Tensile load of 5 kN was applied at the top surface of the model. Fixed support was applied at left, right and bottom surface of the lower plate. Static structural analysis was performed. Figures 4(a) and (b) show the stress distribution region after FEA, whereas Figures 5(a) and (b) depict stress *versus* strain plots of biomimetic and triangular designs, respectively. Table 1 presents of tensile strengths of both designs, implying that biomimetic design exhibited a higher tensile strength than triangular type.



(a) (b)

Figure 4. Stress distribution in (a) biomimetic and (b) triangular designs under tensile load.



(a) (b)

Figure 5. Stress *versus* strain plot of (a) biomimetic and (b) triangular designs under tensile load.

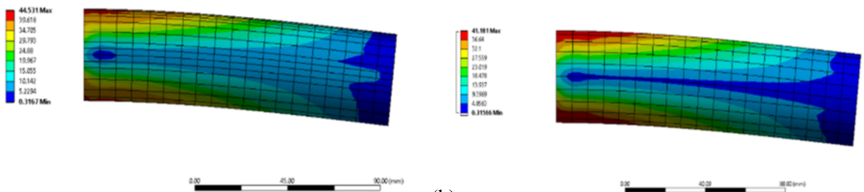
Table 1. Tensile strengths of the biomimetic and triangular suture structures of beetle.

S/No	Design/model	Tensile strength (MPa)	Minimum safety factor	Rank
1	Biomimetic	43.839	0.582	1st
2	Triangular	37.860	0.899	2nd

3.2. Biomimetic lotus stem structure

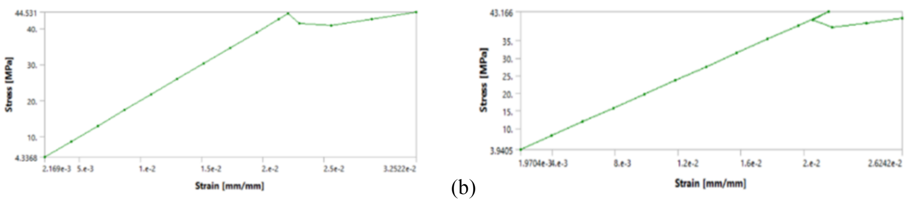
Firstly, a simple bending test was simulated, whereby the left side of the model was kept fixed and load of 2 kN was applied at the right face in downward direction. Secondly, a three-point bending analysis was also simulated on both designs similar to the first case. The left and right sides of the stems were kept fixed and the same load of 2 kN was applied at their middle.

There were eight holes in the circular design with size of 5 mm, each. All dimensions of the designs were kept same with that biomimetic design. Figures 6 and 8(a) and (b) show the stress distribution region and Figures 7 and 9(a) and (b) depict the stress *versus* strain plots for simple and three-point bending tests, respectively. In addition, Table 2 presents the bending strengths for both designs, whereby biomimetic design recorded higher bending or flexural strengths when compared with the conventional circular design under both normal/simple and three-point bending loadings.



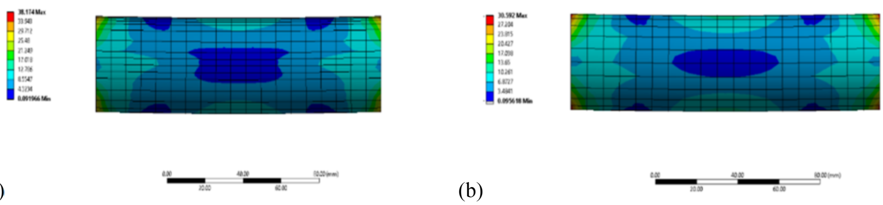
(a) (b)

Figure 6. Stress distribution in (a) biomimetic and (b) circular designs under simple bending load.



(a) (b)

Figure 7. Stress *versus* strain plots for (a) biomimetic and (b) circular designs under simple bending load.



(a) (b)

Figure 8. Stress distribution in (a) biomimetic and circular designs under three-point bending load.

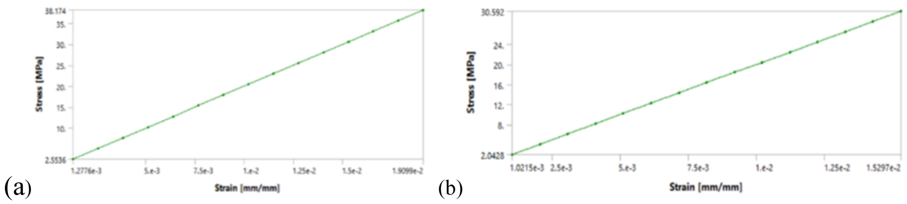


Figure 9. Stress *versus* strain plots for (a) biomimetic and circular designs under three-point bending load.

Table 2. Bending strengths of the biomimetic and circular lotus stem structures.

S/No	Design/model	Bending strength (MPa)		Rank
		Simple	Three-point	
1	Biomimetic	44.050	38.174	1st
2	Circular	43.166	30.592	2nd

3.3. Biomimetic trabecular bone structure

A compressive test was simulated under a load of 1.2 kN at the top of the various models. The lower surface of the design was kept fixed. Figures 10(a)-(d) show the FEA (stress distribution) of the biomimetic design, other square, fillets on all edges and repeated patterns, respectively. All dimensions, such as overall height, width and thickness, were kept same for all the four different models. Figures 11(a)-(d) depict the stress versus strain plots of all the four designs, while Table 3 presents the compressive strengths of the various designs. It was observed that the biomimetic design exhibited the highest compressive strength of 50.266 MPa, followed by the fillet pattern with a compressive strength of 45.538 MPa, when compared with other designs. The lowest or minimum value of 6.238 MPa recorded by the square design can be attributed to the highest stress concentration at its four edges or corners, causing premature material fracture under linear compressive loading.

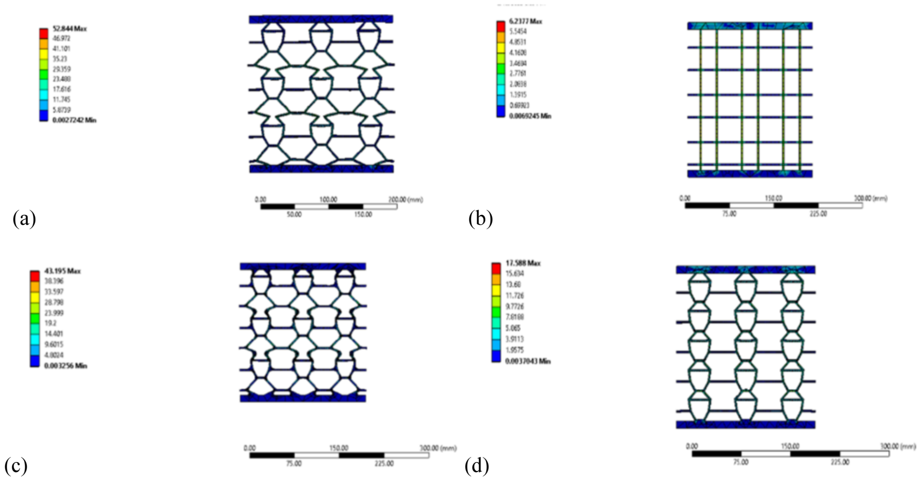


Figure 10. Stress distribution in (a) biomimetic, (b) square, (c) fillet and (d) repeated designs under compressive load.

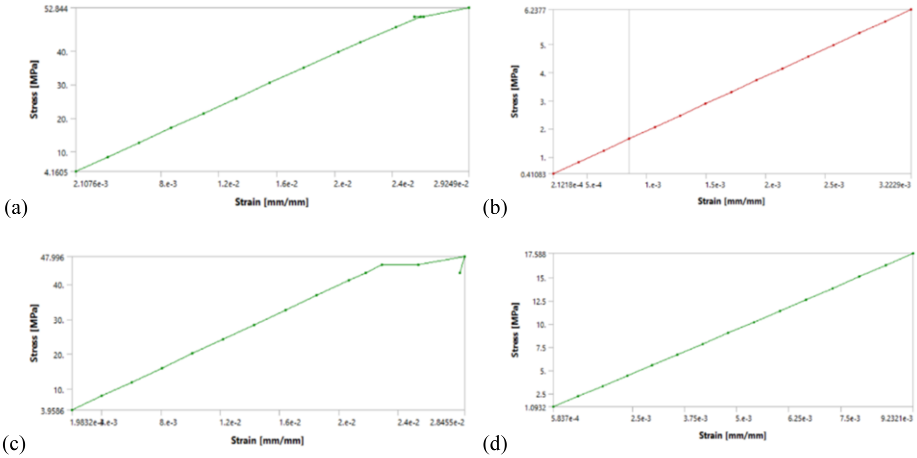


Figure 11. Stress *versus* strain plots for (a) biomimetic, (b) square, (c) fillet and (d) repeated designs under compressive load.

Table 3. Compressive strengths of the biomimetic and other designs of trabecular bone structures.

S/No	Design/model	Compressive strength (MPa)	Rank
1	Biomimetic	50.266	1st
2	Square	6.238	4th
3	Fillet	45.538	2nd
4	Repeated	17.588	3rd

4. Conclusions

The improved mechanical properties (tensile, bending and compressive strengths) of 3D-printed ABS structures have been studied, using simulation approach as well as leveraging on both biomimicry and AM technology. Biomimetic designed beetle, lotus stem and trabecular bone were considered. From the results obtained, the following concluding remarks can be deduced.

The biomimetic structure of beetle recorded higher tensile strength, lotus stem exhibited better simple and three-point bending/flexural strengths and trabecular bone had greater compressive strength when compared with simple/conventional structures. Hence, mechanical properties of engineering structures can be improved based on biomimicry and using AM technology to support several structural applications.

References

[1] A. Johnson, C. Sabu, K. Nivitha, R. Sankar, V.A. Shirin, T. Henna, V. Raphey, H. Gangadharappa, S. Kotta, K. Pramod, Bioinspired and biomimetic micro- and nanostructures in biomedicine, *Journal of Controlled Release* **343** (2022), 724-754.

[2] E.K. Bright, W.G. Brisbine, Biomimicry in architecture: A study of historic and modern precedents, *IOSR Journal of Environmental Science, Toxicology and Food Technology* **15** (2021), 20-27.

[3] S. Wickramasinghe, C. Peng, R. Ladani, P. Tran, Analysing fracture properties of bio-inspired 3D-printed suture structures, *Thin-Walled Structures* **176** (2022), 109317.

[4] Y. Zhu, C. Wang, D. Mynors, Applications and Engineering Analysis of Lotus Roots under External Water Pressure **2016** (2022), 1-8.

[5] A. Ghazlan, T. Ngo, T. Nguyen, S. Linforth, T. Van Le, Uncovering a high-performance bio-mimetic cellular structure from trabecular bone, *Scientific Reports* **10** (2020), 1-13.

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Mechanical and Thermal Performance of Ceramic and Nickel Superalloys Composites for Gas Turbine Blade Applications

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Abstract. Turbines transform thermal energy into work. Traditionally nickel superalloys are used for the turbine blades. In the present paper five ceramic matrix composite materials are investigated as alternatives. The first phase of a rotor blade gas turbine has been structurally and thermally examined in the current work using Finite Element Analysis. The thermal behaviour, as well as the mechanical performance brought on by centrifugal, tangential, and axial forces are calculated. The results indicate which materials can withstand the highest amount of stress under specific thermal and mechanical loads and will indicate which material will have a greater life expectancy.

Keywords. CMC materials, Nickel Superalloys, Composites, Thermal analysis, Structural analysis.

1. Introduction

One of the design objectives when developing turbines is to increase the operating temperature since such an increase result in higher engine efficiency. Additionally, the power-to-weight ratio is a significant feature of gas turbines [1]. The turbine blades should be built so that the steam passage across their surface generates more rotational energy. The goal of turbine blades is to extract energy from hot gases, and creep is regarded as the primary cause of turbine blade failure [2]. The service life of such gas turbine components is affected by their wear, corrosion, fracture, and deformation during their life cycle [3]. If a problem occurs in the turbine section, it will substantially impact the overall engine function and, evidently, the safety of the gas turbine engine [4, 5]. Such damage mechanisms limit the life of ceramic materials under dynamic loads.

The turbine's operating temperature, known as the firing temperature, also influences efficiency, with greater temperatures resulting in better efficiency [2]. However, the thermal conditions the turbine blade metal alloy can withstand limit the turbine inlet temperature. Gas temperatures at the turbine inlet range from 1200^{o}C to 1600^{o}C; however, unusual conditions and overloading have resulted in inlet temperatures as high as 1600^{o}C, resulting in fatigue and blade fracture [6].

The present study presents a case study of oxide and non-oxide ceramic matrix composite (CMC) materials versus nickel superalloys currently used in rotor gas turbine blades using Finite Element Analysis. Thermal and structural analyses with and without thermal loads were undertaken. The output findings compare the average temperatures, deformation, and von Mises stresses, allowing the selection of blade materials.

2. Gas Turbine Blade Materials

Due to their harsh operating conditions, materials used in modern gas turbines are in the forefront of the state of the art [7]. Turbine inlets are under the most challenging conditions operating under extreme temperatures (1400^{O}C - 1500^{O}C), with high pressure, high rotational speed, vibration, small circulation area, and so on [8].

Iron, nickel, and cobalt are the most common materials utilized in the production of blades, with chromium serving as a primary alloying element due to its excellent oxidation resistance [9]. Timken alloys, Hastelloy, Nimonic alloy, and Inconel are the most often used alloys [10]. According to previous case studies Inconel 625, and Hastelloy X are the most used superalloy materials for such applications [11]. Both material mechanical and thermal properties are listed in Table 1.

Materials	Inconel 625	Super Alloy Grade X	Al_2O_3/B_4C (50%Vf)	SiC/SiC (35-45%Vf) Woven Laminate	Al_2O_3/SiO_2 (Nextel 720) Woven-Fabric
Youngs Modulus (GPa)	208	210	382	199.5	143.5
Density (kg/m^3)	8440	7780	3310	2900	2600
Poisson's Ratio	0.29	0.3	0.21	0.19	0.2
Thermal Conductivity (W/mK)	21.3	22	23	13.5	3.495
Thermal Expansion Coefficient ($\mu m/\boldsymbol{m}$℃)	13.1	10	5.3	4.295	1.95
Yield Strength (MPa)	1150	1175	517	294	208.5
Melting Temperature (℃)	1350	1370	2100	2050	1800

Table 1 Properties of selected materials (the first two are nickel superalloys and the rest are CMCs) [15].

The use of ceramics for turbine blades is also being studied, and research is being conducted on this subject [9]. Materials that work under high loads and temperatures have different creep rates, resulting in variable strains. These cause a gradual change in blade morphology over time, with the blades filling the original gap at their tips. Failure occurs because of this contact with the casing.

Because of their light weight, high strength and toughness, and high-temperature capability, ceramic matrix composites are also considered. For many years, research has focused on fibre-reinforced ceramics, unlike monolithic materials, which have appropriate strength at high temperatures but suffer from poor impact resistance [10]. Today's ceramic composites use silicon carbide fibres in a ceramic matrix, such as silicon carbide or alumina [12]. These materials can operate with no additional cooling at temperatures of up to 1200°C, which is slightly higher than what coated nickel alloy systems can achieve. To sustain long-term stability at the highest temperatures in an oxidizing atmosphere, uncooled turbine applications will require an oxide-oxide ceramic material system [13]. Alumina fibres in an alumina matrix are an early example of such a system. Single crystal oxide fibres, which can work at temperatures of 1400°C, can be employed to achieve the greatest load-carrying capacities at high temperatures.

Two oxide and one non-oxide CMC materials have been selected for the present study (Table 1). They were selected based on the approach presented by the authors in [12,13]. The criteria for the material selection considered the aerospace applications' material requirements with regards to their mechanical, physical, and chemical properties, such as high strength, stiffness, fatigue durability, damage tolerance, low density, high thermal stability, high corrosion, and oxide resistance. Commercial criteria such as cost, servicing, and manufacturability were also considered [13, 14].

3. Gas Turbine Blade Model

To examine the damage mechanisms of different nickel superalloy and CMC materials, a gas turbine blade design was built and simulated in ANSYS software (Figure 1). The gas turbine blade is analyzed under two stress categories. The first type is centrifugal stresses caused by angular speeds in the blade, and the second is thermal stresses caused by temperature gradients within the blade material.

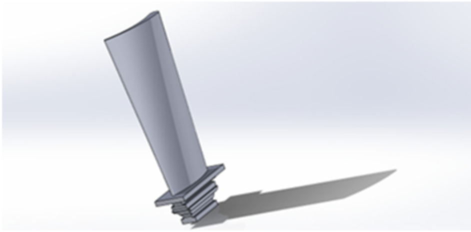

Figure 1 Gas turbine blade design.

To analyze the distribution of applied loads, deformation, temperature, and other consequences during component service, all degrees of freedom (DOF) of a root must be captured. The main loads acting on the blade include gas pressure and force due to momentum change, which permits the blade to revolve.

The Gas turbine blade is fixed to the rotor. The half of the gas turbine blade root is fixed inside the rotor, so the displacement boundary conditions applied to the half of the blade root can be determined as $U_x = U_y = U_z = 0$ and the rotations of all the same nodes are constrained, $R_x = R_y = R_z = 0$. For the rotor blade, the forces components are assumed to be; the axial component: $F_a = 500$ N, for tangential: $F_t = 15$ N, and the centrifugal one: Fc = 1400 N, similar to the values found in literature for FEA stress analysis [9]. Moreover, an axial rotational velocity of 200rad/s and a tangential coordination $r_{hub} = -0.3345$ in the turbine blade is assumed. The tangential coordination was calculated by measuring the distance from the center point of the Jet-A1 combustor liner inlet ($R=\frac{\pi}{4}(D^2 - d^2)$) and then assuming that $r_{hub}=1.5R$ [16].

For the thermal analysis on the gas turbine blade, a maximum of 1200°C is applied on the blade structure as the lower melting point of the comparing materials. A root temperature of 300°C is applied on the rotor of the turbine blade. Moreover, a film coefficient h=464.7 W/m^2C is added to the blade, which is a common value used for computational simulations of rotor blades according to the literature. [17,18]

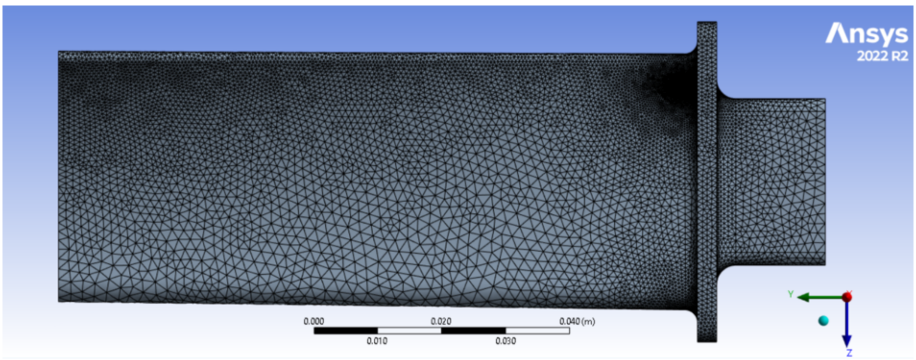

Figure 2 Meshing profile of gas turbine blade model.

For the meshing of the blade, six different grid profiles were tested, with every subsequent mess having 20% finer elements. The final messing was selected where further refinement does not change the predictions by more than 2%. Tetrahedral meshing (curvature and proximity-based) with a constant grow rate of 1.05m was used. The impact of the meshing on the calculations can be seen in Figures 3 and 4.

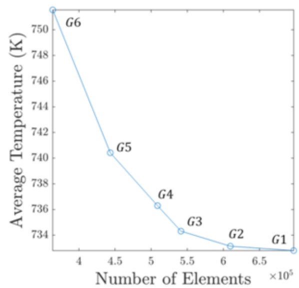

Figure 3 Average Temperature vs Number of Elements grid analysis results.

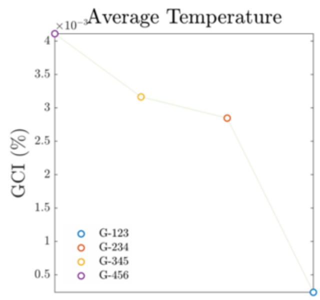

Figure 4 GCI VS Average Temperature analysis results.

4. FEA Thermal and Structural Analysis

Three analyses were carried out for each material: a thermal analysis and two static structural analysis, one with the applied thermal load and one without it. The maximum and average temperatures, stresses, and deformations of each different material were calculated and compared as it can be seen in Tables 2 and 3.

Material	T_{max} (°C)	T_{Avg} (°C)	σ_{max} (MPa)	σ_{Avg} (MPa)	ε_{max} (mm)	ε_{min} (mm)
Inconel 625	1200	734	232.6	28.2	0.80	0.066
Hastelloy X	1200	726	226.38	28.0	0.80	0.066
Nextel 720	1200	843	247.24	28.1	1.16	0.096
Al_2O_3/B_4C	1200	664	247.00	28.1	0.44	0.036
SiC/SiC	1200	711	248.53	28.2	0.83	0.070

Table 2 Thermal and Static Structural without thermal load results.

Material	σ_{max} (MPa)	σ_{Avg} (MPa)	ε_{max} (mm)	ε_{min} (mm)
Inconel 625	6282	1361	1.8	0.25
Hastelloy X	6631.9	1474	1.9	0.27
Nextel 720	769.23	164.5	1.175	0.12
Al_2O_3/B_4C	4492	906	0.79	0.103
SiC/SiC	1922.8	390	0.96	0.105

Table 3 Static Structural analysis results with thermal load results.

Figure 5 Thermal analysis of gas turbine blade.

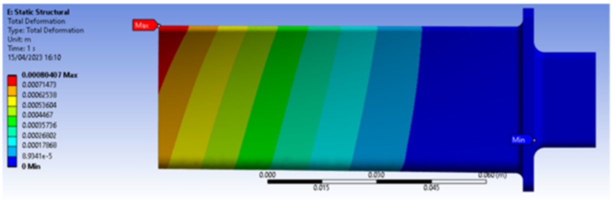

Figure 6 Deformation analysis without thermal load.

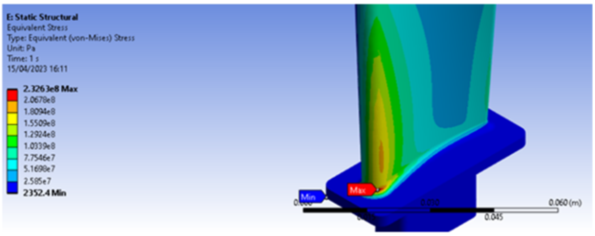

Figure 7 Stress analysis without thermal load.

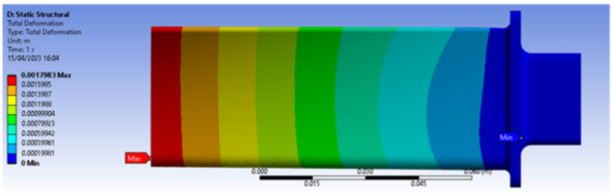

Figure 8 Deformation analysis with thermal load.

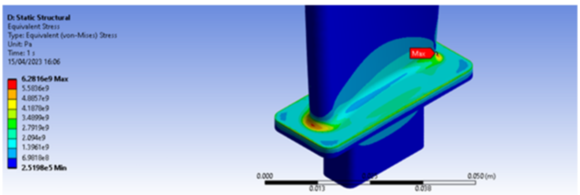

Figure 9 Stress analysis with thermal load.

It can be observed that all selected materials share a maximum temperature of 1200°C. The average temperature varies for each material. Al_2O_3/B_4C and SiC/SiC CMCs showcase lower average temperatures when exposed to 1200°C. This suggests they can effectively mitigate the heat transfer from the hot gas environment to the blade structure. It also indicates that such CMCs have a higher thermal resistance and lower thermal conductivity than nickel superalloys, retaining their cooler temperature under the given operating conditions, minimising heat transfer to the blade structure, and reducing the potential for thermal stresses and material degradation.

Inconel 625 and Hastelloy X demonstrate lower maximum and average stresses compared to Nextel 720, Al2O3/B4C, and SiC/SiC when there is no thermal load applied at the blade structure, demonstrated in Figure 7. This suggests that Inconel 625 and Hastelloy X are better able to withstand the applied loads without exceeding critical stress limits. In terms of deformations, Nextel 720 exhibits the highest maximum deformation, followed by SiC/SiC, Inconel 625, Hastelloy X, and Al2O3/B4C. Similarly, Nextel 720 and SiC/SiC also display larger minimum deformations (showcased in Figure 6) compared to the other materials.

In contrast, Table 3 results indicate the mechanical responses of each material when subjected to the applied thermal loads. The stress values represent the internal forces experienced by the materials (Figure 9), while the deformation values indicate the strain they undergo (Figure 8). It can be observed that Inconel 625 and Hastelloy X demonstrate higher maximum and average stress values compared to Nextel 720, Al2O3/B4C, and SiC/SiC. This suggests that Inconel 625 and Hastelloy X experience greater internal forces and are subjected to higher stress levels under the given thermal conditions. In contrast, Nextel 720, Al2O3/B4C, and SiC/SiC exhibit lower stress values, indicating that these materials can withstand the applied thermal loads with less stress. Similarly, the maximum and minimum deformations of the CMC materials (Nextel 720, Al2O3/B4C, and SiC/SiC) are lower than those of Inconel 625 and Hastelloy X. This implies that the CMC materials exhibit lower deformation or strain when subjected to the applied thermal loads.

These lower stress and deformation values in the CMC materials can be beneficial for the gas turbine blade's performance and lifespan. Lower stresses help to minimize the risk of material failure, while lower deformations contribute to improved structural integrity and dimensional stability. By using CMC materials with lower stress and deformation characteristics, it is possible to enhance the blade's reliability, reduce the likelihood of fatigue or creep-related issues, and potentially extend the component's operational life.

5. Conclusion

The structural and thermal finite element study of the first stage gas turbine blade was performed. The goal of this investigation was to explore the component life in terms of individual and cumulative damage criteria of existing superalloy materials against CMC materials. This would assist in determining which material is preferable based on better performance outcomes.

Turbine applications require materials that keep the temperature as low as possible to maximise the creep life and minimise deformations. From the stress analysis, the materials with lower stress allow for lower minimum and maximum fatigue cycles, which results in higher fatigue life of the application. Furthermore, from the temperature analysis, it was concluded that the lower the temperature, the less cooling air is required. This allows for better overall engine performance.

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References

[1] S. Krishnamoorthi, M. Prabhahar, S. Ali M. Hassan, F. Imam, F. Ahmad. *Design and Analysis of a Gas Turbine Blade by Using FEM.* Recent Advancement in Mechanical Engineering and Industrial Management. AIP Conf. Proceedings 2523, 2023.

[2] B. A. Mohamad, A. Abdelhussien. *Failure analysis of gas turbine blade using finite element analysis*. International Journal of Mechanical Engineering and Technology (IJMET) Volume 7, Issue 3, (2016), 299–305.

[3] J. Hou, B. J. Wicks, R. A. Antoniou. *An investigation of fatigue failures of turbine blades in a gas turbine engine by mechanical analysis*. Engineering Failure Analysis, Volume 9, Issue 2, (2002), 201-211.

[4] D.P Walls, R.E Delaneuville, S.E Cunningham. *Damage tolerance-based life prediction in gas turbine engine blades under vibratory high cycle fatigue*. Journal of Engineering for Gas Turbines and Power, Volume 119, (1997), 143-146

[5] J. Burns. *Gas turbine engine blade life prediction for high cycle fatigue*. The Technical Cooperation Program (TTCP), P-TP1, 1998.

[6] M. Bogdan, J. Blachnio, A. Kulaszka, M. Derlatka. *Assessing the Condition of Gas Turbine Rotor Blades with the Optoelectronic and Thermographic Methods*. Metals, Volume 9, (2019), 31.

[7] M. J. Donachie, S. J. Donachie. *Superalloys: A Technical Guide*. Technology and Engineering, ISBN 0871707497 (2002), 319.

[8] C. A. Estrada. *New Technology used in Gas Turbine Blade Materials.* Scientia et Technica, No 36, ISSN 0122-1701, 2007.

[9] G. Chintala, P. Gudimetla. *Optimum material evaluation for gas turbine blade using Reverse Engineering (RE) and FEA*. Procedia Engineering, Volume 97, (2014) 1332 – 1340.

[10] H. O. Teeple. Nickel and Nickel-Base Alloys. Industrial & Engineering Chemistry, 44 (10), (1952), 2325-2338.

[11] R. H AL-Nafeay, A. O AL-Roubaiy, H Omidvar. *Overview of Joining and Repairing Techniques of Ni-Based Superalloy for Industrial Gas Turbine Applications*. IOP Conf. Ser.: Mater. Sci. Eng. 1094 012141, 2021.

[12] G. Karadimas, K. Salonitis. *Ceramic Matrix Composites for aero-engine applications – a review*. Applied Sciences, Article No. 3017, 13 (5), 2023.

[13] G. Karadimas, K. Salonitis, K. Georgarakis. *Oxide Ceramic Matrix Composite Materials for Aero-Engine Applications: Literature Review.* Proceedings of Advances in Manufacturing Technology, (2021), 1-6.

[14] L. Zhu, N. Li, P.R.N. *Lightweighting in Aerospace Component and System Design.* Tech Briefs, Engineering Solutions for Design and Manufacturing, 2019. Available at: https://www.techbriefs.com/component/content/article/tb/pub/features/articles/33914#:~:text=Selection%20of%20materials%20for%20an,wings%20mainly%20sustain%20bending%20during

[15] Ansys GRANTA EduPack software, ANSYS, Inc., 2022 R2 (www.ansys.com/materials).

[16] J.Xie, J. Pan, Y. Zhu, *Effects of the swirler on the performance of an advanced vortex combustor.* Applied Thermal Engineering, 230, Part A, 2023

[17] R. Colladay. *Turbine Design and Application*; NASA SP 290, Turbine Cooling; National Aeronautics and Space Administration, Lewis Research Center, 3, (1957), 59–101.

[18] G. Creci, M.T. de Mendoça, J.C. Menezes, J.R. Barbosa, J.R. *Heat Transfer Analysis in a Single Spool Gas Turbine by Using Calculated-Estimated Coefficients with the Finite Element Method*. Appl. Sci., *10*, 8328, 2020.

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Development of Banana/Sisal Fiber Reinforced Fully Biodegradable Hybrid Composite Rod – An Effort Towards Sustainable Manufacturing

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Abstract. To fight with global farming, dwindling fossil fuels and waste management issues in agricultural countries; effort has been made to develop fully biodegradable hybrid composite rod from fibers of banana leaf waste and sisal fiber reinforced in polylactic acid (matrix) at a different fiber fraction v/v (0%, 10% (5:5 i.e. B:S), 20%(10:10), 30% (15:15) and 40%(20:20). Rods were made as per ASTM standard (ASTM D7205) by using single screw extruder. The mechanical properties namely: tensile, compression, flexural, bending and impact testing with reference to ASTM standards (ASTM D6641, ASTM D4476 and ASTM D-256 respectively) were evaluated. Results show that pure PLA rod has a maximum tensile strength of 15.82 MPa, compression 33.48 MPa, flexural strength of 13.64 MPa and impact strength 1.98 kJ/m^2. In the case of maximum successful reinforcement (40% by volume), where 20% is banana and 20% is sisal fiber, maximum tensile strength comes out to be 41.32 MPa, compression 77.81 MPa, flexural strength 32.52 MPa and impact strength 4.27 kJ/m^2. Thermal analysis (Differential scanning calorimetry) was also done that shows increase of melting temperature by 14°C-17°C in 40% fiber reinforcement compared to the pure PLA composite. These rods can be successfully utilized in furniture, construction and sports industry.

Keywords. Polylactic Acid, Fully Biodegradable Composite Rod, Mechanical and Thermal Properties.

1. Introduction

Composite materials consists of two or more constituent materials having different chemical or physical properties and when mixed together, produce a material having characteristics completely different from parent materials. In this era of development of new materials with good properties, is going to be a challenge when different processing methods are available with their merits and demerits concerned with reinforcement compatibility with matrix. Composites are classified as non- biodegradable and biodegradable in nature. Biodegradable can be partially or fully,

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depending upon the type of matrix and reinforcement. So where the biodegradability is the main concern, PLA is proved to be an emerging and high potential material as matrix for product development. At present PLA (Polylactic Acid) is widely used in most of the research works and till date work on PLA is going on. PLA are high modulus polymers having high strength and are thermoplastic in nature. Due to their biodegradable nature and common process of extraction and utilization of various biodegradable wastes, its uses are increasing day by day in all the fields of engineering and science. At the initial stage of research of biodegradable polymer, PGA (Poly- glycolic acid) was the first to be synthesized followed by PLA (poly-lactic acid) for their use as implant materials for the repair of various types of tissues (1) (2) (4). In medical field, PLA has been used as a drug delivery matrices and internal fixation of fractured bones (3). Moreover the renowned automotive industries like Mercedes Benz, Tata Motors, General Motors etc. are using these sisal and banana fibers for making plastic based components of their automobiles. Some uses of bio-based composites include internal door trim, seat-back trim, dashboard supports, rear shelves and exterior parts, such as transmission covers etc. These fibers are also used as reinforcement in constructional sector (5-8). Banana plant is a valuable and important bio resource existing in around 120 countries. The area of around 48 lakh hectares has been covered by this resource with annual production of around 100 million (9). The residues coming from the bunch of fruit and the trunk make it more valuable among other plants. Sisal belongs to the family of Asparagaceae. This plant grows in the arid and humid environment. Sisal production throughout world is around 4.5 million tons annually. In India there has been a yield of about 2.5 ton (dry fiber) per hectare annually from the sisal plant.

2. Development of Composite Rod

Composite rod has been developed by treating the reinforcement and matrix to enhance the interfacial bonding between PLA and banana/sisal.

2.1 Material and its Treatment

Both the fibers (Banana and Sisal) were extracted from the leaves of the respective plants. First of all fibers were dried in open sunlight for the removal of moisture for 24 hours for further chopping of the fibers.

(a) (b) (c)

Figure 1. Chopped Banana Fibers (a); Sisal Fibers (b); PLA Pallets (c)

So to develop the BSFRC rod, treatment of fibers is must to enhance the bonding between PLA, banana fibers and sisal fibers so that better physical and chemical properties can be obtained. For the extrusion of rod, there has been a need of fibers in chopped form. So after drying the banana leaves, sisal fibers chopping has been done in mixer grinder to get the size of 600 µm as per requirement (shown in Figure. 1 (a) and 1 (b) respectively). Thereafter to remove the dust and other unwanted contents from the chopped fibers, washing of fibers is done with the use of distilled water at temperature range of 55-65°C for around 1 hour and then they were laid to be dried in open air for the time of 48 hours at room temperature. To remove the lignin form the fibers, NaOH treatment (10%) was given at room temperature, and then again washed with distilled water before drying in open air. Polylactic acid pallets as shown in Figure. 1 (c) of 3052D grade were also dried in oven for 2 hours at the temperature of 70°C to remove the moisture from the pallets so that proper interfacial bonding between fibers and matrix can be attained during the extrusion process.

2.2 Development of Extrusion set up

To get the required size of rod as per ASTM standard, die must be developed accordingly. For the better solidification of rod at the exit, there has been a need of temperature controlled system to manage the temperature gradient over the length of developed die. Mild steel die has been made to extrude the rod. As per the requirement of ASTM D7205, the internal diameter of die has been made. Die is covered by four precisely controlled heaters so that proper solidification can be attained during the extrusion of the composite rod. Complete extrusion set up along with die has been shown in figure no 2.

Figure 2. Single Screw Extruder

2.3 Fabrication of Composite Rod

To develop the composite rod, fibers are mixed in the ratio of 0% (pure PLA), 10% (5% banana and 5% sisal), 20% (10% banana and 10% sisal) 30% (15% banana and 15% sisal) and 40% (20% banana and 20% sisal) (v/v) respectively in PLA matrix. To mix PLA with fibers, coconut oil (less than 1% by volume) is used so that the fibers adhere to PLA granules. Then the required mixture is put down into the barrel having speed of 30 rpm (optimum speed with experiments) and temperature in the range of 130-1600˚C (3 heaters). Samples were made according to ASTM D7205 (shown in Figure. no 3) and named as PLA, PLA/BS1, PLA/BS2, PLA/BS3 and PLA/BS4 having a volume ratio of banana fibers and sisal fibers as 0%, 10%, 20%, 30% and 40% respectively as shown in Figure. no 4.

Figure 3. Single Screw Extruder Sketch showing dimensions of rod as per ASTM D 7205

(a) (b) (c) (d) (e)

Figure 4. Developed Rods- PLA(a); PLA/BS1(b); PLA/BS2(c); PLA/BS3(d); PLA/BS4(e)

3. Results and Discussion

3.1 Mechanical Strength

Figure. no 5(a) to 5(e) indicates the relative variation in mechanical strength of specimens prepared at various fiber fractions of banana and sisal fibers. With the increase in fiber ratio, the strength of composite rod increases. This trend continuous up to 40% fiber fraction.

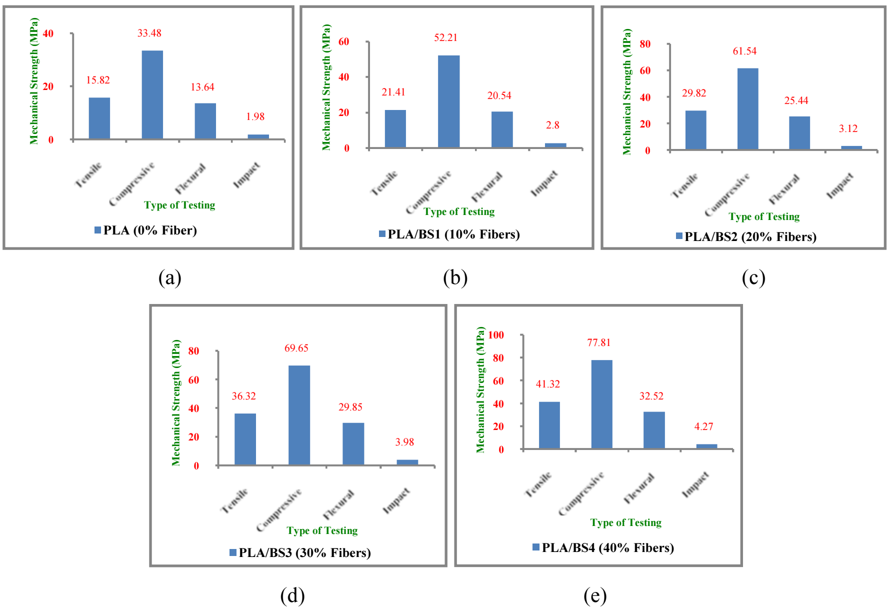
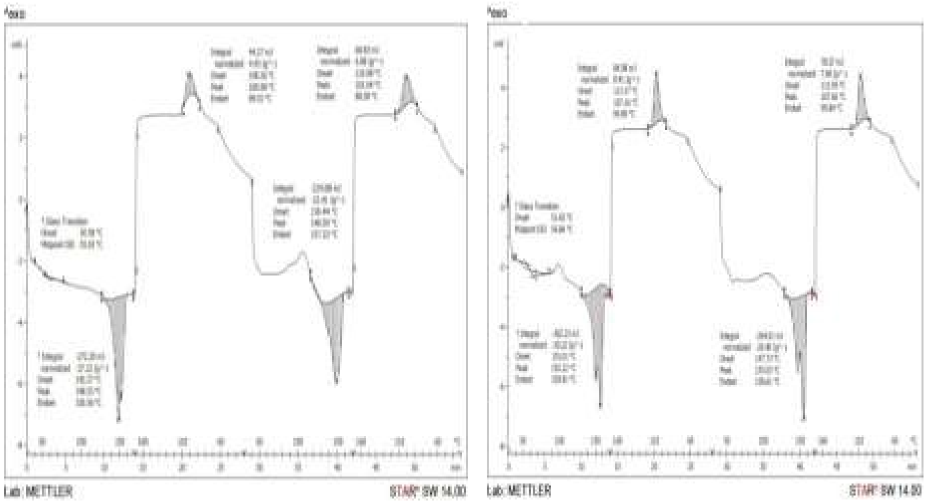


Figure 5. Mechanical Strength of the- pure PLA rod (a); pure PLA/BS1 rod (b); pure PLA/BS2 rod (c); pure PLA/BS3 rod (d); pure PLA/BS4 rod (e)

All these strength values are maximum when the fiber fraction ratio is 40%. The reason behind this was good bonding between the fibers and the matrix. So overall there has been an increase of 161.18 % in tensile strength, 132.40 % in compression strength, 138.41 % in flexural strength and 115.65 % in impact strength with reinforcement of fibers in polylactic acid as compare to pure PLA sample.

3.2 Thermo-mechanical Analysis

It is one very important method to investigate the effects of temperature on the polymers known as glass transition. The ratio of heat flow and heating rate is known as heat capacity of the product under consideration. This testing (DSC) was conducted on the METTLER TOLEDO Star 3 machine. The DSC curves are shown in (Figure. 6 (a) and (b)) for the neat PLA rod and banana sisal fiber reinforced composite rod sample having fiber volume fraction of 40%. Temperature range for the cycle was set between 30°C to 160°C to investigate the thermal transitions. In concern with the melting of the composite sample, it has been observed that melting began in temperature range of 142°C -148°C for neat PLA rod sample (as shown in Figure. no 6 (a)) while for banana and sisal fiber reinforced composite rod sample with 40% fiber fraction, melting starts between 151°C to 155°C. So it is concluded that with the reinforcement of fibers, melting point of developed composite goes up by 14°C-17°C as compare to the neat PLA sample which proved strengthening of composite.



(a) (b)

Figure 6. DSC curve for neat PLA sample (a); DSC curve for PLA/B4 sample (b)

In this work, waste fibers are used in chopped form and good tensile strength has been obtained by developing the fully biodegradable composite rods through extrusion process. Some of the applications where these rods can replace the synthetic rods or wood based composites are: Guide rails, Road markers, Flag whips, Wickets, Greenhouse structures, Selfie stick and Construction of furniture etc.

4 Conclusion

The following conclusions were drawn from the mechanical and thermo-mechanical analysis:

- Full biodegradable composite in form of rod has been developed successfully where both matrix and reinforcement are biodegradable.
- Extrusion found to be the successful method for making composite products like rod by using any type of fiber in chopped form.
- Tensile, compression, flexural strength increased by around 2.5 times at 40% fiber reinforcement having tensile strength of 41.32 MPa at 40% reinforcement whereas for neat PLA it was just 15.82 MPa, in compression testing, maximum strength was 77.81 MPa at 40% reinforcement and 33.48 MPa with neat PLA and in flexural testing, value found to be 32.52 MPa at 40% reinforcement and 13.64 MPa with neat PLA.
- In case of impact testing, strength observed was around 2 times with maximum value of 4.27kJ/m^2 at 40 % reinforcement and 1.98 kJ/m^2 when neat PLA sample was tested.
- Differential scanning calorimetry (DSC) revealed that the melting point of composite enhanced by around 15.5°C with 40% reinforcement as compare to neat PLA that shows enhancement in the properties of the developed composite.

Acknowledgements

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References

[1] E.J Fruzza and E.E Schmitt, A new Absorbable Suture, *Journal of Biomedical Materials Research*, **5** (1971), 68-73.

[2] A.M Reed, and D. K. Gilding, Biodegradable Polymers for use in Surgery: PGA/PLA Homo- and Copolymers, *Polymer*, **22** (1981), 494–498.

[3] M. Vert, S.M. Li, G. Spenlehauer and P. Guerin, Bioresorbability and Biocompatibility of Aliphatic Polyesters, *Journal of Materials Science: Materials in Medicine*, **3** (1992), 432–446.

[4] B.D Ratner, A.S. Hoffman, F.J Schoen and J.E. Lemons, Biomaterials Science: An Introduction to Materials in Medicine, *Society of Biomaterials, Academic Press*, (1996), 37–130.

[5] Reck, Bernd, and J Türk, Thermally curable aqueous acrylic resins–a new class of duroplastic binders for wood and natural fibers, *Die Angewandte Makromolekulare Chemie*, **272** (1999), 5-10.

[6] Panthapulakkal, Suhara, and M. Sain, Injection-molded short hemp fiber/glass fiber-reinforced polypropylene hybrid composites—Mechanical, water absorption and thermal properties, *Journal of applied polymer science*, **103** (2007), 2432-2441.

[7] Herrera-Estrada, Lina, S. Pillay, and U. Vaidya, Banana fiber composites for automotive and transportation applications, *8th annual automotive composites conference and exhibition (ACCE)*, (2008), 16-18.

[8] Nigrawal, Archana, A.K. Sharma, and F.Z. Haque. *Sisal Fibre Based Polymeric Composites*, *Fiber-Reinforced Plastics*, Intech Open, 2021.

[9] https://nhb.gov.in/area-pro/database-2011.pdf, assessed on 15 January, 2023.

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Design and the Development of an Anemometer Positioning System

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Abstract. *Measurement of air flow through a fan is required during routine testing of several student projects using an existing two-metre-long wind tunnel at the University. Measurements of air velocity uses a handheld weather kit anemometer which is connected to a data logger. Inaccuracies in holding the equipment resulted in the basis of a project. This paper investigates and reviews the findings of the project, based on designing, prototyping, and evaluating a suitable system to hold the anemometer and allow positioning of it at any desired position within the cross-section of the wind tunnel. A rail system allows the anemometer to be positioned in the Z-axis for shorter wind tunnels, or in close proximity to fans without the tunnel or ducting. The paper shows the methodology of the design process, the development of a working prototype and the implementation of the initial readings.*

Keywords: Experimental methods; design and manufacture, design, and simulation.

1. Introduction

A regular project held in the first year for manufacturing students is to design and manufacture fan blades. The fan performance is currently determined by evaluating the velocity of the downstream airflow, a value which is obtained through experimentation within a wind tunnel. Currently, airflow velocity is measured by means of a handheld anemometer positioned at the exit of the wind tunnel (**Figure 1**). Holding the anemometer for long periods can induce errors in the readings. Ligęsa (2018) discusses some of these errors. This formed the basis for the project: to design, manufacture and evaluate a rail system, where an anemometer can be mounted and used in conjunction with a data logger. Furthermore, it was also suggested that the uniformity of airflow can be evaluated by placing the anemometer at any position within the specified envelope of airflow, thereby capturing a velocity distribution across a designated measurement plane. The data logger has a number of modes, where a timed duration of data collection is required for statistical analysis. This reinforces the need for the

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positioning system as hand movements are likely to induce further errors when undertaking timed experiments.

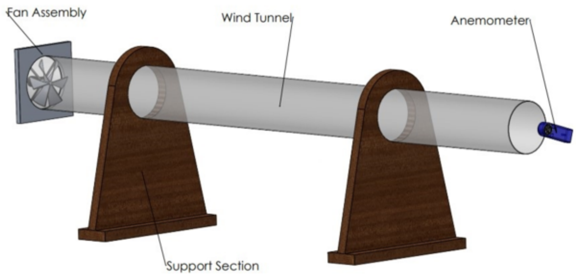

Figure 1. Existing set-up of the tunnel with positions of the fan and anemometer.

2. Project Methodology

Following the implementation of a Gantt chart, project risk analysis and review of resources, the development of a full product design specification (PDS) was carried out. Candidate solutions were then proposed based on the requirements of the PDS and available materials that would allow the project to be prototyped to the project budget of £200.

The four concept designs **(Figure 2)** were evaluated using the Analytical Hierarchy Process (AHP). Saaty (1987) reviews the key benefits of this analytical tool for decision-making, which is highly justified for this type of project.

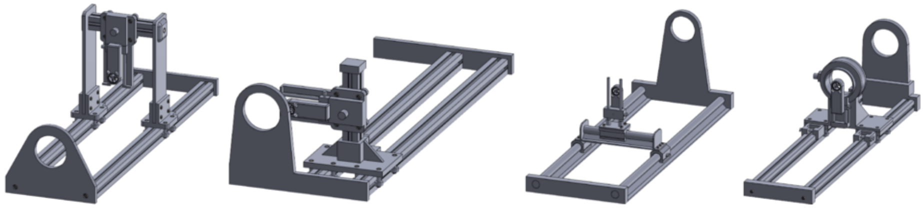

Figure 2. Four concept designs for the proposed new positioning system

Within the concept designs there was a strong desire to utilise the University's facilities; in particular laser cutting, additive manufacturing and traditional project workshop. The system had to accommodate the existing anemometer, which forms part of a weather kit. Dimensions are shown in **Figure 3**.

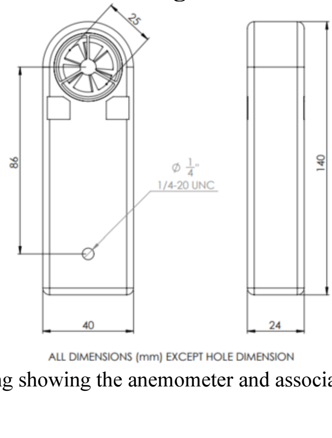

Figure 3. Drawing showing the anemometer and associated dimensions.

Currently a 2 m long single wind tunnel is used for project work, but the University is keen to acquire more wind tunnels of different lengths to enable a wider scope of projects. The building stage of the project was around 8 weeks, which constrained the manufacturing time. Designs needed to minimize costly outsourced parts, whilst balancing the in-house machining. Part sizes and the final design were based on worst-case scenario loading calculations, and the final design was evaluated using finite element analysis (FEA) to review von mises stresses and displacements of members.

3. Detailed design

The final design, as shown in **Figure 4**, presented a range of challenges. It is important to emphasize the need to fully evaluate the potential resources for this type of bespoke project. One of the first key issues was to source a type of economical bearing to use for the radial movement of the anemometer on the carriage. Given the high cost of bearings, a common serving table bearing, known as a "Lazy Susan" was utilised as the main bearing. This was very cost effective did not require any modifications. The rail system had been investigated early in the project during the definition stage as part of the feasibility study. Similar previous projects with rail-type components had employed aluminium alloy extrusion which is readily available in a range of sections and sizes. A 20 mm x 20 mm V-slot was selected which was available with runners.

Another major part of the design was the gantry which utilised prefabricated plates, although extra members were needed to join them together. A relief gap was included between the two gantry plates to mitigate issues with poor alignment of the extrusion rails. This may not have presented itself as a problem on completion of the project, however over time misalignment can occur due to repeated use and accidental mishandling. **Figure 5** shows the linear stage spacers that were incorporated into the carriage system and locking nuts, which were removed from bicycle quick-release spindles.

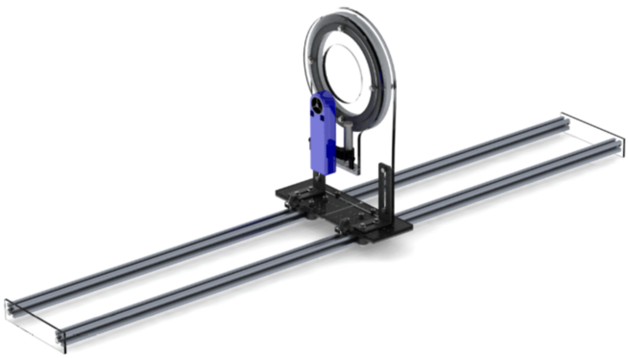

Figure 4. Final design of the complete rail system.

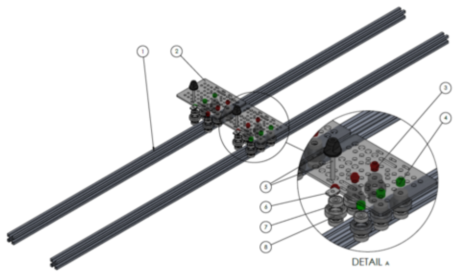

Figure 5. Gantry plates, bottom plate assembly including locking nuts.

A design for manufacture and assembly (DFMA) approach was sought, to help facilitate the production and assembly. Principles were sought from a range of sources and are covered extensively by Bayoumi (2000). Areas of the design required moving parts which had to be locked into position. The vertical movement of the anemometer required a column mount or dual mounts with a lockable moving bracket. This was more difficult to source than the extrusion, as the design needed to allow for the existing anemometer and the surrounding parts. Existing camera mounting equipment offers a range of brackets in sizes which are suitable. These were obtained but did requiring further machining (shortening, facing off and tapping a thread for end caps at the top and the mounts at the bottom). One of the latter challenges was to provide a locking method for the main rotating bearing. Initially, parts were planned to be fabricated, however the complexity and lead-time, it was decided that using toggle clamps, as shown in **Figure 6** as these could be fitted directly onto the main supporting member. Two clamps are required, since at some positions a single clamp would interfere with the bolts on the main bearing.

Materials selection was carried out using appropriate materials selection software. The most suitable polymeric sheet for this project considers polycarbonate. However, this would have increased the project cost and increased the lead time on delivery. For a working prototype model, PMMA (acrylic) was readily available. Calculations on the stresses and displacements were completed and verified the suitability for use in the prototype. The sheet acrylic was used for most of the large section pieces. Laser cutting was efficient and there were a few changes to the plate designs were required after student-mentor meetings, which required fresh pieces to be cut. This did not add any lead time and minimal costs, which had an advantage over additive manufacturing in this case.

Figure 6. Toggle clamp used to lock the main bearing.

The main concerns governing the final design were to ensure that friction, rigidity, alignment, and repeatability were not compromised in any way. Rigidity was verified using finite element analysis (FEA) software. Manufacturing/modifying parts took around 8 hours. This allowed time for initial testing.

3.1. Testing and FEA simulation-based results evaluation

Finite Element Analysis (FEA) was conducted on parts to ensure that the factor of safety was appropriate for all conditions. The factors in some areas were considerably higher than they needed to be; although there was no benefit from removing more material and this would have resulted in higher deflections. The maximum stress from static simulation was found to be 9.2 MPa with a minimum factor of safety (FOS) to be 19 **(Figure 7)**.

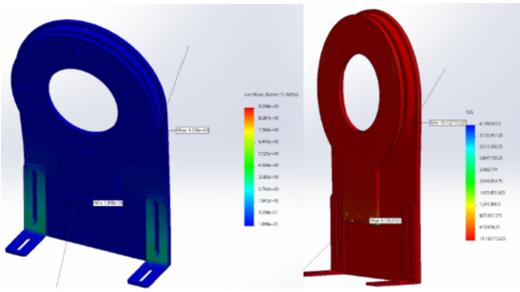

Figure 7. FEA static structural simulation shown maximum stress and factor of safety (FOS).

Previous tensile testing of this particular grade of PMMA was found to be 50 MPa. The presence of holes for bolts added stress concentration sites which could not easily be avoided. Impact forces are not anticipated for this type of testing however any attempt to remove material may have made the structure more prone to localised brittle failure through accidental impacts. Weight was not excessive and any attempt at reduction through optimisation could have had similar consequences.

Computational Fluid Dynamic (CFD) modelling was carried out prior to testing, so that some comparisons could be made to the actual initial testing. **Figure 8** shows the results, which evaluated the velocity streams moving through the main bearing and the pressure on the assembly.

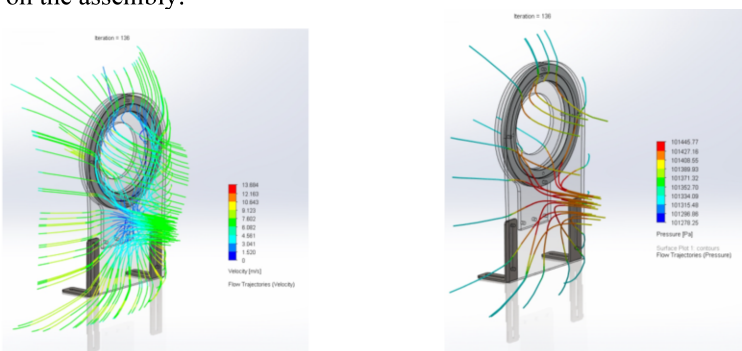

Figure 8. CFD modelling of the air velocity (left image) and pressure (right image) on the main plate.

The initial testing was limited to the length of the wind tunnel, as well as some close proximity testing to a fan. A grid of velocity measurement points was devised, and readings could then be taken with the data logger at these points. The layout is shown in **Figure 9**. The data logger was operated in statistics mode, which requires a timed interval from which the maximum, minimum, mean, and standard deviation are computed with a graph displaying the output overall the interval.

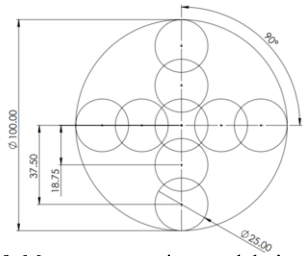

Figure 9. Measurement points used during initial testing.

4. Conclusions

The project culminated in the production of a successful working prototype, as shown in **Figure 10**.

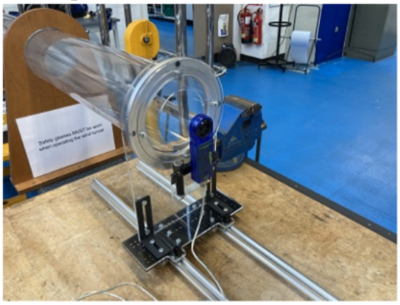

Figure 10. Positioning system set up at the end of the wind tunnel to carry out initial testing.

This was tested and yielded interesting results. One area that could be developed further is to consider adding a coordinate measurement system. concentrations in design work as well promote laboratory testing. The next stage requires a set of shorter length wind tunnels which would allow for testing in the Z-plane. Another possible expansion of this project could include using a smaller anemometer, or possibly even a pitot tube, which could yield more results in the field area of testing in the X-Y plane. Reduction of variables in wind speed is another area of improvement, which would allow for comparisons between measurement equipment used on the wind tunnels, as well as projects. There is a large scope of research activities which can be carried out, although factors affecting the anemometer need to be evaluated, as discussed by Morris, Beck, and Hosni (2001) before projects researching into the fans (or wind tunnels) can be carried out. This successful project will allow for future projects to now be undertaken which is likely to attract interest from students, sponsoring companies, and staff within the engineering department.

References

[1] Ligęza, P. (2018). Model and simulation studies of the method for optimization of dynamic properties of tachometric anemometers. *Sensors*, *18*(8), 2677.

[2] Saaty, R. W. (1987). The analytic hierarchy process—what it is and how it is used. *Mathematical modelling*, *9*(3-5), 161-176.

[3] Bayoumi, A. M. E. (2000). Design for manufacture and assembly (DFMA): Concepts, benefits and applications. In *Current advances in mechanical design and production VII* (pp. 501-509). Pergamon.

[4] Morris, D. M., Beck, B. T., & Hosni, M. H. (2001). Experimental determination of the effects of turbulence intensity on the performance of rotating vane anemometers. *ASHRAE Transactions*, *107*, 215.

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Automatic Process by Turning and Single Roller Burnishing Process on 6063 Al Alloy: Optimization and Implementation

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Abstract. This research studies the feasibility of automatically combining the final turning and roller burnishing processes on Aluminum alloy 6063 (Al6063). Identifying the optimal process parameters yields the desired surface quality. The burnishing process is widely used to enhance the machining quality by improving the surface finish, fatigue layer, and corrosion resistance. this research designed the single roller burnishing tool with spring constant for the final fishing process by automatic tool change on the CNC lathe machine. An important part was conducted experimental design methods to optimize the parameters affecting the burnishing process and implementation. The results showed the parameters affecting the surface roughness after burnishing are feed rate and burnishing force. The implementation of the model prediction can be reduced the surface roughness from 0.365 µmRa to 0.090 ± 0.002µm Ra and 0.927 ± 0.04µmRz. while being able to generate the affected layer of approximately 60 µm.

Keywords. Automatic process of Al6063, single roller burnishing tool, work affected layer, final finishing surface.

1. Introduction

6063 Aluminum alloy (Al6063) is commonly utilized in such applications due to its high strength-to-weight ratio and excellent corrosion resistance. Al6063 mainly contains magnesium (Mg) and silicon (Si) with the strength of the alloy. It provides a good surface finish after machining. The requirements of the high finish surface, it commonly performed on several surface treatment processes after machining. This leads to a long period and a loss of surface texture and dimensional accuracy. In addition, the machining process of the Al6063 shaft cannot achieve the surface finish at the nanometre level and the mirror finishing surface that is lower than 0.1 µm has not been thoroughly addressed and researched in such a typical method.

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Various researchers have attempted to determine the effectiveness of the parameters affecting turning operations on CNC lathes. A surface roughness of 0.36 µm*Ra* was obtained by the automatic turning of Al6063 alloy on CNC lathes using Takushi analysis [1] and the machining of aluminum alloy grades 6063 with tungsten carbide (WC+Co) insert by deep cryogenic treatment gives a surface roughness of 0.373 µm*Ra* with optimal parameters [2]. They demonstrated the effectiveness of the parameters in turning Al6063. The burnishing process is widely used as the super-finishing process to enhance the machining quality by improving the surface finish, fatigue layer, and corrosion resistance. And it is also well known as the plastic formation process. Important mechanistic characteristics of that process. After the machining process, the mechanism presses against the surface at a point (peak to valley) causing a new rearrangement of subsurface structures as a result, it improves surface hardness, which increases the fatigue layer at surface stress points the methods utilized to improve the surface finish at the nano-level.

Numerous studies investigated the controlling constant burnishing force that can be classified into various methods such as the use of hydraulic pressure to apply the burnishing force of hardened steel [3] a hydrostatic burnishing tool affecting residual stress of AISI 8620 steel [4] the burnishing tool uses a constant compression of the spring [5-7] these burnishing tools have been applied to different materials. Due to the use of hydraulic pressure, it is suitable for burnishing in workpieces with high surface hardness. On the other hand, the burnishing tool with spring constant force most are suitable for applications where ductile properties and surface hardness are not very hard materials.

Therefore, this research designed the single roller burnishing tool for the final fishing process by automatic tool change on the CNC lathe machine. An important part was conducted experimental design methods to optimize the parameters affecting the burnishing process and implementation.

2. Experiment procedure

2.1. The single roller burnishing tools.

This experiment aims to design a burnishing tool with spring constant pressure and considered the shapes of the burnishing roller and tip. Previous research studies, it was found that there are many techniques for burnishing tools such as flat-faced roller burnishing tips [8] a ball or sphere diameter of 6 mm [9], and Single toroidal roller burnishing tips [7] etc. In this study, the single toroidal roller burnishing tip was considered due to free rotation during the process. Able to press workpieces having a complex shape, a burnishing tool has been designed as shown in Fig. 1A. The distinctive feature of this tool is during the burnishing process the spring shaft cannot be twisted and rotated while pressing because it was controlled by the spring shaft hole with a guiding groove. A single roller is made from hardened tool steel having a radius of 5 mm installed with a pin bearing inside. The spring compression of the burnishing tool was performed on the compression testing machine as shown in Fig.1B. Three levels of spring stiffness are selected for the burnishing force conditions: 25 N/mm for 50 N, 40 N/mm for 200 N, and 80 N/mm for 350 N respectively.

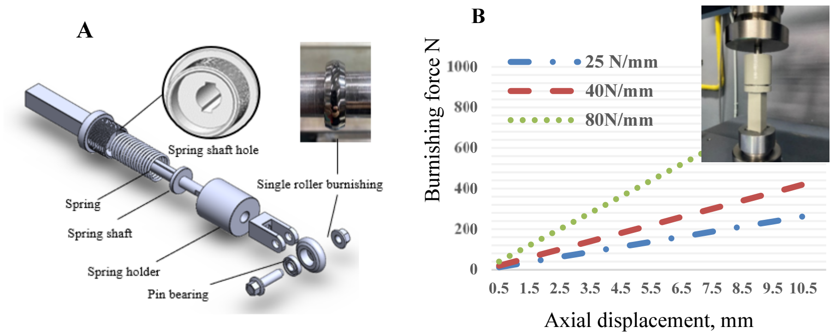

Figure 1. The 3D exploded view of a single roller burnishing tool (A) and spring compression test (B)

2.2. Experimental setup and initial turning conditions.

The experiment was carried out at the CNC lathe machining center (HAAS ST-20L). The roller burnishing tool was installed on automatic tool changers as shown in Fig. 2. This study was performed consisted of 3 main processes: the first is a rough turning process to remove the outer of the workpiece approximately -0.5 mm, the second is finished turning, in which the parameters have been studied in the previously achieved machining of aluminum alloy within 0.373 µm*Ra* which can be applied in this finish turning of Al6063 [1-2]. The turning parameters are a spindle speed of 2500 RPM, feed rate of 0.5 mm/rev and depth of cut of 100 µm with cutting tool insert MITSUBISHI code TNMG160402L-2G NX2525. When the accuracy of 10 pieces was determined, the surface roughness values were 0.365 ± 0.08µm*Ra* and 2.359 ± 0.5µm*Rz*. Therefore, these parameters were chosen as initial turning conditions. And the final process is roller burnishing tool.

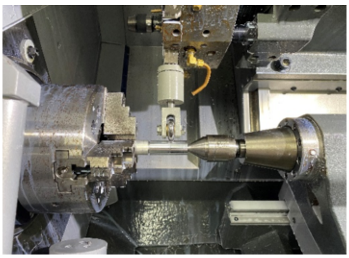

Table 1. The cutting parameters and their levels.

Machining parameter		Low	center	High
Feed rate (mm/rev)	**(A)**	0.001 (-1)	0.005 (0)	0.01 (1)
Spindle speed (RPM)	**(B)**	500 (-1)	1250 (0)	2000 (1)
burnishing force (N)	**(C)**	50 (-1)	200 (0)	350 (1)

Figure 2. The installation of the burnishing tool on the CNC lathe machine.

2.3. Analysis of Variance (ANOVA)

In machining, the influence of spindle speed, feed rate and burnishing force on surface roughness were investigated. The burnishing experiments were conducted based upon the centered of central composite design (CCD) methodology with 2 replications. Thus, total of cutting tests including 40 run orders that were carried out as per design matrix. Furthermore, machining parameters and their levels used for burnishing are shown in Table 1.

3. Experimental results and discussion

3.1. Statistical analysis

we obtained the analysis of variance of surface roughness as shown in table 2. The analysis was performed at significance level of 0.05. Thus, it means factor will be main effect or interaction effect on surface roughness when their term has p-value less than 0.05.

Table 2. Analysis of variance of surface roughness value

Model	0.8305	9	0.0923	38.26	< 0.0001	significant
A-Feed rate	0.0187	1	0.0187	7.74	0.0092	
B-Spindle speed	1.86E-06	1	1.86E-06	0.0008	0.978	
C- Burnishing force	0.4518	1	0.4518	187.36	< 0.0001	
AB	0.0012	1	0.0012	0.4871	0.4906	
AC	0.0123	1	0.0123	5.09	0.0315	
BC	0.0012	1	0.0012	0.5145	0.4787	
A^2	0.032	1	0.032	13.25	0.001	
B^2	0.0003	1	0.0003	0.129	0.722	
C^2	0.1002	1	0.1002	41.55	< 0.0001	
Residual	0.0723	30	0.0024			
Lack of Fit	0.0514	5	0.0103	12.26	< 0.0001	significant
Pure Error	0.021	25	0.0008			
Cor Total	0.9028	39				
R-sq = 91.99% R-sq(adj) = 89.58% R-sq(pred) = 85.94%						

A variance analysis of the surface roughness (Ra) components was made with the objective of analyzing the influence of feed rate, spindle speed, and burnishing force. The main factors significantly influence on the surface roughness were feed rate and burnishing force. Especially, burnishing force has strongest main effect on surface roughness. The interaction effect on the surface roughness were between feed rate and burnishing force. While the square term of feed rate and the square term of burnishing force have the effect on surface roughness. The interaction plots are shown in Fig.3A, illustrate the evolution of the surface roughness.

Figure 3B shows the optimized plot of the burnishing parameters. By adjusting the position of the vertical chain line, variation in the output is evaluated. Which, the optimized values of the burnishing process are feed rate of 0.0056 mm/min, Spindle speed of 2000 RPM and burnishing force of 110.61 N. the optimizer model provides the surface roughness value is 0.0799 µm*Ra*

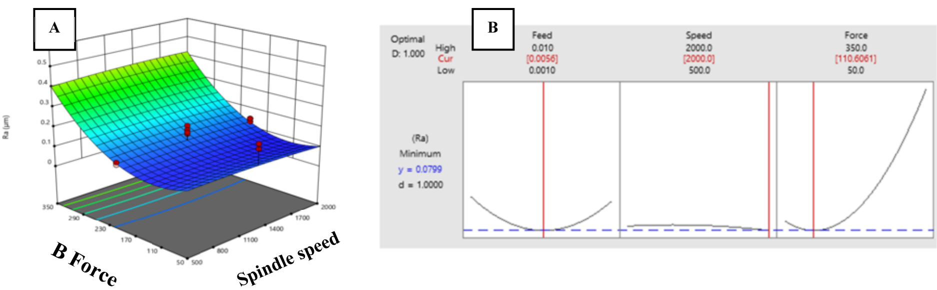

Figure 3. The interaction of burnishing parameters: Feed rate & Burnishing force (A) and the optimize of surface roughness model (B).

3.2. Implementation of the surface roughness obtained by the optimized parameters.

Figure 4A shows a comparison of the two finished surfaces generated by the final turning and the roller burnishing tool, which seen the burnishing process will be smoother than the final turning when observed from the letters reflected on the surface of the workpiece. In addition, when observing the magnified SEM image as shown in Fig. 4B, the surface is smooth without previous machining marks and waviness on the surface. The implementation of this process can be automatically reduced the surface roughness from 0.365 µm to 0.088 µm*Ra* under the conditions of the model prediction at a spindle speed of 2000 RPM, feed rate of 0.005 mm/rev, and burnishing force of 110N as shown in Figure 4C. In addition, the accuracy of 10 pieces, it was found that the surface roughness values were 0.090 ± 0.002µm*Ra* and 0.927 ± 0.04µm*Rz*. And the roundness value of the burnishing process can be reduced from 6.2 ± 1.2 µm to 3.3 ± 0.2 µm due to uniform rolling pressure, resulting in the workpiece being better roundness. The results can be confirmed that the burnishing tool under this model prediction can be used in an application for aluminum Al6063.

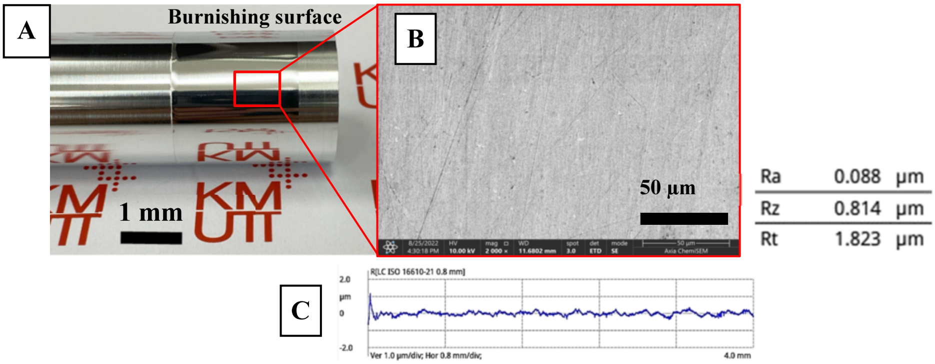

Figure 4. The finished surface of Al6063 by Final turning and burnishing tool (A), the magnified SEM image (B), and the surface roughness of the burnishing process(c)

3.3. Surface cross-section analysis from EBSD and hardness

Figure 5A shows surface cross-section images by EBSD, the subsurface structure after the roller burnishing tool can be seen in the grain on top has a finer size and flattened shape with a depth of approximately 50-70 µm from the edge of a workpiece. which can be assumed that this phenomenon is caused by the roller burnishing force while being able to generate the affected layer. When considering the hardness value as shown in Fig. 5B, it was found that the hardness value from the workpiece edge increased by about 140 HV and gradually decreased until reaching the normal hardness value at 81 HV at a depth of about 60 µm.

4. Conclusion

An automatic combining the final turning and roller burnishing processes on Aluminum alloy 6063 (Al6063) specimens was established through an experimental study. The following conclusions can be made.

- The following ideal single burnishing process parameters were determined using a CCD experiment and model prediction under a minimum roughness: Using a spindle speed of 2000 RPM, a burnishing force of 110 N, and a feed rate of 0.005 mm/rev, the average roughness is expected to Ra =0.0799µm*Ra*.
- The implementation of the model prediction can be reduced the surface roughness from 0.365 µm*Ra* to 0.090 ± 0.002µm*Ra* and 0.927 ± 0.04µm*Rz*.
- The EBSD analysis results confirm the effectiveness of the roller burnishing tool of (Al6063) able to generate the affected layer of 50-70 µm with significant increase the surface hardness on the edge by 72 %

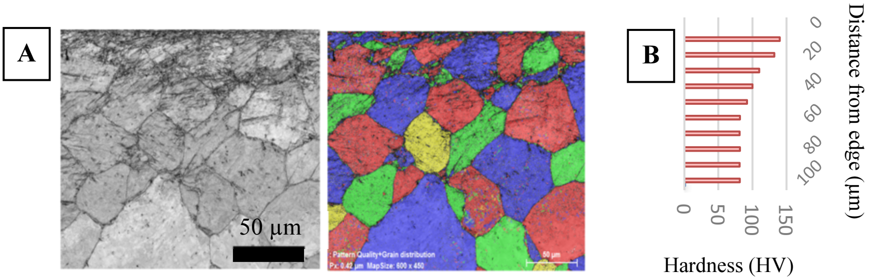

Figure 5. The EBSD image of Al 6063 surface cross-section generated by burnishing tool (A) and Hardness from edge (B)

References

[1] A Saravanakumar, A., Karthikeyan, S. C., Dhamotharan, B., and kumar, V. G. (2018). Optimization of CNC Turning Parameters on Aluminum Alloy 6063 using TaguchiRobust Design. Materials Today: Proceedings 5, (2017), 8290–8298.

[2] Arunkarthikeyan, K.and Balamurugan, K. Studies on the effects of deep cryogenic treated WC–Co inserts on turning of Al6063 using multi-objective optimization. SN Appl. Sci. 2, 2103 (2020). https://doi.org/10.1007/s42452-020-03940-3

[3] Liviu Luca, Sorin Neagu-Ventzel, and IoanMarinescu, Effects of working parameters on surface finish in ball-burnishing of hardened steels, Precision Engineering 29, (2005), 253-256

[4] Abdulaziz J. Alshareef, Ioan D. Marinescu, Ibrahim M. Basudan, Bader M. Alqahtani, and Mohammed Y. Tharwan, Ball-burnishing factors affecting residual stress of AISI 8620 steel, The International Journal of Advanced Manufacturing Technology 107, (2020), 1387–1397

[5] Ramon Jerez-Mesa, Jose Antonio Travieso-Rodriguez, Giovanni Gomez-Gras, Jordi Lluma-Fuentes, Development, characterization and test of an ultrasonic vibration-assisted ball burnishing tool, Journal of Materials Processing Technology 257, (2018), 203-212

[6] V. Jaya Prasad, K. Sam Joshi, V.S.N. Venkata Ramana, and R. Chiranjeevi, Effect of Roller Burnishing on Surface Properties of Wrought AA6063 Aluminium Alloys, Material today proceeding 5, Issue 2, Part 2, (2018), 8033-8040

[7] G.V.Duncheva, J. T. Maximov, V. P. Dunchev, A. P. Anchev, T. P. Atanasov and Jiri Capek, Single toroidal roller burnishing of 2024-T3 Al alloy implemented as mixed burnishing process, The International Journal of Advanced Manufacturing Technology 111, (2020), 3559–3570

[8] Samuel José Casarin, Luiz Eduardo De Angelo Sanchez, Eduardo Carlos, Bianchi, Vicente Luiz Scalon, Renan Luis Fragelli, Eduardo Luiz De Godoi, and Maria Da Penha Cindra Fonseca, Effect of burnishing on Inconel 718 workpiece surface heated by infrared radiation, Materials and Manufacturing Processes, V.48, (2021), 1853-1864

[9] M.R. StalinJohn, A. WelsoonWilson, A. Prasad Bhardwaj, Avinav Abraham, and B.K. Vinayagam, An investigation of ball burnishing process on CNC lathe using finite element analysis, Simulation Modelling Practice and Theory 62, (2016), 88-101

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Investigating the Influence of Fiber Orientation on Tensile and Flexural Properties of Additively Manufactured Continuous Glass Fiber-Reinforced Nylon Composites

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Abstract. Additive Manufacturing (AM) has revolutionized the manufacturing industry by enabling the fabrication of complex and customized components with unprecedented design freedom. In recent years, there has been a significant focus on extending the capabilities of AM to produce fiber reinforced composites, which offer exceptional mechanical properties and enhanced performance characteristics. This article evaluates the tensile and flexural (three-point bending) properties of additively manufactured continuous glass fiber-reinforced nylon composites (CGFRNCs). Composites are designed using constant fiber volume fraction (V_f) and variable fiber orientations ($\boldsymbol{\theta}$) by US-based Markforged's 'Mark Two' 3D printer. V_f is 27% for all composite coupons and $\boldsymbol{\theta}$ is varied by 0°, 45°, 90°, and 135° (or -45°). Experimental results show the maximum tensile strength of 225.78 MPa for 0° and maximum flexural strength of 82.84 MPa also for 0°. Damage analysis has been carried out in X-ray Micro Computed Tomography.

Keywords. Additive Manufacturing, Composites, Fiber orientation.

1. Introduction

Additive Manufacturing (AM), also known as 3D printing, is a layer-by-layer technique of joining successive layers of materials on top of each other to create objects from digital 3D CAD model data, opposed to traditional subtractive manufacturing [1,2]. AM has recently attracted significant interest over traditional manufacturing techniques, owing to its several benefits such as the ability to fabricate complex shapes, design flexibility, mass customization, low manufacturing costs, automated processes, reduced waste, improved dimensional accuracy, and fast prototyping [3]. Nowadays composites are popularly being manufactured by additive manufacturing. Hence, this work focuses on effective design for additive manufacturing (DFAM), fiber parameterization, and optimization to get effective mechanical properties. Ibrahim M Alarfi et. al. [4] reported the tensile and flexural strength for short glass and carbon fiber reinforced nylon composites. Andrew N Dickson et. al. [5] reported the tensile and flexural strength for continuous glass, carbon, and kevlar fiber reinforced nylon composites for 0° fiber orientation only. Our study claims the variation of fiber orientation using a fixed fiber volume fraction for glass fiber reinforced nylon composites.

2. Materials and methods

For making composites by Additive Manufacturing, Nylon-6 filament of 1.75 mm diameter was used as a matrix material and continuous glass fiber bundle of 0.3 mm diameter was used as a reinforcement material. Both materials were purchased from Markforged, USA. Markforged produces its own proprietary materials for its 3D printers. 'Mark Two', a thermoplastic composite 3D printer by Markforged was used to manufacture these composites. This printer has two nozzles fitted in a single extruder where one nozzle is for matrix material, and another is for reinforcing fiber. Before usage, Nylon-6 was kept in a Pelican-1430 modified dry box that was sealed against the infiltration of moisture. The fiber bundle contains 1000 individual fiber tows and appeared to be each of 10 μm diameter based on Scanning Electron Microscopy (SEM) images. These tows are infused and held together by a sizing agent i.e., also Nylon-6. Printing starts with the deposition of Nylon-6 by nozzle-1 followed by deposition of glass fiber by nozzle-2. Fig. 1 shows the nylon-6 and glass fiber spools followed by 'Mark Two' 3D printer, schematic of CFF process, and geometries of tensile and flexural specimens.

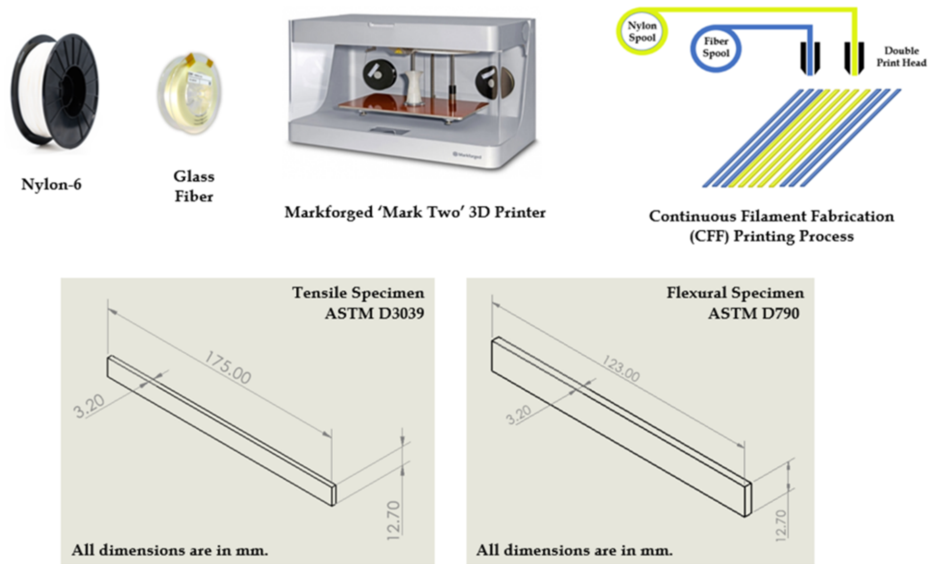

Figure 1. Materials, methods, and specimens' geometry

3. Results and discussion

3.1. Experimental results

Tensile and flexural tests were performed on Zwick Roell 250 UTM machine. For tensile test, the specimen is securely clamped between upper and lower jaws, encompassing 50 mm on each side, resulting in a gauge length of 75 mm. Flexural specimens was having span length of 51.2 mm that is 16 times of specimen thickness. And the load was applied to the centre of the specimen. Constant rate of elongation (CRE) theory was followed to perform both tensile and flexural test by applying constant strain rate of 2 mm/min and 2.2 mm/min respectively.

Tensile strength ($\boldsymbol{\sigma_t}$) is a measure of elongation force applied per unit cross-sectional area and is calculated as

$$\boldsymbol{\sigma_t = F/A}$$

Flexural strength can be calculated as,

$$\boldsymbol{\sigma_f = \frac{3FL}{2bh^2}}$$

And flexural strain will be calculated as,

$$\boldsymbol{\in_f = \frac{6h\delta}{L^2}}$$

Where, $\boldsymbol{\sigma_f}$ - Flexural stress, $\boldsymbol{\in_f}$ - flexural Strain, **F** – force applied, **b** – specimen width, **h** - specimen thickness

$\boldsymbol{\delta}$ – deflection, L – span length, A – cross-sectional area

3.1.1. Effect of fiber orientation on tensile strength

TNG1 specimen, with a fiber orientation of 0°, exhibited the highest tensile strength of 225.78 MPa. This outcome can be attributed to the fact that the fibers in this configuration were aligned parallel to the applied load, allowing for efficient load transfer along the fiber axis. On the other hand, the TNG2 specimen with a 90° fiber orientation demonstrated significantly lower tensile strength of 20.06 MPa. In this case, the fibers were oriented perpendicular to the loading direction, leading to reduced load-bearing capacity and increased vulnerability to fiber delamination and interfacial failure. Similarly, the TNG3 specimen with a 45° fiber orientation displayed a tensile strength of 24.76 MPa, indicating a compromised load-bearing capability due to the inclined alignment of fibers. Finally, the TNG4 specimen, which incorporated a combination of 0°, 45°, 90°, and -45° fiber orientations, exhibited an intermediate tensile strength of 181.67 MPa.

Table 1. Tensile strength data of specimens

Sample ID	Fiber orientation	Tensile Strength (MPa)	Tensile Strain (%)	Tensile Modulus (GPa)
TNG1	0°/0°/0°/0°	225.78	5.01	3.95
TNG2	90°/90°/90°/90°	20.06	15.63	0.497
TNG3	45°/45°/45°/45°	24.76	12.25	0.505
TNG4	0°/45°/90°/-45°	181.67	5.28	4.48

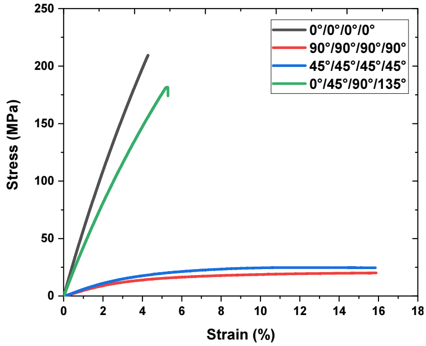

Figure 2. Stress strain curve for tensile strength

3.1.2. Effect of fiber orientation on flexural strength

FNG1 specimen, with a fiber orientation of 0°/0°/0°/0°, exhibited the highest flexural strength of 82.84 MPa. This result can be attributed to the fact that the fibers were aligned parallel to the applied load, allowing for efficient load transfer and resistance to bending stresses. In contrast, the FNG2 specimen, with a 90°/90°/90°/90° fiber orientation, displayed a significantly lower flexural strength of 24.93 MPa. In this configuration, the fibers were oriented perpendicular to the loading direction, leading to reduced load-bearing capacity and increased vulnerability to interlaminar shear and delamination. Similarly, the FNG3 specimen with a 45°/45°/45°/45° fiber orientation exhibited a flexural strength of 31.24 MPa, indicating a compromised load-bearing capability due to the inclined alignment of fibers. The FNG4 specimen, incorporating a combination of 0°, 45°, 90°, and -45° fiber orientations, demonstrated an intermediate flexural strength of 69.83 MPa.

Table 2. Flexural strength data of specimens

Sample ID	Fiber orientation	Flexural Strength (MPa)	Flexural Strain (%)	Flexural Modulus (GPa)
FNG1	0°/0°/0°/0°	82.84	4.87	2.78
FNG2	90°/90°/90°/90°	24.93	8.77	0.685
FNG3	45°/45°/45°/45°	31.24	8.48	0.707
FNG4	0°/45°/90°/-45°	69.83	8.63	2.2

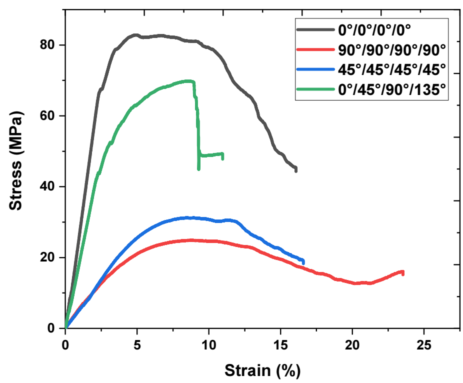

Figure 3. Stress strain curve for flexural strength

3.2. Micro CT analysis

In addition to evaluating mechanical properties, micro-computed tomography (micro-CT) was employed to investigate the internal damage mechanisms in the composite specimens subjected to varying fiber orientations. The micro-CT analysis allowed for a detailed examination of the fiber composite structure, providing insights into specific failure modes. For 0°/0°/0°/0° and 0°/45°/90°/-45° orientations, the analysis revealed the presence of fiber splitting, which refers to the separation of individual fibers along their length. This phenomenon was observed due to the high tensile stresses experienced by the fibers aligned parallel to the loading direction. In contrast, for the 90°/90°/90°/90° orientation, micro-CT imaging highlighted the occurrence of fiber delamination, where the layers of fibers separated from each other, resulting in a loss of interfacial strength. Finally, the 45°/45°/45°/45° orientation exhibited significant fiber breakage, where fibers fractured under the combined effect of tensile and shear stresses. These micro-CT findings can be utilized to optimize the design and manufacturing processes, ultimately leading to the development of composites with improved structural integrity and enhanced resistance to failure.

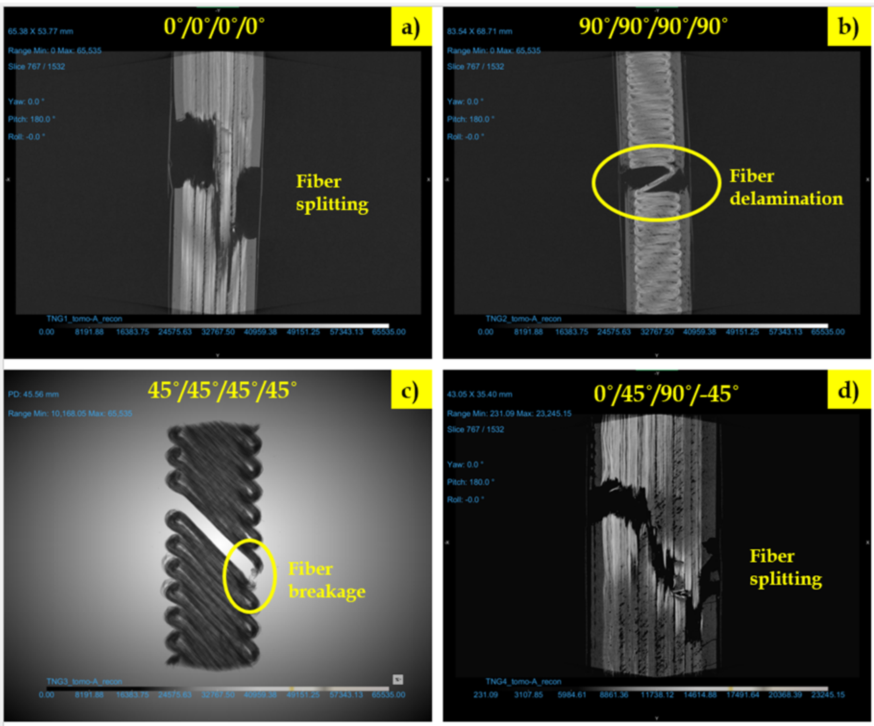

Figure 4. Micro CT images of fractured specimens

Conclusion

In conclusion, our study investigated the effects of varying fiber orientation on the tensile and flexural strength of composite materials, while keeping the fiber volume fraction constant. By examining four different orientations (0°, 45°, and 90°), as well as a combination of 0°/45°/90°/-45°, we aimed to understand the influence of fiber alignment on the mechanical properties of the composites. Our findings indicate that the 0° fiber orientation consistently yielded the highest tensile and flexural strengths among all tested configurations. This result suggests that aligning the fibers parallel to the loading direction enhances the load-bearing capacity of the composite material. These findings have significant implications for the design and manufacturing of composite structures, as they highlight the importance of carefully considering fiber orientation to achieve optimal mechanical performance. Future research can explore additional factors, such as the effect of different fiber volume fractions and matrix materials, to further enhance our understanding of composite behavior and improve the performance of composite materials in various applications.

Acknowledgements

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References

[1] N. Guo and M. C. Leu, "Additive manufacturing: technology, applications and research needs," *Front. Mech. Eng. 2013 83*, vol. 8, no. 3, pp. 215–243, May 2013, doi: 10.1007/S11465-013-0248-8.A.N. Author, Article title, *Journal Title* **66** (1993), 856–890.

[2] S. A. M. Tofail, E. P. Koumoulos, A. Bandyopadhyay, S. Bose, L. O'Donoghue, and C. Charitidis, "Additive manufacturing: scientific and technological challenges, market uptake and opportunities," *Mater. Today*, vol. 21, no. 1, pp. 22–37, Jan. 2018, doi: 10.1016/J.MATTOD.2017.07.001.

[3] M. Attaran, "The rise of 3-D printing: The advantages of additive manufacturing over traditional manufacturing," *Bus. Horiz.*, vol. 60, no. 5, pp. 677–688, Sep. 2017, doi: 10.1016/j.bushor.2017.05.011.

[4] I. M. Alarifi, "Investigation into the Structural, Chemical and High Mechanical Reforms in B4C with Graphene Composite Material Substitution for Potential Shielding Frame Applications," *Mol. 2021, Vol. 26, Page 1921*, vol. 26, no. 7, p. 1921, Mar. 2021, doi: 10.3390/MOLECULES26071921.

[5] A. N. Dickson, J. N. Barry, K. A. McDonnell, and D. P. Dowling, "Fabrication of continuous carbon, glass and Kevlar fibre reinforced polymer composites using additive manufacturing," *Addit. Manuf.*, vol. 16, pp. 146–152, Aug. 2017, doi: 10.1016/j.addma.2017.06.004.

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Local Differential Privacy-Based Data-Sharing Scheme for Smart Utilities

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Abstract. The manufacturing sector is a vital component of most economies, which leads to a large number of cyberattacks on organisations, whereas disruption in operation may lead to significant economic consequences. Adversaries aim to disrupt the production processes of manufacturing companies, gain financial advantages, and steal intellectual property by getting unauthorised access to sensitive data. Access to sensitive data helps organisations to enhance the production and management processes. However, majority of the existing data-sharing mechanisms are either susceptible to different cyber-attacks or heavy in terms of computation overhead. In this paper, a privacy-preserving data-sharing scheme for smart utilities is proposed. First, a customer's privacy adjustment mechanism is proposed to make sure that end-users have control over their privacy, which is required by the latest government regulations, such as the General Data Protection Regulation. Secondly, a local differential privacy-based mechanism is proposed to ensure privacy of the end-users by hiding real data based on the end-user preferences. The proposed scheme may be applied for different industrial control systems, whereas in this study, it is validated for energy utility use case consisting of smart intelligent devices. The results show that the proposed scheme may guarantee the required level of privacy with an expected relative error in utility.

Keywords. Data-sharing, Local Differential Privacy, Manufacturing, Privacy-preserving mechanism, Smart Utility.

1. Introduction

The manufacturing sector, which is the backbone of world economies, experiences a large number of cyber-attacks that are performed by attackers to disrupt production processes, compromise, or steal sensitive information, and gain financial advantages. By integrating Information Technology (IT) and Operational Technology (OT) systems, organisations open new avenues for adversaries. Vulnerabilities in the manufacturing sector may be caused by different factors, such as the economic impact of disruption, legacy systems, and the integration of IT and OT systems. The results of cyber-attacks range from financial losses and compromised intellectual property to the disruption of operation processes.

More than 75% of organisations in manufacturing sector unpatched Common Vulnerabilities and Exposures (CVEs), whereas nearly 40% of these organisations suffered malware infections in 2022 [1]. Cloud adoption within the manufacturing sector has become a solution to support remote workers. Around 38% of respondents experienced an account compromise at least one, whereas the average for all other industries was around 31% [2]. According to the report [3], around 85% of organisations had very little visibility into their OT environments, where 77% of organisations had poor network segmentation, 70% had outside connections to their Industrial Control Systems (ICSs), and 44% of companies shared credentials between IT and OT systems.

In this work, a smart utility environment is considered as a use case of the proposed approach, whereas the proposed model can be applied across all utility infrastructures. Manufacturing companies produce components that are used by smart utility companies, as well as industrial Internet of Things (IoT) devices, such as smart meters that are deployed on the end-users' side. In this specific use case, the end-users' energy usage data that are generated by the smart meters should be protected from any types of cyber-attacks. Although access to utility usage data brings many benefits, there is a number of challenges regarding end-users' privacy. These data are considered as "personal data", which means that the operation of smart meters within the EU must be in line with the General Data Protection Regulation (GDPR) [4]. Currently, security and privacy of the end-users and their data are highly prioritised in many countries including EU [5], UK [6], [7], Australia [8].

Differential Privacy (DP) has become one of the most popular approaches to ensure privacy of end-users' data, and it is widely utilised both in academia and industry. By utilising DP, controllable noise is added to the original data, thus hiding the sensitive data from other parties. Most of the existing DP-based schemes do not allow the end-user to control the level of privacy. To fill this gap, this paper proposes a Local Differential Privacy (LDP)-based data-sharing mechanism that preserves privacy of the end-users, whereas the end-users are able to control the level of privacy. The main contributions of this paper are as follows:

- A mechanism that allows end-users adjust and control the level of privacy (privacy budget) based on their preferences.
- A data-sharing scheme that utilises local differential privacy to ensure privacy of end-users' sensitive data.

The rest of this paper is organised as follows. Section II summarises the related works. The system model of a smart utility environment is presented in Section III. The proposed data-sharing scheme is presented in Section IV. Simulation results are presented in Section V. Finally, the conclusion is given in Section VI.

2. Related Work

DP has become a very popular technique to ensure data privacy by controlling the amount of noise added to the data. To reduce the risk of privacy leakage, Zhao et al. [9] proposed a strategy using differential privacy, which can protect end-users' data from being stolen by other parties in the process of data exchange. Lako et al. [10] proposed differentially private algorithms based on the discrete Fourier transform and the discrete wavelet transform, whereas the noise is added on the aggregator's side. To preserve an individual end-user's privacy, Gai et al. [11] proposed a privacy-preserving data aggregation scheme that satisfies LDP based on randomised responses, where sensitive data are perturbed by randomised response on the end-user's side. Although these schemes ensure end-users' privacy, there is no option for the end-user to control the level of privacy, which is required by the regulations, such as [4]. In addition, there are only a few data-sharing schemes that propose to add noise on the end-user's side.

Another popular approach to ensure end-users privacy during the data exchange is to utilise cryptographic techniques, such as Homomorphic Encryption (HE). To address the issues regarding privacy and security in a fog-based environment, Zhao et al. [12] proposed a privacy-preserving data aggregation scheme using Somewhat Homomorphic Encryption (SHE), which requires a trusted authority that is responsible for the registration of different parties. To provide flexible and efficient data aggregation, while maintaining data integrity and data privacy, Qian et al. [13] proposed a lightweight data aggregation scheme using HE. Zhang et al. [14] proposed a lightweight and fault-tolerant data aggregation scheme using modified version of the symmetric HE, random masking techniques, and Shamir secret-sharing mechanism. To reduce the complexity of certificate management, as well as to enhance security and privacy of end-users' data, a certificate-based data aggregation scheme is proposed in [15], which utilises homomorphic encryption. Although encryption-based data aggregation schemes ensure end-users' data privacy, a trusted authority is required for registration purposes or distribution of secret materials. In addition, encryption-based schemes add additional computation overhead compared to the DP-based models.

3. System Model

Fig. 1 shows the structure of a smart utility environment consisting of N end-users, a Data Communications Company (DCC) gateway, and grid operators including Electricity System Operator (ESO), Energy Suppliers (ESs), and Authorized Third Parties (ATPs). A Smart Meter (SM), which is deployed at the end-user's side, measures the electricity consumption of the end-user, and submits the data to the Communications Hub (CH). End-users' data are encrypted and sent to the grid operators through the DCC infrastructure. DCC has no access to end-users' data because the data are encrypted using grid operators' keys. ESs, ESO, and ATPs decrypt end-users' data using their private keys to perform their tasks and manage the electricity grid. In case of a key leakage attack, or an insider attack on the operators' side, privacy of the end-user might be disclosed, namely conclusions about the end-user's behaviour might be drawn by accessing sensitive data [16]. To address this issue, this work allows end-users to set the required level of privacy, based on which a controllable noise is added to the original data before encryption.

Let $\mathrm{N} = \{1, 2, 3, ..., \mathrm{N}\}$ denote the set of the end-users, where n is the index of the end-user and $\mathrm{n} \in \mathrm{N}$, whereas the total number of end-users is given by $\mathrm{N} \triangleq |\mathrm{N}|$. A smart meter that is deployed on the end-user's side measures the electricity consumption in real-time and stores measurements in memory. The interval at which a smart meter records and stores measurements may vary depending on the smart meter model. In this work, a smart meter stores electricity measurements at the end of each time slot, where each time slot is of 30 minutes. This reflects the minimum time interval, at which a grid operator may access end-users' data. Let $\mathrm{T} = \{1, 2, 3, ..., \mathrm{T}\}$ denote the set of all time slots when electricity measurements are stored in a smart meter's memory, where t is the time slot index and $\mathrm{t} \in \mathrm{T}$, whereas the total number of time slots is given by $\mathrm{T} = 48$.

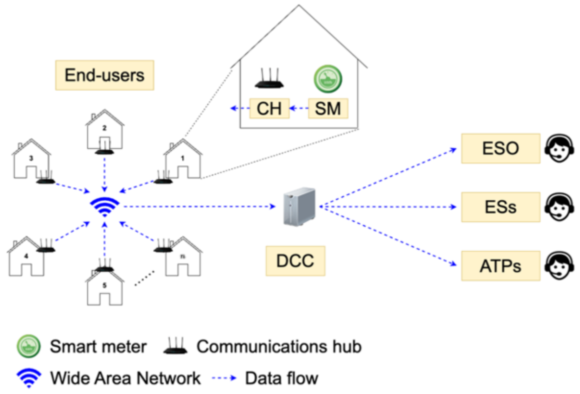

Figure 1 System Model

Let QD_n denote the electricity consumption profile for the end-user n for one day, and it is defined as follows:

$$QD_n = \{QD_{n1}, QD_{n2}, \ldots, QD_{nT}\}, \quad n \in \mathrm{N} \tag{1}$$

where QD_{nt} is the level of electricity consumption for the end-user n in a time slot t and $QD_{nt} \in QD_n$.

4. Proposed Scheme

In this section, a privacy-preserving data-sharing scheme for smart utility environment using local differential privacy is presented. A smart meter measures electricity consumption of the end-user and stores these measurements (QD_{nt}) in memory. End-users have control over the level of privacy that affects the amount of noise added to the original data. After the noise is added, data are encrypted and sent to the grid operators. Thus, a smart meter stores the level of privacy set by user and utilises ϵ-differentially private algorithm to modify electricity measurements before reporting them.

Definition 1 (ϵ-local differential privacy). A randomised algorithm M: $D \rightarrow S$ satisfies ϵ-local differential privacy iff for any output $s \in S$, and two neighbouring datasets $d, d' \in D$:

$$\frac{Pr[\mathcal{M}(d) = s]}{Pr[\mathcal{M}(d') = s]} \leq e^{\epsilon} \tag{2}$$

where $Pr[\mathrm{M}(d) = s]$ is the probability of the mechanism M outputting the result s given the input d, S is the set of all possible outputs that an algorithm M can produce, and ϵ is the privacy budget that bounds the probability of M outputting the same result for any pair of values d, d' [17]. A smaller value of ϵ provides stronger privacy guarantee, and larger ϵ provides weaker privacy guarantee. Two datasets (d, d') are called neighbouring datasets, iff d' can be produced by adding, removing, or modifying exactly one element from d. Let f: $D \rightarrow \mathrm{R}$ denote the function that maps datasets (D) to real numbers. In this work, f outputs the mean of electricity consumption readings (QD_n) of the end-user n for one day, which is expressed as follows:

$$f(QD_n) = \frac{1}{T}\sum_{t=1}^{T} QD_{n_t} \tag{3}$$

To introduce required noise to the result of a query (*f*) on individual dataset *d*, Laplace mechanism that relies on the sensitivity (L_1-sensitivity) of *f* is used.

Definition 2 (*L_1*-sensitivity). Given a query function $f(\cdot)$, its L_1-sensitivity Δf is the maximum L_1 distance between the results of *f* over any pair of neighbouring datasets *d* and d', which can be expressed as follows:

$$\Delta f = \max_{d,d'} ||f(d) - f(d')|| \tag{4}$$

The Laplace distribution is one of the most popular mechanisms to introduce noise to the result of a query function *f*. The probability density function of the Laplace distribution centered around 0 with the scale factor $b = \Delta f/\epsilon$ is defined as follows:

$$Lap(x|b) = \frac{1}{2b}\ exp\ (-\frac{|x|}{b}) \tag{5}$$

The LDP mechanism (M) using the Laplace distribution generates and injects the random noise drawn from the Laplace distribution to query function *f*, whereas the scale of the noise is calibrated due to the sensitivity of *f*. The Laplace mechanism preserves ϵ-local differential privacy, and is defined as follows:

$$\mathcal{M}_L(x, f(\cdot), \epsilon) = f(x) + Lap(b) \tag{6}$$

Let Δf_n^{max} denote the maximum historical sensitivity for the end-user *n*, which is stored in a smart meter's memory. At the end of the day, a smart meter calculates the sensitivity of *f* based on the measurements of electricity consumption (QD_n) recorded during the day. First, all the possible modifications of a dataset *d* ($d = QD_n$) are generated by removing entries one-by-one from d. Let $D' = \{D'_1, D'_2, \ldots, D'_K\}$ denote the set of all possible modifications of an original dataset *d*, where *k* is the index of a modification and $k \in K$, whereas the total number of modifications is given by $K \triangleq |D'| = T(T-1)$.

By iterating over D' and calculating the sensitivity for all possible pairs of neighbouring datasets, a new sensitivity Δf_n^{new} is obtained and stored in a smart meter's memory if $\Delta f_n^{new} > \Delta f_n^{max}$. It should be noted that to reduce the memory usage, a smart meter may generate the modifications of the original dataset *d* one-by-one.

Each end-user has control over the required level of privacy. In other words, the end-user may adjust the privacy budget parameter ϵ based on his preferences. If the end-user decides to set ϵ to be a small value, it will provide strong privacy guarantee, which affects the quality of the services provided by grid operator, such as an electricity bill that is provided by ES. Otherwise, if ϵ is set to be a large value, it will provide weak privacy guarantee, while the quality of the services provided by the grid operators will be better. Thus, the end-user may decide on privacy versus utility by tuning the privacy budget ϵ. Let ϵ_n denote the privacy budget determined by the end-user *n*. Each end-user may set different privacy budgets for each day of a week or set one privacy budget for a workweek and another for a weekend depending on circumstances. By combining the end-user's privacy budget ϵ_n, the sensitivity Δf_n^{max}, the proposed local differential private mechanism may be defined as follows:

$$\mathcal{M}_L(x, f(\cdot), \epsilon_n) = f(x) + Lap(\frac{\Delta f_n^{max}}{\epsilon_n}) \tag{7}$$

where x is the electricity consumption profile for the end-user n for one day. Since a query function f produces the mean of electricity consumption readings, a grid operator needs to multiply the mean value by T to get the total electricity consumption for the end-user n in a particular day. Let C_n denote the total energy consumption for the end-user n for one day, which a grid operator (ES) receives. Let P_n denote the energy usage cost for the end-user n for one day, which can be calculated as follows:

$$Pn = C_n * \lambda_{buy} \tag{8}$$

where λ_{buy} is the buying price of energy from the utility grid in a particular day. It has to be noted that in this work, a simple energy usage cost calculation is used to show how the privacy budget set by the end-user affects the quality of the services provided by a grid operator (energy supplier).

5. Results

This section presents the simulation results to evaluate the proposed LDP-based data-sharing scheme for a smart utility environment, which consists of 50 end-users ($N = 50$) using real electricity consumption data from [18]. Fig. 2 (a) shows the electricity consumption for two randomly chosen end-users for one day. An increase in electricity consumption for the User 2 can be observed at 10 a.m. and at 4 p.m., which means that the User 2 is highly likely at home and uses some appliances. Conversely, the electricity consumption for the User 1 does not change significantly during the day. Based on the electricity consumption data for the User 1, someone could conclude that nobody is at home turning appliances on and off, which discloses the User 1 privacy. Thus, User 1 may decide to increase the level of privacy by adjusting the privacy budget ϵ_n.

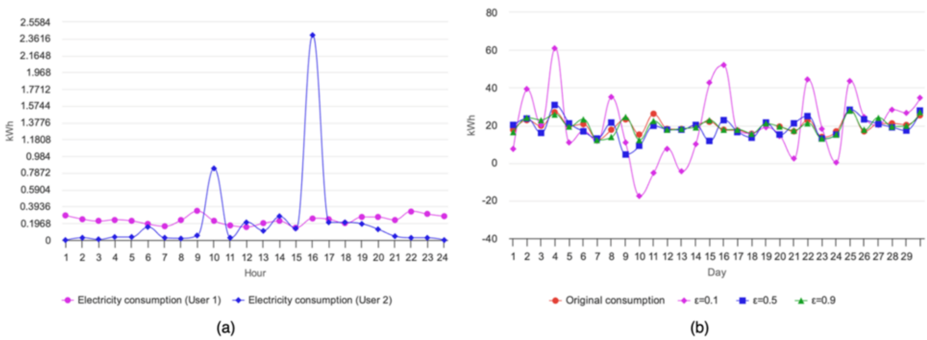

Figure 2 (a) Electricity consumption for two randomly chosen end-users for one day **(b)** Dependency of the change in electricity consumption on the privacy budget (ϵ_n) for a randomly chosen end-user for a period of 30 days

Fig. 2 (b) shows the dependency of change in electricity consumption on different privacy budgets (ϵ_n) for a randomly chosen end-user for a period of 30 days. It can be seen that the lower the privacy budget ϵ_n, the more change in electricity consumption may be observed. For example, when the privacy budget ϵ_n is set to 0.9, the electricity consumption pattern is almost the same as original with tiny deviations. Changes in electricity consumption may be clearly observed when the privacy budget ϵ_n is set 0.5, namely on day 9 and 15. The largest fluctuations in electricity consumption may be observed when the privacy budget ϵ_n=0.1.

With the increasing scale factor b of Laplace distribution, the amount of noise increases. Taking into account that the sensitivity Δf_n^{max} changes dynamically depending on the measurements of electricity consumption, the ratio $\Delta f_n^{max}/\epsilon_n$ may lead to a variable scale factor b, which is used in the Laplace mechanism to generate noise. Thus, if the end-users do not adjust the privacy budget ϵ_n, it may lead to an unexpected energy usage cost because of unexpected b. Let P'_n denote the energy usage cost for the end-user n for a particular day, which is calculated based on the noisy consumption data as follows:

$$P'_n = C'_n * \lambda_{buy} \tag{9}$$

where C'_n is the noisy consumption data for the end-user n for one day, which is calculated by injecting noise to the original data C_n. Let RE denote the relative error that reflects the difference between the original energy usage cost P_n and the energy usage cost P'_n, which is calculated based on the noisy consumption data. RE is calculated as follows:

$$RE = \frac{P'_n - P_n}{P_n} * 100\% \tag{10}$$

Fig. 3 (a) shows the dependency of the relative error RE in the energy usage cost on the scale factor b for 5 randomly chosen end-users for one day. RE is calculated 10 times for each end-user and for each scale factor b, whereas the final RE is the maximum RE observed during 10 iterations. It can be seen that when the scale factor b is lower than 0.008, the RE is lower than 10%, whereas the first time $RE \geq 10\%$ is observed at b=0.008 (RE = 16.5%). The first occurrence of the $RE \geq 60\%$ is observed when the scale factor b is equal to 0.032 (RE = 65.09%). Finally, RE = 155.5% is observed when b=0.05. In other words, Fig. 3 (a) suggests possible scale factors b that can be used in the Laplace distribution to get expected level of noise. For example, if the end-user agrees to pay up to 10% more for the energy, the privacy budget ϵ_n needs to be adjusted in a way, so that $\Delta f_n^{max}/\epsilon_n < 0.008$.

In this work, three levels of privacy are selected based on the results in Fig. 3 (a), namely Low Privacy (b = 0.008) with the $RE \leq 10\%$, Medium Privacy (b = 0.032) with the $RE \leq 60\%$, and High Privacy (b = 0.05) with the $RE \leq 100\%$. Thus, if the end-user selects the Medium Privacy level, an expected RE should not exceed 60%.

Fig. 3 (b) shows the dependency of the absolute relative error in the energy usage cost on the level of privacy for a randomly chosen end-user for a period of 30 days. It can be seen that for the Low Privacy level, the amount of noise added is small, and RE does not exceed 10%. If the end-user selects the Medium Privacy level, the RE in the energy usage cost increases compared to the Low Privacy level, while it does not exceed 60%. Finally, if the end-user needs the High Privacy level, the fluctuations in the energy usage cost are larger compared to the Medium and Low Privacy levels, whereas RE does not exceed 100%. Let us take as an example, the sensitivity Δf_n^{max} = 0.0055 on day 4. For the Low Privacy level, the privacy budget ϵ_n should be equal to 0.6875, so that $\Delta f_n^{max}/\epsilon_n$ = b = 0.008, with a resulting RE = 0.23%. Similarly, for the High Privacy level, ϵ_n is equal to 0.07 because the sensitivity Δf_n^{max} = 0.0035 on day 9. Thus, a large increase in the energy usage cost may be observed on day 9 for High Privacy level, whereas RE = 99.36%.

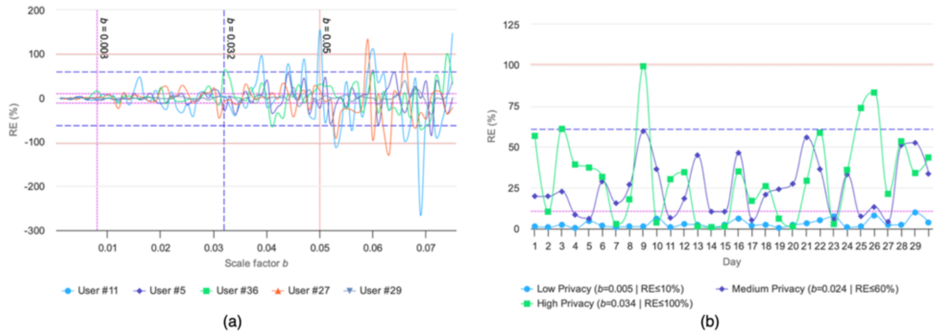

Figure 3 (a) Dependency of the relative error *RE* in the energy usage cost on the scale factor *b* for 5 randomly chosen end-users for one day **(b)** Dependency of the relative error *RE* in the energy usage cost on the level of privacy for a randomly chosen end-user for a period of 30 days

The results show in more detail how the different variables (sensitivity, epsilon, and scale factor b) in the proposed privacy preserving scheme affect each other and the final energy cost for a user. Overall, the proposed scheme allows the user to opt out of sharing fine grained data about energy consumption with the provider in exchange for a higher energy cost. More importantly, the user can manage the level of privacy and the resulting cost increase. It is possible since the noise is added to the original end-user's electricity consumption data based on the sensitivity Δf_n^{max} of a query function *f* and the privacy budget ϵ_n, which is controlled by the end-user. The ratio $\Delta f_n^{max}/\epsilon_n$ determines the scale factor *b* that is used in the Laplace mechanism to generate controllable noise. The greater the scale factor *b*, the greater the noise is injected to the original data. Since the sensitivity Δf_n^{max} depends on the end-user's electricity consumption data, the privacy budget needs to be adjusted in a way, so that the ratio $\Delta f_n^{max}/\epsilon_n$leads to an accurate scale factor *b*, based on which the noise is generated. If the end-user does not adjust the privacy budget ϵ_n, it may lead to unexpected results in terms of the amount of noise added, as well as the energy usage cost.

6. Conclusion

In this paper, a LDP-based data-sharing scheme for a smart utility environment is proposed. To ensure end-users' privacy, a local deferentially private mechanism is proposed that takes into account end-users' preferences regarding the level of privacy. End-users may adjust the required level of privacy (privacy budget) on daily, weekly, or monthly basis, thus controlling the trade-off between privacy and utility. The simulation results show that the proposed scheme may guarantee the required level of privacy with an expected error in the utility (energy usage cost). To ensure the required level of privacy, as well as to make sure that relative error in the energy usage cost does not exceed an expected level, the privacy budget needs to be tuned regularly and carefully.

One of the possible directions for the future work is to design a mechanism that will automatically adjust the privacy budget based on the dynamically changing sensitivity, according to the end-user's preferred level of privacy (low, medium, or high).

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References

[1] Informa UK Limited, *Critical Manufacturing Sector in the Bull's-eye*, 2023 (accessed Aug 15, 2023). https://www.darkreading.com/ics-ot/ critical-manufacturing-sector-in-the-bulls-eye.

[2] Informa UK Limited, *Manufacturing Sector in 2022 Is More Vulnerable to Account Compromise and Supply Chain Attacks in the Cloud than Other Verticals*, 2022 (accessed Aug 15, 2023). https://www.darkreading.com/cloud/manufacturing-sector-in-2022-ismore-vulnerable-to-account-compromise-and-supply-chain-attacks-inthe-cloud-than-other-verticals.

[3] DRAGOS, INC., *2021 ICS CYBERSECURITY YEAR IN REVIEW*, 2021 (accessed Aug 15, 2023). https://hub.dragos.com/2021-year-in-review.

[4] Department for Energy Security & Net Zero (DESNZ), *Smart Metering Implementation Programme: review of the Data Access and Privacy Framework*, 2018 (accessed Aug 10, 2023). https://www.gov.uk/government/publications/smart-metering-implementation-programmereview-of-the-data-access-and-privacy-framework.

[5] Official Journal of the European Union, *DIRECTIVE (EU) 2019/944 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on common rules for the internal market for electricity and amending Directive 2012/27/EU*, 2019 (accessed Aug 09, 2023). https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri= CELEX:32019L0944&from=EN#d1e2607-125-1.

[6] Department for Energy Security & Net Zero (DESNZ), Energy white paper: Powering our net zero future, 2020 (accessed Aug 3, 2023). https://www.gov.uk/government/publications/energy-whitepaper-powering-our-net-zero-future.

[7] The National Cyber Security Centre (NCSC), The smart security behind the GB Smart Metering System, 2016 (accessed Aug 3, 2023). https://www.ncsc.gov.uk/information/the-smart-securitybehind-the-gb-smart-metering-system.

[8] Australian Competition and Consumer Commission (ACCC), *The Consumer Data Right*, 2023 (accessed Aug 11, 2023). https://www.accc.gov.au/by-industry/banking-and-finance/theconsumer-data-right.

[9] D. Zhao, C. Zhang, X. Cao, C. Peng, B. Sun, K. Li, and Y. Li, "Differential privacy energy management for islanded microgrids with distributed consensus-based admm algorithm," *IEEE Transactions on Control Systems Technology*, vol. 31, no. 3, pp. 1018–1031, 2023.

[10] F. Leukam Lako, P. Lajoie-Mazenc, M. Laurent, and C. Vorakulpipat, "Privacy-preserving publication of time-series data in smart grid," *Sec. and Commun. Netw.*, vol. 2021, jan 2021.

[11] N. Gai, K. Xue, B. Zhu, J. Yang, J. Liu, and D. He, "An efficient data aggregation scheme with local differential privacy in smart grid," *Digital Communications and Networks*, vol. 8, no. 3, pp. 333–342, 2022.

[12] S. Zhao, F. Li, H. Li, R. Lu, S. Ren, H. Bao, J.-H. Lin, and S. Han, "Smart and practical privacy-preserving data aggregation for fog-based smart grids," *IEEE Transactions on Information Forensics and Security*, vol. 16, pp. 521–536, 2021.

[13] J. Qian, Z. Cao, X. Dong, J. Shen, Z. Liu, and Y. Ye, "Two secure and efficient lightweight data aggregation schemes for smart grid," *IEEE Transactions on Smart Grid*, vol. 12, no. 3, pp. 2625–2637, 2021.

[14] X. Zhang, W. Tang, D. Gu, Y. Zhang, J. Xue, and X. Wang, "Lightweight multidimensional encrypted data aggregation scheme with fault tolerance for fog-assisted smart grids," *IEEE Systems Journal*, vol. 16, no. 4, pp. 6647–6657, 2022.

[15] G. K. Verma, P. Gope, N. Saxena, and N. Kumar, "Cb-da: Lightweight and escrow-free certificate-based data aggregation for smart grid," *IEEE Transactions on Dependable and Secure Computing*, vol. 20, no. 3, pp. 2011–2024, 2023.

[16] European Data Protection Supervisor (EDPS), *TechDispatch #2: Smart Meters in Smart Homes*, 2019 (accessed Aug 9, 2023). https://edps.europa.eu/data-protection/our-work/publications/techdispatch/techdispatch-2-smart-meters-smart-homes en.

[17] C. Dwork, F. McSherry, K. Nissim, and A. Smith, "Calibrating noise to sensitivity in private data analysis," *Journal of Privacy and Confidentiality*, vol. 7, p. 17–51, May 2017.

[18] U. P. Networks, *SmartMeter Energy Consumption Data in London Households*, 2022 (accessed Aug 8, 2023). https://data.london.gov.uk/ dataset/smartmeter-energy-use-data-in-london-households.

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