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Abstract:	

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ABSTRACT

Purpose - Despite the existence of some studies around green outcomes and the green deployment of operational excellence (OPEX) strategies, the analysis of the interaction and prioritisation of their implementation barriers has been neglected. The purpose of this study is to investigate the interaction and prioritisation of barriers to green deployment of OPEX projects in the manufacturing sector.

Design/methodology/approach - In line with the organisational capability and fuzzy set theories, we employed different Multi-Criteria Decision Making (MCDM) techniques to model the interaction and prioritisation of barriers.

Findings - Our findings indicate a significant complexity in how the barriers interact and are prioritised so they can be effectively mitigated to facilitate the green deployment of OPEX projects.

Originality - This is an original study for a paradigm shift enlightening the view of manufacturing managers, process owners and OPEX practitioners when mitigating the barriers to green deployment of OPEX projects to maintain more resource and energy-efficient OPEX projects with sustained outcomes.

Key words - operational excellence, green manufacturing, barriers, project management, environmental sustainability, multi-criteria decision-making

1. Introduction

Operational Excellence (OPEX) initiatives like Six Sigma and Lean Six Sigma (LSS) improve efficiency, customer satisfaction, and profitability by reducing waste and defects and enhancing quality in manufacturing, making them crucial for economic sustainability (Antony et al., 2024; Al Zaabi et al., 2024; and Singh et al., 2023). However, balancing economic and environmental goals is challenging for many organizations (Xu et al., 2023; Farrukh et al., 2021; Ahmad et al., 2021; Ye et al., 2020; and Ahmed et al., 2020). Integrating OPEX with green credentials, known as green OPEX, is essential for sustainable development, supporting manufacturers in achieving economic and environmental goals efficiently (Kawsan et al., 2023; Sun et al., 2023; Yadav and Gahlot, 2022; Farrukh et al., 2020; Parmar and Desai, 2020). While outcome-oriented approaches to reduce waste in the final product are well-studied (Antony et al., 2024., and Parmar and Desai, 2020), the green deployment of OPEX projects with lower environmental impact throughout their lifecycle is often neglected due to a focus on economic and quality objectives (Shokri et al., 2021; Gaikward and Sunnapwar, 2021; Farrukh et al., 2020). This reflects the difference between OPEX and green OPEX as the former has more economic focus on outcome compared to the latter that manifests both economic focus on outcome and environmental focus on the project deployment in balance despite the actual structure of methodologies such as lean and LSS remain the same and many of the barriers towards them seem to be identical (Shokri et al., 2022; Shokri et al., 2021). Having supported by the literature, these barriers have been identified collectively for OPEX initiatives such as lean, Kaizen and LSS (Shokri et al., 2022; Shokri et al., 2021). Recent studies highlight the importance of assessing conflicting measures in OPEX integration with green manufacturing to maximize benefits with minimal effort and energy (Skalli et al., 2024; Shokri et al., 2022; Shokri et al., 2021).

Sustained green deployment of OPEX projects enhances economic and operational capability (Yadav and Gahlot, 2022; Krishnan et al., 2022). However, manufacturing managers need a systematic assessment of barriers and their interactions to mitigate them and understand drivers for efficient OPEX project deployment. This study, based on organisational capability theory, focuses on barriers as critical to readiness assessment for developing capability through effective OPEX project deployment (Shokri et al., 2022).

Barriers should be considered as any restriction that impedes deploying any activity with increased capability (Shokri et al., 2021; Kaswan et al., 2021). An extensive literature on various green OPEX project frameworks (Sreedharan, 2018; and Cherrafi et al. 2017) supported by a recent scoping review (Shokri et al., 2021) suggested a literature gap regarding the lack of empirical studies to address the interaction and prioritisation of the barriers to the green deployment of OPEX projects. Therefore, our study is critically required to model interactions and prioritization of barriers systematically and through a more in-depth, empirical and subjective analysis to embrace the green deployment of OPEX projects in manufacturing that remains a gap (Shokri et al., 2022; Shokri et al., 2021). This study, therefore, aims to model the interaction and prioritisation of barriers to the green implementation of OPEX in the manufacturing sector through a Multi-Criteria Decision Making (MCDM) hybrid approach as a valid empirical in-depth subjective analysis. Based on this knowledge gap, the research question addressed by the present research is: *"What are the main barriers to green OPEX deployment, how do they interact and are prioritized?"*. The objectives to address this question and the aim of the study are: 1) confirm the research gap in the existing literature; 2) identify the barriers to green OPEX integration through a literature review; 3) model the interaction of the identified barriers through MCDM hybrid techniques; and 4) prioritise the barriers through fuzzy Analytical Hierarchy Process (AHP). We intend to respond to this research gap and address how managers and OPEX project owners can help their organisations mitigate the barriers in the green deployment of OPEX projects with the lens of analysing the interactions and prioritisation of barriers to the deployment of such projects. Our study contributes to the green OPEX literature (Shokri, et al., 2022; Singh et al., 2021; Yadav et al, 2018) by investigating and modelling the interaction and prioritisation of barriers to the green deployment of OPEX projects. Our study also strongly contributes to practice by enlightening the views of managers and their decision-making and practical aspects of OPEX project management to address the complexity of planning to mitigate the barriers to green deployment of OPEX projects.

This paper is organised into different sections that include a literature review of green OPEX and its barriers. This is followed by the data collection and data analysis, which include different techniques of an MCDM hybrid approach. Then, the findings and discussion are presented alongside the theoretical contributions of the study. Finally, the conclusions derived from our study and its findings as well as the managerial contribution and recommendation for future studies are presented.

2. Literature review

The objective of this research is to review existing literature to identify and justify research gaps in the field. The initial focus is on the integration of green OPEX, which is based on organisational capability theory that is defined as "the ability of an organisation to perform a coordinated set of tasks, utilizing organisational resources, for the purpose of achieving a particular end result" and provides a competitive edge to manufacturers (Hudnukar, et al., 2019). Green OPEX integration addresses the limitations of green manufacturing and OPEX, promoting economic, social, and environmental sustainability in the manufacturing sector (Hussain et al., 2023). Recent literature reviews on green OPEX project readiness, including barriers (Shokri et al., 2021), reveal a lack of models for understanding and prioritizing these barriers. Despite the benefits of green OPEX, systematic evaluations of its sustainability effectiveness are scarce (Yadav et al., 2023). Current literature highlights that green OPEX projects are still in the conceptual stage, lacking specific frameworks for managing transition roadblocks (Shokri et al., 2021; 2022). The importance of a comprehensive evaluation of barriers and their interactions for maintaining competitive advantage is emphasized (Yadav et al., 2023). This research incorporates fuzzy set theory to account for human judgment errors and complexities, translating linguistic variables into fuzzy metrics (Xu et al., 2023; Li et al., 2023; Solangi et al., 2021; Kul et al., 2020).

2.1. Green OPEX integration

OPEX projects aim to enhance shareholder value by achieving superior quality, speed, customer satisfaction, and cost-efficiency through process improvements that combine Lean and Six Sigma methodologies (Antony et al., 2024., Al Zaabi et al., 2024; Yazdi et al., 2021; and Costa, 2021). They also promote environmental sustainability by significantly reducing waste and defects in production processes and product development (Hussain et al., 2023; Belhadi et al., 2021; Costa et al., 2021; Gupta et al., 2019; Cherrafi et al., 2017). The success of OPEX projects heavily depends on productivity, resource, and production planning and control, necessitating consideration of energy and resource productivity to ensure sustained and green project completion (Kaswan et al., 2023; Singh et al., 2021; Shokri et al., 2022; Krishnan et al., 2022).

Transitioning from a customer and quality-centric to a more stakeholder-centric OPEX involves significant challenges and requires readiness assessment (Hussain et al., 2023; Shokri et al., 2022; Kaswan et al., 2021; Yadav et al., 2018). One major challenge is the contradiction between increased capacity and yield from OPEX projects and the unnecessary increase in resource and energy use (Shokri et al., 2022; Habidin and Yusof, 2012). Additionally, existing readiness frameworks list barriers without reflecting their interdependencies or interactions, complicating the assessment process (Hudnurkar et al., 2019; Yadav et al., 2018; Kumar et al., 2016).

2.2.Barriers to the Green deployment of OPEX

Barriers to organisational change towards approaches like green OPEX integration are defined as restrictions that impede progress (Solangi et al., 2021; Sreedharan et al., 2018). For the scope of our study, progress includes readiness, implementation and fulfilment with achieving objectives. This includes failure factors that emerge during implementation (Solangi et al., 2021). In respect to Organisational Capability theory, barriers are recognised as deficiency to any task completion as part of organisational capability (Hudnukar et al., 2019). Identifying and prioritizing these barriers is crucial to avoid failure in green OPEX integration (Shokri et al., 2022; Kaswan et al., 2021). While many studies have identified barriers similar to those in traditional OPEX (Kaswan et al., 2021; Belhadi et al., 2020; Farrukh et al., 2020), major obstacles include inadequate top management and employee commitment, resistance to change, fear, insufficient resources and knowledge, cultural change, lack of environmental policy, capital investment, narrow target orientation, poor infrastructure, lack of data clarity, insufficient environmental drive and competence, weak legislation, and competition and uncertainty. The effectiveness of overcoming these barriers depends on the OPEX implementation maturity and the size of the organization (Shokri et al., 2022; Trianni et al., 2016).

In a detailed review, several key findings emerged. A significant barrier to green OPEX integration is the complexity in terms of conflict between economic measures like customer satisfaction and environmental credentials like energy use (De Freitas et al., 2017; Cherrafi et al., 2016). While Kumar et al. (2016) studied the inter-dependency of top barriers, their focus was on OPEX for green outcomes rather than the green deployment of OPEX projects. Kaswan et al. (2021) prioritized environmental, managerial, and organisational barriers but again focused on OPEX with green outputs. A broader study highlighted the negative environmental impact of increased capacity and sales resulting from OPEX implementation (Albliwi et al., 2015). Despite various suggested green OPEX frameworks (Sreedharan, 2018; Cherrafi et al., 2017; Mkhaimer et al., 2017), there is still a need for a specific framework that models and prioritizes the interaction of barriers for green OPEX project deployment. Table 1 summarizes existing studies and their limitations in this area.

Table 1 appears here

Table 1 shows that the concept of green OPEX integration began in the mid-2010s, followed by analyses and case studies on its green outcomes. This led to recommendations for a paradigm shift towards green deployment of OPEX projects. However, no studies have identified barriers to green OPEX deployment or analyzed their interaction and prioritization through in-depth subjective analysis (Shokri et al., 2022; Shokri et al., 2021). This highlights a research gap in developing a framework for modeling these interactions and prioritizations.

Therefore, this study focused on the MCDM methodology to address this research question, as detailed in Section 1.

3. Methodology

In this section, we outline our research methodology for data collection and analysis. Following the precedent set by studies in similar fields (Kaswan, 2019; Yadav et al., 2018; Kumar et al., 2016), we utilized MCDM hybrid techniques like ISM and fuzzy AHP. These techniques are ideal for in-depth subjective modeling of the interaction and prioritization of barriers to green OPEX deployment. MCDM techniques effectively handle complex, multi-faceted decision-making processes, either individually or in combination (Hussain et al., 2023; Kul et al., 2020; Xu et al., 2019). The complexity due to trade-offs and subjectivity of identifying and prioritizing green OPEX barriers, compounded by varying human judgments, make MCDM techniques particularly suitable for this study (Yadav et al., 2018; Kumar et al., 2016).

3.1. Data collection

We used a panel of experts for data collection with appropriate sample size, which is a standard method for subjective MCDM qualitative analysis techniques such as ISM and fuzzy AHP, particularly when capturing vague human judgment (Kaswan, 2019; Yadav et al., 2018; Kumar et al., 2016). We selected sixteen UK-based OPEX practitioners and consultants through purposive sampling, targeting those with over 10 years of experience in leading or consulting OPEX projects in the UK manufacturing sector who have full experience of OPEX expected as an expert. We only focused on the UK region due to being responsive to previous UK-based studies raising this gap (Shokri et al., 2022). This approach ensured the experts were highly skilled and proficient in decision-making. We capped the sample size to sixteen since we were faced with almost a clear saturation at this point. This sample size or even less for any expert panel method has also been addressed by many other studies following the same MCDM methodology of ISM-MICMAC and fuzzy AHP (Dai and Solangi, 2023; Kaswan, 2019; Yadav et al., 2018; and Kumar et al., 2016).

The survey instrument included sixteen barriers to green OPEX integration, identified through extensive literature review and global expert survey analysis from previous studies (Shokri et al., 2022; Shokri et al., 2021). These barriers encompassed issues such as Lack of Clear Vision (LCV), Poor Recognition (PR), Poor Top Management and Leadership Commitment (PTMC), Lack of Organisational Resources (LOR), and Poor Infrastructure (PI) (Shokri et al., 2022; Shokri et al., 2021; Kaswan, 2021). These barriers, detailed in Table 2, were deemed sufficient for modelling interaction and prioritization, having been identified as major obstacles to green OPEX deployment in previous studies through sophisticated factor analysis (Shokri et al., 2022; Shokri et al., 2021).

Table 2 appears here

We conducted open-ended interviews with each panel expert, discussing barriers to green OPEX integration. This discussion has been set for each expert to verify our own findings from the recent literature about the barriers of OPEX and green OPEX in general. At the end of each interview, experts were asked to complete a quick survey to score the importance of the barriers using a five-point Likert scale (significantly important, very important, important, fairly important, and not important) and to indicate any interactions between barriers. This is a critical process to facilitate our ISM-MICMAC analysis and has been used by previous studies doing similar analysis (Dai and Solangi, 2023; Kaswan, 2019; Yadav et al., 2018; and Kumar et al., 2016) . This approach aimed to establish a "leads to" contextual relationship, where one barrier influences another. This method was based on the principle that one barrier leads to another, facilitating the development of a contextual relationship between the variables (Kumar et al., 2016).

3.2 Data analysis

We employed a three-stage hybrid approach of ISM-MICMAC and fuzzy AHP (figure 1) for interaction and prioritization modelling of factors in complex environments, considering vague subjective human judgment (Kaswan, 2019; Kumar et al., 2016).

Interpretive Structural Modelling (ISM): The first phase involved ISM, a well established logical methodology used to analyse interactions among variables in complex situations with subjective human judgment, creating a systematic relationship between these variables (Kharub et al., 2024; Kaswan, 2019; Kumar, 2016).

MICMAC Analysis: The second phase, MICMAC (cross-impact matrix multiplication applied to classification), analysed variables based on their driving power and dependencies (Kumar, 2016).

Fuzzy AHP: The final phase modelled the prioritization of barriers using the fuzzy AHP technique. This method is extensively used and powerful for solving complex decision problems, as supported by previous studies (Dai and Solangi, 2023; Xu et al., 2023; Can, 2023; Yadav et al., 2018; Sirisawat and Kiatcharoenpol, 2018).

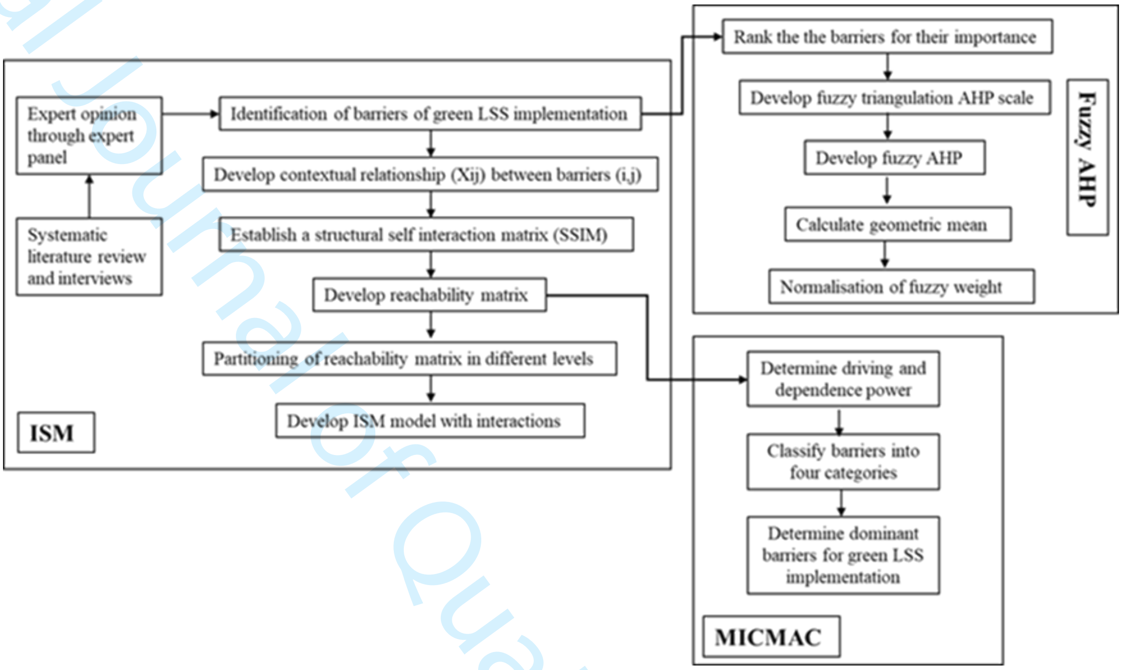

Figure 1 - ISM-MICMAC and fuzzy AHP hybrid methodology

Phase 1 – Interaction model through ISM

Step 1- Identify barriers to green OPEX implementation

Having conducted an extensive literature review and the recent scoping review of the barriers to Green OPEX integration (Shokri et al., 2021), the proposed framework of barrier to green deployment of OPEX projects (Shokri et al., 2022), and our open-ended interview with panel experts to verify them for the matter of subjectivity, we identified sixteen barriers to the green deployment of OPEX projects for our MCDM analysis, see Table 3. Any barrier wasn't supported by the expert during face-to-face interview, would be eradicated straight away from the survey before sharing with the experts to respond. This means these sixteen barriers have already been verified by the interviews with experts.

Table 3 appears here

Step 2- Develop contextual relationship (Xij) between barriers (i,j)

In order to establish the contextual relationships amongst variables, panel experts were requested to identify the contextual relationship between barriers. The final decision about the direction of the relationship was reached through a granted consensus by panel experts. The following four symbols were used to denote the direction of the relationship between the barriers (i and j), respecting the standard of the ISM methodology (Kharub et al., 2024; and Kumar et al., 2016).

V- Barrier i affects barrier j;

A-Barrier j affects barrier I;

X-Barrier i and barrier j affect each other; and

O-Barrier i and barrier j are unrelated

Step 3 - Establish a structural self-interaction matrix (SSIM)

Having developed the direction of contextual relationships and direction between barriers, the SSIM was established to demonstrate the formulated relationships based on the four above symbols (Kharub et al., 2024; Kaswan, 2019; and Kumar et al., 2016). The SSIM is presented in Table 3.

Step 4 - Develop reachability matrix

This step started with the binary matrix known as the initial reachability matrix by substituting each entry of the SSIM presented in Table 4 to "0" or "1". The following rules applied to this: If the (i,j) entry was "V", the substitute number in the initial reachability matrix became "1" and the (j,i) entry became "0". If the (i,j) entry was "A", the substitute number in the initial reachability matrix became "0" and the (j,i) entry became "1". If the (i,j) entry was "X", the substitute number in the initial reachability matrix became "1" and likewise the (j,i) entry became "1". Finally, if the (i,j) entry was "O", the substitute number in the initial reachability matrix became "0" and likewise the (j,i) entry became. "0".

Table 4 appears here

Having developed the initial reachability matrix, we needed to apply the transitivity rule to this matrix. This rule states that if variable X affects variable Y, and variable Y affects variable Z, variable X essentially affects variable Z. The final reachability interaction after applying the transitivity rule is depicted in Table 5. This suggested that any interaction with "1*" indicated the bridged interaction after applying this rule. The "driving power" and "dependence power" for each barrier were also determined by summing up the "1" numbers in each row (i,j) to represent driving power and in each column (j,i) to represent dependence power. The driving power for each barrier was the total number of barriers (including itself) that it may have an effect on. The dependence power for each barrier was the total number of barriers (including itself) that affected that barrier. For example, the driving power of LCV was 16 whilst its dependence power was 14. This indicated that LCV wold affect 16 other barriers (including itself) and would be affected by 14 other barriers (including itself).

Table 5 appears here

Step 5 - Partitioning of reachability matrix in different levels

Having used the final reachability matrix, the reachability and antecedent set for each driver were calculated through partitioning (Kharub et al., 2024; and Kaswan, 2019) and are presented in Table 6. The reachability set for each barrier consisted of barriers that would affect the stand, including itself. The antecedent set consisted of barriers that a barrier would affect, including itself. Thereafter, the intersection of these sets for each barrier was derived. A stronger similarity between reachability and intersection sets in each barrier resulted in the assignment of the barrier to the higher level as level I. This continued for other barriers to be assigned to the relevant level through different iterations. The barriers in each level did not affect the barriers in the lower level.

Table 6 appears here

Step 6- Develop the ISM model

The structural ISM model, known as a digraph, was developed to address the interactions between variables after having identified what level each barrier was from the previous step (Figure 2). It is evident from the model that PR, LOR and PI as level IV barriers had a top position in terms of affecting other barriers. Moreover, barriers in the third level (PA, UD, PD, MU, LCV) seem to be affected by barriers in level IV while also affecting other barriers in levels I and II. Accordingly, PTMC, WL, HIC and LE, which were all in the second level, influenced barriers in level I (SR, WE, LIP, CO), which tend to have no influence on any barrier. In reality, all of these barriers at their level had interaction with each other. This made it necessary to analyse the dependence and driving power of each barrier independent of their level, see Table 5.

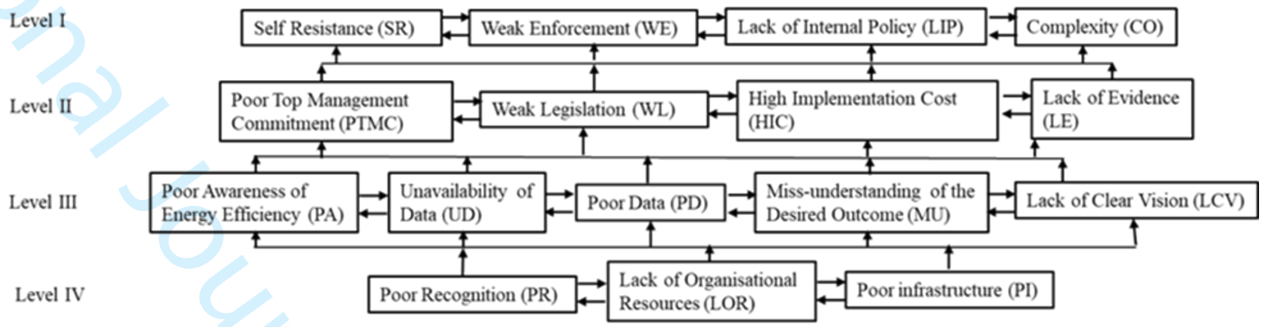

Figure 2 – ISM-based model representing relationship and interaction between barriers

Phase 2 - MICMAC analysis

After having determined the driving and dependence power of each barrier in step 4 of phase 1, a MICMAC analysis (Figure 3) was conducted to validate the result from the ISM analysis (Thomas and Khanduja, 2022) and to classify the barriers into four clusters based on their driving power or influence on other barriers (Kaswan, 2019; and Kumar et al., 2016). The four clusters based on driving and dependence power of barriers were, namely: i)autonomous barriers with weak driving and dependence power; ii)dependent barriers with weak driving power but strong dependence power; iii)linkage barriers with strong driving power as well as strong dependence power; iv)driving barriers with strong driving power and weak dependence power. This suggested that the driver barriers would lead to linkage barriers while driving and linkage barriers would lead to depending barriers (Kumar et al., 2016).

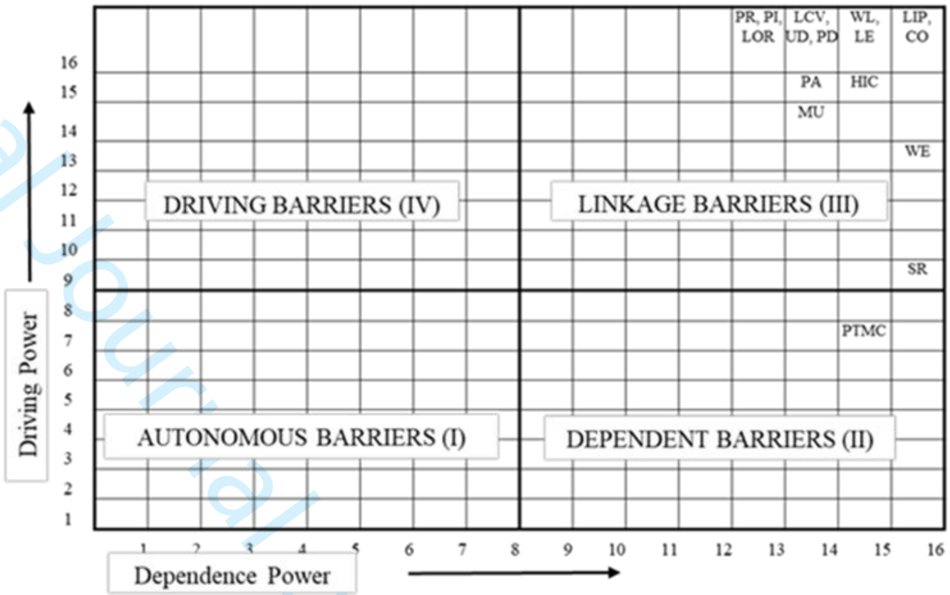

Figure 3 – MICMAC cluster diagram of barriers

Phase 3 – Fuzzy AHP

After having analysed and modelled the interaction between the barriers, the next phase of our data analysis was to conduct a fuzzy AHP analysis to prioritise the barriers. In general, AHP, which was introduced by Saaty in the 1980s, is one of the most extensively used and powerful MCDM methods (Sirisawat and Kiatcharoenpol, 2018). Nevertheless, due to human judgement error-related possibilities, subjectiveness, vagueness and complexity in human judgement and decision-making limitations raised by the expert panel, we identified fuzzy AHP, which was developed by Chang in the 1990s, as the most suitable MCDM technique to prioritise the barriers, similarly to previous studies in the same field (Can, 2023; Thomas and Khanduja, 2022; Yadav et al., 2018; and Sirisawat and Kiatcharoenpol, 2018). Fuzzy AHP allows a better representation of decision-making in complex and uncertain situations (Dai and Solangi, 2023; Xu et al., 2023; Solangi et al., 2021). It integrates the concepts of hierarchical structure analysis and fuzzy set theory to allow decision-makers to incorporate both quantitative and qualitative data into a decision model (Li et al., 2023; Kul et al., 2020). We used the triangular fuzzy AHP in comparison to others to use triangular numbers and express relative importance in pairwise comparison (Li et al., 2023; Can, 2023; Solangi et al., 2021; Ahmed et al., 2020; Lyu et al., 2020). This enabled us to consider human judgement error-related possibilities, subjectiveness, vagueness and complexity in human judgement and decision-making for barriers to prioritisation in the real world.

The fuzzy AHP process started by ranking the importance of the barriers. Having asked the expert panel to score the importance of barriers in the 5-point Likert Score system, in addition to identifying interactions between them, we calculated the Mean, Median and Std of each variable (see Table 7). In consideration of the fuzziness and vagueness of the experts' opinions, we considered both the Mean and Median values together collectively to reflect on the level of importance and ranking.

Table 7 appears here

Then, we defined an appropriate linguistic term for ranking the differences between two variables and then set the fuzzy triangulation scale to represent linguistic terms of importance against differences in ranking (Singh and Rathi, 2022; Xu et al., 2019), see Table 8.

Table 8 appears here

Then, we constructed the fuzzy pairwise comparison matrix in which the fuzzy triangulation scale represented the importance of one variable against the other as per the difference in their ranking (Li et al., 2023; Can, 2023; Solangi et al., 2021; Ahmed et al., 2020; Xu et al., 2019). For instance, whilst the importance of LCV had the same fuzzy triangulation scale against itself (1,1,1), its fuzzy triangulation scale against the importance of PR is (2,3,4) as the difference between its ranking (third) and ranking of PR (sixth) was 3, see Table 7. This indicated that the fuzzy triangulation scale of importance of PR against LCV was (1/2,1/3,1/4), which in decimal point represents (0.5,0.333,0.25). However, this scale needed to be presented with increasing order (0.25,0.333.0.5). This particular section of analysis as pairwise comparison has been cross checked with two more other members of the research team to prevent any error.

Then, the geometric mean of each value of the three triangulation scale values of each barrier was calculated as below:

$$\sqrt[n]{\Pi x} = (\Pi x)^{\frac{1}{n}}$$

where:

- Π = product of …

- x = every value
- n = total number of values
- $\frac{1}{n}$ = reciprocal of n

After determining the total of the first, second and third values of all barriers, the inverse value was calculated by dividing each of the total values by 1. Finally, the inverse values were presented in ascending order.

The fuzzy weight for each value of the triangulation scale for each barrier was then calculated by multiplying the inverse value after applying an ascending order to each value of the triangulation scale of each barrier to determine the fuzzy weight, followed by calculating the average of the triangulation scale values for each barrier, Table 9. However, due to a higher value than 1 of the total average (1.1), we normalised the average weight by dividing each value by 1.1 as the normalised weight to sum up to 1.

Table 9 appears here

4. Findings and discussion

This study builds on previous research highlighting the need for comprehensive, systematic, and in-depth readiness modeling to sustain green OPEX projects with resource efficiency (Shokri et al., 2022; Shokri et al., 2021; Degalwar et al., 2017). It examines how barriers to green OPEX project deployment interact and identifies prioritized barriers using ISM-MICMAC and fuzzy AHP techniques. Sixteen barriers to green OPEX integration were identified through a systematic literature review (Yadav et al., 2023; Shokri et al., 2022; Shokri et al., 2021).

Our findings through the ISM analysis model support previous studies highlighting the inter-dependency among barriers and drivers of green OPEX integration (Hussain et al., 2023; Kumar et al., 2016). The study identifies PR (poor recognition), LOR (lack of resources), and PI (poor infrastructure) as top strategic barriers significantly influencing other barriers. This aligns with previous research on barriers to green OPEX integration (Thomas and Khanduja, 2022; Kaswan et al., 2021; Belhadi et al., 2020; Farrukh et al., 2020). However, unlike Kumar et al. (2016) who focused on green product development and identified lack of management support and fund constraints as top barriers, our study emphasizes the influence of PR, LOR, and PI on barriers like PA (poor attention), UD (understanding deficit), PD (poor data), MU (misunderstanding), and LCV (lack of visionary leadership). These findings suggest that poor recognition and infrastructure, coupled with resource shortages, drive other barriers, ultimately affecting leadership vision and environmental understanding in green OPEX projects, consistent with Kumar et al.'s (2016) ISM findings.

In the next level, PTMC, WL, HIC, and LE were identified as barriers influenced by PA, UD, PD, MU, and LCV, which in turn influenced the remaining barriers. This suggests that poor visionary leadership, inadequate understanding of benefits, and lack of data lead to perceived high investment costs, weak legislation, and lack of evidence, ultimately causing a lack of managerial commitment to change. Notably, unlike other studies on green OPEX integration (Thomas and Khanduja, 2022; Kaswan, 2021; Farrukh et al., 2020), the lack of top management commitment and legislation were not deemed top influencing barriers.

Finally, SR, WE, LIP, and CO were identified as the least influential barriers, being more affected by other barriers. Resistance to change and weak enforcement are at the bottom of the model, requiring other barriers to be minimized or removed. This finding supports previous studies suggesting that policy and enforcement-related barriers to green practices in manufacturing depend on reducing other barriers (Thomas and Khanduja, 2022; Suramanian and Abdulrahman, 2017; Mittal et al., 2014).

The logical groupings (clusters) through MICMAC analysis were conducted to validate the findings obtained from the ISM model (Figure 3). We observed that there was no autonomous barrier among these sixteen barriers. This was in line with previous studies that have clustered barriers to green OPEX integration (Thomas and Khanduja., 2022; Kumar et al., 2016). This suggests there is no barrier with weak dependence and driving power, indicating that all of these barriers play a role in the green deployment of OPEX projects. Similarly, it was observed that there was no driving barrier among all sixteen barriers. This determines that there is no barrier with strong driving and weak dependence power, indicating that there is no independent barrier that would not be influenced by any other barrier. The findings also indicate that PTMC is the only dependent barrier with weak driving power contrary to strong dependence power, which tends to be influenced by all other fifteen barriers. However, there is still a possibility of some modest influence with a weak driving power of 7 (Table 4 and Figure 3). This supports the findings from the ISM analysis presented in Figure 2, which represents PTMC as a level II barrier in interaction, with others influencing only a handful of barriers as SR, WE, LIP and CO being influenced by others. Nevertheless, this finding opposes the findings from Kumar et al., (2016) and Thomas and Khanduja (2022), who found a lack of top management commitment as part of driving barriers with high driving power and very low dependence power.

Finally, all the other fifteen barriers seem to be recognised as the linkage barrier with both strong driving and dependence power. This supports the result of the ISM analysis, which indicates vertical and horizontal interaction between the barriers. Notwithstanding, the finding from Kumar et al., (2016) reflects that barriers associated with strategy and communication seem to be only part of linkage barriers. The weaker position of SR in this cluster (Figure 3) reflects modest driving power (9), contrary to a very strong dependence power (16), assigning it to the Level I barrier in the ISM model influenced by many other barriers and influencing not many. As there are many barriers as the top influencing barrier with the highest driving power (16) and quite high dependence power (13-16), LIP and CO seem to be in the very top right-hand corner of the linkage barrier cluster (Figure 3). This means that despite being considered as level I barriers in the ISM (Figure 2) in terms of interaction, the MICMAC analysis validates their strong position as an influencing barrier. This suggests that they may still have a very strong influence on level IV influencing barriers (PR, LOR, PI) that themselves were also presented with strong dependence power (13) as well as strong driving power (16) (Figure 3).

Therefore, it can be highlighted from the ISM model and MICMAC clustering digraph that the interaction and influence of barriers in the context of green deployment of OPEX projects seem to be complex rather than linear. This is in line with previous studies recommending green OPEX integration as a complex journey (Shokri et al., 2022; Kaswan et al., 2021; and Yadav et al., 2018).

We conducted a fuzzy AHP analysis to prioritise these barriers in terms of importance and to integrate this analysis with ISM-MICMAC interaction/clustering model to develop a MCDM hybrid model to address a critical roadmap towards readiness for this transformation. Our approach to using fuzzy AHP for prioritising barriers to the green deployment of OPEX has been supported by various previous studies in similar fields (Li et al., 2023; Solangi et al, 2021). The normalised weight extracted as part of the fuzzy AHP and presented in Table 8 determined that PTMC (normalized weight of 0.185), LOR (normalized weight of 0.158) and LCV (normalized weight of 0.114) as the highest prioritised barriers to be looked at by scholars and practitioners in readiness for the green deployment of OPEX projects. This means dealing with a lack of visionary leadership and support and insufficient resources must be considered as priorities compared to other barriers. This is in line with the studies by Yadav et al., (2023) and Thomas and Kahnduja (2022). However, they also recommended lack of green awareness as the top priority barrier, which contrasts with our finding recommending similar barriers of PA (with a normalised weight of 0.0393246) and MU (with a normalised weight of 0.0891885) amongst the least prioritised barriers for the green deployment of OPEX projects. Our finding was also in contrast to Hariyani et al. (2023), who stressed MU and CO as top barriers for green OPEX projects in general terms. It is fair to know that their study was conducted only in the construction sector as opposed to our study which considered the manufacturing context.

In relation to the ISM-MICMAC interaction and clustering analysis, it seems that all these three barriers are from three top levels of interaction. It was also found that, unlike LOR and LCV as linkage barriers, PTMC was recognised as the dependent barrier with high dependence and low driving power. This highlights the lack of correlation between high priority with influencing power as PTMC was still considered a top priority barrier to be minimised or removed. This also supports the lack of linearity in the priority-interaction hybrid model for these barriers.

5. Research, theoretical and practical/managerial contributions

5.1. Research and theoretical contributions

Drawing on organisational capability theory (Hudnurkar et al., 2019) and fuzzy set theory (Li et al., 2023; Kul et al., 2020), this study provides a readiness assessment framework for prioritizing and interacting barriers to the green deployment of OPEX projects. It contributes to green manufacturing theories and practices (Gaikward and Sunnapwar, 2021; Ye et al., 2020) and green OPEX integration (Singh et al., 2021; Parmar and Desai, 2020; Farrukh et al., 2020) by mitigating barriers to green practices. Using ISM and fuzzy AHP methods, the study considers real-world subjective judgments in perceiving barrier interactions and prioritization, aligning with the fuzzy set theory approach (Dai and Solangi, 2023; Xu et al., 2023; Li et al., 2023; Kul et al., 2020). It uniquely employs MCDM hybrid techniques to model barrier interactions and prioritization of green deployment of OPEX, as suggested by Shokri et al.

(2022, 2021). This research advances the understanding of readiness towards green OPEX integration (Hussain et al., 2023; Yadav et al., 2023; Kaswan et al., 2023; Singh et al., 2021; Yadav et al., 2018) and follows previous studies on barrier identification, prioritization, and categorization (Li et al., 2023; Thomas and Khanduja, 2022; Solangi et al., 2021; Farrukh et al., 2020; Kumar et al., 2016). Additionally, it complements studies on green OPEX project deployment, which highlighted the uniqueness and novelty of this transformation (Shokri et al., 2021).

5.2. Managerial contribution and practical implications

This study provides managerial and practical contributions for maintaining OPEX projects in a resource-efficient environment with sustained outcomes. It offers valuable insights for managers and OPEX practitioners, aiding them in evaluating their organisational capability for environmentally focused OPEX project deployment. The findings assist senior managers in identifying, classifying, and prioritizing barriers early on to mitigate them effectively as part of readiness assessment for green OPEX projects. Notably, the study reveals that a top-prioritized barrier may not influence others and an influential barrier might not be top-priority, emphasizing the need for a multifaceted review of barriers and their mitigation. Therefore, it is suggested that managers take two different and independent approaches to barriers whether as influential or critical barriers in their decision making.

The study also supports manufacturing process owners and OPEX project leaders in developing roadmaps for OPEX project sustainability, green manufacturing, and training programs. Additionally, it aids managers and policymakers in enhancing practices for energy efficiency, waste reduction, and economic benefits. The findings highlight the importance of creating platforms to expose and reduce hidden environmental impacts, such as unnecessary energy use. The framework informs policymakers and local authorities about their roles in improving legislation, enforcement, resource allocation, and knowledge generation among businesses for sustainable development.

6. Conclusion, limitations and agenda for future research

This study investigated the interaction and prioritization of barriers to the green deployment of OPEX projects in the manufacturing sector using various MCDM analyses, aligned with organisational capability theory. The findings highlight the complexity of these interactions and support the systematic interplay among barriers in a fuzzy environment, which appears unique compared to previous studies on green OPEX integration. The study concluded that barriers can be prioritized independently of their influencing power, indicating no direct correlation between influencing and prioritization models. This non-linear, MCDM hybrid model underscores the complexity of mitigating these barriers due to the interaction and mismatch between influencing power and prioritization. These novel insights are crucial for developing or modifying readiness assessment frameworks for green OPEX integration in the context of sustainable operational excellence.

6.1. Limitations and future research

We acknowledge several limitations for managers and practitioners adopting our framework. Managers in the manufacturing industry must first understand green OPEX integration to effectively use this framework. Barriers may need to be contextualized based on regional and organisational culture, which may limit the framework's generalizability. We recommend integrating the barrier interaction and prioritization framework with a similar framework for drivers to help managers find solutions to some barriers.

While MCDM hybrid data analysis techniques were suitable for our study, the data depended on a modest sample size of the expert panel. We suggest conducting further empirical studies with larger sample sizes using survey questionnaires. Our study, conducted with UK-based manufacturing organizations and practitioners due to responding to previous UK-based studies. However, this can be replicated to other regions. It should also be extended globally and applied to other sectors such as construction, health, and the public sector. Additionally, the same methodological approach could be used for modeling the interaction and prioritization of drivers, as well as the success and failure factors of green OPEX project deployment.

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Table 1 – Existing literature about barriers of green OPEX integration and their shortfall

Author	Country	focus	Limitation
de Freitas et al (2017)	Brazil	Impact of OPEX on 3BL sustainability with global approach through	Not focused on the OPEX project deployment approach
Lucato et al (2015)	Brazil	Propose a procedure to incorporate environmental variables into DMAIC process to increase the eco-efficiency level of the firms	Not focused on the OPEX project deployment approach
de Freitas and Costa (2017)	Brazil	Identify the OPEX impact on organisations with the 3BL sustainability perspective	Not focused on the OPEX project deployment approach
Kumar et al (2016)	India	Identify and categorise barriers of green OPEX implementation for product development	The output or product approach and not OPEX project deployment approach
Yadav et al (2018)	India	Identify barriers of OPEX and prioritisation and ranking of solutions	Focused on the barriers of OPEX success without any indication of integration with green paradigm
Hudnurkar et al (2019)	India	Understand the deficiencies in Six Sigma project capability and empirically validate its impact on project success	Focused only on the project management attribute of OPEX success without any indication of integration paradigm
Ruben et al (2017)	India	Reduce overall defect and environmental impacts zthrough DMAIC	Focused only on the role of OPEX on green manufacturing with product and output approach and not OPEX project deployment approach
Sreedharan V. et al (2018)	India	Propose a Green OPEX Supply Chain model in public sector	Focused only on the OPEX and green supply chain management integration in public sector and not manufacturing
Mkhaimer et al (2017)	Jordan	Propose the OPEX Energy Management model	Focused on a generic OPEX energy management model with no green OPEX deployment approach
Cherrafi et al (2016)	Morocco	Integration of lean manufacturing, Six Sigma and sustainability	A generic model of the green and OPEX integration with no indication of OPEX project deployment approach
Cherrafi et al (2017)	Morocco	Present a framework to effectively integrate and implement green OPEX approaches	A generic model to present the guidance of green OPEX but with output approach and not OPEX project deployment approach
Goh (2013)	Singapore	Directions of improvement in the future of Six Sigma	No focus on green OPEX deployment
Albliwi et al (2015)	UK	Explore the most common themes within OPEX in the manufacturing sector	No indication of green paradigm
Garza-Reyes (2015)	UK	Examine the compatibility and effect of Six Sigma on green and lean integration	Not focused on the green project deployment approach
Aldairy et al (2017)	UK	Develop a knowledge-based system for OPEX maintenance in environmentally sustainable buildings	Focused on the OPEX and green construction integration with the outcome approach and not in the manufacturing sector

Erdil et al (2018)	USA	Embed sustainability into OPEX projects and practices	A generic sustainability model in integration with OPEX and with outcome approach without any focus on green paradigm
Banawi and Bilec (2014)	USA	Develop a systematic and integrated OPEX and green framework to improve environmental impact of construction industry	Focused only on construction sector with output approach of the green OPEX integration
Belhadi et al., (2020)	Morocco	Analysis of integration between big data analytics, environmental practices and OPEX through structural equation modelling	No particular reference to the green deployment of OPEX was made
Farrukh et al., (2020)	New Zealand	Investigate the constructs of green OPEX integration through systematic literature review	No reference was made to the green deployment of OPEX implementation
Walter et al., (2021)	Brazil	Identify and discuss recent developments in Sustainable Lean Six Sigma frame-works	A generic approach to sustsianble OPEX without reference to barriers of green OPEX integration
Belhadi et al., (2021)	Morrocco	Present a framework for an effective integration of big data analysis and OPEX for green manufacturing purposes	No reference was made to the barriers of green OPEX integration
Shokri et al., (2021)	UK	Justify the research gap in regards to green deployment of OPEX projects through systematic literature review	No reference was made to the interaction and prioritisation
Kaswan et al., (2021)	India	Identification, classification and prioritisation of barriers of green OPEX implementation	No reference to green deployment, and barriers were not classified and prioritised through in-depth empirical subjective analysis
Farrukh et al. (2021)	New zeland	Identifying the drivers of green OPEX in developing and developed countries	The focus was on drivers of green OPEX with output orientation rather than barriers of green OPEX implementation
Shokri et al. (2022)	UK	Readiness assessment of transformation towards green deployment of OPEX projects	The interaction and prioritisation model of barriers was not developed
Vadav et al. (2022)	India	Green OPEX methodology for SMEs to improve green outcomes	Focus on the green outcomes of the OPEX projects and for SMEs only
Yadav et al.(2023)	India	Green OPEX projects in the Higher Education sector	Focus on the green outcomes of the OPEX projects and in the public sector only

Table 2 – The expert panel and their background

	Role	Organisation type	Current role experience (yrs)	OPEX projects experience (yrs)
1	MD/consultant	LSS training institution	11	10
2	Global CI Leader	Manufacturing/Machining & tooling	10	10
3	Consultant	Self-employed	25	25
4	Director of business improvement	Facility Management	26	17
5	CEO/consultant	Consultancy firm	20	12
6	CI Manager	Manufacturing/Packaging	27	15
7	Senior CI Programme manager	Manufacturing/Packaging	40	20
8	CEO/consultant	Consultancy firm	41	30
9	Consultant	Self-employed	2.5	10
10	Head of L&D	Manufacturing/pharmaceutical	19	10
11	Principal LSS project lead	Manufacturing/pharmaceutical	24	20
12	VP of business improvement	Manufacturing	15	10
13	Engineer/Continuous Improvement	Manufacturing/Machining & tooling	15	24
14	Central CI manager	Manufacturing/Packaging	24	13
15	Manufacturing engineering manager	Manufacturing/Machining & tooling	30	15
16	CI Manager	Manufacturing/Food Packaging	26	20

Table 3 – Barriers of green deployment of OPEX project

Barriers to green implementation of OPEX projects	**Context**	**Reference**
Lack of clear vision (LCV)	Managers and OPEX practitioners in the manufacturing sector have insufficient visionary leadership pursuing on green deployment of OPEX projects	Yadav et al., (2023); Shokri et l., (2022); Shokri et al., (2021); Kaswan (2021); Farrukh et al., (2020); Kumar et al (2016)
Poor recognition (PR)	Managers and OPEX practitioners in the manufacturing sector do not recognise green OPEX practice or project	Yadav et al., (2023); Shokri et l., (2022); Shokri et al., (2021); Kaswan (2021); Farrukh et al., (2020); Kumar et al (2016)
Poor top management and leadership commitment (PTMC)	Managers and OPEX leaders in the manufacturing sector have no commitment to pursue on green deployment of OPEX	Yadav et al., (2023); Shokri et l., (2022); Shokri et al., (2021); Kaswan (2021); Farrukh et al., (2020); Kumar et al (2016)
Staff Resistance (SR)	Operatives from different departments in the manufacturing setting resist against change to OPEX project utilisation	Yadav et al., (2023); Shokri et l., (2022); Shokri et al., (2021); Kumar et al (2016)
Weak legislation (WL)	There is insufficient clarity in environmental legislation in the manufacturing sector about green project management	Yadav et al., (2023); Shokri et l., (2022); Shokri et al., (2021); Kaswan (2021); Farrukh et al., (2020); Kumar et al (2016)
Weak enforcement (WE)	There is insufficient enforcement by manufacturing managers to establish green OPEX projects by project managers	Yadav et al., (2023); Shokri et l., (2022); Shokri et al., (2021); Kaswan (2021); Farrukh et al., (2020)
Lack of internal policy (LIP)	There is no internal policy in the relevant departments in the manufacturing sector to pursue on green deployment of OPEX projects	Yadav et al., (2023); Shokri et l., (2022); Shokri et al., (2021); Kumar et al (2016)
High implementation cost (HIC)	The cost of green deployment of OPEX is high for the manufacturing managers	Yadav et al., (2023); Shokri et l., (2022); Shokri et al., (2021); Kumar et al (2016)

Lack of organisational resources (LOR)	There are insufficient resources in the manufacturing setting for green deployment of OPEX	Yadav et al., (2023); Shokri et l., (2022); Shokri et al., (2021); Kumar et al (2016)
Complexity (CO)	Green deployment of OPEX projects seems to be complex due to conflict between economic and environmental measures in the manufacturing sector	Yadav et al., (2023); Shokri et l., (2022); Shokri et al., (2021); Kaswan (2021); Yadav et al., (2018); Cherrafi et al., (2017); De Freitas et al., (2017); Kumar et al (2016)
Lack of evidence (LE)	There is no evidence in the manufacturing sector supporting importance and benefits of green deployment of OPEX projects	Yadav et al., (2023); Shokri et l., (2022); Shokri et al., (2021); Kaswan (2021)
Poor infra-structure (PI)	There is insufficient infra-structure in the manufacturing sector to support green deployment of OPEX projects	Yadav et al., (2023); Shokri et l., (2022); Shokri et al., (2021); Kaswan (2021); Farrukh et al., (2020); Kumar et al (2016)
Poor awareness of energy efficiency (PA)	Managers in the manufacturing sector have insufficient awareness of benefits of green deployment of OPEX projects	Yadav et al., (2023); Shokri et l., (2022); Shokri et al., (2021)
Unavailability of data and information (UD)	There is insufficient data available for environmental aspects of OPEX projects in the manufacturing setting	Yadav et al., (2023); Shokri et l., (2022); Shokri et al., (2021); Kaswan (2021)
Poor data (PD)	The available environmental data is insufficient to be used for the OPEX projects in the manufacturing setting	Yadav et al., (2023); Shokri et l., (2022); Shokri et al., (2021)
Miss-understanding of the desired outcome (MU)	Leaders and OPEX managers in the manufacturing sector mis-understand outcomes and values of the green OPEX projects.	Yadav et al., (2023); Shokri et l., (2022); Shokri et al., (2021)

Table 4- SSIM of barriers

	MU	PD	UD	PA	PI	LE	CO	LOR	HIC	LIP	WE	WL	SR	PTMC	PR
LCV	A	X	V	A	V	O	V	V	O	V	V	A	V	V	A
PR	V	V	V	A	O	A	A	A	X	A	V	V	V	V	
PTMC	A	A	A	A	A	A	V	A	X	V	V	X	V		
SR	A	A	A	A	X	A	A	A	O	A	O	X			
WL	X	V	V	V	V	V	V	O	O	V	V				
WE	V	A	A	A	X	A	X	V	A	V					
LIP	V	A	A	A	V	X	A	A	O						
HIC	O	A	A	V	A	V	A	X							
LOR	V	A	X	V	A	V	X								
CO	V	V	V	O	A	X									
LE	V	A	X	V	O										
PI	V	X	O	O											
PA	V	X	V												
UD	V	X													
PD	V														

Table 5- Final reachability matrix of barriers

	LCV	PR	PTMC	SR	WL	WE	LIP	HIC	LOR	CO	LE	PI	PA	UD	PD	MU	**Driving power**
LCV	1	*1	1	1	*1	1	1	*1	1	1	*1	1	*1	1	1	*1	**16**
PR	1	1	1	1	1	1	*1	1	*1	*1	*1	*1	*1	1	1	1	**16**
PTMC	0	0	1	1	1	1	1	1	0	1	0	0	0	0	0	0	**7**
SR	*1	0	*1	1	1	*1	*1	0	0	*1	*1	1	0	0	0	0	**9**
WL	1	*1	1	1	1	1	1	*1	*1	1	1	1	1	1	1	1	**16**
WE	0	*1	0	*1	0	1	1	*1	1	1	*1	1	*1	*1	*1	1	**13**
LIP	*1	1	*1	1	*1	*1	1	*1	*1	*1	1	1	*1	*1	*1	1	**16**
HIC	*1	1	1	*1	*1	1	*1	1	1	*1	1	0	1	*1	*1	*1	**15**
LOR	*1	1	1	1	*1	*1	1	1	1	1	1	*1	1	1	*1	1	**16**
CO	*1	1	*1	1	*1	1	1	1	1	1	1	*1	*1	1	1	1	**16**
LE	*1	1	1	1	*1	1	1	*1	*1	1	1	*1	1	1	*1	1	**16**
PI	*1	*1	1	1	*1	1	*1	1	1	1	*1	1	*1	*1	1	1	**16**
PA	1	1	1	1	*1	1	1	*1	*1	*1	*1	0	1	1	1	1	**15**
UD	*1	*1	1	1	*1	1	1	1	1	*1	*1	*1	*1	1	1	1	**16**
PD	1	*1	1	1	*1	1	1	1	1	*1	1	1	1	1	1	1	**16**
MU	*1	0	1	1	1	*1	*1	*1	0	*1	*1	*1	*1	*1	*1	1	**14**
Depending power	**14**	**13**	**15**	**16**	**15**	**16**	**16**	**15**	**13**	**16**	**15**	**13**	**14**	**14**	**14**	**14**	**233/233**

Table 6 – Barriers partitioning

Barrier	Reachability Set	Antecedent Set	Intersection set	Level
LCV	LCV,PR,PTMC,SR,WL,WE,LIP,HIC,LOR,CO,LE,PI,PA,UD,PD,MU	LCV,PR,SR,WL,LIP,HIC,LOR,CO,LE,PI,PA,UD,PD,MU	LCV,PR,SR,WL,LIP,HIC,LOR,CO,LE,PI,PA,UD,PD,MU	III
PR	LCV,PR,PTMC,SR,WL,WE,LIP,HIC,LOR,CO,LE,PI,PA,UD,PD,MU	LCV,PR,WL,WE,LIP,HIC,LOR,CO,LE,PI,PA,UD,PD	LCV,PR,WL,WE,LIP,HIC,LOR,CO,LE,PI,PA,UD,PD	IV
PTMC	PTMC,SR,WL,WE,LIP,HIC,CO	LCV,PR,PTMC,SR,WL,LIP,HIC,LOR,CO,LE,PI,PA,UD,PD,MU	PTMC,SR,WL,LIP,HIC,CO	II
SR	LCV,PTMC,SR,WL,WE,LIP,CO,LE,PI,PA,UD,PD,MU	LCV,PR,PTMC,SR,WL,WE,LIP,HIC,LOR,CO,LE,PI,PA,UD,PD,MU	LCV,PTMC,SR,WL,WE,LIP,CO,LE,PI,PA,UD,PD,MU	I
WL	LCV,PR,PTMC,SR,WL,WE,LIP,HIC,LOR,CO,LE,PI,PA,UD,PD,MU	LCV,PR,PTMC,SR,WL,LIP,HIC,LOR,CO,LE,PI,PA,UD,PD,MU	LCV,PR,PTMC,SR,WL,LIP,HIC,LOR,CO,LE,PI,PA,UD,PD,MU	II
WE	PR,SR,WE,LIP,HIC,LOR,CO,LE,PI,PA,UD,PD,MU	LCV,PR,PTMC,SR,WL,WE,LIP,HIC,LOR,CO,LE,PI,PA,UD,PD,MU	PR,SR,WE,LIP,HIC,LOR,CO,LE,PI,PA,UD,PD,MU	I
LIP	LCV,PR,PTMC,SR,WL,WE,LIP,HIC,LOR,CO,LE,PI,PA,UD,PD,MU	LCV,PR,PTMC,SR,WL,WE,LIP,HIC,LOR,CO,LE,PI,PA,UD,PD,MU	LCV,PR,PTMC,SR,WL,WE,LIP,HIC,LOR,CO,LE,PI,PA,UD,PD,MU	I
HIC	LCV,PR,PTMC,SR,WL,WE,LIP,HIC,LOR,CO,LE,PA,UD,PD,MU	LCV,PR,PTMC,WL,WE,LIP,HIC,LOR,CO,LE,PI,PA,UD,PD,MU	LCV,PR,PTMC,WL,WE,LIP,HIC,LOR,CO,LE,PA,UD,PD,MU	II
LOR	LCV,PR,PTMC,SR,WL,WE,LIP,HIC,LOR,CO,LE,PI,PA,UD,PD,MU	LCV,PR,WL,WE,LIP,HIC,LOR,CO,LE,PI,PA,UD,PD	LCV,PR,WL,WE,LIP,HIC,LOR,CO,LE,PI,PA,UD,PD	IV
CO	LCV,PR,PTMC,SR,WL,WE,LIP,HIC,LOR,CO,LE,PI,PA,UD,PD,MU	LCV,PR,PTMC,SR,WL,WE,LIP,HIC,LOR,CO,LE,PI,PA,UD,PD,MU	LCV,PR,PTMC,SR,WL,WE,LIP,HIC,LOR,CO,LE,PI,PA,UD,PD,MU	I
LE	LCV,PR,PTMC,SR,WL,WE,LIP,HIC,LOR,CO,LE,PI,PA,UD,PD,MU	LCV,PR,SR,WL,WE,LIP,HIC,LOR,CO,LE,PI,PA,UD,PD,MU	LCV,PR,SR,WL,WE,LIP,HIC,LOR,CO,LE,PI,PA,UD,PD,MU	II
PI	LCV,PR,PTMC,SR,WL,WE,LIP,HIC,LOR,CO,LE,PI,PA,UD,PD,MU	LCV,PR,SR,WL,WE,LIP,LOR,CO,LE,PI,UD,PD,MU	LCV,PR,SR,WL,WE,LIP,LOR,CO,LE,PI,UD,PD,MU	IV
PA	LCV,PR,PTMC,SR,WL,WE,LIP,HIC,LOR,CO,LE,PA,UD,PD,MU	LCV,PR,WL,WE,LIP,HIC,LOR,CO,LE,PI,PA,UD,PD,MU	LCV,PR,WL,WE,LIP,HIC,LOR,CO,LE,PA,UD,PD,MU	III
UD	LCV,PR,PTMC,SR,WL,WE,LIP,HIC,LOR,CO,LE,PI,PA,UD,PD,MU	LCV,PR,WL,WE,LIP,HIC,LOR,CO,LE,PI,PA,UD,PD,MU	LCV,PR,WL,WE,LIP,HIC,LOR,CO,LE,PI,PA,UD,PD,MU	III
PD	LCV,PR,PTMC,SR,WL,WE,LIP,HIC,LOR,CO,LE,PI,PA,UD,PD,MU	LCV,PR,WL,WE,LIP,HIC,LOR,CO,LE,PI,PA,UD,PD,MU	LCV,PR,WL,WE,LIP,HIC,LOR,CO,LE,PI,PA,UD,PD,MU	III
MU	LCV,PTMC,SR,WL,WE,LIP,HIC,CO,LE,PI,PA,UD,PD,MU	LCV,PR,WL,WE,LIP,HIC,LOR,CO,LE,PI,PA,UD,PD,MU	LCV,WL,WE,LIP,HIC,CO,LE,PI,PA,UD,PD,MU	III

Table 7- Importance ranking of the barriers

Barriers	Mean	Median	Stdv	Level of importance	Ranking
PTMC	5	5	0	Significantly high	1
LOR	4.2	4	0.837	Very high	2
LCV	4	5	1.732	Very high	3
HIC	3.8	4	1.643	Very high	4
MU	3.8	4	0.447	Very high	4
UD	3.4	3	0.548	High	5
PR	3.2	3	0.447	High	6
WE	3.2	3	0.837	High	6
PA	3.2	3	1.095	High	6
PD	3.2	3	0.447	High	6
SR	3	3	1	High	7
WL	3	3	1.225	High	7
LIP	2.8	3	1.483	High	8
LE	2.8	3	0.837	High	8
PI	2.6	3	1.342	High	9
CO	2.2	2	1.304	Fairly high	10

Table 8 – fuzzy numeric triangulation against ranking differences

Equivalent Saaty scale	Fuzzy triangulation scale	Ranking difference
1	Equally Important (Eq. Imp) (1,1,1)	0 or 1 difference in ranking
3	Weakly Important (W. Imp) (2,3,4)	2 or 3 difference in ranking
5	Fairly Important (F. Imp) (4,5,6)	4 or 5 difference in ranking
7	Strongly Important (S. Imp) (6,7,8)	6 or 7 difference in ranking
9	Absolutely Important (A. Imp) (9,9,9)	8 or 9 difference in ranking

Table 9– Normalised weight of each barrier

	Fuzzy Weight			Ave	Normalised weight
LCV	0.0809	0.1179	0.1689	0.1	0.1154151
PR	0.0308	0.0425	0.0603	0	0.041954
PTMC	0.1337	0.1927	0.2713	0.2	0.1876565
SR	0.0224	0.0304	0.0428	0	0.0300177
WL	0.0224	0.0304	0.0428	0	0.0300177
WE	0.0291	0.0407	0.0583	0	0.0401991
LIP	0.0142	0.0198	0.0295	0	0.0199479
HIC	0.0599	0.0904	0.1337	0.1	0.0891885
LOR	0.1136	0.1645	0.2323	0.2	0.1602413
CO	0.0075	0.0104	0.0154	0	0.0104818
LE	0.0139	0.0194	0.0288	0	0.0195132
PI	0.0105	0.0147	0.0221	0	0.0148556
PA	0.0285	0.0398	0.0569	0	0.0393246
UD	0.0403	0.0571	0.0809	0.1	0.0559993
PD	0.0403	0.0571	0.0809	0.1	0.0559993
MU	0.0599	0.0904	0.1337	0.1	0.0891885
Total				1.1	1

Responses to the reviewers' comments

Dear editor in chief, Associate Editor and reviewers,

The reviews have raised some very helpful issues with our paper and provided insightful comment during the second round of the review. We are really grateful for the reviewers' constructive comments. As a consequence, we have made changes to the paper in association to your comments. The following sections refer to each specific review point in turn, explaining where and how we have amended the paper. We think the paper is now a much stronger piece and we hope it deals with the reviewer's comments in a satisfactory manner. We deal with each reviewer's comments in turn.

Reviewer 1:

Comment - I would suggest revising the stated research question. The content is fine, but the phrasing seems awkward. Perhaps it is use removing the first 'and' in the sentence.
Response – Thank you for your comment. We took this comment on board and removed the first "and" from the Research Question. Please, see the last line in page 2.

Comment - the first research objective could be rephrased as "confirm the gap..."
Response – Thank you for the comment; we took it on board and changed the wording as instructed. Please, see the beginning of page 3.

Comment - it may be worth considering moving section 6.1 to immediately follow the theoretical contributions instead of within the conclusion section.
Response – Thank you for the comment. We have taken the comment on board and re-located the practical/managerial contribution to follow the research and theoretical contribution under section 5.

Comment - I would also 'water down' this section by removing the "significant", as this is certainly open to interpretation - particularly in the practical sphere.
Response – Thank you for the comment. We removed the "significant" word for section 5. Please, check sub-heading 5.2 as the practical/managerial contribution.

Reviewer 2:

Comment 1 - What do the authors mean by barriers in the scope of this study? Do these barriers pertain to the implementation and readiness, completing the project, or achieving the objectives?
Response – Thank you for your comment. As per definition by Solangi et al., (2021) and Sreedharan et al., (2018), barriers are anything impending progress. However, we took your comment on board and added one sentence to clarify this. Please, see first paragraph under section 2.2.

Comment 2 - The authors mentioned, " We intend to respond to this research gap and address how managers and OPEX project owners can help their organisations mitigate the risks of failure in the green deployment". How does prioritizing barriers help reduce the risk of failure? Do these barriers actually cause project failure? Why did the authors not consider failure factors as barriers?

Response – Thank you for your comment. We have replace the wording of "risk of failure" with "barriers" to avoid confusion. Please, see the first paragraph in page 3. We considered barriers rather than failure factors as barriers tend to include some failure factors too. Barriers are broader to include pre-implementation or readiness aspects as well as implementation and completion, whereas failure factors are normally emerged during implementation. This has already been addressed by adding a sentence under section 2.2. Table 2 that provides 16 barriers also reflect this as some of them are pre-implementation or in readiness phase.

Comment 3 - Although the authors identify a gap in the literature, they do not clearly explain why this research is needed.
Response – Thanks for your comment. This has been addressed in the third paragraph under Introduction section where we referred to gap supported by the literature followed by our explanation of why this study is required. Please, see third paragraph under Introduction section as:
An extensive literature on various green OPEX project frameworks (Sreedharan, 2018; and Cherrafi et al. 2017) supported by a recent scoping review (Shokri et al., 2021) suggested a literature gap regarding the lack of empirical studies to address the interaction and prioritisation of the barriers to the green deployment of OPEX projects. Therefore, our study is critically required to model interactions and prioritization of barriers systematically and through a more in-depth, empirical and subjective analysis to embrace the green deployment of OPEX projects in manufacturing that remains a gap (Shokri et al., 2022; Shokri et al., 2021).

Comment 4 - The authors identified 16 barriers, but it is unclear why these specific barriers were chosen for green OPEX in manufacturing, as they seem applicable to any initiative, whether OPEX, green OPEX, or other project types in manufacturing, service, or construction sectors. I suggest briefly explaining how each barrier specifically impacts green OPEX in the manufacturing context.
Response – Thank you for the comment. We have selected these barriers as we extracted them from references associated to OPEX and green OPEX integration in the manufacturing sector. We also took your comment on board and added further explanation of how each barrier impacts green OPEX and is relevant to it in the manufacturing sector by adding the "Context" as the middle column of table 3 to briefly explain how each barrier impacts the green OPEX. Please, check table 3.

Comment 5 - The authors highlighted in the literature review section "A significant barrier to green OPEX integration is the conflict between economic measures like customer satisfaction and environmental credentials like energy use", why this barrier was not included?
Response – Thank you for your comment. This has already been considered and wrapped under the "Complexity" in the literature as we have already referred to it as one barrier. However, to avoid confusion we re-worded the sentence in the second paragraph under section 2.2, and also you can find further clarification in table 3 against "Complexity" where we added the context.

Comment 6 - Regardless of the implementation objectives of achieving economic and environmental goals efficiently, what is the difference between green OPEX and OPEX? Does the implementation of OPEX methodologies such as Six Sigma or LSS technically differ when applied for green outcomes? Can the identified barriers be generalized to all OPEX methodologies including Kaizen, Lean, Six Sigma and LSS?
Response – Thanks for your comment. This has been taken on board and we have added a few lines to reflect the difference between two and stressed that despite differences many barriers

may be identical for both. We have also indicated these barriers are common collectively for lean, Kaizen and LSS. Please, see first paragraph under the Introduction section.

Comment 7 - How the sample size was determined? Why were all the selected participants from the UK? One of the selection criteria is that participants have at least 10 years. Could including less experienced practitioners change the findings, as they may encounter more significant barriers due to their limited experience?
Response – We determined this sample size due to saturation of our findings through discussion/interview with experts and also supported by other previous studies using the same MCDM methodologies of ISM-MICMAC and fuzzy AHP. We have also selected only the UK market due to being responsive to previous relevant studies raising the gap that were also UK-based. We have added further explanation to clarify these points. Please, see first paragraph under section 3.1. We also approached experts with the greater experience than 10 years of using OPEX as we wanted to make sure that they have as much practical experience as possible in OPEX using them as expert in our study as the expert panel.

Comment 8 - Table 2 is not referenced in the text
Response – Thank you for your comment. We have now corrected this and made reference to the table 2 in the text.

Comment 9 - I suggest rewriting the methodology section and separating it from the results. It is not clear, contains some contradictions and needs further clarification and significant refinement. For example, the authors first mentioned "survey instrument" and then "we conducted open-ended interviews". Is the research designed as a two-stage process, where interviews are conducted first to identify barriers, followed by data collection for an MCDM analysis?
Response – Thank you for your comment. We appreciate your points and tried to do further refinements where required. However, you may wish to have another look that the methodology with three different phases explained in it is separate with the results and discussion section (Section 4). Whatever has been added as part of three phases in the methodology are actually the methods. We also appreciate your comment about the confusion of terms of survey and interviews and took this comment on board and made corrections with some explanations. The survey has been a tail of the open-ended interview at the same time asking experts to respond to it as an important part of our data collection for the ISM-MICMAC method. However, we added further clarification in section 3.1. Please, see the third paragraph under section 3.1.

Comment 10 - Table 3 reports the barriers identified from extensive literature reviews and interviews while the author previously mentioned "The survey instrument included sixteen barriers to green OPEX integration, identified through extensive literature review and global expert survey analysis from previous studies". What is the source of each barrier? which were derived from the literature and which emerged from the interviews?
Response – Thanks for your comment. We appreciate your comment and took it on board. We have re-designed table 3 by providing individual references for each individual barrier for further clarification. However, top two references are Shokri et al., (2022) and Shokri et al., (2021) with more relevant studies to the scope of our study and with the global survey (Shokri et al., 2022). We have verified all of these sixteen barriers through our open-ended interview before asking them to score their importance and interaction on the quick survey instrument. This mens any barrier not supported by the interviewees would be eradicated

from the survey before being shared physically with the interviewee to respond. We have clarified this. Please, see phase 1 under section 3.2.

Comment 11- The data collection and analysis are not clear. Why were open-ended interviews chosen over surveys, given that participants were asked to rate each barrier on a five-point scale, which is typically a closed-ended format?
Response – Thank you for your comment. We appreciate your point and made further clarifications of why open-ended interviews and survey were used. Using open-end interview was to-fold: 1)to verify findings from literature; 2)to build discussion and set scenery before asking experts to respond to the survey. The survey questionnaire was handed over to the expert after open-ended interview discussion to respond. This was also a usual method for any similar ISM-MICMAC analysis in pervious studies. Please, see the third paragraph under section 3.1.

Comment 12- Why was AHP employed in this study, given that the authors have already established contextual relationships by ISM-MICMAC, which could serve as a form of prioritization? Please, clarify how AHP complements ISM-MICMAC.
Response – Thank you for your comment. We appreciate your comment; but we conducted fuzzy AHP to prioritise the barriers as part of the aim of the study. The ISM-MICMAC is used to model the interaction and classify them in four groups and they do not do any prioritisation. Please, see first two lines under phase 3 describing the purpose of fuzzy AHP.

Comment 13- AHP typically involves pairwise comparisons where each barrier is compared directly against every other barrier. How was the pair-wise comparison matrix developed? Did respondents complete it or based on author's comparison? The authors mention asking the expert panel to score the importance of barriers using a 5-point Likert scale, but Table 8 indicates the use of Saaty's 9-point scale.
Response – Thank you for your comment. We appreciate your point. However as described in the first, third and fourth paragraphs under phase 3 and table 8, we used triangular fuzzy AHP analysis, and the 9-point scale of fuzzy AHP was set based on fuzzy triangulation scale that itself was developed from linguistic terms representing the difference between rankings of each barrier as per table 7. The rankling was developed based on the scores of importance in the survey instrument provided by experts. Authors have seen this analysis in the previous triangular fuzzy AHP studies (Li et al., 2023; Can, 2023; Solangi et al., 2021; Ahmed et al., 2020; Lyu et al., 2020) relevant to the scope of this study.

Comment 14- What are the hierarchical levels in AHP? Have the authors considered using categorization to simplify the pair-wise comparisons? Without categorization, a 16x16 comparison matrix could introduce potential errors or inconsistencies. How did the authors address this issue to ensure the robustness of their analysis given that the consistency ratio is not calculated?
Response – Thanks for the comments. We appreciate the comments made by the reviewer. However, the hierarchical levels in this triangular fuzzy AHP analysis have been set as per Fuzzy triangulation scale from ranking differences between barriers as per table 8. This is a common method to be done without complex computation methods. We developed a large table in spreadsheet and the analysis has been cross-checked by two more members of the team to prevent any error. We have acknowledged this in the main body. Please, see the fourth paragraph under phase 3. We could not fit the table into the paper due to the large size. But, it is available on request to be sent off separately as the supplementary document for review.

Authors have seen similar triangular fuzzy AHP analysis in the previous triangular fuzzy AHP studies (Li et al., 2023; Can, 2023; Solangi et al., 2021; Ahmed et al., 2020; Lyu et al., 2020) relevant to the scope of this study.

Comment 15- How the levels of importance in Table 7 labeled as "significantly high," "fairly high," etc. were developed?
Response – Thank you for your comments. This is a standard way of scaling in the non-composited triangular fuzzy AHP analysis. The scaling was developed based on both Mean and Median values due to the fuzziness of the analysis. Please, see the explanation in the first paragraph in page 12. This has been used by academics and practitioners and authors have seen this analysis in the previous triangular fuzzy AHP studies (Li et al., 2023; Can, 2023; Solangi et al., 2021; Ahmed et al., 2020; Lyu et al., 2020) relevant to the scope of this study. Please, see the first paragraph under phase 3.

Comment 16- It is not clear which and how to address barriers. The authors state "Notably, the study reveals that a top prioritized barrier may not influence others, and an influential barrier might not be top priority". Should organizations focus on addressing top priorities, influential barriers, or both? How should they approach the least ranked barriers in this context?
Response – Thank you for your comment. We appreciate the comment. But, this is exactly part of the finding of our study having contribution into management decision making. We are suggesting that managers take two different and independent approaches to barriers whether as influential or critical barriers in their decision making. We appreciate this needed to be clearer; hence, we added the sentence at the end of first paragraph under section 5.2.

Comment 17- How is the study align with organizational capability theory?
Response – We followed the study by Hudnurkar et al., (2019) where authors discussed around project capability deficiency. In their study organisational capability theory was defined as: "Organisational capability is defined as "the ability of an organisation to perform a coordinated set of tasks, utilizing organisational resources, for the purpose of achieving a particular end result". In this study (Hudnurkar et al., 2019), "barriers" have been identified as the set of deficiency to perform a set of tasks impending the success of the task. Therefore, as our study focuses on "barriers of green deployment of OPEX" as deficiency to preform the task, we aligned our study with this theory.
However, for further clarification, we added the definition of the organisational capability and how it aligns with our study (barriers of green deployment of OPEX) in the paper. Please, see section 2 and the first paragraph under section 2.2.

Comment 18- The managerial implications are not clear. How can organizations use the findings in their practical green OPEX implementations?
Response – Thanks for your comment. We believe further changes to the managerial implication made it stronger. The second paragraph under this section provides clear answer to how Organisations can use the findings in their practical green OPEX implementation. In summary, the findings support managers to develop roadmap for their green OPEX deployment and also consider hidden environmental inefficiencies in their project management.