INTERNATIONAL JOURNAL OF INDUSTRIAL MANAGEMENT
ISSN: 2289-9286 e-ISSN: 2590-3594
VOLUME 17, NO. 3, 2023, 138 – 151
DOI: https://doi.org/10.15282/ijim.17.3.2023.9062

RESEARCH ARTICLE

CHALLENGES AND OPPORTUNITIES FOR ACHIEVING OPERATIONAL SUSTAINABILITY OF BOILERS IN THE CONTEXT OF INDUSTRY 4.0

Spandan Basak Payel[1], S.M. Faysal Ahmed[1], Nabila Taseen[2], Md. Tanvir Siraj[3]*, and Muhammad Rubayat Bin Shahadat[4]

[1]Department of Mechanical Engineering, Bangladesh University of Engineering and Technology (BUET), Dhaka 1000, Bangladesh
[2]School of Business & Economics, North South University (NSU), Dhaka 1229, Bangladesh
[3]Department of Industrial and Production Engineering, Bangladesh University of Engineering and Technology (BUET), Dhaka 1000, Bangladesh
[4]Department of Mechanical Engineering, Hajee Mohammad Danesh Science and Technology University, Dinajpur 5200, Bangladesh

ABSTRACT - This research aims to explore the challenges and opportunities for achieving operational sustainability of boilers in the context of Industry 4.0, using the Stepwise Weight Assessment Ratio Analysis (SWARA) method. The integration of Industry 4.0 technologies has the potential to revolutionize the way boilers are operated, offering benefits such as improved energy efficiency, reduced emissions, and enhanced safety. However, effective implementation of these technologies requires addressing the associated challenges and opportunities. This study ranks the challenges and opportunities based on expert feedback using the SWARA method, highlighting the most pressing issues and areas for improvement. By the feedback from 15 industrial and academic experts, the results suggest that 'workforce transformation' and 'data management and integration' are the leading challenges, while 'improved energy efficiency' and 'enhanced safety' are the most significant opportunities for achieving operational sustainability of boilers in the context of Industry 4.0. This research can inform and guide the development of policies, strategies, and solutions aimed at improving the sustainability of boilers in a rapidly changing technological landscape, and assist industrial managers in finding strategic management for sustainable boiler operation.

ARTICLE HISTORY
Received : 06-02-2023
Revised : 10-03-2023
Accepted : 30-03-2023
Published : 21-09-2023

KEYWORDS
Boiler operation
Industry 4.0
Sustainability
Challenges
Opportunities
SWARA method

1.0 INTRODUCTION

Industry 4.0, also known as the Fourth Industrial Revolution, is characterized by the integration of advanced technologies such as the Internet of Things (IoT), artificial intelligence (AI), robotics, big data, and so on into traditional manufacturing processes (Al-Mughairy & Shrivastava, 2022). Boilers play a crucial role in many industries, providing heat and steam to production processes (Rahman et al., 2022). However, the operation of boilers can be energy-intensive and result in significant greenhouse gas emissions. Achieving operational sustainability of boilers is therefore a pressing challenge in the context of Industry 4.0 (Kibulungu & Laseinde, 2023). Policymakers have become increasingly concerned with energy sustainability in light of recent global energy supply disruptions caused by events such as the Covid-19 pandemic and political crises such as the Russia-Ukraine war (Chofreh et al., 2021; Ingram et al., 2023). As a result, operational sustainability in boilers has become a key focus in the pursuit of a more sustainable energy future.

Boilers are used in various industries for generating steam to drive turbines, heating and processing in chemical plants, sterilization and pasteurization in the food and beverage industry, heating and finishing in the textile and leather industry, providing heat in hospitals, schools, and other buildings, heating and humidification in paper mills, and many more (Bari et al., 2022; Rahman et al., 2022; Wang, 2017). They also produce hot water in hotels, resorts, and other commercial facilities. Boilers are crucial in many industrial processes, providing heat and steam to power production and meet the heating needs of various facilities (Munsamy & Telukdarie, 2022).

Traditional boiler operation typically involves manual monitoring and control of the heating system, with limited use of automation and digital technologies. In contrast, Industry 4.0 involves the integration of advanced technologies to optimize and streamline production processes (Cheah & Tan, 2020). In the context of boiler operation, Industry 4.0 brings new opportunities for improved energy efficiency and sustainability through real-time monitoring, predictive maintenance, and advanced control algorithms that can optimize boiler performance and reduce energy waste (Kibulungu & Laseinde, 2023). Additionally, Industry 4.0 also enables decentralized and data-driven decision-making, enabling greater collaboration and flexibility in production processes, including the operation of boilers.

Amid this situation, some research questions are raised.

RQ1: What are the major challenges to achieving operational sustainability of boilers in the context of Industry 4.0?

***CORRESPONDING AUTHOR | Md. Tanvir Siraj** | ✉ tanvir25392@gmail.com

RQ2: What opportunities can Industry 4.0 technologies offer for enhancing the operational sustainability of boilers?

RQ3: What is the priority ranking of the identified challenges and opportunities in the context of industrial management?

Despite the widespread use of boilers in various industries, there is a gap in the literature regarding the study of their operational sustainability in the context of Industry 4.0. While there have been numerous studies on boiler operations, none have specifically addressed the challenges and opportunities for achieving operational sustainability in the era of advanced technologies and automation. For instance, several recent studies have illustrated different aspects of boiler operation and maintenance strategies in an Industry 4.0 environment with a depiction of various industries like the manufacturing industry (Hardy et al., 2021; Harjamulya et al., 2019; Jha et al., 2022; Lim et al., 2021; Olkiewicz et al., 2021; Tsai, 2018; Urgese et al., 2021), power generation industry (Arakelyan et al., 2021; Kluczek et al., 2021; Muhammad Ashraf et al., 2020; Munsamy and Telukdarie, 2022; Toit & Laubscher, 2018), urban heating system (Warsokusumo et al., 2020; Woon et al., 2022), petrochemical industry (Wang, 2017), and so on. However, none of these studies have explored the topic of this current research, which seeks to provide further insights into the area of industrial management. As a result, this study employs the SWARA method to analyze the challenges and opportunities related to achieving the operational sustainability of boilers in the context of Industry 4.0. The goal of this analysis is to provide a more comprehensive understanding of the issues and potential solutions, to better inform decision-making by managers and policymakers.

The SWARA method is significant because it provides a systematic and structured approach for analyzing and ranking (Keršuliene et al., 2010). The SWARA method is based on experts' feedback, which allows for a more comprehensive and accurate assessment of the issues. By using the SWARA method, it is possible to prioritize the most pressing challenges and opportunities and to determine which areas require the most attention and resources. In the literature, the SWARA method has been utilized for prioritizing risk remedial actions (Siraj et al., 2022), ranking of cost overrun factors (Balali et al., 2022), supply chain risk assessment (Sivageerthi et al., 2022), ranking of the personnel (Popović et al., 2021), performance analysis (Ayyildiz et al., 2021), and so on. However, the SWARA method has never been applied to analyze the challenges and opportunities for achieving the operational sustainability of boilers in the context of Industry 4.0.

The integration of Industry 4.0 technologies offers new opportunities for improved energy efficiency and reduced emissions, but it also presents new challenges and a need for a deeper understanding on how to optimize and sustainably operate boilers in this rapidly evolving industrial landscape (Kluczek et al., 2021). Therefore, this research will contribute to the industrial management literature by fulfilling the following research objectives:

RO1: To identify and assess the challenges faced by the boilers industry in achieving operational sustainability in the context of Industry 4.0.

RO2: To determine the opportunities for improving the operational sustainability of boilers using Industry 4.0 technologies.

RO3: To prioritize the challenges and opportunities through the use of the SWARA method to inform and guide the development of policies and solutions aimed at improving the sustainability of boilers in the Industry 4.0 era.

2.0 CONCEPTUALIZING THE CHALLENGES AND THE OPPORTUNITIES BY REVIEWING THE LITERATURE

Sustainable boiler operation involves reducing negative impacts on the environment, improving energy efficiency, ensuring long-term operational reliability and cost-effectiveness, and promoting social responsibility (Gopal & Panchal, 2023). It is achieved through the integration of best practices, technology, and processes that balance economic, environmental, and social considerations. Promoting sustainable boiler operation in the context of Industry 4.0 aligns with the broader trend towards sustainable and responsible business practices, and can help organizations to build a positive reputation and attract socially conscious consumers (Cheah & Tan, 2020). However, existing literature has identified some challenges as well as opportunities that require systematic review and analysis.

Since no prior research has examined the operational sustainability of boilers within the framework of Industry 4.0, this study had to expand the literature review to encompass some closely related fields to this study. After conducting a thorough review of the literature on challenges and opportunities related to Industry 4.0 in various domains, including manufacturing, supply chain, energy, operations, maintenance, and management, a primary list of randomly selected 13 challenges and 12 opportunities was compiled. To validate the inclusion of these challenges and opportunities, whether they are relevant or not to this study scope, experts (see Figure 1 for experts' profiles in brief) were surveyed using a simple 'yes' or 'no' questionnaire. Besides this, they were asked to contribute to any additional challenges or opportunities based on their expertise. However, the experts did not add any new challenges or opportunities to the list. But, based on their feedback, 3 challenges ("need for real-time monitoring", "shifting energy infrastructure", and "skepticism towards new technology") and 2 opportunities ("reducing the number of human workforces" and "reducing downtime") were removed due to the lack of relevance or making repetitions with others. Thus, this study compiled a list of 10 challenges and 10 opportunities for further analysis in this study, based on the consensus among the experts. This was done to maintain simplicity in the calculations and to present the information visually in a clear manner for industrial managers and policymakers.

2.1 Challenges

Our determined 10 challenges based on the literature review and experts' feedback can be found in Table 1. Further descriptions of the challenges are depicted as follows. The existing literature has indicated technical challenges as a crucial factor that hinders the achievement of sustainable boiler operation in the context of Industry 4.0. These technical challenges can range from the integration of advanced technologies, cybersecurity concerns, and lack of proper infrastructure and expertise, among others (Li & Yu, 2022; Wyrwicka & Mrugalska, 2017).

Data management and integration are critical for sustainable boiler operation in the context of Industry 4.0 (Malhotra et al., 2021). With the integration of advanced technologies, large amounts of data are generated and need to be effectively managed to provide valuable insights and inform decision-making. Effective data management and integration are crucial for ensuring the proper functioning of the boiler and its components, as well as optimizing energy efficiency, reducing emissions, and improving safety (Warsokusumo et al., 2020). However, there are challenges associated with data management and integration, such as the need for standardized protocols, to ensure data quality, and ensuring data security.

Table 1. Identified challenges to achieving operational sustainability of boiler in Industry 4.0

Denotation	Challenges	Source
C1	Technical challenges	Li and Yu, 2022; Wyrwicka and Mrugalska, 2017
C2	Data management and integration	Malhotra et al., 2021; Warsokusumo et al., 2020
C3	Cybersecurity	Ustundag et al., 2018; Ding et al., 2022
C4	Workforce transformation	Mukti et al., 2021; Shaharudin et al., 2021
C5	Regulation and standardization	Pozdneev et al., 2019
C6	Economic and financial challenges	Hina et al., 2022
C7	Complex system interoperability	Yan et al., 2017; Ding et al., 2018
C8	Scalability and flexibility	Oluyisola et al., 2022
C9	Human-machine interaction	Krupitzer et al., 2020; Malavazi, 2022
C10	Social and ethical implications	Cheah and Tan, 2020

Cybersecurity is a significant challenge that has been identified in existing literature as an obstacle to achieving sustainability in the context of Industry 4.0 (Ustundag et al., 2018). With the increasing reliance on technology and digital systems in the operation of boilers, the risk of cyber-attacks, hacking, and other security threats is also increasing (Ding et al., 2022). These security breaches can compromise the confidentiality, integrity, and availability of critical data, leading to a wide range of negative consequences, including safety risks, reduced energy efficiency, and increased emissions.

Workforce transformation has been identified as another critical challenge in the existing literature for achieving sustainability in the context of Industry 4.0 (Mukti et al., 2021). The integration of Industry 4.0 technologies and digitalization has resulted in the need for new skills, competencies, and processes within the workforce. This requires significant investments in employee training and development to ensure that workers have the necessary knowledge and skills to operate and maintain these systems. Moreover, the workforce must be able to adapt to the new technologies and processes and integrate them into their daily work practices, which may require changes to the organizational structure, job roles, and responsibilities (Shaharudin et al., 2021). Failure to address the workforce transformation challenge could result in a lack of adoption and ineffective implementation of Industry 4.0 technologies, undermining the potential benefits for sustainable boiler operation.

Regulation and standardization is an important challenge for sustainable boiler operation in the context of Industry 4.0 as it requires the development of new standards and regulations that align with the changing technological landscape. The lack of harmonization and coordination across different countries, industries, and regulatory bodies can lead to confusion and slow the implementation of these technologies (Pozdneev et al., 2019).

Economic and financial challenges can take many forms and include issues such as increasing costs for energy and resources, changes in the global market, and the need for investment in new technologies and equipment. Additionally, there may be difficulties in securing funding for such investments, as well as the need to allocate budgets and manage finances in a manner that supports sustainability goals (Hina et al., 2022).

Complex system interoperability is the ability of various technical systems and components to work together seamlessly and efficiently (Yan et al., 2017). In the context of sustainable boiler operation, this can pose a critical challenge as multiple systems are involved, each with its unique requirements, interfaces, and protocols (Dai et al., 2013). The existing literature highlights that a lack of interoperability can result in decreased productivity, increased downtime, and higher maintenance costs, all of which can impact sustainability in the context of Industry 4.0 (Ding et al., 2018).

Scalability and flexibility refer to the ability of the boiler operation system to adapt and accommodate the increasing demands and changes in the industry while ensuring the sustainability of the system (Edlund et al., 2011). The system should be able to be easily expanded or reduced to accommodate new production requirements without compromising its efficiency and performance. The lack of scalability and flexibility may result in inefficiencies, increased costs, and decreased sustainability, making it a critical challenge that needs to be addressed (Oluyisola et al., 2022).

Human-machine interaction refers to the interface between the human operators and the technology systems that control the boilers (Krupitzer et al., 2020). This interaction is crucial for ensuring the safe, efficient, and reliable operation of boilers. In the context of Industry 4.0, the integration of advanced technologies requires a new level of interaction between humans and machines. Human-machine interaction can also be affected by various factors, such as the design of the control systems, the training and experience of the operators, and the availability of real-time data and feedback (Malavazi, 2022).

In the existing literature, the social and ethical implications of Industry 4.0 have been identified as a critical challenge. This encompasses a range of considerations such as the impact on employment, privacy concerns arising from the increased use of data and automation, and ethical considerations surrounding the responsible use of new technologies in the workplace (Cheah & Tan, 2020).

2.2 Opportunities

Our determined 10 opportunities based on the literature review and experts' feedback can be found in Table 2. Further descriptions of the opportunities are depicted as follows.

Table 2. Identified opportunities to achieve operational sustainability of boiler in Industry 4.0

Denotation	Opportunities	Source
O1	Increased automation	Oluyisola et al., 2022
O2	Improved energy efficiency	Mohamed et al., 2019; Ding et al., 2018
O3	Optimized performance	Ding et al., 2018
O4	Predictive maintenance	Yan et al., 2017; Behzad et al., 2019
O5	Data-driven decision-making	Ding et al., 2018; Muhammad Ashraf et al., 2020
O6	Increased productivity	Yusof and Mohammad, 2022
O7	Improved environmental performance	Carvalho et al., 2020; Oláh et al., 2020
O8	Competitive advantage	Hollander, 2018; Urgese et al., 2021
O9	Enhanced safety	Kibulungu and Laseinde, 2023
O10	Enhanced customer experience	Lee et al., 2022; Cheah and Tan, 2020

Increased automation by the implementation of advanced technology, such as automation systems, can improve the efficiency and sustainability of boiler operations. Automation can reduce human error and increase the accuracy of operational processes, leading to improved energy efficiency and reduced maintenance costs (Oluyisola et al., 2022).

Improved energy efficiency refers to the ability of boilers to operate more efficiently and effectively, leading to reduced energy consumption and lower costs for industrial operations (Mohamed et al., 2019). In the context of Industry 4.0, this opportunity is achievable through the integration of advanced technologies, which enable real-time monitoring, analysis, and optimization of energy usage. By leveraging these technologies, boilers can be designed and operated more sustainably, reducing their carbon footprint and improving their overall energy efficiency (Ding et al., 2018).

Optimized Performance refers to the ability to enhance the overall functioning of boilers, leading to improved efficiency and reduced downtime (Ding et al., 2018). This can be achieved through the integration of advanced technologies and data analytics in the context of Industry 4.0.

Predictive maintenance is an opportunity for sustainable boiler operation in the context of Industry 4.0, as it enables the use of advanced technologies and data analysis to predict when maintenance is necessary, reducing downtime and increasing the efficiency of operations (Yan et al., 2017). By using data from sensors, machine learning algorithms, and other technologies, predictive maintenance can help identify potential issues before they become problems, leading to more efficient and cost-effective maintenance practices and ultimately improving the overall performance of boilers (Behzad et al., 2019).

Data-driven decision-making refers to the process of making informed decisions based on data analysis and insights. In the context of sustainable boiler operation in Industry 4.0, data-driven decision-making is considered an opportunity because it enables organizations to optimize their operations and make decisions based on real-time data (Ding et al., 2018). This can lead to improved energy efficiency, reduced downtime, and increased productivity. By leveraging advanced technologies, organizations can collect and analyze large amounts of data from their boilers and other equipment, which can then be used to make informed decisions that promote sustainable boiler operation (Muhammad Ashraf et al., 2020).

The adoption of Industry 4.0 technologies and practices in the operation of boilers has the potential to increase productivity. This is achieved through the integration of advanced technologies into the production process, which can lead to improved efficiency, optimized performance, and informed decision-making (Yusof & Mohammad, 2022). The use of these technologies can also help to automate certain tasks, freeing up personnel to focus on higher-value activities and further increasing overall productivity (Munsamy & Telukdarie, 2022).

Improved Environmental Performance refers to the ability to reduce the negative impact of boiler operation on the environment through the implementation of Industry 4.0 technologies. This can be achieved by reducing emissions, improving energy efficiency, and reducing waste through the use of real-time monitoring and data analysis. The integration of advanced technologies can provide a more comprehensive understanding of the environmental impact of boiler operation, enabling organizations to make informed decisions that promote sustainability (Carvalho et al., 2020; Oláh et al., 2020).

Implementation of sustainable boiler operation in the context of Industry 4.0 can bring about a competitive advantage for organizations (Hollander, 2018). This can be achieved through the optimization of operational processes and the integration of advanced technologies, leading to improved performance, increased productivity, and more efficient use of resources, thereby giving the organization a competitive edge in the market (Urgese et al., 2021).

Enhanced safety is an opportunity that refers to the potential for Industry 4.0 technologies and practices to improve the safety of boiler operations through the ability to quickly respond to any potential safety hazards (Kibulungu & Laseinde, 2023). Additionally, Industry 4.0 can also provide improved training and support for workers, which can help to reduce the risk of accidents and incidents in the workplace.

Implementation of sustainable boiler operation within the context of Industry 4.0 has the potential to enhance the customer experience. This can be achieved through the integration of advanced technologies which can lead to improved operational efficiency, increased productivity, and a more streamlined and personalized customer experience (Lee et al., 2022). Additionally, Industry 4.0 can also bring about a shift towards a more data-driven approach to decision-making, providing real-time insights into customer preferences and behavior, and enabling organizations to tailor their offerings and services to meet the evolving needs of their customers (Cheah & Tan, 2020).

3.0 METHODOLOGY AND CALCULATIONS

This study applied a structured framework to identify and analyze the challenges and opportunities for achieving operational sustainability of boilers in the context of Industry 4.0 which can be found in Figure 1 and a detailed description of the methodological calculations can be found in the following subsections.

3.1 SWARA method

Keršuliene et al. (2010) first proposed the SWARA method in 2010 in the decision-making literature, which is mathematically simpler than other expert opinion-based decision-making tools such as AHP or DEMATEL. Additionally, the comparatively simpler evaluation score collection steps ensure consistency in decision-making among participating experts. A panel of experts, including production managers, maintenance managers, and professors of industrial management, was formed purposively for this study (refer to Figure 1). In decision-making research, purposive selection of experts rather than random sampling is preferred to align with the study objective, and the size of the expert panel can range from one expert to multiple (Bari et al., 2022). In this study, 15 experts were surveyed, with 33.33% of participants selected from each field of expertise. Details of the procedural steps of the SWARA method (Siraj et al., 2022) are described below:

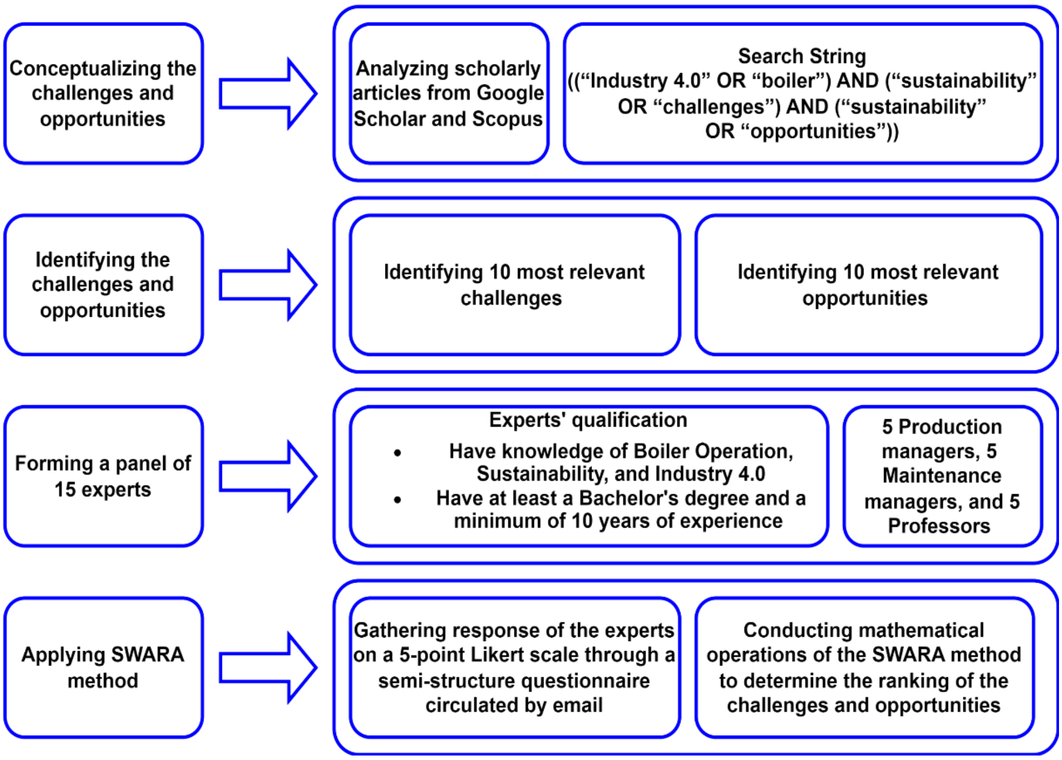

Figure 1. The structural framework of the research

Step 1. Fifteen experts participated in a survey where they evaluated challenges and opportunities through a questionnaire using a 5-point Likert scale, as displayed in Table 3.

Table 3. 5-point Likert scale for gathering experts' opinion

Linguistic Variable	Numerical Value
Very Low	1
Low	2
Medium	3
High	4
Very High	5

The experts' feedback on each challenge (and opportunity) was calculated using the geometric mean method, producing aggregated values within the range of [1,5]. These values were then converted to decimal score values ($\boldsymbol{p_j}$) through a simple linear calculation, with a range of [0,1]. These decimal scores were used in later steps of the SWARA method.

Step 2. Rank the challenges (and opportunities) based on the expert's preferences in descending order.

Step 3. Calculate the relative importance ($\boldsymbol{s_j}$) of the challenges (and the opportunities) starting from the second most preferred one. This is done by subtracting the score of that challenge (and the opportunity) ***j-1*** from the challenge (and the opportunity) ***j***, using Equation (1).

$$\boldsymbol{s_{j-1}} = \boldsymbol{p_j} - \boldsymbol{p_{j-1}} \tag{1}$$

Step 4. Determine the comparative coefficient ($\boldsymbol{k_j}$) by applying Equation (2).

$$\boldsymbol{k_j} = \begin{cases} 1, & \boldsymbol{j} = 1 \\ \boldsymbol{s_j} + 1, & \boldsymbol{j} > 1 \end{cases} \tag{2}$$

Step 5. Calculate the recalculated weight ($\boldsymbol{q_j}$) by using Equation (3).

$$\boldsymbol{q_j} = \begin{cases} 1, & \boldsymbol{j} = 1 \\ \dfrac{\boldsymbol{k_{j-1}}}{\boldsymbol{k_j}}, & \boldsymbol{j} > 1 \end{cases} \tag{3}$$

Step 6. Compute the final weights of the challenges (and the opportunities) (w_j) by using Equation (4).

$$w_j = \frac{q_j}{\sum_{j=1}^{n} q_j} \tag{4}$$

3.2 Calculations

The gathered evaluation scores for the selected challenges by the 15 experts can be found in Table 4, in which the aggregated scores and the decimal scores have been determined as well.

Table 4. Evaluation of the selected challenges by the panel of experts

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
Expert 1	2	3	1	4	4	2	3	2	3	1
Expert 2	2	4	1	5	3	2	4	2	2	1
Expert 3	1	4	1	4	3	1	3	2	3	1
Expert 4	3	3	2	4	3	1	3	1	3	1
Expert 5	4	5	2	4	3	1	4	1	2	2
Expert 6	2	4	2	5	3	1	3	1	4	2
Expert 7	2	3	2	5	3	1	3	1	3	1
Expert 8	3	3	2	5	3	1	4	2	3	1
Expert 9	2	4	1	5	3	1	3	2	2	1
Expert 10	2	4	2	4	4	1	3	1	2	2
Expert 11	1	4	1	4	4	1	4	1	2	1
Expert 12	2	3	1	4	4	1	3	1	3	2
Expert 13	2	4	2	5	3	2	3	2	3	1
Expert 14	1	4	2	4	3	1	3	1	3	2
Expert 15	1	4	1	5	3	1	4	1	3	1
Aggregated score	1.838	3.689	1.447	4.439	3.239	1.149	3.302	1.320	2.671	1.260
Decimal score (*Pj*)	0.368	0.738	0.289	0.888	0.648	0.230	0.660	0.264	0.534	0.252

Relative weights of the challenges based on what the ranking is done can be found in Table 5.

Table 5. Relative weights of the challenges

Challenges	Pj	Sj	Kj	qj	wj
C4	0.888		1.000	1.000	0.143
C2	0.738	0.150	1.150	0.870	0.124
C7	0.660	0.077	1.077	0.807	0.115
C5	0.648	0.013	1.013	0.797	0.114
C9	0.534	0.114	1.114	0.716	0.102
C1	0.368	0.167	1.167	0.614	0.087
C3	0.289	0.078	1.078	0.569	0.081
C8	0.264	0.026	1.026	0.555	0.079
C10	0.252	0.012	1.012	0.548	0.078
C6	0.230	0.022	1.022	0.536	0.077

The gathered evaluation scores for the selected opportunities by the 15 experts can be found in Table 6, in which the aggregated scores and the decimal scores have been determined as well.

Table 6. Evaluation of the selected opportunities by the panel of experts

	O1	O2	O3	O4	O5	O6	O7	O8	O9	O10
Expert 1	1	5	2	2	2	4	3	2	4	4
Expert 2	2	5	2	1	2	3	3	2	4	4
Expert 3	2	5	3	2	1	4	4	2	5	3
Expert 4	2	5	3	3	2	4	3	1	5	3
Expert 5	2	4	2	2	1	4	4	1	5	3
Expert 6	3	5	2	3	3	4	3	1	5	3

Table 6. (cont.)

	O1	O2	O3	O4	O5	O6	O7	O8	O9	O10
Expert 7	3	5	3	2	3	3	3	2	5	3
Expert 8	3	5	2	3	2	4	3	2	5	4
Expert 9	2	5	3	2	3	4	3	3	4	3
Expert 10	2	4	4	3	2	5	4	3	5	2
Expert 11	2	5	3	4	2	4	3	2	5	3
Expert 12	1	5	2	3	3	4	4	2	5	3
Expert 13	2	5	2	3	3	4	4	3	5	2
Expert 14	1	5	3	3	2	5	3	2	4	4
Expert 15	2	5	3	3	2	4	3	1	4	3
Aggregated Score	1.888	4.853	2.531	2.483	2.087	3.966	3.302	1.803	4.642	3.069
Decimal Score (Pj)	0.378	0.971	0.506	0.497	0.417	0.793	0.660	0.361	0.928	0.614

Relative weights of the challenges based on what the ranking is done can be found in Table 7.

Table 7. Relative weights of the opportunities

Opportunities	Pj	Sj	Kj	qj	wj
O2	0.971		1.000	1.000	0.143
O9	0.928	0.042	1.042	0.959	0.137
O6	0.793	0.135	1.135	0.845	0.121
O7	0.660	0.133	1.133	0.746	0.106
O10	0.614	0.047	1.047	0.713	0.102
O3	0.506	0.108	1.108	0.644	0.092
O4	0.497	0.010	1.010	0.637	0.091
O5	0.417	0.079	1.079	0.591	0.084
O1	0.378	0.040	1.040	0.568	0.081
O8	0.361	0.017	1.017	0.559	0.080

4.0 RESULTS AND DISCUSSIONS

The ranking of the challenges based on their relative weights have been determined as C4> C2> C7> C5> C9> C1> C3> C8> C10> C6 (see Table 5 and Figure 2) and the opportunities as O2> O9> O6> O7> O10> O3> O4> O5> O1> O8 (see Table 7 and Figure 3). The SWARA method has assigned a relative weight to each of the challenges and opportunities, thereby providing a quantitative measure of their relative importance to aid decision-makers.

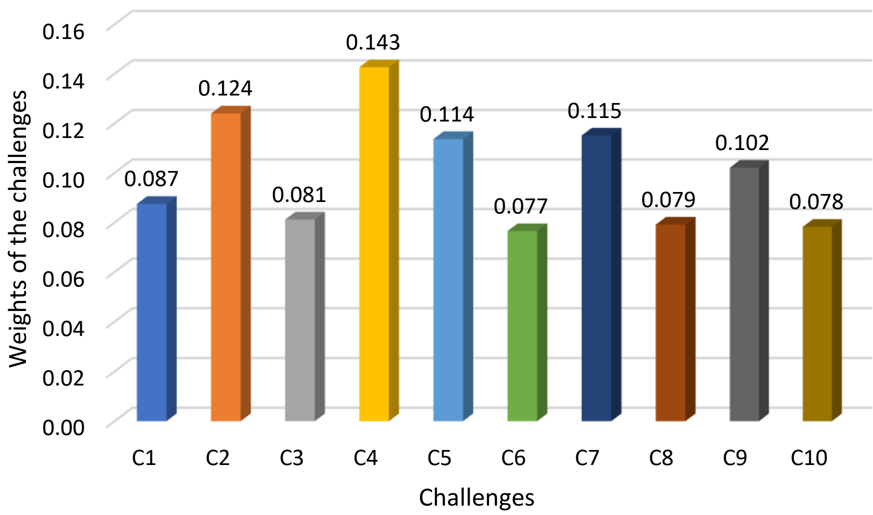

Figure 2. Ranking of the challenges

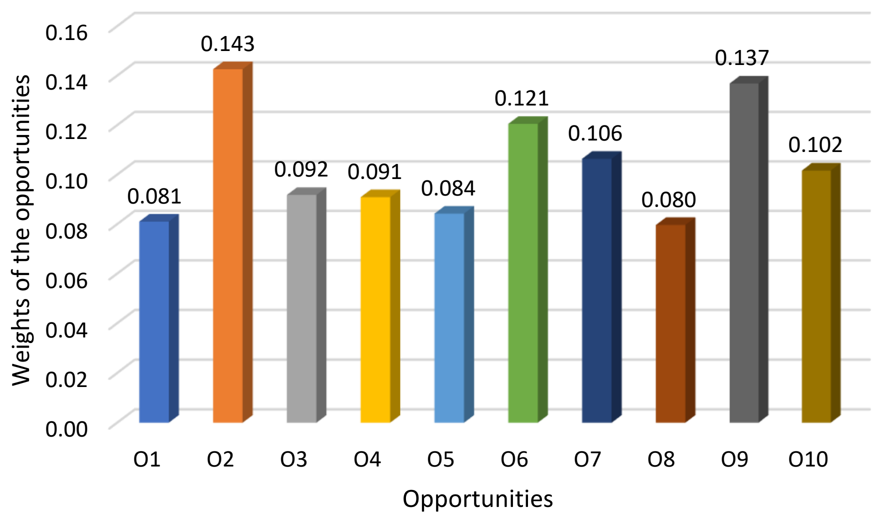

Figure 3. Ranking of the opportunities

4.1 Validation of the results through sensitivity analysis

Sensitivity analysis is required to check the validity and robustness of a decision-making study, as the calculation steps often lead to an unstable solution of such a study (Pramanik et al., 2021). A widely recognized technique to conduct sensitivity analysis for a prioritization or ranking-based study is to impose different weights on different responding experts (Akter et al., 2022). We have created 3 case scenarios, where we varied the weights of scores provided by the experts. In case scenario 1, we have taken the weight of Expert 1 (E1) as 16% and the rest as 6%, in case scenario 2, we have taken the weight of Expert 2 (E2) as 16% and the rest as 6%, and in case scenario 3, we have taken the weight of Expert 3 (E3) as 16% and the rest as 6%. We have applied the same technique for validating both rankings. We have found a similarity in the results in all the cases which is depicted in Figure 4 and Figure 5.

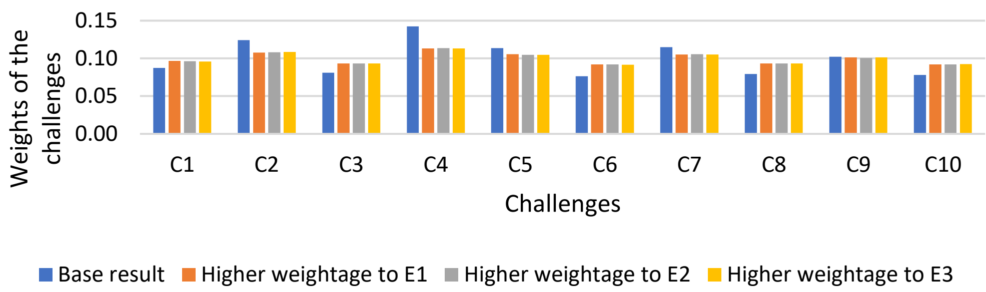

Figure 4. Sensitivity analysis for the ranking of the challenges

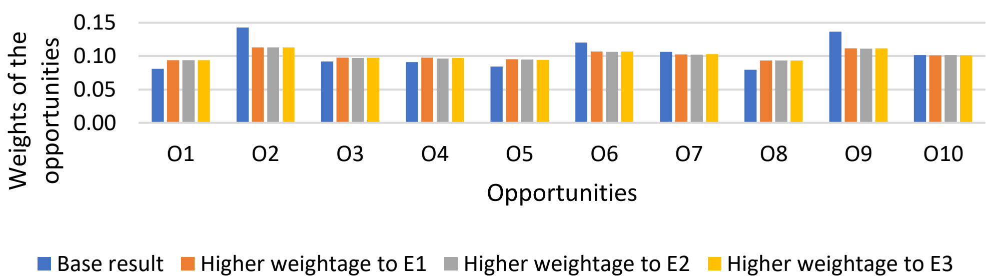

Figure 5. Sensitivity analysis for the ranking of the opportunities

Figures 4 and 5 demonstrate that the rankings obtained in this study remain consistent even when the weightage assigned to the experts is altered in different case scenarios. However, the weights assigned to the challenges and opportunities differ from the original or base result, which can be attributed to the influence of one expert's opinion over others. This phenomenon of weightage changes in different case scenarios, while maintaining the base result, is common in a sensitivity analysis. Such changes may result in a relative shift in the weight-to-weight ratio for the challenges (and opportunities) (Akter et al., 2022). Nevertheless, the stability observed in both rankings indicates the robustness of our study's results. Therefore, our obtained result from this study is validated as a ranking framework that can be used with confidence.

4.2 Discussing obtained results regarding the challenges

The results regarding the challenges are illustrated in Figure 2 below. It depicts that the top three challenges, ranked by relative weight, are C4 (workforce transformation), C2 (data management and integration), and C7 (complex system interoperability) with weights of 0.143, 0.124, and 0.115 respectively. When considering strategies to mitigate implementation challenges and ensure sustainable boiler operation within the context of Industry 4.0, managers and policymakers should prioritize the highest-ranked challenges. This is because resource limitations may constrain decision-making processes. Thus, a hierarchical or tiered approach to mitigating these challenges is likely to be both realistic and effective. Furthermore, addressing the most significant challenges first can have a positive impact on mitigating the remaining challenges. For instance, workforce transformation has been determined as the topmost ranked challenge for sustainable boiler operation in the context of Industry 4.0 because it involves the integration of new technology, processes, and skills into the workforce, which can be a significant and complex undertaking. The existing workforce may not have the necessary skills or experience to operate and maintain advanced technology, leading to operational inefficiencies and potential safety risks (Mukti et al., 2021; Shaharudin et al., 2021). By effectively addressing the challenge of workforce transformation, it can help mitigate other existing challenges such as data management and integration, cybersecurity, and human-machine interaction. This is because the skilled and trained workforce will be better equipped to handle the implementation and operation of Industry 4.0 technologies and processes, reducing the risk of errors and security breaches. Additionally, the improved collaboration between human operators and technology will result in more optimized performance, increased productivity, and enhanced safety, leading to a more sustainable boiler operation. Therefore, by addressing this challenge, other challenges may become more manageable and easier to resolve.

According to the result, data management and integration is the second most crucial challenge for sustainable boiler operation in the context of Industry 4.0 as it refers to the effective organization, management, and integration of data generated from various sources such as sensors, devices, and equipment used in the operation of boilers. The challenge lies in ensuring that the data is accurate, up-to-date, and easily accessible for analysis and decision-making purposes (Malhotra et al., 2021; Warsokusumo et al., 2020). Effective data management and integration can mitigate other challenges by providing real-time information for predictive maintenance, optimizing performance, and improving energy efficiency. It can also facilitate data-driven decision-making, enabling organizations to make informed decisions that can improve overall sustainability and reduce risks. Additionally, well-managed data can provide valuable insights into the operation of boilers and support continuous improvement efforts, enabling organizations to identify and resolve challenges proactively. The third most critical challenge is complex system interoperability or seamless integration of multiple systems and technologies which is critical to ensuring efficient and reliable boiler operation. A lack of interoperability between different systems and technologies can result in communication gaps and errors, leading to decreased efficiency, decreased productivity, and increased downtime (Ding et al., 2018; Yan et al., 2017). By addressing complex system interoperability, other challenges such as technical challenges, cyber security, and human-machine interaction can be mitigated. A well-integrated system ensures that all components are communicating effectively, reducing the risk of errors and improving the overall performance of the boiler operation. The integration of multiple systems also enables data sharing and exchange, which can lead to better decision-making, improved productivity, and increased automation. Similarly, by the ranking order, all of the challenges are considered to be more critical and significant than those ranked lower. It is therefore reasonable to conclude that addressing the highest-ranked challenges, as determined by the study results, can serve as an effective foundation for implementing a hierarchical approach to resolving other challenges.

4.3 Discussing obtained results regarding the opportunities

The results regarding the opportunities are illustrated in Figure 3. It depicts that the top three opportunities, ranked by relative weight, are O2 (improved energy efficiency), O9 (enhanced safety), and O6 (increased productivity) with weights of 0.143, 0.137, and 0.121 respectively.

In the pursuit of maximizing opportunities and maintaining sustainable boiler operation in the context of Industry 4.0, decision-makers should give priority to the opportunities ranked highest in importance. Resource constraints can often limit the decision-making process, so a step-by-step or prioritized approach to exploiting these opportunities is likely to be feasible and successful. By first focusing on the most valuable opportunities, the likelihood of realizing the benefits of the other opportunities is increased. For instance, improved energy efficiency is considered the top-most ranked opportunity for sustainable boiler operation in the context of Industry 4.0 due to several reasons. Firstly, the energy efficiency of boilers has a direct impact on operational costs, as it reduces fuel consumption and thus saves money. Secondly, improved energy efficiency also results in lower carbon emissions, which aligns with the increasing demand for environmentally friendly solutions. By improving energy efficiency, other opportunities can be leveraged in the context of sustainable boiler operation. For example, enhanced energy efficiency can result in a longer lifespan of boilers, which supports the implementation of predictive maintenance strategies, thus improving reliability and reducing downtime. Additionally, reduced energy consumption also leads to reduced demand for energy resources, helping to mitigate potential energy supply shortages and price volatility. Furthermore, improved energy efficiency can result in increased competitiveness, as it allows boilers to operate more effectively, improving the overall performance of the organization (Ding et al., 2018; Mohamed et al., 2019).

According to the result, enhanced safety is considered the second most significant opportunity for sustainable boiler operation in the context of Industry 4.0 because of the potential to reduce the risk of accidents and injuries to workers and the general public. A safe work environment not only benefits the workers but also has a positive impact on the company's reputation, as well as reducing the cost of insurance and potential lawsuits (Kibulungu & Laseinde, 2023). Additionally, a safe work environment also helps to foster employee satisfaction and loyalty, which can improve productivity and efficiency. The implementation of Industry 4.0 technologies, such as real-time monitoring and predictive maintenance, can enhance safety by allowing operators to identify potential hazards and address them before they become a problem. This, in turn, can help to take advantage of other existing opportunities, such as increased productivity, improved performance, and enhanced customer experience, as a safer work environment contributes to a more positive work culture and overall better outcomes. Increased productivity is the third-most ranked opportunity for sustainable boiler operation in the context of Industry 4.0 as it directly impacts the profitability and efficiency of the operation. By adopting Industry 4.0 technologies and practices, sustainable boiler operations can improve their productivity by streamlining processes, reducing downtime, and maximizing resource utilization. Improved productivity can help to take advantage of other existing opportunities by allowing organizations to achieve more with fewer resources, which can lead to cost savings and increased competitiveness (Munsamy & Telukdarie, 2022; Yusof & Mohammad, 2022). Additionally, improved productivity can also lead to better customer satisfaction as operations can deliver services and products more efficiently, enhancing the customer experience. Moreover, increased productivity can also have a positive impact on the environment, as more efficient operations consume fewer resources and generate less waste, leading to improved environmental performance. Thus, increased productivity can act as a catalyst to help organizations take full advantage of other existing opportunities in sustainable boiler operations. Similarly, the opportunities are ranked according to their importance, with those ranked higher being considered more crucial and impactful than those ranked lower. It can be concluded that focusing on the highest-ranked opportunities, as indicated by the results, provides a strong basis for a hierarchical approach to realizing the benefits of other opportunities.

5.0 IMPLICATIONS OF THE STUDY IN THE CASE OF ACHIEVING SUSTAINABILITY

The results of this study have significant implications for organizations looking to achieve operational sustainability of boilers in the context of Industry 4.0. To overcome the challenges and take advantage of the opportunities, organizations must adopt a holistic approach that takes into account the various interrelated factors that impact sustainable boiler operation. The findings of this study can be used as a roadmap for organizations to achieve sustainable boiler operation, including:

- Addressing the workforce transformation challenge by investing in training and development programs for employees and integrating technology in the workplace.
- Developing robust data management and integration strategies to ensure the seamless flow of data between different systems and applications, thereby reducing the risk of data loss or security breaches.
- Improving complex system interoperability by implementing standardized protocols and open-source platforms that allow different systems and applications to communicate and exchange data.
- Maximizing energy efficiency by investing in advanced technologies such as digital twins and artificial intelligence to optimize performance and reduce energy consumption.
- Enhancing safety by investing in advanced safety systems and procedures, and by conducting regular safety audits to ensure that safety protocols are being followed.
- Increasing productivity by adopting agile and flexible production processes that can adapt to changing market conditions and customer needs.
- Utilizing data-driven decision-making to make informed decisions that optimize performance and reduce waste.
- Improving environmental performance by reducing emissions and implementing sustainable practices that protect the environment.
- Achieving a competitive advantage by adopting industry-leading technologies and best practices that set the organization apart from its competitors.
- Enhancing the customer experience by adopting customer-centric processes and technologies that provide a seamless and personalized experience for customers.

Overall, this study highlights the importance of a systematic and integrated approach to achieving the operational sustainability of boilers in the context of Industry 4.0. Organizations that take these findings into account and adopt a proactive approach to sustainable boiler operation are likely to be better positioned to overcome the challenges and realize the opportunities presented by this rapidly evolving technological landscape. This study has significant implications for achieving the sustainable development goals (SDG) set by the United Nations as well. The study highlights the crucial role that technology and human resources play in achieving sustainability. The findings have significant implications for the implementation of sustainable development goals and provide valuable insights for policymakers and industry leaders to take action toward a sustainable future. The study highlights the importance of improving energy efficiency, which aligns with SDG 7 on affordable and clean energy. The emphasis on enhancing safety in boilers operations aligns with SDG 3 on good health and well-being. The findings on increased productivity and improved environmental performance align with SDG 8 on decent work and economic growth and SDG 14 on life below water, respectively.

Moreover, the study's focus on the challenges related to data management and integration, complex system interoperability, and workforce transformation highlights the importance of technology and human resources in achieving sustainability. These challenges and opportunities have implications for the implementation of the SDGs, as they provide a roadmap for the development and deployment of technologies and processes that can support sustainable development.

6.0 CONCLUSION

The study aimed to identify the challenges and opportunities for achieving operational sustainability of boilers in the context of Industry 4.0. By applying the SWARA method, 10 challenges and 10 opportunities were ranked in terms of their significance. The study highlights the importance of addressing workforce transformation, data management and integration, and complex system interoperability as the top three challenges, and improving energy efficiency, enhancing safety, and increasing productivity as the top three opportunities for sustainable boiler operation.

One of the limitations of the study is that it is based on a limited number of sources and expert opinions. Further research is needed to validate the results and to incorporate the perspectives of a wider range of stakeholders, such as boiler operators, policymakers, and consumers.

Future research could explore in more detail the interplay between the identified challenges and opportunities and how they can be effectively addressed to achieve sustainable boiler operation in the context of Industry 4.0. Additionally, it would be beneficial to investigate how the findings of the study can be applied in practice to support decision-making and policy development. In conclusion, the study provides a useful starting point for further research on sustainable boiler operation in the context of Industry 4.0 and contributes to the development of strategies and solutions for sustainable energy use in the industry.

REFERENCES

Akter, S., Debnath, B., & Bari, A. M. (2022). A grey decision-making trial and evaluation laboratory approach for evaluating the disruption risk factors in the Emergency Life-Saving Drugs supply chains. *Healthcare Analytics, 2,* 100120.

Al-Mughairy, M., & Shrivastava, P. (2022). Skills and competencies requirements in industry 4.0 for entry-level project management positions: An industry perspective. *International Journal of Industrial Management*, *15*(1), 78-88.

Arakelyan, E. K., Kosoy, A. A., Mezin, S. V., & Pashchenko, F. F. (2021). Application of the basic principles of" Industry 4.0" in the intellectualization of automated control systems of modern thermal power plants. *Procedia Computer Science, 184*, 865-870.

Ayyildiz, E., Yildiz, A., Taskin Gumus, A., & Ozkan, C. (2021). An integrated methodology using extended SWARA and DEA for the performance analysis of wastewater treatment plants: *Turkey case. Environmental Management, 67*(3), 449-467.

Balali, A., Moehler, R. C., & Valipour, A. (2022). Ranking cost overrun factors in the mega hospital construction projects using Delphi-SWARA method: An Iranian case study. *International Journal of Construction Management, 22*(13), 2577-2585.

Bari, A. M., Siraj, M. T., Paul, S. K., & Khan, S. A. (2022). A Hybrid Multi-Criteria Decision-Making approach for analysing operational hazards in heavy fuel oil-based power plants. *Decision Analytics Journal*, *3*, 100069.

Behzad, M., Kim, H., Behzad, M., & Behambari, H. A. (2019). Improving sustainability performance of heating facilities in a central boiler room by condition-based maintenance. *Journal of Cleaner Production, 206*, 713-723.

Carvalho, A. C. P., Carvalho, A. P. P., & Carvalho, N. G. P. (2020). Industry 4.0 technologies: what is your potential for environmental management?. In Industry 4.0-Current Status and Future Trends. IntechOpen.

Cheah, S. C., & Tan, C. L. (2020). Knowledge Management, Organizational Ambidexterity, and Manufacturing Performance in the Era of Industry 4.0: A Proposed Model. *International Journal of Industrial Management, 5*, 10-19.

Chofreh, A. G., Goni, F. A., Klemeš, J. J., Moosavi, S. M. S., Davoudi, M., & Zeinalnezhad, M. (2021). Covid-19 shock: Development of strategic management framework for global energy. *Renewable and Sustainable Energy Reviews, 139*, 110643.

Dai, X., Yang, B., Zhong, Y. F., & Guo, Y. H. (2013). The Artificial Neural Network On-line Monitoring Model of Boiler Efficiency. In Advanced Materials Research (773, 239-243). Trans Tech Publications Ltd.

Ding, S., Gu, W., Lu, S., Yu, R., & Sheng, L. (2022). Cyber-attack against heating system in integrated energy systems: Model and propagation mechanism. *Applied Energy, 311*, 118650.

Ding, Y., Liu, J., Xiong, J., Jiang, M., & Shi, Y. (2018, October). Optimizing boiler control in real-time with machine learning for sustainability. In Proceedings of the 27th ACM International Conference on Information and Knowledge Management (2147-2154).

Edlund, K., Bendtsen, J. D., & Jørgensen, J. B. (2011). Hierarchical model-based predictive control of a power plant portfolio. *Control Engineering Practice, 19*(10), 1126-1136.

Gopal, N., & Panchal, D. (2023). Fuzzy decision support system for sustainable operational performance optimization for boiler unit in milk process industry. *Applied Soft Computing, 135*, 109983.

Hardy, T., Arora, A., Pawlak-Kruczek, H., Rafajłowicz, W., Wietrzych, J., Niedźwiecki, Ł., & Mościcki, K. (2021). Non-Destructive Diagnostic Methods for Fire-Side Corrosion Risk Assessment of Industrial Scale Boilers, Burning Low Quality Solid Biofuels—A Mini Review. *Energies*, *14*(21), 7132.

Harjamulya, H., Rusmin, P. H., Hidavat, E. M., & Syaichu-Rohman, A. (2019, September). Design and implementation of mpc for energy optimization of boiler in batch distillation column. In 2019 6th International Conference on Electrical Engineering, Computer Science and Informatics (EECSI) (205-210). IEEE.

Hina, M., Chauhan, C., Kaur, P., Kraus, S., & Dhir, A. (2022). Drivers and barriers of circular economy business models: Where we are now, and where we are heading. *Journal of Cleaner Production, 333,* 130049.

Hollander, R. (2018). Sustained competitive advantage using Industry 4.0 technologies (Bachelor's thesis, University of Twente).

Ingram, T., Wieczorek-Kosmala, M., & Hlaváček, K. (2023). Organizational Resilience as a Response to the Energy Crisis: Systematic Literature Review. *Energies, 16*(2), 702.

Jha, U. C., Sai, R. J., Reddy, M. K., & Singh, A. (2022). Analysis of Predictive Maintenance in Industry 4.0: A review. *International Journal of Mechanical Engineering, 7*, 103-109

Keršuliene, V., Zavadskas, E. K., & Turskis, Z. (2010). Selection of rational dispute resolution method by applying new step-wise weight assessment ratio analysis (SWARA). *Journal of business economics and management, 11*(2), 243-258.

Kibulungu, J. W., & Laseinde, O. T. (2023). Automatic Control System Based on Industry 4.0, PLC, and SCADA. In Intelligent Sustainable Systems: Selected Papers of WorldS4 2022, 1(183-197). Singapore: Springer Nature Singapore.

Kluczek, A., Żegleń, P., & Matušíková, D. (2021). The use of Prospect theory for energy sustainable industry 4.0. *Energies, 14*(22), 7694.

Krupitzer, C., Müller, S., Lesch, V., Züfle, M., Edinger, J., Lemken, A., ... & Becker, C. (2020). A survey on human machine interaction in industry 4.0. arXiv preprint arXiv:2002.01025.

Lee, C. K., Chen, M. S., Zainudin, N. M., Fauzi, M. A., & Toh, T. C. (2022). Transformation of industrial revolution 4.0 in the construction industry: Understanding drivers & barriers with dematel algorithm. *International Journal of Industrial Management, 16*(1), 31-43.

Li, X., & Yu, X. (2022). Robust regulation for superheated steam temperature control based on data-driven feedback compensation. *Applied Energy, 325*, 119918.

Lim, C. H., Lim, S., How, B. S., Ng, W. P. Q., Ngan, S. L., Leong, W. D., & Lam, H. L. (2021). A review of industry 4.0 revolution potential in a sustainable and renewable palm oil industry: HAZOP approach. *Renewable and Sustainable Energy Reviews, 135*, 110223.

Malavazi, G. M. (2022). Reducing Clogs in Power Boiler Biomass Feeding System. Biomass. *Biorefineries and Bioeconomy*, 121-144.

Malhotra, S., Singh, T., & Agarwal, V. (2021). Assessment of Challenges for Implementation of Industrial Internet of Things in Industry 4.0. In Industry 4.0 Technologies for Business Excellence (127-139). CRC Press.

Mohamed, N., Al-Jaroodi, J., & Lazarova-Molnar, S. (2019). Leveraging the capabilities of industry 4.0 for improving energy efficiency in smart factories. *IEEE Access, 7*, 18008-18020.

Muhammad Ashraf, W., Moeen Uddin, G., Muhammad Arafat, S., Afghan, S., Hassan Kamal, A., Asim, M., ... & Krzywanski, J. (2020). Optimization of a 660 MWe supercritical power plant performance—a case of Industry 4.0 in the data-driven operational management part 1. *Thermal efficiency. Energies, 13*(21), 5592.

Mukti, S. K., Ahirwar, A. V., & Agrawal, A. (2021). Industry 4.0: Advances and Applications. Industry 4.0: Advances and Applications, 1-35.

Munsamy, M., & Telukdarie, A. (2022). Discrete event modelling for evaluation and optimisation of power utility energy demand. *Journal of Industrial Engineering and Management, 15*(1), 124-141.

Oláh, J., Aburumman, N., Popp, J., Khan, M. A., Haddad, H., & Kitukutha, N. (2020). Impact of Industry 4.0 on environmental sustainability. *Sustainability, 12*(11), 4674.

Olkiewicz, M., Olkiewicz, A., Wolniak, R., & Wyszomirski, A. (2021). Effects of Pro-Ecological Investments on an Example of the Heating Industry—Case Study. *Energies, 14*(18), 5959.

Oluyisola, O. E., Bhalla, S., Sgarbossa, F., & Strandhagen, J. O. (2022). Designing and developing smart production planning and control systems in the industry 4.0 era: a methodology and case study. *Journal of Intelligent Manufacturing, 33*(1), 311-332.

Popović, M., Popović, G., & Karabašević, D. (2021). Determination of the importance of evaluation criteria during the process of recruitment and selection of personnel based on the application of the SWARA method. *Ekonomika, 67*(4), 1-9.

Pozdneev, B. M., Levchenko, A. N., Ovchinnikov, P. E., & Sharovatov, V. I. (2019). Integration of the automated control systems at a manufacturing enterprise. *Russian Engineering Research, 39*, 1057-1060.

Pramanik, P. K. D., Biswas, S., Pal, S., Marinković, D., & Choudhury, P. (2021). A comparative analysis of multi-criteria decision-making methods for resource selection in mobile crowd computing. *Symmetry, 13*(9), 1713.

Rahman, M. A., Karmaker, C. L., Ahmed, T., Khan, M. I., Morshed, A. M., & Ali, S. M. (2022). Modelling the causes of boiler accidents: implications for economic and social sustainability at the workplace. *Heliyon*, e09601.

Shaharudin, M. S., Zulkifli, W. N., Gui, A., & Fernando, Y. (2021). Drivers Human Resources 4.0: Technological, Organisational & Environmental of Human Resources 4.0 at Malaysian Private Companies. *International Journal of Industrial Management, 12*(1), 306-318.

Siraj, M. T., Bari, A. M., Haq, M. M., & Al Islam, M. F. (2022) Prioritization of Fire Risk Remedial Actions in the Ready-Made Garment Industry of Bangladesh: A Hybrid MCDM Approach. Proceedings of the 5th European International Conference on Industrial Engineering and Operations Management, Rome, Italy, July 26-28, 2022, 115-127.

Sivageerthi, T., Bathrinath, S., Uthayakumar, M., & Bhalaji, R. K. A. (2022). A SWARA method to analyze the risks in coal supply chain management. *Materials Today: Proceedings, 50*, 935-940.

Toit, P. D., & Laubscher, R. (2018). Industry 4.0, artificial intelligence and its application in a bagasse-fired power plant. In Proceedings of the Annual Congress-South African Sugar Technologists' Association (No. 91, 310-317). South African Sugar Technologists' Association.

Tsai, W. H. (2018). Green production planning and control for the textile industry by using mathematical programming and industry 4.0 techniques. *Energies, 11*(8), 2072.

Urgese, G., Azzoni, P., van Deventer, J., Delsing, J., & Macii, E. (2020, April). An Engineering Process model for managing a digitalised life-cycle of products in the Industry 4.0. In NOMS 2020-2020 IEEE/IFIP Network Operations and Management Symposium (1-6). IEEE.

Ustundag, A., Cevikcan, E., Ervural, B. C., & Ervural, B. (2018). Overview of cyber security in the industry 4.0 era. *Industry 4.0: managing the digital transformation*, 267-284.

Wang, J. (2017). Theoretical research and application of petrochemical Cyber-physical Systems. *Frontiers of Engineering Management, 4*(3), 242-255.

Warsokusumo, T., Aditya, M., Prahasto, T., Haryanto, I., & Widodo, A. (2020, November). Real-time online monitoring for maintaining energy efficiency performance of power generation system. In AIP Conference Proceedings (Vol. 2296, No. 1, p. 020054). AIP Publishing LLC.

Woon, K. S., Phuang, Z. X., Taler, J., Varbanov, P. S., Chong, C. T., Klemeš, J. J., & Lee, C. T. (2022). Recent Advances in Urban Green Energy Development Towards Carbon Neutrality. *Energy, 267*, 126502.

Wyrwicka, M. K., & Mrugalska, B. (2017, July). Industry 4.0-towards opportunities and challenges of implementation. In 24th International Conference on Production Research (382-387).

Yan, J., Meng, Y., Lu, L., & Li, L. (2017). Industrial big data in an industry 4.0 environment: Challenges, schemes, and applications for predictive maintenance. *IEEE Access*, *5*, 23484-23491.

Yusof, M. F. M., & Mohammad, R. (2022). Risk Management Framework: A Review for Boiler Operations In Malaysia. In Proceedings of International Conference on Engineering Business Management (ICEBM2022) 20–21 August 2022.