Moderating factors influencing the implementation of Industry 4.0 Technologies in Solid Waste Management: Evidence from South Africa's category A Municipality of Cape Town

[1]Velaphi Mabiletsa &[2]Kemlall Ramdass

[1&2] University of South Africa

43568009@mylife.unisa.ac.za(Corresponding author)

ABSTRACT

What are the moderating factors influencing the implementation of Industry 4.0 technologies in solid waste management in South Africa's Category A municipality of Cape Town?Anchored in Socio-Technical Systems Theory, the study answers this research question through the use of qualitative research methods. Data from was collected from semi-structured interviews with 12 municipal officials who were purposefully sampled and it wereanalysed thematically.The results show two main themes. Industry 4.0 technologies scalability is either enhanced or limited by organizational capacity factors, which include data management for Internet of things or Artificial intelligence monitoring, technology readiness, public participation, and human resource investment. Institutional and regulatory enablers emphasize the need for research and development innovation, weigh the dangers of unemployment against waste-to-energy and Artificial intelligence integration, enforce solid waste management regulations, and provide financing for incentives and compliance.Policy recommendations include mandating integrated data platforms with public application programming interface, reskilling incentives, and ring-fenced solid waste management funding to foster equitable circular economy transitions. These insights offer valuable lessons for South African municipalities, with future research urged on quantitative validation and longitudinal pilot.

Keywords: Category A municipality; industry 4.0 technologies;solid waste management; South Africa

JEL CODES:O33; Q53

1. INTRODUCTION

The current wave of industrial transformation, known as Industry 4.0 (IR 4.0), is defined by the integration of cyber-physical systems, cloud computing, the Internet of Things, artificial intelligence, and sophisticated data analytics to produce more adaptable, effective, and independent production and service delivery (Khan et al., 2023). IR 4.0 technologies have the potential to improve waste collection routing, fleet and equipment predictive maintenance, automated sorting and recycling procedures, real-time landfill and treatment operations monitoring, and data-driven governance that promotes the circular economy in the context of solid waste management (SWM) (Kanojia et al., 2021).Solid waste management is still a crucial municipal duty in both developed and developing economies with significant effects on the environment, public health, and the economy (Zhang et al., 2024). SWM systems include techniques for prevention, reduction, reuse, and recycling in addition to waste creation, collection, transportation, treatment, and disposal(Amaka et al., 2025).

SWM is a significant aspect in municipal budgets in South Africa, and it frequently requires significant operational flexibility to deal with changing waste composition, participation from the informal sector, and quickly expanding urban populations (City of Cape Town waste data program, 2022). In South Africa, municipalities fall under the following categories: Category A- metropolitan municipalities which covers large cities for example Cape Town, Category B –municipality covering smaller towns and cities, and Category C- municipalities covering districts (South African government 2025).Although the total amount of waste generated is higher, it was determined in 2024 that the City of Cape Town disposes of about 1.13 million tonnes of waste annually at landfills, of which 73% is Municipal Solid Waste (MSW) generated by residents and 27% is from the private sector. Large volumes of waste are managed through landfill disposal (City of Cape Town 2024).However, the City of Cape Town is facing landfill capacity challenges and this poses threats to the ability of the metropolitan municipality to address SWM (City of Cape Town 2025). This therefore, may call for the modern use of industry 4.o technologies in SWM as land is a scarce resources and the municipality is facing landfillshortages. The aim of the study is stated below:

(1) To investigate the moderating factors influencing the implementation of Industry 4.0 technologies in solid waste management in South Africa's category A municipality of City of Cape Town.

Viswanathan &Telukdarie, (2022) researched on the role of 4IR technologies in SWM. The study used a bibliometric analysis and the results from the study indicated that SWM value

chain is shaped by the use of modern technology. However, this study did not cover City of Cape Town, so it remains unknown on the factors needed to fully implement 4IR technologies for effective SWM especially in category A municipality.

Hutete et al., (2025) used interviews to examine the factors which affect adoption of 4IR technology for water governance in rural district municipality in Eastern Cape Province of South Africa. Although the study covered issues centred on 4IR technologies, nothing on SWM was addressed and it was only devoted to water governance. A different study was carried out by Almelhem et al., (2025) and it focused on Industry 4.0 for sustainable reverse waste collection. This study was done using systematic literature review and it was established that successful 4IR technology adoption is dependent on supportive policies implemented by the government. This study did not cover City of Cape Town and does not contain the perspectives of experts (which can be gathered through interviews) who deal with SWM. Although diverse scholars such as (Almelhem et al., 2025;Hutete et al., 2025; Viswanathan &Telukdarie, 2022) researched on 4IR technologies, no study to the best knowledge of the authors has addressed the necessary factors needed to influence the adoption of 4IR technologies in Category A municipality of Cape Town. The current study will close this research gap.

This research is significant in that it offers empirical insights into how modern technology uptake can be promoted by concentrating on Cape Town, a major South African city with significant waste generation and complex service delivery. The study's policy-relevant implications and research goal that tackles scalability, equity, and resilience make it noteworthy as well. These findings will affect municipal budgeting, regulatory design, and capacity-building programs in Africa and similar urban contexts.The study intends to provide nuanced lessons for other category A municipalities and similarly situated urban contexts looking to use IR 4.0 to improve sustainable waste management outcomes by examining moderating factors in a large metropolitan city. By bridging the gap between theoretical potential and actual implementation, the findings are anticipated to contribute to both academic discourse on IR 4.0 in SWM and practical municipal governance in South Africa.

The rest of the paper is structured like this: Section 2 covers the theoretical framework. In section 3, the methodology is described. The findings and discussion, policy recommendations and suggestions for future studies are presented in Section 4. Section 5 presents the study's conclusion.

2. THEORATICAL FRAMEWORK

This section presents the theoretical framework. The research is anchored on the Socio-technical systems theory.

2.1 Socio-Technical Systems Theory

Eric Trist and Fred Emery developed Socio-Technical Systems Theory (STS) in the 1950s (Walker et al., 2008). The technical system and the social system are two interrelated subsystems that make up organizations, according to the fundamental premise of socio-technical systems theory (Molleman&Broekhuis, 2001). While the social system contains people, skills, positions, values, leadership, and organizational structures, the technical system consists of tools, technologies, procedures, and workflows (Pasmore et al., 2019). Instead of emphasizing technological efficiency at the expense of organizational and human elements, STS theory posits that optimal performance is attained when both systems are collaboratively optimized (Botla, 2018).

Another fundamental premise is that the adoption of technology invariably modifies decision-making procedures, power dynamics, and work practices, making human adaptation a crucial success factor (Bolatan et al., 2022). Additionally, STS makes the assumption that systems function in a larger context, which means that outside factors like laws, rules, and social norms have an impact on the uptake and application of technology (Thomas, 2024). Therefore, the values of flexibility, participation, and employee involvement are crucial because they allow organizations to adapt technologies to local circumstances instead of imposing inflexible, technology-driven solutions.

This study, which attempts to examine the moderating factors impacting the adoption of Industry 4.0 technologies in solid waste management in the City of Cape Town, is pertinent to socio-technical systems theory. Waste bins with Internet of Things capabilities, data analytics, automation, and intelligent routing systems are examples of Industry 4.0 technologies that go beyond simple technological solutions(Seun, 2025). Human competencies, organizational preparedness, governance frameworks, and stakeholder acceptance are all equally important for the successful implementation of municipal solid waste management (Woldesenbet, 2021). How these technologies are incorporated into current waste management systems in a Category A municipality like Cape Town is directly influenced by moderating factors including worker skills, leadership support, organizational culture, regulatory compliance, and public engagement.

In the South African municipal setting, where issues like socioeconomic disparities, institutional capacity limitations, and talent shortages might attenuate technical benefits, STS theory is especially pertinent (Mamokhere, 2025). Through the use of Socio-Technical Systems Theory, this study acknowledges that the social, organizational, and institutional aspects of municipal service delivery must be aligned with modern digital systems in order for Industry 4.0 technologies to be implemented effectively. The theory is therefore very suitable for this research since it offers a comprehensive framework for analyzing why some Industry 4.0 efforts are successful while others encounter opposition or poor performance.

3. METHODOLOGY

Qualitative research methods served as the foundation for the study. Permission to gather the data was given by the university's ethics committee and the City of Cape Town metropolitan government. The target group for the study was the upper, middle, and lower level employees of management in the City of Cape Town metropolitan municipality. In this research,purposeful sampling was used to select the research participants needed for data gathering (Ahmed, 2024). By selecting people with expertise or experience, purposeful sampling facilitates the collection of rich, detailed, and contextually relevant data (Tajik et al., 2024). To put it another way, because purposeful sampling concentrates on specific individuals or groups, it can save more time and money than random sample (Nyimbili & Nyimbili, 2024). No consistent or standard numerical criterion can be used to calculate the sample size in qualitative research (Daniela, 2021). Hennink and Kaiser (2022) state that a sample size of 9–17 should be utilized in qualitative research to reach data saturation. The study's sample size of twelve participants exceeded the minimum of nine suggested by Hennink and Kaiser (2022).

This sample was obtained by the use of purposeful sampling. The most important prerequisite for data collection is reaching data saturation, especially when using interviews (Rahimi &Khatooni, 2024). Data for this study was gathered via online interviews.A semi-structured interview guide was used to collect the data. Each interview was recorded on tape. Interviews were used because they gave the researcher the opportunity to ask perceptive questions that made it possible to gather more information about the subject (Monday, 2020; Ruslin et al., 2022). After speaking with the twelfth person, the researcher concluded the interviews since no new information was found.

To analyze the data collected from the interviews, thematic data analysis was employed. This approach was used because it is flexible and allows for a deeper analysis of the themes found in the research, both of which are advantageous for accomplishing the objectives of the study (Naeem et al., 2023). By employing thematic analysis to look beyond clear patterns, the researcher was able to explore the participants' underlying meanings, experiences, and perceptions (Buetow, 2025). This is particularly useful in understanding complex, situation-specific issues such as institutional, technological, or environmental barriers to Industry 4.0 adoption.

4. RESULTS AND DISCUSSION

The findings and discussion are shown in this section. All the twelve participants that took part in the data collection exercise were given pseudo names. This was done to conceal their identity and the to fulfil the ethical requirements as per standard research practises. Participant 1-12 were therefore given pseudo names RN1-RN12 respectively. In this analysis, an extract of the views of the participants will be used. To add more, the analysis will be supported by the use of references. The extracted themes and codes are displayed in the table below.

Table 1: Main themes and codes

THEME	CODES
Organizational Capacity Factors	Technical skills, financial constraints and data infrastructure gaps
Institutional and Regulatory Enablers	Stakeholder collaboration, regulatory and supportive frameworks, governance structures

Source: Researcher’s Construct (2025)

Table 1 shows that the two themes that were obtained from the data were: organizational capacity factors. The associated codes were technical skills, financial constraints and data infrastructure gaps. The second theme that was established in the institutional and regulatory enablers. The associated codes for this theme were stakeholder collaboration, regulatory frameworks, governance structures.

THEME 1:Organizational Capacity factors

This theme covered key issue that relate to the City of Cape Town metropolitan municipality. The views of the respondents are presented below and they are not put in any chronological order. It should also be noted that, if other respondents do not appear, their views were the same with the ones mentioned, hence they were excluded to avoid unnecessary duplication.

Responses

"Well, I think that data management is very important for the City of Cape Town to manage waste effectively" RN1 – interviewed (November 2024).

"AI, IoT, and automation or harnessing more modern technology is the key"RN2 – interviewed (November 2024).

"In my view, the public must be part and parcel of the SWM initiatives such as using 4IR methods" RN6 – interviewed (November 2024).

"Community engagement and the use of technology are the ways l think our city can manage the waste challenges" RN10 – interviewed (November 2024).

"To achieve desired targets in SWM, human capital investment must be prioritised"- RN12 – interviewed (November 2024).

Analysis of responses in line with the theme

The interview responses under Theme 1: Organizational Capacity Factors show how the City of Cape Town's internal capabilities influence how Industry 4.0 (4IR) technologies are implemented in solid waste management (SWM). Participants emphasized in all of their comments that using 4IR tools in a Category A metropolitan municipality setting requires efficient data management, technological preparedness, and stakeholder participation.

One respondent argued that "data management is very important for the City of Cape Town to manage waste effectively" (RN1, November 2024).The implication of respondent 1 is that, the success of technologies like artificial intelligence (AI) and the Internet of Things (IoT) depends on data management, which is a fundamental organizational capacity aspect (Emon & Khan, 2025).This is further supported by Atofarati, Adogbeji, &Enweremadu (2025) who posited that reliable and integrated data systems allow for performance tracking, routing

optimization, and real-time waste production monitoring in the context of SWM. However, sophisticated 4IR technologies run the risk of failing or performing poorly in the absence of such systems. Therefore, by either facilitating or limiting the efficacy of 4IR technologies in municipal operations, data management functions as a moderating factor.

Another responder stated that "AI, IoT, and automation or harnessing more modern technology is the key," clearly connecting organizational capabilities to the adoption of contemporary technologies (RN2, November 2024). This statement emphasizes how important participants believe that using 4IR tools is essential to solving the city's waste problems and not just optional. However, sufficient technical expertise, institutional support, and a strong infrastructure are necessary for the successful use of AI, IoT, and automation (Fuqaha &Nursetiawan, 2025). The degree to which these technologies can be integrated, scaled, and maintained inside the City of Cape Town's SWM system is therefore influenced by organizational capacity.

The information from the interviews emphasizes that organizational capability is social and participative in addition to being technical. According to one participant, "community engagement and the use of technology are the ways I think our city can manage the waste challenges" (RN10, November 2024), while another emphasized that "the public must be part and parcel of the SWM initiatives such as using 4IR methods" (RN6, November 2024). These viewpoints highlight the significance of community involvement as an additional aspect of organizational capability (Rijal, 2023). The municipality's capacity to create inclusive, user-friendly, and context-sensitive 4IR programs depends on how well it encourages behavioural change and public participation. For instance, technological infrastructure and connections based on trust are necessary for digital platforms and mobile applications that report illegal dumping, schedule collections, or provide incentives for recycling (Olawade et al., 2024). By influencing citizen buy-in, compliance, and co-production in SWM, community involvement thereby moderates the adoption and impact of 4IR technologies.

Overally, the above analysis show that the City of Cape Town's organizational capacity plays a crucial moderating role in the adoption of 4IR technologies for solid waste management. The results thus indicate that in order to fully realize the potential of Industry 4.0 in promoting sustainable and inclusive solid waste management in South Africa's Category A municipalities, organizational capacity across data, technology, and stakeholder engagement dimensions must be strengthened.

THEME 2: Institutional and Regulatory Enablers

This theme was based on institutional and regulatory barriers. The views of the participants are presented below:

Responses

“Research and innovation on the needed technology.” RN3 - interviewed (November 2024)

“We must remember that in order to efficiently sort waste and lessen the effects on the environment, we must integrate systems like waste-to-energy and artificial intelligence.”RN7 - interviewed (November 2024).

“Advanced technology such as robots are needed, though it can lead to high unemployment, so a balance is needed.” RN7 - interviewed (November 2024).

“We require more supportive polices targeted on SWM and these policies must be implemented” RN8 - interviewed (November 2024).

Funding towards waste, monitoring and compliance and provision of incentives can help to manage solid waste and RN9 - interviewed (November 2024).

Analysis of responses in line with the theme

Participant perspectives from Cape Town demonstrate that institutional and regulatory enablers in solid waste management (SWM) prioritize finance mechanisms, policy frameworks, and innovation assistance to solve implementation constraints. Despite being presented as facilitators, this theme highlights ongoing regulatory gaps, with respondents emphasizing the need for focused interventions to support Industry 4.0 technologies like automation, IoT, and artificial intelligence.

The opinions of the respondents show important goals for removing institutional obstacles. RN3 promotes "research and innovation on the needed technology," emphasizing the lack of funding for R&D, which is crucial for the development of new technologies. While warning that "advanced technology such as robots... can lead to high unemployment, so a balance is needed," RN7 highlights the integration of "systems like waste-to-energy and artificial intelligence" to improve sorting efficiency and environmental mitigation. This highlights the need for comprehensive policy design that incorporates workforce reskilling.While RN9 asserts that "funding towards waste, monitoring and compliance and provision of incentives can help to manage solid waste," emphasizing fiscal and oversight enablers, RN8 demands

"more supportive policies targeted on SWM and these policies must be implemented," criticizing enforcement flaws.

These observations clearly relate to the study, but they also reflect participant concerns: insufficient R&D stifles innovation (echoing RN3); regulatory gaps in the labor transition increase automation-related unemployment risks (RN7); and financial shortages combined with lax compliance prevent scalability (RN8, RN9).

Overally, the findings from the study showsmoderators like policy consistency, budgetary allocation, and enforcement by reframing enablers as aspirational imperatives. In the context of Category A municipalities, strengthening these through innovation, compliance incentives, and integrated planning can overcome obstacles and encourage sustainable SWM and circular economy transitions (Hurtado 2023).

This study met its objective to investigate moderating factors influencing Industry 4.0 (4IR) technology implementation in solid waste management (SWM) in Cape Town. Internal moderating elements for Theme 1 were determined to be: data management facilitating IoT/AI monitoring; technological preparedness through AI, IoT, and automation; public involvement in 4IR techniques; and investment in human capital. R&D innovation, waste-to-energy or AI integration balanced against automation-induced unemployment, enforced SWM policies, and financing for monitoring and incentives were the external moderators highlighted in Theme 2, which focused on institutional and regulatory enablers. The opinions of all the respondents show how institutional (policy, financing, innovation) and organizational (data, skills, engagement) elements interact as important moderators for sustained SWM in settings with limited resources.

Policy recommendations

This section offers the policy recommendations that are essential for converting empirical findings on moderating factors into practical strategies, bridging the gap between the organizational and institutional challenges of Cape Town and the sustainable implementation of Industry 4.0 (4IR) in solid waste management (SWM).

First, mandated integrated data systems with a public application programming interface are required: For real-time SWM monitoring, City of Cape Town governments must make investments in centralized IoT-enabled data systems. By facilitating routing optimization and predictive analytics, this approach would lessen illicit dumping and moderate the effectiveness of 4IR.

Second, reskilling incentives linked to 4IR adoption must be implemented. In order to address potential unemployment issues and the need for human capital, the City of Cape Town metropolitan municipality should introduce subsidies for workforce training in automation, artificial intelligence, and waste-to-energy systems**.** Finally, we advise that SWM-specific funding and compliance regimes be enforced: Set aside ring-fenced funds, such as 5% of municipal revenue, for policy enforcement, R&D innovation, and performance-based rewards. This guarantees scalable, inclusive 4IR integration by fortifying institutional enablers.

Suggestions for future studies

Future studies should expand this research on moderating factors for Industry 4.0 (4IR) technologies in solid waste management (SWM) within Cape Town by addressing the following issues. Future research can consider the use of quantitative methods such as the use surveys or econometric modelling. This can be useful to address the shortcomings of qualitative methods used in this study. Second, comparative case studies with other South African Category A metros (for example, City of Johannesburg, City of Tshwane) could reveal contextual nuances on the subject matter

5. CONCLUSION

The moderating factors impacting the application of Industry 4.0 (4IR) technologies in solid waste management (SWM) within the City of Cape Town, a Category A metropolitan municipality in South Africa, have been effectively shown by this study. Two important moderators for Industry 4.0 (4IR) in Cape Town's SWM were identified through thematic analysis. Data management for IoT/AI monitoring, technical preparedness, public involvement, and human capital investment are examples of organizational capacity factors. Institutional and regulatory enablers emphasize the need for R&D that strikes a balance between unemployment and waste-to-energy/AI. money and incentives, as well as enforced policies. Mandatory data platforms with public APIs, reskilling incentives, and ring-fenced SWM financing for fair transitions were among the policy ideas put out. This qualitative investigation concludes by confirming that the transformative potential of 4IR in SWM depends on the comprehensive moderation of institutional and organizational aspects. Cape Town can lead the way in sustainable urban waste governance by bolstering data infrastructure, skills, regulations, and funding. This will provide lessons for Category A municipalities in South Africa and worldwide.

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