**Analysing the Adoption Barriers of Low-Carbon Operations: A Step Forward for Achieving Net-Zero Emissions**

**Abstract**

In November 2021, the 26th United Nations Climate Change Conference (COP26) was held in Glasgow, UK, the global leaders from nearly 200 countries stressed taking immediate action on the climate issue and how to ensure global net-zero emissions by 2030. It is possible to accelerate the transition to low-carbon energy systems, the present study seeks to identify and analyse key barriers to Low Carbon Operations (LCO) in emerging economies. A critical literature review was undertaken to recognise the barriers linked to the adoption of LCO. To validate these barriers, an empirical study with a dataset of 127 respondents from the Indian automobile industry was conducted. The validated barriers were analysed using Best Worst Method (BWM) and Decision-Making Trial and Evaluation Laboratory (DEMATEL) techniques. BWM is used to determine the priority ranking of barriers, while the DEMATEL method is employed to elucidate the cause-effect inter-relationships among the listed barriers. The results suggest that ‘*Economic*’ is the most influential category of barriers followed by ‘*Infrastructure*’ and ‘*Operational*’. The results also show that the barriers ‘*Economic*’, ‘*Environmental*’, ‘*Infrastructure*’ and ‘*Organizational Governance*’ belong to the cause group. Some significant managerial implications are recommended to overcome these barriers and to assist firms in the successful adoption of LCO and achieving net-zero emissions. The work was carried out in the automotive industry in India but provides findings that may have wider applicability in other developing countries and beyond.

***Keywords:*** Low Carbon Operations; Climate Issue; Resource policy; Net-Zero Emissions; Environmental Sustainability.

1. **Introduction**

Currently, all people and every society are facing the issues of global warming and climate change (UNEP, 2018; Yamashita and Fujii, 2022; Sonnett, 2022). Increased industrialisation throughout the world is consuming huge amounts of fossil resources, resulting in higher carbon emissions (Wong et al., 2012; Liu and Song 2017; Wang and Zhang 2020). As an alternative, Böttcher and Müller (2015) introduced the term ‘low-carbon operations’ (LCO) defined as ‘*integrating carbon efficiency into the planning, execution and control of business processes to obtain competitive advantage’*. However, the adoption of LCO in an organization depends on many activities such as planning, execution and control of the system (de Sousa Jabbour et al., 2018; Zhou et al., 2022) but it is a forward step to contribute for achieving COP26 commitments by ensuring global net-zero emissions by 2030 (Dwivedi et al., 2022).

Over the last two decades, there has been a paradigm shift in the global economic landscape. Due to significant Gross Domestic Products (GDP) and increasing populations, emerging economies like China and India now play a key role in global growth and provide greater investment opportunities for business (Tamvada et al., 2022; Singh et al., 2022). The emerging economies are now performing well in terms of improving customer service, generating employment and reducing poverty (Mathivathanan et al., 2018). However, the emerging economies are also major greenhouse gas emitters, leading to threats of climate crisis if industries are not able to address these concerns (Singh and Singh, 2018; Zahan and Chuanmin, 2021). According to 2018 United Nations Environment Programme, carbon emissions from fossil fuels and industrial processes make a major contribution to emission and global climate change (UNEP, 2018). This means LCO are the ideal for all industrial operations in all countries, from an environmental point of view (Saint Akadiri et al., 2020).

In India, the automobile sector has become one of the major pillars of the economy (Mathivathanan et al., 2018). The industry has taken up an aggressive stance as society recognises the negative impact it has had on the environment. The performance of the Indian automobile industry in meeting environmental targets has been well below satisfactory levels, which may in part be due to the lenient regulatory framework that governs these companies (Luthra et al., 2018; Nizam et al., 2020) but is also assumed to be due to the perceived barriers to change which make low-carbon operations difficult to achieve. The automobile industry is also actively involved in many sustainability programmes to make their businesses more sustainable; the zero-carbon mission initiative is one of them. In this sense, an effective institutional level framework is very important to LCO adoption (Chen et al., 2020). Such a framework can assist business to create adaptive and responsive capacities to manage potential hurdles and implement policies in pursuit of LCO (Luo et al., 2017). This further helps the industry to achieve the goals of lower greenhouse gas (GHG) generation and higher business sustainability (Kedia, 2016).

The environment pollution threat is rising; taking this threat seriously, the Indian government introduced the ‘National Electric Mobility Mission’ to promote the use of electric vehicles (Kumar and Padmanaban, 2019). Under this scheme, the Indian government is trying to provide financial support to all parties involved with vehicle use and production. This initiative demonstrates government support in limiting the use of traditional resources and improving public health. However, the concepts of cleaner production and low carbon emission technology are still far from full acceptance in the automotive sector in India (Suresh et al., 2010; Mathivathanan et al., 2018; Shayganmehr et al., 2021). As will be shown, research that can guide companies on LCO is somewhat undeveloped in the literature (Furlan et al., 2017; de Sousa Jabbour et al., 2019).

Driven by the urgent need to improve operations from the environmental perspective, this research seeks to address two key questions. Firstly, what are the key barriers to LCO that are perceived by the managers? Secondly, how can these barriers be examined according to their priority and organised in terms of their causal relationships? Understanding the nature of the barriers will facilitate future interventions to allow progress to be made.

The study therefore aims to analyse the barriers to adopting LCO in the automobile industry in India. The following research objectives are set out:

1. To identify and validate the barriers to LCO;
2. To assess the priority ranking of the barriers to LCO;
3. To identify the causal relationships between listed barriers to LCO;
4. To recommend relevant suggestions to overcome the barriers to LCO.

After studying relevant literature, the key barriers to LCO were identified. To confirm these barriers, Exploratory Factor Analysis (EFA) was conducted (Field, 2009). A dataset of 127 responses from the Indian automobile industry was used for empirical analysis. Best Worst Method (BWM) was used to prioritise the validated barriers based on their importance weights (Rezaei, 2015; Rezaei et al., 2016). The DEMATEL method was used to establish the causal relationships between barriers (Hsu et al., 2013; Govindan et al., 2020).

Following the introduction, the literature describing the existing background knowledge for the work is given in Section 2. The research methodology and the analysis with results are provided in section 3 and 4. The findings and discussion are given in Section 6 and 7. Finally, Section 8 covers the concluding remarks and directions for future research.

1. **Literature Review**

We present the literature in two main areas – a conceptual background on LCO and related barriers and identifying the open questions for this research.

* 1. **LCO and related barriers**

Carbon emission management has become a significant subject at corporate and decision-making level (Tang et al., 2015; Shen et al., 2018; Stefanelli et al., 2021; Zheng and Ge, 2022). Scholars and practitioners across the globe now accept the need to tackle carbon emissions at both macro and micro levels. The acceptance of LCO practices can assist different industrial sectors, as has begun to be seen in sectors such as automobile manufacturing, in efforts to eliminate negative impacts on the environment. There are three key operational areas where carbon management practices are of paramount importance:

* *Products:* Manufacturers needs to engage in low carbon products to generate low carbon emissions and utilize energy, material and resources effectively (Fahimnia et al., 2015; Liu et al., 2017). The parts produced for an automobile company can also be made low carbon using contemporary approaches like Big Data (Seles et al., 2018).
* *Manufacturing*: A proactive approach towards manufacturing can assist managers to improve their operational capabilities to achieve LCO (Micheli, and Mantella, 2018). The adoption of LCO can also facilitate manufacturers in analysing impacts of carbon cap and trade mechanisms in manufacturing and remanufacturing decisions (Chang et al., 2015). The use of the contemporary environmentally friendly processes can further support the implementation of LCO to produce sustainable products (Dong et al., 2018). This would also help manufacturers in improving product stewardship for low carbon management and high sustainable business development (Wong et al., 2012; Tamvada et al., 2022).
* *Supply chain (SC):* There is an increased attention to ecological consciousness in the design and operation of SCs. The SC is a key element in the automobile industry, responsible for delivering of parts to the major manufacturers. In automotive industry, the SC has a complex structure. Therefore, managers need to examine the issues of GHG generation and sustainability in a SC context (Tang et al., 2015). Currently, the automobile industry generates huge amounts of pollution and emits hazardous gases in its various stages of production, distribution, and disposal of automotive components. The automotive sector accounts for 17% of global GHG emissions (United Nation Climate Change, 2018). To reach a potential USD 1 trillion market for electric vehicles, the industry also has to make huge changes in their supply chain design (United Nation Climate change, 2018). Successful implementation of LCO is associated with a robust supply chain or logistics arrangement regardless of the company managing it (Jabbour et al., 2015; Ji et al., 2017; Singh et al., 2022). For example, manufacturers can engage with their stakeholders for higher environmental performance and select suppliers who are conscious to environment sustainable manufacturing (Wong et al., 2012; Liu et al., 2019) and using LCO practices, to cut down emissions.

We acknowledge that a fourth area, the emissions from motor vehicles during their use, is of vital importance from carbon reduction in general. However, for this paper we regard the design and use of vehicles as beyond the operations management arena and confine ourselves to the emissions from production operations.

Carbon Trust reported (2006) that evaluating carbon practices across supply chains can help manufacturers to minimise the carbon emissions in each activity of product life. This would further lead to cost savings and improve operational efficiency. In 2009, McKinsey and Company provided a quantitative basis and trade-off between carbon emissions reduction and cost (McKinsey and Company’s 2009). Since then, many studies have been conducted in different perspectives. Böttcher and Müller (2013) examined how the drivers and practice of LCO play a significant role in cutting carbon emissions, but the study did not look at barriers to LCO. Furlan et al. (2017) studied the importance of LCO for organisational sustainability. In their empirical study, they conducted interviews with many experts, tried to create a link with the SC, and suggested the future scope of research in low carbon and supply chain management. They mentioned the need for work evaluating adoption of LCO practices from an operational context. In 2017, Bai et al. (2017) developed a framework for a zero-carbon logistics support practice and provided relational practices to show organisations and their ancillary suppliers how to develop robust chains and work towards zero-carbon targets. Srivastav et al. (2018) examined how organisations throughout the world are undergoing a low carbon transition to improve their societal and environmental gains and called for research in integrating low carbon transition with supply chain design. de Sousa Jabbour et al. (2018) performed a systematic literature review and discussed the importance of LCO in an industrial context. They classified barriers as technology issues, policy, governance, market and the economic.

Meyers et al. (2016) conducted an audit base study of six EU nations to evaluate product specific energy consumption and means to limit carbon emissions. Cost effectiveness, technology and governance related to management were the major barriers for them to reduce carbon emissions. Meath et al. (2016) supported the same barriers. Liu and Song (2017) discussed the pre-requisites and contracting model in the zero-carbon support mechanism by taking two cases for installing zero carbon practices in the context of the textile logistics from China. This work highlighted several obstacles - scarcity of energy sources, infrastructure, lack of clean technology etc. in adopting the management practices required for zero carbon emission. In addition to this, De Wolf et al. (2017) discussed the importance of governance in LCO practices.

The concept of LCO and the development of sustainable environmental initiatives needs strong organisational commitment (Liu et al., 2018). However, there are several problematic issues, such as lack of political commitment, weak policy mechanism and high set up costs; these may obstruct the smooth implementation of LCO in a company (Vagnoni and Moradi, 2018).

de Sousa Jabbour et al. (2018) suggested companies to identify barriers to LCO. A further empirical investigation is needed so that companies are able to overcome these barriers and adopt LCO more easily. No study is available in the current literature that examines the priority ranking and causal relationships of barriers to LCO in a developing economy context. Hall et al. (2020) investigated the applicability of innovative business models to achieve low carbon entrepreneurship and management in the energy system in United Kingdom.

Bai et al. (2017) show that there is a lack of research to understand the importance of LCO practices to counter industry greenhouse gas emissions. The initiatives taken by the government and the automobile companies in India are not strong enough to achieve a proper adoption of LCO (Mathivathanan et al., 2018). Although several attempts have been made by researchers all over the world to understand low carbon practices (Suresh et al., 2010), no proportionate successes or results have been achieved so far. The lack of awareness among the automobile companies also adds to the existing literature gaps for LCO (Gouldson and Sullivan., 2013; Long et al., 2016; Singh et al., 2022).

* 1. **Research needs**

This research seeks to reveal the barriers to LCO in the context of the automobile industry. This involves identifying the barriers, ranking their importance, and identifying any causal relationships between barriers, in order to be able to make suggestions for approaches that may be used to overcome the barriers and move towards LCO. Considering the importance of emerging economies, we focus on India as an example.

The barriers were identified from literature and prioritised using EFA and BWM-DEMATEL.

Aligned with the objectives of our study, we use the term “barriers” for any situation, problem or difficulty whether perceived or real that deters a manager from planning and implementing LCO.

To find the exhaustive list of barriers, we searched the literature using the following keywords: barriers, obstacles, hurdles, low carbon emission, low carbon operation management. The various data bases such as Scopus, Science Direct, EBSCO, Emerald, Wiley, Taylor and Francis were searched and by considering only peer reviewed journal and English language articles, 43 articles were selected using the systematic literature review approach of Tranfield et al. (2003) and Centobelli et al. (2017) considering the scope and aim of this study. A forward and backward snowball approach was used for final screening. The barriers related to adoption of LCO distilled from the previous studies (see Table 1). These were used as the basis of the main research that will be described in the next section.

 **Table 1:** Barriers to LCO from literature

|  |  |  |
| --- | --- | --- |
| **No.** | **Barriers** | **Sources** |
| 1 | Cost effectiveness  | Liu and Song (2017); van Doren et al (2018); Dissanayake et al (2020); Singh et al. (2022) |
| 2 | High set up cost  | Hsu et al. (2013); Furlan et al. (2017); de Sousa Jabbour et al. (2018); Victor-Gallardo et al. (2022) |
| 3 | Low credit rating  | Furlan et al. (2017); De Jesus and Mendonça (2018); Arent at al. (2022)  |
| 4 | Lack of market gain  | Xodo (2011); Gray et al. (2017); Zhao et al. (2018); Chapungu et al. (2022) |
| 5 | Lack of low carbon competitiveness | Hsu et al. (2013); Tang et al. (2015); Kedia (2016); Fragkos et al. (2017); Zhao et al. (2018); Dissanayake et al (2020) |
| 6 | Commercialization  | Fragkos et al. (2017); Melville et al. (2017); Liu et al. (2022) |
| 7 | Lack of motivation for low carbon focused procurement  | Hsu et al. (2013); Zimmer et al. (2015); Zhao et al. (2018); Vimal et al. (2022) |
| 8 | Lack of awareness  | Gouldson & Sullivan (2013); Tang et al. (2015); Long et al. (2016); Muduli et al. (2020); Singh et al. (2022) |
| 9 | Lack of supporting finance by financial Institutions  | Zimmer et al. (2015); Li et al. (2020); Ohene et al. (2022) |
| 10 | Less mobilized private fund for LCO related activities  | Suresh et al. (2010); Polzin (2017); Melville et al. (2017); de Sousa Jabbour et al. (2018) |
| 11 | Information asymmetry  | Mulugetta and Urban (2010); Liu and Song (2017); Polzin (2017) |
| 12 | Environmental regulations  | Mulugetta and Urban (2010); Tan et al. (2017); Singh et al. (2022) |
| 13 | Resources unavailability  | Lee et al. (2017); Callaway et al. (2018) |
| 14 | Air quality  | Golub et al. (2009); Bush et al. (2017) |
| 15 | Issues related to energy transition from fossil fuels  | Hsu et al. (2013); Shen et al. (2018) |
| 16 | Lack of renewable energy options | Polzin (2017); Callaway et al. (2018); Kim et al. (2020) |
| 17 | Lack of political commitment  | van Doren et al. (2018); Victor-Gallardo et al. (2022)  |
| 18 | Lack of renewable energy sources | Ahlborg and Hammar (2014); Polzin (2017); van Doren et al (2018) |
| 19 | Lack of specific laws  | Bush et al. (2017); Geels et al. (2018) |
| 20 | Lack of low carbon supply chain management  | Tan et al. (2017); Shen et al. (2017); Emodi et al. (2017); Singh et al. (2022) |
| 21 | Lack of testing nodes in LCO practices | Suresh et al. (2010); Li et al. (2017) |
| 22 | Lack of proper policy mechanism | Bush et al. (2017); Rosenbloom et al. (2018); Chen et al. (2020) |
| 23 | Lack of potential vendors | Evans and Karvonen (2014); Vimal et al. (2022) |
| 24 | Slow vehicle electrification | Emodi et al. (2017); Vagnoni and Moradi (2018) |
| 25 | Lack of capacity building and green training  | Golub et al. (2009); Babatunde and Perera (2017) |
| 26 | Scarcity of energy sources | Meyers et al. (2016); Liu and Song (2017); Babatunde and Perera (2017) |
| 27 | Lack of low carbon technology  | Luo et al. (2017); Meyer and Xin (2017); Shen et al. (2018) |
| 28 | Lack of operational efficiency  | He (2016); Hall et al. (2017); Geroe (2022). |
| 29 | Carbon risk assessment  | Li et al. (2017); Vagnoni and Moradi (2018) |
| 30 | Lack of carbon governance  | De Wolf et al. (2017); Liu et al. (2018) |
| 31 | Lack of performance assessment  | He (2016); Hall et al. (2017); Singh et al. (2022) |
| 32 | Lack of top management commitment  | Evans and Karvonen (2014); De Wolf et al. (2017); Rosenbloom et al. (2018); Vimal et al. (2022) |
| 33 | Lack of green motivation  | Hsu et al. (2013); Liu et al. (2018); Sindhwani et al. (2022) |

1. **Research Methodology**

The methodology adopted for this research is shown in Fig.1.

**Fig. 1** Research methodology

Extensive literature review

Industry and field experts’ inputs

Identification of barriers and sub-barriers for adopting LCO in emerging economies’ perspectives

Identification of Barriers

Empirical Investigation of Barriers

Design a survey questionnaire to measure the importance of barriers

Check reliability and validity of data

Employ exploratory factor analysis (EFA) to identify the main barriers and its respective sub-barriers

Determine the best and worst criteria by the experts

Determine the experts’ preference of best/worst criterion w.r.t. others on the basis of 1-9 scale

Calculate the and initial relation matrix

Calculate consistency ratio using consistency index

Gather experts’ data on the basis of 0-4 scale

Calculate sums of rows/columns of matrix

Calculate the average matrix

BWM Method

Set the threshold value

DEMATEL Method

Normalized initial relation matrix

Calculate total relationship matrix

 Yes

 No

Construct cause-effect map

Calculate final weight

Discussions of findings and managerial implications

CR close to zero

An empirical investigation provides theoretical foundation to the problem and using both qualitative and quantitative approaches give more strength to theoretical foundation (Bryman, 1988; Newman and Benz, 1998; Kothari, 2004). Empirical research aims to provide knowledge through direct and indirect experiences of respondents. In this work, an effort is made to identify and evaluate the barriers to adopting LCO in the automotive industry. The barriers listed from literature need to be confirmed by respondent’s opinions in terms of their applicability. Therefore, the research team collected data from large, middle and small companies in the emerging Indian automobile industry using both online and offline modes of data collection. In this way, we empirically validated the barriers to adopting LCO. Moreover, we further determined the relative weights and cause-effect relationship of barriers and their respective sub-barriers. Checks were made for bias, and the Cronbach alpha (Nunnally, 1978; Hair et al., 2010) was used for the reliability and validity of data. To classify the barriers into various categories, EFA (Field, 2009) was employed.

BWM was applied to reveal the relative significance of the barriers. BWM is able to solve decision-making problems with multiple criteria. This method has some unique advantages, for instance, more consistent results, it provides flexibility to the decision maker to select the best (high effect) and worst criteria (less effect) among all and provides more reliable results in less time due to the smaller number of pair-wise comparisons (Rezaei, 2015). BWM is a well-established method and have used in various domains (Torabi et al., 2016). However, the BWM method does not have the capability to map the relationships among barriers. For this aspect, the DEMATEL method is best suited and has the capacity to generate inter-relationships among them (Hsu et al., 2013; Govindan et al., 2016; Kazançoglu et al., 2020). It is a well-established method to know the cause-effect interrelationship in the form of digraph and is widely used by researchers in various domains (Rahman and Subramanian, 2012).

* 1. **Data collection and development of questionnaire**

To check the statistical establishment of all barriers, an empirical investigation was carried out. A questionnaire (see Appendix A) was designed and a pre-tested the survey instruments with senior professionals with strong exposure to LCO in the automobile sector was conducted. As a result, some of questions were re-worded to bring more clarity and avoid confusion. The survey was administered to Indian automobile companies with a covering letter specifically mentioning that the respondent and organization details will be kept strictly confidential. Initially, convenience sampling method was used for data collection but after discussions, some participants, helped the research team to reach more participants through their references to other companies. The questionnaire, along with the cover letter, was sent to 350 operation managers in different large, medium and small size companies. After two weeks, a reminder mail sent. The research team was able to collect 158 respondents’ data. After careful investigation, 127 responses were used; these were complete in all aspects and were considered as an acceptable sample size for analysis (Hair et al., 2010).

1. **Data analysis and results**

Various statistical tools were used to evaluate the data collected in this research; other details are given below. The respondent details are given in Table 2.

Table 2: Profile of the participants

|  |  |  |
| --- | --- | --- |
| **Characteristics**  | **Total** | **Percentage (%)** |
| Qualification  | Graduation  | 77 | 60.63 |
| Masters | 41 | 32.28 |
| Doctorate | 2 | 1.57 |
| Others, please specify…  | 7 | 5.51 |
| Work experience  | Less than 5 years  | 10 | 7.87 |
| 5 to 10 years  | 55 | 43.31 |
| 11 to 15 years | 44 | 34.65 |
| 16-20 years  | 15 | 11.81 |
| Above 20 years  | 3 | 2.36 |
| Background  | Senior Manager  | 10 | 7.87 |
| Manager | 32 | 25.20 |
| Middle Manager | 47 | 37.01 |
| Supervisor | 28 | 22.05 |
| Other, please specify… | 10 | 7.87 |
| Participants from  | Large size firm (Annual turnover exceed 10 crore INR equivalent to 115M US$) | 47 | 37.01 |
| Medium size firm (Annual turnover between 5 – 10 crore INR equivalent to 57 – 115M US$) | 61 | 48.03 |
| Small size firm (Annual turnover more than 25 lakh INR but does not exceed 5 crore INR equivalent to between 2.8 - 57M US$) | 19 | 14.96 |

* + 1. **Measurement of biasness**

In the process of data collection, biased opinions of respondents may affect the responses. Therefore, the following measures were considered to deal with biased responses of respondents in validating the barriers (Tittle and Hill, 1967):

1. We kept the responses of experts as anonymous (Podsakoff et al., 2003).
2. We conveyed the aim and objectives of the research to the respondents. They were asked to give their most relevant response. With this procedure, we were able to record their most consistent response and further limit the chances of biasness in their responses (Podsakoff et al., 2012).

Harman's one-factor test was used to test for common method bias (Harman, 1976; Podsakoff et al., 2003). The result of the unrotated factor solution with a single factor is 19.83 which is less than 50 % of variance, showing the common bias problem is not significant. To compare between early and late responses, and offline and online data, a t-test was employed (Podsakoff et al., 2012) and no significant difference at *p* ˃ 0.05 was observed.

* + 1. **Reliability and Validity checks**

To check the accuracy of respondent data, reliability tests help to assess the ‘goodness’ of a measure (Field, 2009). To check convergent validity, the factor-loading concept is used; the value obtained is greater than 0.5, which is acceptable (Field, 2009). Cronbach’s alpha α is commonly applied to judge reliability (Nunnally, 1978). The overall Cronbach alpha value is 0.788, which is acceptable (Field, 2009). The factor loading of each item is greater than 0.5, which shows the internal consistency of the instruments used (Nunnally, 1978) and convergent validity of the instruments. After establishing the factor structure of LCO barriers using EFA, the factor-wise (main barrier) Cronbach alpha value is calculated; the range of 0.750 - 0.944 justifies the convergent validity of the instruments (Hair et al., 2010).

* + 1. **Exploratory factor analysis (EFA)**

EFA is the technique used most frequently among all the multivariate models to establish the factor structure (Bryman and Bell, 2015). Without loss of information, EFA helps us find factors structure of dimensions (Hair et al., 2010), therefore, EFA is employed to identify the factor structures of all the identified barriers to adopting LCO. Both the EFA technique and the reliability tests were conducted. The collected data is fulfilled the criteria for applying EFA, for instance, The KMO significant value is 0.787 which is higher than 0.6 (Bryman and Bell, 2015). Bartlett’s Test of Sphericity is also significant at *p* < 0.01), and the obtained sampling adequacy value is greater than 0.50 for each barrier (Hair et al., 2010). Through EFA, all listed barriers were classified into seven categories (see Table 3); total variance is 74.16%. The factor loading of each barrier under its respective category is in the range of 0.611 - 0.935 that are greater than 0.60. The commonalities range is 0.504 to 0.889, also above the acceptable limit of 0.40 (Field, 2009). The barriers ‘air quality’ and ‘lack of testing nodes in LCO practices’ were dropped from further analysis because of low loading as per the acceptable level 0.60 (Hair et al., 2010).

**Table 3:** EFA analysis results

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Barriers** | **Sub-barriers (Code)** | **Loading** | **Commonalities** | **Cronbach α** |
| **Economic****(EB)**  | Cost effectiveness (EB1) | 0.883 | 0.807 | 0.929 |
| High set up cost (EB2) | 0.856 | 0.789 |
| Supporting finance (EB3)  | 0.854 | 0.756 |
| Lack of motivation for low carbon focused procurement (EB4) | 0.797 | 0.678 |
| Low credit rating (EB5) | 0.793 | 0.758 |
| Less mobilized private fund for LCO related activities (EB6) | 0.752 | 0.738 |
| **Market** **(MB)** | Lack of low carbon competitiveness (MB1) | 0.825 | 0.695 | 0.862 |
| Commercialization (MB2) | 0.809 | 0.655 |
| Lack of awareness (MB3) | 0.793 | 0.625 |
| Lack of market gain (MB4) | 0.739 | 0.680 |
| Information asymmetry (MB5)  | 0.729 | 0.715 |
| **Environmental/resources****(EnB)** | Environmental regulations (EnB1)  | 0.935 | 0.504 | 0.899 |
| Lack of renewable energy options (EnB2) | 0.933 | 0.891 |
| Resources unavailability (EnB3) | 0.891 | 0.900 |
| Issues related to energy transition from fossil fuels (EnB4) | 0.622 | 0.838 |
| **Policy/****regulatory** **(PB)**  | Lack of political commitment (PB1) | 0.810 | 0.723 | 0.750 |
| Lack of resources to electrify renewable energy (PB2) | 0.786 | 0.708 |
| Lack of proper policy mechanism (PB3) | 0.767 | 0.696 |
| Lack of specific carbon law (PB4) | 0.738 | 0.724 |
| **Infrastructure****(IB)** | Lack of low carbon supply chain management (IB1) |  0.833 | 0.652 | 0.796 |
| Slow vehicle electrification (IB2) | 0.787 | 0.551 |
| Lack of capacity building and green training (IB3) | 0.719 | 0.687 |
| Scarcity of energy sources (IB4) | 0.611 | 0.726 |
| **Operational****(OB)**  | Lack of low carbon technology (OB1) | 0.918 | 0.889 | 0.944 |
| Lack of operational efficiency (OB2)  | 0.918 | 0.833 |
| Lack of potential vendors (OB3) | 0.900 | 0.826 |
| Carbon risk assessment (OB4) | 0.896 | 0.865 |
| **Organizational Governance****(OGB)** | Lack of top management commitment (OGB1) | 0.856 | 0.819 | 0.860 |
| Lack of carbon governance (OGB2) | 0.836 | 0.791 |
| Lack of performance assessment (OGB3) | 0.836 | 0.819 |
| Lack of green motivation (OGB4) | 0.753 | 0.652 |

* 1. ***Priority ranks of barriers using BWM***

Prof. Rezaei developed BWM in 2015 (Rezaei, 2015) to solve decision-making problems. BWM is based upon pairwise comparisons of the selected best/worst barrier to the other barriers (Rezaei et al., 2016). Compared to other MCDM methods, BWM is more consistent and provides more reliable results (Govindan et al., 2020). Below are the following steps in BWM:

**Step 1:** The barriers need to be recognized through critical review of literature and expert inputs. For this step, data was collected from a decision-making team of fifteen experts. These experts have a minimum of ten years’ work experience in production planning, control and related domains. The authors made arrangements for personal interaction with experts and explained the objectives of the study. Details of the team of expertsrelated to their education, experience and responsibilities are considered during data collection.

**Step 2:** A questionnaire was designed (as shown in Appendix A) based on a 1-9 scale. The result of best-to-others preference is given as follows:

, (1)

where corresponds the significance of the best barrier *B* (high effect) over barrier *j*.

Similarly,thepreference of each of the other barriers over the worst barrier (least effect), using 1 for the worst barrier (less effect) and 9 for the most significant is defined. The others-to-worst preference is given as follows:

, (2)

where corresponds the significance of the barrier *j* over the worst barrier *W*.

Furthermore, the experts were asked to give their assessment for each barrier compared with the barriers that they thought were the most and least important. Results are shown in Table 4 -Table 5.

Table 4: Best to other barriers to adoption of LCO

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Experts** | **Best** | **E** | **M** | **En** | **P** | **I** | **O** | **OG** |
| DM1 | E | 1 | 6 | 9 | 5 | 2 | 3 | 4 |
| DM2 | P | 3 | 2 | 5 | 1 | 4 | 6 | 8 |
| DM3 | O | 2 | 5 | 6 | 4 | 6 | 1 | 3 |
| DM4 | P | 4 | 7 | 6 | 1 | 3 | 2 | 5 |
| DM5 | OG | 8 | 3 | 4 | 6 | 2 | 5 | 1 |
| DM6 | P | 5 | 9 | 3 | 1 | 6 | 2 | 4 |
| DM7 | M | 6 | 1 | 2 | 5 | 3 | 9 | 4 |
| DM8 | E | 1 | 5 | 8 | 6 | 2 | 4 | 3 |
| DM9 | I | 3 | 5 | 2 | 6 | 1 | 4 | 7 |
| DM10 | I | 2 | 4 | 6 | 3 | 1 | 6 | 5 |
| DM11 | O | 8 | 2 | 5 | 3 | 4 | 1 | 6 |
| DM12 | E | 1 | 9 | 4 | 3 | 5 | 2 | 6 |
| DM13 | OG | 5 | 8 | 3 | 6 | 2 | 4 | 1 |
| DM14 | OG | 6 | 2 | 5 | 3 | 8 | 4 | 1 |
| DM15 | I | 4 | 2 | 7 | 5 | 1 | 3 | 6 |

Table 5: Worst to other barriers to adoption of LCO

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Experts** | **Worst** | **E** | **M** | **En** | **P** | **I** | **O** | **OG** |
| DM1 | O | 7 | 6 | 2 | 5 | 3 | 4 | 1 |
| DM2 | En | 5 | 3 | 1 | 6 | 2 | 7 | 4 |
| DM3 | P | 2 | 4 | 7 | 1 | 6 | 4 | 3 |
| DM4 | En | 3 | 5 | 1 | 4 | 7 | 2 | 6 |
| DM5 | M | 4 | 1 | 6 | 3 | 5 | 2 | 7 |
| DM6 | I | 6 | 2 | 4 | 7 | 1 | 3 | 5 |
| DM7 | E | 1 | 7 | 3 | 6 | 2 | 4 | 5 |
| DM8 | En | 4 | 2 | 1 | 7 | 3 | 5 | 6 |
| DM9 | O | 5 | 7 | 3 | 2 | 4 | 6 | 1 |
| DM10 | O | 4 | 7 | 6 | 2 | 5 | 3 | 1 |
| DM11 | P | 7 | 4 | 2 | 1 | 6 | 3 | 5 |
| DM12 | O | 3 | 6 | 2 | 5 | 7 | 4 | 1 |
| DM13 | O | 7 | 3 | 5 | 2 | 4 | 1 | 6 |
| DM14 | I | 7 | 2 | 5 | 3 | 1 | 6 | 4 |
| DM15 | O | 6 | 2 | 5 | 4 | 3 | 1 | 7 |

**Step 3:** Calculate the weight of each barrier. Based on the study of Rezaei (2015), to determine the optimal weights of the barrier, the maximum absolute differences, for all *j* should be minimized. The problem statement is written as:

, (3)

The linear programming formulation can be used to solve this problem:

Min ξ

Subjected to

 (4)

The Eq.4 must have a unique type of solution.

The optimal weights are noted after solving the above linear programming problem. The following formula is used to measure the consistency of the responses:

(5)

Appendix B1 illustrates information about the consistency index. From this, it can be inferred that the lower the ‘consistency ratio’, the higher the reliability of the comparisons (Rezaei et al., 2016).

Using Eq. (5), the consistency of each expert matrix is checked; all values are close to zero. The consistency ratio and ξ\*values for all fifteen experts are shown in Appendix B2 of Appendix B. After using all steps of the BWM method, the weight of each barrier is calculated for each expert’s matrix. In the final step, the average weight is calculated for all the experts’ matrices. The final weights and ranks are shown in Table 6. The same step is followed to collect the weights of the sub-barriers. Table 6 shows the weight, local rank as per weight, final weight, based on the calculation of each sub-barrier, with its main barrier weight; the global rank is given accordingly.

**Table 6**: Final rank of barriers to LCO adoption

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Barriers**  | **Relative weight/****(Rank)** | **Sub-barriers** | **Relative weight** | **Local rank** | **Global****weight** | **Global rank** |
| **EB** | 0.249/(1) | EB1 | 0.310 | 1 | 0.077 | 2 |
| EB2 | 0.180 | 3 | 0.044 | 7 |
| EB3 | 0.090 | 5 | 0.022 | 21 |
| EB4 | 0.080 | 6 | 0.019 | 26 |
| EB5 | 0.120 | 4 | 0.029 | 15 |
| EB6 | 0.220 | 2 | 0.054 | 5 |
| **MB** | 0.123/(5) | MB1 | 0.240 | 2 | 0.029 | 15 |
| MB2 | 0.280 | 1 | 0.034 | 11 |
| MB3 | 0.090 | 4 | 0.011 | 30 |
| MB4 | 0.150 | 3 | 0.018 | 27 |
| MB5 | 0.240 | 2 | 0.029 | 15 |
| **EnB** | 0.089/(7) | EnB1 | 0.280 | 2 | 0.024 | 20 |
| EnB2 | 0.200 | 3 | 0.017 | 28 |
| EnB3 | 0.380 | 1 | 0.033 | 12 |
| EnB4 | 0.130 | 4 | 0.011 | 30 |
| **PB**  | 0.133/(4) | PB1 | 0.270 | 2 | 0.035 | 10 |
| PB2 | 0.170 | 3 | 0.022 | 21 |
| PB3 | 0.390 | 1 | 0.051 | 6 |
| PB4 | 0.170 | 3 | 0.022 | 21 |
| **IB** | 0.159/(2) | IB1 | 0.380 | 1 | 0.060 | 3 |
| IB2 | 0.160 | 4 | 0.025 | 19 |
| IB3 | 0.270 | 2 | 0.042 | 8 |
| IB4 | 0.190 | 3 | 0.030 | 14 |
| **OB** | 0.153/(3) | OB1 | 0.380 | 1 | 0.058 | 4 |
| OB2 | 0.220 | 3 | 0.033 | 12 |
| OB3 | 0.150 | 4 | 0.022 | 21 |
| OB4 | 0.250 | 2 | 0.038 | 9 |
| **OGB** | 0.094/(6) | OGB1 | 0.340 | 1 | 0.094 | 1 |
| OGB2 | 0.150 | 4 | 0.014 | 29 |
| OGB3 | 0.290 | 2 | 0.027 | 18 |
| OGB4 | 0.220 | 3 | 0.020 | 25 |

* 1. ***Determining causal relationships between barriers***

DEMATEL can build a cause-effect structure of attributes (Gabus and Fontela, 1972;). DEMATEL is able to divide all attributes into two groups, cause and effect. This helps the researcher to visualise relationships among attributes and construct cause-effect models (Govindan et al., 2020). The steps involved for conducting DEMATEL along with the analysis of study are explained below.

**Step 1:** The same team of experts were asked to assess the relationships among the barriers () on a scale from 0 to 4 (0 = no influence to 4 = very high influence). The opinions of experts were translated into a direct relation matrix. Next, the average direct relation matrix (A) is formed using Eq. (4) as shown in Table 7.

***A*** = a*ij* *=*  where *p* is number of experts, (4)

**Table 7:** Average matrix for the barriers to LCO

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Barriers** | EB | MB | EnB | PB | IB | OB | OGB |
| EB | 0.000 | 1.428 | 1.642 | 1.428 | 1.357 | 1.392 | 1.607 |
| MB | 1.500 | 0.000 | 1.678 | 1.464 | 1.678 | 1.285 | 1.392 |
| EnB | 1.678 | 1.678 | 0.000 | 1.642 | 1.392 | 1.535 | 1.285 |
| PB | 1.571 | 1.428 | 1.035 | 0.000 | 1.214 | 1.500 | 1.571 |
| IB | 1.500 | 1.535 | 1.500 | 1.500 | 0.000 | 1.535 | 1.535 |
| OB | 1.214 | 1.357 | 1.250 | 1.535 | 1.464 | 0.000 | 1.464 |
| OGB | 1.392 | 1.785 | 1.321 | 1.785 | 1.785 | 1.321 | 0.000 |

**Step 2**: The matrix normalization is obtained applying Eqs. (5 and 6) as shown in Table 8.

 (5)

 (6)

**Table 8:** Normalized initial direct-relation matrix

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Barriers** | EB | MB | EnB | PB | IB | OB | OGB |
| EB | 0.000 | 0.152 | 0.174 | 0.152 | 0.144 | 0.148 | 0.171 |
| MB | 0.159 | 0.000 | 0.178 | 0.155 | 0.178 | 0.136 | 0.148 |
| EnB | 0.178 | 0.178 | 0.000 | 0.174 | 0.148 | 0.163 | 0.136 |
| PB | 0.167 | 0.152 | 0.110 | 0.000 | 0.129 | 0.159 | 0.167 |
| IB | 0.159 | 0.163 | 0.159 | 0.159 | 0.000 | 0.163 | 0.163 |
| OB | 0.129 | 0.144 | 0.133 | 0.163 | 0.155 | 0.000 | 0.155 |
| OGB | 0.148 | 0.190 | 0.140 | 0.190 | 0.190 | 0.140 | 0.000 |

**Step 3**: Compute the total relation matrix (*T*) using Eq. (7):

 (7)

Define as and as , these are obtained from Eqs. (8 and 9) as below:

 (8)  (9)

Where *tij* is total relation matrix, for *i, j* = 1, 2, …., *n*.

The relation matrix is computed in Table 9 with impact result of LCO adoption shown in Table 10.

 **Table 9:** Total relation matrix (*T*) pertaining to the barriers to LCO

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Barriers** | EB | MB | EnB | PB | IB | OB | OGB |
| EB | 2.351 | *2.563* | 2.399 | *2.594* | *2.485* | 2.412 | *2.498* |
| MB | *2.523* | 2.465 | 2.435 | *2.632* | *2.543* | 2.436 | *2.515* |
| EnB | *2.577* | *2.657* | 2.321 | *2.688* | *2.561* | *2.495* | *2.547* |
| PB | 2.364 | 2.428 | 2.226 | 2.327 | 2.412 | *2.476* | *2.3669* |
| IB | *2.542* | *2.626* | 2.439 | *2.656* | 2.412 | *2.476* | *2.5470* |
| OB | 2.329 | 2.415 | 2.236 | 2.460 | 2.355 | 2.150 | 2.350 |
| OGB | *2.599* | *2.713* | *2.488* | *2.747* | *2.6380* | *2.522* | 2.371 |
|  |

**Table 10:** Impact results of LCO adoption

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Barriers** | ***r*** | ***c*** | ***r + c*** | ***r - c*** | **Impact** |
| EB | 17.306 | 17.287 | 34.594 | 0.018 | Cause |
| MB | 17.551 | 17.870 | 35.421 | -0.319 | Effect |
| EnB | 17.848 | 16.547 | 34.396 | 1.300 | Cause |
| PB | 16.351 | 18.107 | 34.459 | -1.756 | Effect |
| IB | 17.701 | 17.338 | 35.040 | 0.363 | Cause |
| OB | 16.297 | 16.787 | 33.085 | -0.490 | Effect |
| OG | 18.180 | 17.297 | 35.478 | 0.883 | Cause |

**Step 4**: Draw the digraph. For this, the threshold value (α) is calculated using Eq. (10),

(10)

where illustrates the number of elements in matrix. All values greater than the threshold value (2.474) were retained and italicized in the matrix *T* in Table 10; the rest of the values were eliminated. The network relationship map (NRM) is conducted e.g., the value of *t12* (2.563) ˃ α (2.474); that shows the strength of the relationship, for instance, economic barrier to market barrier means EB affects MB. This means that EB impacts MB in adopting LCO practices in automotive industry in India. Further to this, for instance, OB is not influencing other barriers as all values are below than threshold value for OB.

Similarly, all the relationships based on threshold value and matrix *T* are constructed as visualised in Fig.2.

**Fig.2** Network relationship map of the main barriers

As per DEMATEL analysis the barriers ‘Economic’ ‘Economic’, ‘Environment’, ‘Infrastructure’ and ‘Organization Governance’ are the cause group barriers (as shown in Table 10). The barriers are ‘Market’, ‘Policy/regulatory’, ‘Operational’ and ‘Organization Governance’, are in effect group, meaning that these barriers are influenced by others. Fig.2 represents the causal relationship among the barriers. The same steps are followed for sub-barriers and the result are presented Table 11, with network maps visualized in Fig.3.

**Table 11:** Impact results of LCO adoption of sub-barriers with each barrier of LCO

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Barriers**  | **Sub-barriers** | ***r + c*** | ***r - c*** | **Impact** |
| EB  | EB1 | 22.804 | -0.870 | Effect |
| EB2 | 22.261 | -1.025 | Effect |
| EB3 | 23.025 | 0.102 | Cause |
| EB4 | 22.874 | -0.424 | Effect |
| EB5 | 22.259 | 0.420 | Cause |
| EB6 | 22.506 | 1.797 | Cause |
| MB | MB1 | 13.542 | -1.059 | Effect |
| MB2 | 13.883 | 0.432 | Cause |
| MB3 | 13.601 | -0.306 | Effect |
| MB4 | 13.934 | -0.965 | Effect |
| MB5 | 15.519 | 0.501 | Cause |
| EnB | EnB1 | 15.722 | -0.511 | Effect |
| EnB2 | 15.297 | 1.713 | Cause |
| EnB3 | 15.015 | -0.514 | Effect |
| EnB4 | 15.722 | -0.511 | Effect |
| PB | PB1 | 17.815 | -1.152 | Effect |
| PB2 | 17.016 | 0.127 | Cause |
| PB3 | 17.962 | 0.146 | Cause |
| PB4 | 17.054 | 0.878 | Cause |
| IB | IB1 | 12.458 | 0.132 | Cause |
| IB2 | 11.265 | -0.515 | Effect |
| IB3 | 10.959 | 1.305 | Cause |
| IB4 | 12.459 | -0.921 | Effect |
| OB | OB1 | 14.068 | 0.639 | Cause |
| OB2 | 13.924 | 1.499 | Cause |
| OB3 | 13.464 | 0.519 | Cause |
| OB4 | 14.214 | -0.340 | Effect |
| OGB | OGB1 | 16.590 | 0.740 | Cause  |
| OGB2 | 17.530 | -1.155 | Effect |
| OGB3 | 17.662 | 0.151 | Cause |
| OGB4 | 16.908 | 0.264 | Cause |

 **Fig.3** Network relationship digraph of the sub-barriers

**5. Results and findings**

From the BWM analysis, the priority order of these barriers is Economic (EB) – Infrastructure (IB) – Operational (OB) – Policy/regulatory (PB) – Market (MB) – Organizational Governance (OGB) – Environmental/resources (EnB). From DEMATEL analysis, among all the main barriers, Economic, Environmental/resources, Infrastructure and Organizational Governance belong to the cause group. Market, Policy/regulatory and Operational belong to the effect group.

From this analysis, all the priority factors fall under cause group except operational barriers. This may be because ‘operational’ barrier is an internal barrier and effected by many external factors, at the same time highly important for the entire process system.

The analysis shows that ‘economic’ barrier with weight score of 24.9% is the main cause barrier followed by infrastructure. Policy/regulatory is one of the main priority barriers but it is an effect group barrier. It is because of inadequate administrative capacities to facilitate coordinated efforts towards government’s initiatives to achieve low carbon emission targets. For instance, initiatives such as ‘Demonetization’, ‘Make in India’ were highly promising but not very successful and even created uncertainty among all types of businesses and investors. India is an emerging economy; therefore, strong steps are required to implement low carbon initiatives which can impact policy positively.

Each category of barrier has its respective sub-barriers, which have also been prioritised based on their priority weights. The cause-effect relationship models among barriers have also been constructed. The results obtained are described more fully in the following sub-sections.

***5.1 Economic barrier category***

Economic barrier category ranks first and belongs to the cause group barrier. The result indicates that it is the main obstacle in adoption of LCO in the Indian automobile industry and the most influential barrier to others. There are six sub-barriers under this category; their priority ranking is given as cost effectiveness (EB1) - less mobilized private fund for LCO related activities (EB6) - high set up cost (EB2) - low credit rating (EB5) - lack of supporting finance (EB3) - Lack of motivation for low carbon focused procurement (EB4). The sub-barriers EB3, EB5 and EB6 belong to the cause group; EB1, EB2 and EB4 are in the effect group. Among all cause group sub-barriers, less mobilized private fund for LCO related activities (EB6) has the highest (r-c) value of 1.79, signifying that it has the greatest influence on the other sub-barriers. Among all sub-barriers, the most weighted is cost effectiveness followed by lack of investment with scores of 31 and 22 respectively.

***5.2 Infrastructure barrier category***

Infrastructure barrier category is prioritized next among all barriers with relative weight of 15.9. This entails four specific sub-barriers; their priority ranking is: lack of low carbon supply chain management (IB1) - lack of capacity building and green training (IB3) - scarcity of energy sources (IB4) - slow vehicle electrification (IB2) with weight scores of 38, 27, 19 and 16 respectively. Among all sub-barriers, IB1 and IB3 fit to the cause group; IB2 and IB4 fit to the effect group. The cause group barrier ‘lack of capacity building and green training’ has the highest influence score of 1.305; this signifies that capacity building and green training is the main influencing barrier in this category, followed by lack of low carbon supply chain management with a score of 0.132.

***5.3 Operational barrier category***

Operational barrier category is the third most important priority rank with a weight score of 15.3. This category has four sub-barriers. The rank in importance of these barriers is: lack of low carbon technology (OB1) - carbon risk assessment (OB4) - lack of operational efficiency (OB2) - lack of potential vendor (OB3) with weight scores of 38, 25, 22 and 15 respectively. The barriers lack of low carbon technology (OB1), lack of operational efficiency (OB2) and lack of potential vendor (OB3) belong to the cause group; carbon risk assessment (OB4) is in the effect group.

***5.4 Policy/regulatory barrier category***

‘Policy/regulatory’ barrier category has the fourth ranking among all the main categories of in barriers. This main barrier category contains four sub-barriers. In terms of priority, these are lack of proper policy mechanism (PB3) - lack of political commitment (PB1) - lack of resources to electrify renewable energy (PB2) and lack of specific law (PB4) with weight score of 39, 27, and 17. The barriers PB2, PB3 and PB4 fit to the cause group while PB1 is in the effect group. Among all cause group sub-barriers, lack of specific law (PB4) has the maximum highest (r-c) value of 0.878, meaning that PB4 has utmost effect on the other sub-barriers.

***5.4 Market barrier category***

The fifth ranked barrier category is market barrierwith a weight score of 12.3. This main barrier overarches five specific sub-barriers and priority rank is; commercialization (MB2) - lack of low carbon competitiveness (MB1) and information asymmetry (MB5) - lack of market gain (MB4) - lack of awareness (MB3) with weight score of 28, 24, 15 and 9 respectively. The barriers MB2 and MB5 belong to the cause group with values 0.432 and 0.501 respectively; this signifies that information asymmetry is the most influential barrier to all sub-barriers.

***5.6 Organizational governance barrier category***

The organizational governance barrier category is ranked sixth with a weight score of 9.4. This main barrier category contains four sub-barriers. The sub-barrier lack of top management commitment (OGB1) is ranked first followed by lack of performance assessment (OGB3) with the weight score of 34 and 29 respectively. The sub-barriers lack of green motivation (OGB4) and lack of carbon governance (OGB2) are ranked third and fourth respectively. The barrier lack of top management commitment belongs to the cause group with the highest influence score of 0.740 followed by lack of green motivation with a value of 0.264.

***5.7 Environmental/resources barrier category***

The last ranking is the environmental barrier category with a weight score of 8.9. This main category of barrier contains four sub-specific barriers. Arranged in terms of priority, these are resources unavailability (EnB3) - environment regulations (EnB1) - lack of renewable energy options (EnB2) - issues related to energy transition from fossil fuels (EnB4) with weight score of 38, 28, 20 and 13 respectively. The barrier EnB2 belongs to the cause group, indicating that this barrier has the highest influence of the entire system with a value of 1.713.

1. **Discussion**

Economic ***barrier category*** - The result indicates that it is the main obstacle in adoption of LCO in the Indian automobile industry and the most influential barrier to others. de Sousa Jabbour et al. (2018) also support in their study that economic barrier is the main obstacle in the adoption of LCO and achieving net-zero emissions. Many researchers have reported that ‘economic barriers’ is one of the key challenges in adoption of LCO (Jabbour et al., 2016; Furlan et al., 2017; De Jesus and Mendonça, 2018). According to the research of Fahimnia et al. (2015) and Liu and Song (2017), they suggested tax rebate/subsidy and incentive mechanism are important economic mechanism to attain the low-carbon mission. Furlan et al. (2017) reported that financial support investment can motivate the LCO.

Infrastructure ***barrier category*** - The infrastructure is important to support low carbon practices in an industry in the literature, de Sousa Jabbour et al. (2018) also highlighted the importance of infrastructure in LCO adoption. Huang et al. (2016) also proposed that infrastructure transforming are essential steps in adoption of LCO. Tan et al. (2017) and Emodi et al. (2017) also suggested that the lack of low carbon SCM is among the most weighted sub-barriers as logistics and commercial transportation is among the prime contributors to rising carbon emission. This effect is explained in terms of quantum and volume as transportation vehicles emit more carbon than other sources. Energy inefficiency is another reason for the slow implementation of LCO as the proper energy volumes required to establish the framework for zero carbon vehicles is still not at optimum levels. Seles et al. (2018) suggested that firms react to the climate issues by investing in training, R&D in addition to effective planning of capacity planning through co-operation with other organizations.

Operational ***barrier category*** - The study of Hall et al. (2017) and Shen et al. (2018) suggested that an efficient operational system is of paramount importance for an industry to adopt LCO effectively and achieving net-zero emissions.. Shen et al. (2018) found in their research due to increased industrialisation and greater demands of customers, business organizations may struggle with the issue of operational inefficiency. Therefore, it is very important for automobile companies must support sustainable environment initiatives by using the latest low carbon technology to reach a desired outcome of robust environmentally friendly models to overcome the issue of operational inefficiency. A welcoming approach to embracing more technologically innovative ideas would help implementation of LCO. Companies should also harness the intellectual ideas which often surface during discussions or meetings and take them to the implementation stage to seek solutions to the relevant problems they are faced with. Ball and Lunt (2018) suggested that lean tools and techniques can help industry to reduce waste and improve operational efficiencies in adopting LCO.

Policy/regulatory ***barrier category*** - The research carried out by Micheli and Mantella (2018) reported that the policy/regulatory barrier is one of key concern in in adopting LCO and other researchers like Luthra et al. (2016); Micheli and Mantella (2018) are also supported our finding. However, Black et al. (2015) showed that policy is a causal factor, which is in contrast to findings of our study. The reason was as they used secondary data in their study and so the consistency of results depends on how much old the data used by them. India is an emerging economy and most business decisions are affected by political influence in the country. Therefore, it is necessary that government and regulatory authorities must implement carbon control policies and specific regulations to motivate the industry to implement LCO in their organizations. Bush et al. (2017) suggested that political stability is very much required not only to motivate the industry to implement LCO but also to develop strong policy mechanisms to achieve zero carbon neutrality. While, Luthra et al. (2016) proposed that the weak policy mechanism and lack of political commitment towards making a sustainable development are the most influential political barriers, it has been observed that the enthusiasm of the policy makers is weak with a lack of strong motivation.

Market barrier ***category*** – The Indian automobile industry is facing tough competition in the market at both international and domestic levels, as per literature this finding has been supported by Rehmatulla and Smith (2015). The industry manufactures products while considering customer needs and demands. Therefore, the involvement of stakeholders in a value chain is not only of paramount importance for business sustainability but it is necessary to adopt LCO given current environmental awareness in society. Jabbour et al. (2015) suggested that the involvement of all stakeholders will help business organizations to take strategic decision such as to switch to renewable sources and invest in the development of LCO. In another study, Luthra and Mangla, (2018) stated that information asymmetry plays a vital role in achieving a specific goal. Information asymmetry involves how the industry spreads information regarding any green initiative so that all stakeholders know their roles and responsibilities. Gouldson et al. (2013) and Long et al. (2016) stated that stakeholders’ awareness and their active participation play an important role in pushing industries to adopt LCO. To make gains in the market, management should encourage private investors and provide asymmetry information about green initiatives that are planned. In this way they are able to not only increase the brand reputation of the organization, but also to maximum their profit. Thus, information asymmetry plays a vital role in achieving a specific goal.

Organizational governance ***barrier category*** - Liu et al. (2018) proposed that it is very important to have not only management commitment but also dedicated organisational governance to achieve low carbon emissions, which also supported by Hsu et al. (2013), while Seles et al. (2018) suggested that organizations with better governance support voluntarily disclosing their actions regarding the mitigation of GHGs in promoting LCO. Meyer and Xin (2017) supported in their research that top management commitment is necessary to develop a sustainable business environment management should also welcome intellectual ideas from both within the organisation and outside the organisation to promote their green initiative plans. Hsu et al. (2013) suggested that company management may encounter challenges when adopting LCO because of lack of awareness of the work force. Motivational steps should be taken. For instance, IBM invited presentations from employees on energy and environment practice at work. This signifies that management commitment towards the environment and society is most important for adoption of any green initiative like LCO.

***Environmental/resources barrier category -*** The business organizations’ employee find difficult to adopt LCO due to non-awareness of new environmental regulations. Thus, awareness about new environment regulations is also very important among employees to effectively adopt LCO, as also supported by Furlan Matos Alves et al. (2017). Thus, managers should consider issues emanating from the environmental regulations. This suggests that a lack of renewable energy options is acting as a major hurdle in constraining the implementation of LCO. For example, to reduce fossil fuel use, more available renewable energy options would help. In line with this, industry could achieve zero carbon missions through effective adoption of renewable sources (Tan et al., 2017; Callaway et al., 2018). It often happens that firms want to adopt green ideas but a lack of resources prevents them from doing so.

The findings of this research are further compared with the previous works (see Table 12).

**Table 12:** Comparison of findings with the previous works

|  |  |  |
| --- | --- | --- |
| **Barrier category** | **Results in agreement with** | **Results in contrast with** |
| Economic  | de Sousa Jabbour et al. (2018); Gaur et al. (2021) | - |
| Infrastructure | de Sousa Jabbour et al. (2018); Gaur et al. (2021) | - |
| Operational | Shen et al. (2018); de Sousa Jabbour et al. (2020) | - |
| Policy/regulatory | Luthra et al. (2016); de Sousa Jabbour et al. (2018); Micheli and Mantella (2018); Gaur et al. (2021) | Black et al. (2015) |
| Market | Rehmatulla and Smith (2015); de Sousa Jabbour et al. (2018); de Sousa Jabbour et al. (2021) | - |
| Organizational governance | Hsu et al. (2013); de Sousa Jabbour et al. (2018); Kannan et al. (2022) | - |
| Environmental/resources | Furlan Matos Alves et al. (2017); de Sousa Jabbour et al. (2020) | - |

**7. Implications for managers and policymakers**

In this study, we empirically identified and investigated the barriers to adopting LCO. Moreover, we further determined the relative weights and cause-effect relationship of barriers and their respective sub-barriers. The study finding makes significant contributions in both theoretical and practical perspectives for adopting LCO initiatives and provides fruitful insights for managers and policy-makers.

*7.1 Implications and theoretical contributions*

The contributions of this research are threefold. First, the study attempts to identify the barriers and their respective sub-barriers empirically in the context of the automobile sector, which concentrates on adopting a zero-carbon emission paradigm, and which has started thinking about relevant environmentally friendly initiatives to reduce carbon pollution (Luthra et al., 2018; Praveena and Aris, 2021).

Second, the unique and the topmost theoretical contribution is to provide the clear picture of best (strongest) and worst (weakest) and cause-effect interrelationship among the LCO oriented barriers and their respective categories. The best and worst category of the barriers helps the managers to know their priority rank and/or relative importance (using BWM) which further help them to focus accordingly to overcome these barriers (Shen et al., 2017) and improve operational carbon efficiency in their company. The DEMATEL approach provides fruitful insights for the managers to understanding the cause-effect interrelationship among the barriers (Shieh et al., 2010). Managers needs to give higher attention to causal group barriers to stabilise effect group barriers for adopting LCO practices successfully.

*7.2 Implications and practical contributions*

The external factors (e.g. energy transition, stakeholder pressure, economic pressure etc.) are forcing the industry to adopt a zero-carbon emission paradigm. Because of this pressure and their commitment towards environment and society, all types of industries have started thinking about relevant environmentally friendly initiatives to reduce carbon pollution. The outcomes of this study give a clear picture about barriers of adoption of LCO and provides suggestions and recommendations to adopt LCO in an industrial context.

* Government is a key stakeholder in managing carbon emission related issues. Thus, in case of an emerging economy like India, government should motivate automotive industry managers to reduce environmental pollution and attain a low carbon goal (Singh et al., 2022). The Indian automobile industry is lacking in emission free practices due to lack of infrastructure; therefore, management should think about the development of infrastructure for the adoption of LCO. The Indian government should take steps to establish appropriate supportive polices in this regard and should invite private investors to try to create better infrastructure.
* From an organisational context, managers may also explore some novel initiatives for LCO adoption. Initiatives like credit mechanism, venture capital, finance mechanism etc. may encourage successful adoption of LCO to enhance zero carbon emission practices. Stakeholders’ awareness and their active participation play an important role in pushing industries in the automobile sector to adopt LCO. Thus, management should encourage and involve different stakeholders (external as well as internal) to not only decrease their greenhouse emissions, but also to increase their organizational brand image. These may also include awareness programs for stakeholders as well as support for local innovation ideas.
* For implementing LCO successfully, the industry should create long-term policies. They should adopt certification from various standards such as ISO 14064 and PAS 2050 and implement carbon-auditing processes (McKinnon, 2010). This would encourage engagement with businesses to reduce carbon emissions and natural resource energy consumptions (Vimal et al. (2022). Managers should seek to reduce fossil fuel use in automotive sector, more available renewable energy options can help to achieve this. An effective use of renewable energy can assist automotive industry to adopt LCO.
* The automobile industry in India is lacking in emission-free practices due to lack of infrastructure, facilities etc. Therefore, management should think about the development of infrastructure and facilities for successful adoption of LCO in Indian automotive context. In line with this, automobile companies must support sustainable environment initiatives (green, circular economy, lean, sustainability) by using the latest low carbon technology to reach a desired outcome of robust environmentally friendly models Vimal et al. (2022). In doing so, it helps to promote uses of low carbon technology while making the operational system more efficient and flexible. Technological advancements and big data management facilitate automotive managers in lowering carbon emissions and building a sustainable society (El-Kassar and Singh, 2018).
* The automobile industry in India is facing tough competition in the market at both international and domestic levels. Developing skills among the workforce is important to promote green initiative plans in business. Initially, company management may encounter challenges when adopting LCO because of lack of awareness of the workforce. In this sense, management may initiate training and development programs among employees. In addition, among employee, awareness about new environment regulations is also very important.

**8. Conclusions**

Low carbon management has become one of the topical areas of discussion for the academic community. Scholars and practitioners across the globe have accepted the need for zero carbon emission or carbon neutrality implementation at both macro and micro levels. In this study, an attempt is made to evaluate the barriers to LCO in developing economies like India by examining the automobile industry.

de Sousa Jabbour et al. (2019) posed a research question ‘*What are the barriers that could inhibit companies’ adoption of low carbon operation management practices?’* They concluded that an empirical investigation is required so that companies are able to overcome these barriers and are able to adopt LCO effectively. This paper is an attempt to develop studies in this direction and to provide unique contributions in the context of both theoretical and methodological viewpoints.

This research applies BWM and DEMATEL methods to establish the priority and reveal the causal relationships of barriers. The priority rank of identified categories of barriers is given as economic barriers – infrastructure barriers – operational barriers – political barriers – market barriers – organizational governance barriers – environmental barriers. Further in this analysis, the barriers economic, environmental, infrastructure and organisational governance belong to the cause group; market, political and operational barriers fall into the effect group.

From findings, the economic is the main obstacle in adoption of LCO in the Indian automobile industry and the most influential barrier to others followed by Infrastructure. Therefore, it is an indication that the industry needs support from the Indian Government in term of tax rebate/subsidy and incentive to attain the low-carbon goal and build the infrastructure to support low carbon practices. No doubt the specific law is required to motivate the industry to implement LCO in their organizations but the political stability is very much required not only to motivate the industry to implement LCO but also to develop strong policy mechanisms to achieve zero carbon neutrality. A welcoming approach of automobile companies would support sustainable environment initiatives by using the latest low carbon technology to reach a desired outcome of robust environmentally friendly models to overcome the issue of operational inefficiency.

It is true that the industry manufactures products while considering customer needs and demands but the involvement of stakeholders in a value chain is not only of paramount importance for business sustainability but it is necessary to adopt LCO given current environmental awareness in society. It is very important to have not only management commitment but also dedicated organisational governance to achieve low carbon emissions that top management commitment is necessary to develop a sustainable business environment, but management should also welcome intellectual ideas from both within the organisation and outside the organisation to promote their green initiative plans. Awareness about new environment regulations is also very important among employees to effectively adopt LCO. The study also suggests that a lack of renewable energy options is a major hurdle in implementing LCO.

This research offers several directions for further research. The listing of barriers was done through literature and experts’ feedback. There could be some more categories of barriers and its respective barriers to LCO, but we restricted the literature-based barrier list to most applicable to Indian automotive sector. Some barriers may become outdated with time, and some new challenges may emerge with time and advancements in technology. This study is limited to the automobile industry; the study context may be extended to other industrial sectors in future. In future, research studies can be conducted in the context of managing carbon emissions in a circular economy. Further research may be conducted to measure the internal capabilities of an organisation in the adoption of LCO and its impact on organisational performance.

**Acknowledgement**

The authors would like to express our thanks to Dr Stephen Childe for his helpful comments on this paper.

**References**

Ahlborg, H., & Hammar, L. (2014). Drivers and barriers to rural electrification in Tanzania and Mozambique–Grid-extension, off-grid, and renewable energy technologies. *Renewable Energy*, 61, 117-124.

Arent, D. J., Green, P., Abdullah, Z., Barnes, T., Bauer, S., Bernstein, A., ... & Turchi, C. (2022). Challenges and opportunities in decarbonizing the US energy system. *Renewable and Sustainable Energy Reviews*, *169*, 112939.

Babatunde, S. O., & Perera, S. (2017). Barriers to bond financing for public-private partnership infrastructure projects in emerging markets: A case of Nigeria. *Journal of Financial Management of Property and Construction*, 22(1), 2-19.

Bai, C., Sarkis, J., & Dou, Y. (2017). Constructing a process model for low-carbon supply chain cooperation practices based on the DEMATEL and the NK model. *Supply Chain Management: An International Journal*, 22(3), 237-257.

Ball, P., & Lunt, P. (2020). Lean eco-efficient innovation in operations through the maintenance organisation. *International journal of production economics*, *219*, 405-415.

Black, G., Black, M. A. T., Solan, D., & Shropshire, D. (2015). Carbon free energy development and the role of small modular reactors: a review and decision framework for deployment in developing countries. *Renewable and Sustainable Energy Reviews*, *43*, 83-94.

Böttcher, C. F., & Müller, M. (2015). Drivers, Practices and Outcomes of Low‐carbon Operations: Approaches of German Automotive Suppliers to Cutting Carbon Emissions. *Business Strategy and the Environment*, *24*(6), 477-498.

Bryman, A (1988). Quantity and Quality in Social Research, London, Routledge

Bryman, A., & Bell, E. (2015). *Business Research Methods*. Oxford University Press, USA.

Bush, R. E., Bale, C. S., Powell, M., Gouldson, A., Taylor, P. G., & Gale, W. F. (2017). The role of intermediaries in low carbon transitions–Empowering innovations to unlock district heating in the UK. *Journal of Cleaner Production*, *148*, 137-147.

Callaway, D. S., Fowlie, M., & McCormick, G. (2018). Location, location, location: The variable value of renewable energy and demand-side efficiency resources. *Journal of the Association of Environmental and Resource Economists*, 5(1), 39-75.

Carbon Trust (2006), Carbon footprints in the supply chain: The next step for business: available at <https://www.carbontrust.com/resources/reports/footprinting/carbon-footprints-in-the-supply-chain-the-next-step-for-business> / (assessed 08-03-2019)

Centobelli, P., Cerchione, R., & Esposito, E. (2017). Developing the WH2 framework for environmental sustainability in logistics service providers: A taxonomy of green initiatives. *Journal of Cleaner Production*, 165, 1063-1077.

Chang, X., Xia, H., Zhu, H., Fan, T., & Zhao, H. (2015). Production decisions in a hybrid manufacturing–remanufacturing system with carbon cap and trade mechanism. *International Journal of Production Economics*, 162, 160-173.

Chapungu, L., Nhamo, G., Chikodzi, D., & Maoela, M. A. (2022). BRICS and the Race to Net-Zero Emissions by 2050: Is COVID-19 a Barrier or an Opportunity?. *Journal of Open Innovation: Technology, Market, and Complexity*, *8*(4), 172.

Chen, D., Ignatius, J., Sun, D., Goh, M., & Zhan, S. (2020). Pricing and equity in cross-regional green supply chains. *European Journal of Operational Research*, 280(3), 970-987.

De Jesus, A., & Mendonça, S. (2018). Lost in Transition? Drivers and Barriers in the Eco-innovation Road to the Circular Economy. *Ecological Economics*, 145, 75-89.

de Sousa Jabbour, A. B. L., Chiappetta Jabbour, C. J., Sarkis, J., Gunasekaran, A., Furlan Matos Alves, M. W., & Ribeiro, D. A. (2019). Decarbonisation of operations management–looking back, moving forward: a review and implications for the production research community. *International Journal of Production Research*, 57(15-16), 4743-4765.

de Sousa Jabbour, A. B. L., Chiappetta Jabbour, C. J., Sarkis, J., Latan, H., Roubaud, D., Godinho Filho, M., & Queiroz, M. (2021). Fostering low-carbon production and logistics systems: framework and empirical evidence. *International Journal of Production Research*, *59*(23), 7106-7125.

de Sousa Jabbour, A. B. L., Vazquez‐Brust, D., Chiappetta Jabbour, C. J., & Andriani Ribeiro, D. (2020). The interplay between stakeholders, resources and capabilities in climate change strategy: converting barriers into cooperation. *Business Strategy and the Environment*, *29*(3), 1362-1386.

De Wolf, C., Pomponi, F., & Moncaster, A. (2017). Measuring embodied carbon dioxide equivalent of buildings: A review and critique of current industry practice. *Energy and Buildings*, 140, 68-80.

Dissanayake, S., Mahadevan, R., & Asafu-Adjaye, J. (2020). Evaluating the efficiency of carbon emissions policies in a large emitting developing country. *Energy Policy*, 136, 111080.

Dong, F., Yu, B., Hadachin, T., Dai, Y., Wang, Y., Zhang, S., & Long, R. (2018). Drivers of carbon emission intensity change in China. *Resources, Conservation and Recycling*, *129*, 187-201.

Dwivedi, Y. K., Hughes, L., Kar, A. K., Baabdullah, A. M., Grover, P., Abbas, R., ... & Wade, M. (2022). Climate change and COP26: Are digital technologies and information management part of the problem or the solution? An editorial reflection and call to action. *International Journal of Information Management*, *63*, 102456.

El-Kassar, A. N., & Singh, S. K. (2018). Green innovation and organizational performance: the influence of big data and the moderating role of management commitment and HR practices. *Technological Forecasting and Social Change*, 144, 483-498.

Emodi, N. V., Emodi, C. C., Murthy, G. P., & Emodi, A. S. A. (2017). Energy policy for low carbon development in Nigeria: A LEAP model application. *Renewable and Sustainable Energy Reviews*, *68*, 247-261.

Evans, J., & Karvonen, A. (2014). ‘Give Me a Laboratory and I Will Lower Your Carbon Footprint!’—Urban Laboratories and the Governance of Low‐Carbon Futures. *International Journal of Urban and Regional Research*, 38(2), 413-430.

Fahimnia, B., Sarkis, J., Choudhary, A., & Eshragh, A. (2015). Tactical supply chain planning under a carbon tax policy scheme: A case study. *International Journal of Production Economics*, 164, 206-215.

Field, A. (2009). *Discovering statistics using IBM SPSS statistics*. Sage publications.

Fragkos, P., Tasios, N., Paroussos, L., Capros, P., & Tsani, S. (2017). Energy system impacts and policy implications of the European Intended Nationally Determined Contribution and low-carbon pathway to 2050. *Energy Policy*, *100*, 216-226.

Furlan Matos Alves, M. W., Lopes de Sousa Jabbour, A. B., Kannan, D., & Chiappetta Jabbour, C. J. (2017). Contingency theory, climate change, and low-carbon operations management. *Supply Chain Management: An International Journal*, 22(3), 223-236.

Gaur, A. S., Fitiwi, D. Z. and Curtis, J. (2021). Heat pumps and our low-carbon future: A comprehensive review. *Energy Research & Social Science*, 71, 101764.

Geroe, S. (2022). ‘Technology not taxes’: A viable Australian path to net zero emissions?. *Energy Policy*, *165*, 112945.

Goh, S. H. (2019). Barriers to low-carbon warehousing and the link to carbon abatement. *International Journal of Physical Distribution & Logistics Management*, 49(6); 679-704.

Golub, A., Hertel, T., Lee, H. L., Rose, S., & Sohngen, B. (2009). The opportunity cost of land use and the global potential for greenhouse gas mitigation in agriculture and forestry. *Resource and Energy Economics*, 31(4), 299-319.

Gouldson, A., & Sullivan, R. (2013). Long-term corporate climate change targets: What could they deliver? *Environmental Science & Policy*, 27, 1-10.

Govindan, K., Muduli, K., Devika, K., & Barve, A. (2016). Investigation of the influential strength of factors on adoption of green supply chain management practices: An Indian mining scenario. *Resources, Conservation and Recycling*, *107*, 185-194.

Govindan, K., Shankar, K. M., & Kannan, D. (2020). Achieving sustainable development goals through identifying and analyzing barriers to industrial sharing economy: A framework development. *International Journal of Production Economics*, 227, 107575.

Gray, D., Laing, R., & Docherty, I. (2017). Delivering lower carbon urban transport choices: European ambition meets the reality of institutional (mis) alignment. *Environment and Planning A*, *49*(1), 226-242.

Hair, J. F. Black. WC, Babin, BJ, Anderson RE, (2010) Multivariate data analysis, a global perspective. New Jersey. Pearson. Ed, 7, 816.

Hall, S., Foxon, T. J., & Bolton, R. (2017). Investing in low-carbon transitions: energy finance as an adaptive market. *Climate Policy*, *17*(3), 280-298.

Hall, S., Mazur, C., Hardy, J., Workman, M., & Powell, M. (2020). Prioritising business model innovation: What needs to change in the United Kingdom energy system to grow low carbon entrepreneurship? *Energy Research & Social Science*, 60, 101317.

Harman, H.H., 1976. *Modern Factor Analysis*, third ed. University of Chicago Press, Chicago, IL.

He, J. K. (2016). Global low-carbon transition and China's response strategies. *Advances in Climate Change Research*, 7(4), 204-212.

Hsu, C. W., Kuo, T. C., Chen, S. H., & Hu, A. H. (2013). Using DEMATEL to develop a carbon management model of supplier selection in green supply chain management. *Journal of Cleaner Production*, 56, 164-172.

Huang, B., Jiang, P., Wang, S., Zhao, J., & Wu, L. (2016). Low carbon innovation and practice in Caohejing High-Tech Industrial Park of Shanghai. *International Journal of Production Economics*, 181, 367-373.

Ji, J., Zhang, Z., & Yang, L. (2017). Carbon emission reduction decisions in the retail-/dual-channel supply chain with consumers' preference. *Journal of Cleaner Production*, 141, 852-867.

Kannan, D., Solanki, R., Kaul, A., & Jha, P. C. (2022). Barrier analysis for carbon regulatory environmental policies implementation in manufacturing supply chains to achieve zero carbon. *Journal of Cleaner Production*, *358*, 131910.

Kazançoglu, Y., Ada, E., Ozturkoglu, Y., & Ozbiltekin, M. (2020). Analysis of the barriers to urban mining for resource melioration in emerging economies. *Resources Policy*, *68*, 101768.

Kedia, S. (2016). Approaches to low carbon development in China and India. *Advances in Climate Change Research*, 7(4), 213-221.

Kim, J., Seung, H., Lee, J., & Ahn, J. (2020). Asymmetric preference and loss aversion for electric vehicles: The reference-dependent choice model capturing different preference directions. *Energy Economics*, 104666.

Kothari, C. R. (2004). *Research methodology: Methods and techniques*. New Age International.

Kumar, R., & Padmanaban, S. (2019). Electric vehicles for India: overview and challenges. *IEEE India Informatics*, *14*, 139.

Lee, C. T., Hashim, H., Ho, C. S., Van Fan, Y., & Klemeš, J. J. (2017). Sustaining the low-carbon emission development in Asia and beyond: Sustainable energy, water, transportation and low-carbon emission technology. *Journal of Cleaner Production*, *146*, 1-13.

Li, Y., Lim, M. K., Hu, J., & Tseng, M. L. (2020). Investigating the effect of carbon tax and carbon quota policy to achieve low carbon logistics operations. *Resources, Conservation and Recycling*, 154, 104535.

Li, Z., Meng, N., & Yao, X. (2017). Sustainability performance for China's transportation industry under the environmental regulation. *Journal of Cleaner Production*, *142*, 688-696.

Liu, J., Zhou, Y., Yang, H., & Wu, H. (2022). Net-zero energy management and optimization of commercial building sectors with hybrid renewable energy systems integrated with energy storage of pumped hydro and hydrogen taxis. *Applied Energy*, *321*, 119312.

Liu, K., & Song, H. (2017). Contract and incentive mechanism in low-carbon R&D cooperation. *Supply Chain Management: An International Journal*, 22(3), 270-283.

Liu, T., Wang, Y., Song, Q., & Qi, Y. (2018). Low-carbon governance in China–Case study of low carbon industry park pilot. *Journal of Cleaner Production*, *174*, 837-846.

Liu, X., Yu, X., & Gao, S. (2019). A quantitative study of financing efficiency of low‐carbon companies: A three‐stage data envelopment analysis. *Business Strategy and the Environment*, *28*(5), 858-871.

Liu, Y., Yang, D., & Xu, H. (2017). Factors influencing consumer willingness to pay for low‐carbon products: A simulation study in China. *Business Strategy and the Environment*, *26*(7), 972-984.

Long, T. B., Blok, V., & Coninx, I. (2016). Barriers to the adoption and diffusion of technological innovations for climate-smart agriculture in Europe: evidence from the Netherlands, France, Switzerland and Italy. *Journal of Cleaner Production*, 112, 9-21.

Luo, Z., Gunasekaran, A., Dubey, R., Childe, S. J., & Papadopoulos, T. (2017). Antecedents of low carbon emissions supply chains. *International Journal of Climate Change Strategies and Management*, 9(5), 707-727.

Luthra, S., & Mangla, S. K. (2018). Evaluating challenges to Industry 4.0 initiatives for supply chain sustainability in emerging economies. *Process Safety and Environmental Protection*, 117, 168-179.

Luthra, S., Mangla, S. K., Shankar, R., Prakash Garg, C., & Jakhar, S. (2018). Modelling critical success factors for sustainability initiatives in supply chains in Indian context using Grey-DEMATEL. *Production Planning & Control*, 29(9), 705-728.

Luthra, S., Mangla, S. K., Xu, L., & Diabat, A. (2016). Using AHP to evaluate barriers in adopting sustainable consumption and production initiatives in a supply chain. *International Journal of Production Economics*, *181*, 342-349.

Mathivathanan, D., Kannan, D., & Haq, A. N. (2018). Sustainable supply chain management practices in Indian automotive industry: A multi-stakeholder view. *Resources, Conservation and Recycling*, 128, 284-305.

McKinnon, A. C. (2010). Product‐level carbon auditing of supply chains: environmental imperative or wasteful distraction?. *International Journal of Physical Distribution & Logistics Management*, *40*(1/2), 42-60.

McKinsey & Company’s (2009), Pathways to a Low-Carbon Economy available at <https://www.mckinsey.com/~/media/mckinsey/dotcom/client_service/sustainability/cost%20curve%20pdfs/pathways_lowcarbon_economy_version2.ashx> (assessed 19-08-2022)

Meath, C., Linnenluecke, M., & Griffiths, A. (2016). Barriers and motivators to the adoption of energy savings measures for small-and medium-sized enterprises (SMEs): the case of the Climate-Smart Business Cluster program. *Journal of Cleaner Production*, 112, 3597-3604.

Melville, N. P., Saldanha, T. J., & Rush, D. E. (2017). Systems enabling low-carbon operations: the salience of accuracy. *Journal of Cleaner Production*, 166, 1074-1083.

Meyer, K. E., & Xin, K. R. (2017). Managing talent in emerging economy multinationals: Integrating strategic management and human resource management. *The International Journal of Human Resource Management*, 29(11), 1827-1855.

Meyers, S., Schmitt, B., Chester-Jones, M., & Sturm, B. (2016). Energy efficiency, carbon emissions, and measures towards their improvement in the food and beverage sector for six European countries. *Energy*, 104, 266-283.

Micheli, G. J., & Mantella, F. (2018). Modelling an environmentally-extended inventory routing problem with demand uncertainty and a heterogeneous fleet under carbon control policies. *International Journal of Production Economics*, 204, 316-327.

Muduli, K. K., Luthra, S., Kumar Mangla, S., Jabbour, C. J. C., Aich, S., & de Guimarães, J. C. F. (2020). Environmental management and the “soft side” of organisations: Discovering the most relevant behavioural factors in green supply chains. *Business Strategy and the Environment*, *29*(4), 1647-1665.

Mulugetta, Y., & Urban, F. (2010). Deliberating on low carbon development. *Energy Policy*, 38(12), 7546-7549.

Newman, I., & Benz, C. R. (1998). *Qualitative-quantitative research methodology: Exploring the interactive continuum*. SIU Press.

Nizam, H. A., Zaman, K., Khan, K. B., Batool, R., Khurshid, M. A., Shoukry, A. M., ... & Gani, S. (2020). Achieving environmental sustainability through information technology:“Digital Pakistan” initiative for green development. *Environmental Science and Pollution Research*, 27(9), 10011-10026.

Nunnally, J. C. (1978). *Psychometric theory*. New York, NY: McGraw-Hill.

Ohene, E., Chan, A. P., & Darko, A. (2022). Prioritizing barriers and developing mitigation strategies toward net-zero carbon building sector. *Building and Environment*, 109437.

Podsakoff, P. M., MacKenzie, S. B., & Podsakoff, N. P. (2012). Sources of method bias in social science research and recommendations on how to control it. *Annual Review of Psychology,* 63, 539-569.

Podsakoff, P. M., MacKenzie, S. B., Lee, J. Y., & Podsakoff, N. P. (2003). Common method biases in behavioral research: A critical review of the literature and recommended remedies. *Journal of Applied Psychology*, 88(5), 879.

Polzin, F. (2017). Mobilizing private finance for low-carbon innovation–A systematic review of barriers and solutions. *Renewable and Sustainable Energy Reviews*, *77*, 525-535.

Praveena, S. M., & Aris, A. Z. (2021). The impacts of COVID-19 on the environmental sustainability: a perspective from the Southeast Asian region. *Environmental Science and Pollution Research*, 28(45), 63829-63836.

Rahman, S., & Subramanian, N. (2012). Factors for implementing end-of-life computer recycling operations in reverse supply chains. *International Journal of Production Economics*, 140(1), 239-248.

Rehmatulla, N., & Smith, T. (2015). Barriers to energy efficient and low carbon shipping. *Ocean Engineering*, *110*, 102-112.

Rezaei, J. (2015). Best-worst multi-criteria decision-making method. *Omega*, 53, 49-57.

Rezaei, J., Nispeling, T., Sarkis, J., & Tavasszy, L. (2016). A supplier selection life cycle approach integrating traditional and environmental dimension using the best worst method. *Journal of Cleaner Production*, *135*, 577-588.

Rosenbloom, D., Haley, B., & Meadowcroft, J. (2018). Critical choices and the politics of decarbonization pathways: Exploring branching points surrounding low-carbon transitions in Canadian electricity systems. *Energy Research & Social Science*, 37, 22-36.

Saint Akadiri, S., Alola, A. A., Alola, U. V., & Nwambe, C. S. (2020). The role of ecological footprint and the changes in degree days on environmental sustainability in the USA. *Environmental Science and Pollution Research*, *27*(20), 24929-24938.

Seles, B. M. R. P., de Sousa Jabbour, A. B. L., Jabbour, C. J. C., de Camargo Fiorini, P., Mohd-Yusoff, Y., & Thomé, A. M. T. (2018). Business opportunities and challenges as the two sides of the climate change: Corporate responses and potential implications for big data management towards a low carbon society. *Journal of Cleaner Production*, 189, 763-774.

Shayganmehr, M., Kumar, A., Garza-Reyes, J. A., & Moktadir, M. A. (2021). Industry 4.0 enablers for a cleaner production and circular economy within the context of business ethics: A study in a developing country. *Journal of Cleaner Production*, *281*, 125280.

Shen, B., Ding, X., Chen, L., & Chan, H. L. (2017). Low carbon supply chain with energy consumption constraints: Case studies from China’s textile industry and simple analytical model. *Supply Chain Management: An International Journal*, 22(3), 258-269.

Shen, L., Wu, Y., Lou, Y., Zeng, D., Shuai, C., & Song, X. (2018). What drives the carbon emission in the Chinese cities?-A case of pilot low carbon city of Beijing. *Journal of Cleaner Production*, 174, 343-354.

Shieh, J. I., Wu, H. H., & Huang, K. K. (2010). A DEMATEL method in identifying key success factors of hospital service quality. *Knowledge-Based Systems*, *23*(3), 277-282.

Sindhwani, R., Singh, P. L., Behl, A., Afridi, M. S., Sammanit, D., & Tiwari, A. K. (2022). Modeling the critical success factors of implementing net zero emission (NZE) and promoting resilience and social value creation. *Technological Forecasting and Social Change*, *181*, 121759.

Singh, J., Pandey, K. K., Kumar, A., Naz, F., & Luthra, S. (2022). Drivers, barriers and practices of net zero economy: An exploratory knowledge based supply chain multi-stakeholder perspective framework. *Operations Management Research*, 1-32.

Singh, S., Barve, A., Muduli, K., Kumar, A., & Luthra, S. (2022). Evaluating roadblocks to implementing a green freight transportation system: an interval valued intuitionistic fuzzy digraph matrix approach. *IEEE Transactions on Engineering Management* (**DOI:** [10.1109/TEM.2022.3188643](https://doi.org/10.1109/TEM.2022.3188643))

Sonnett, J. (2022). Climate change risks and global warming dangers: a field analysis of online US news media. *Environmental Sociology*, *8*(1), 41-51.

Srivastav, S., Fankhauser, S., & Kazaglis, A. (2018). Low-Carbon Competitiveness in Asia. *Economies*, *6*(1), 2018.

Stefanelli, N. O., Jabbour, C. J. C., Amui, L. B. L., de Oliveira, J. H. C., Latan, H., Paille, P., & Hingley, M. (2021). Unleashing proactive low‐carbon strategies through behavioral factors in biodiversity‐intensive sustainable supply chains: Mixed methodology. *Business Strategy and the Environment*, 30(5), 2535-2555.

Suresh, M. V. J. J., Reddy, K. S., & Kolar, A. K. (2010). 4-E (Energy, Exergy, Environment, and Economic) analysis of solar thermal aided coal-fired power plants. *Energy for Sustainable Development*, 14(4), 267-279.

Tamvada, J. P., Narula, S., Audretsch, D., Puppala, H., & Kumar, A. (2022). Adopting new technology is a distant dream? The risks of implementing industry 4.0 in emerging economy SMEs. *Technological Forecasting and Social Change*, *185*, 122088.

Tan, S., Yang, J., Yan, J., Lee, C., Hashim, H., & Chen, B. (2017). A holistic low carbon city indicator framework for sustainable development. *Applied Energy*, *185*, 1919-1930.

Tang, S., Wang, W., Yan, H., & Hao, G. (2015). Low carbon logistics: Reducing shipment frequency to cut carbon emissions. *International Journal of Production Economics*, 164, 339-350.

Tittle, C. R., & Hill, R. J. (1967). Attitude measurement and prediction of behavior: An evaluation of conditions and measurement techniques. *Sociometry*, 199-213.

Torabi, S. A., Giahi, R., & Sahebjamnia, N. (2016). An enhanced risk assessment framework for business continuity management systems. *Safety Science*, *89*, 201-218.

Tranfield, D., Denyer, D., & Smart, P. (2003). Towards a methodology for developing evidence‐informed management knowledge by means of systematic review. *British Journal of Management*, 14(3), 207-222.

UNEP (United Nations Environment Programme), (2018). Emissions gas report, 2018. <https://www.unenvironment.org/resources/emissions-gap-report-2018>

United Nation Climate change (2018), Global Car Industry Must Shift to Low Carbon to Survive – CDP: available at <https://unfccc.int/news/global-car-industry-must-shift-to-low-carbon-to-survive-cdp> (assessed 08-03-2019)

Vagnoni, E., & Moradi, A. (2018). Local government's contribution to low carbon mobility transitions. *Journal of Cleaner Production*, *176*, 486-502.

van Doren, D., Driessen, P. P., Runhaar, H., & Giezen, M. (2018). Scaling-up low-carbon urban initiatives: Towards a better understanding. *Urban Studies*, *55*(1), 175-194.

Victor-Gallardo, L., Roccard, J., Campos, P., Malley, C. S., Lefevre, E. N., & Quirós-Tortós, J. (2022). Identifying cross-sectoral policy synergies for decarbonization: towards short-lived climate pollutant mitigation action in Costa Rica. *Journal of Cleaner Production*, 134781.

Vimal, K. E. K., Kumar, A., Sunil, S. M., Suresh, G., Sanjeev, N., & Kandasamy, J. (2022). Analysing the challenges in building resilient net zero carbon supply chains using Influential Network Relationship Mapping. *Journal of Cleaner Production*, 134635.

Wang, Q., & Zhang, F. (2020). Does increasing investment in research and development promote economic growth decoupling from carbon emission growth? An empirical analysis of BRICS countries. *Journal of Cleaner Production*, 252, 119853.

Wong, C. W., Lai, K. H., Shang, K. C., Lu, C. S., & Leung, T. K. P. (2012). Green operations and the moderating role of environmental management capability of suppliers on manufacturing firm performance. *International Journal of Production Economics*, 140(1), 283-294.

Xodo, A. (2011). Gaining competitive advantage through a low carbon economy: China vs Europe. *International Journal of Energy Sector Management*, 5(4), 442-446.

Yamashita, A. S., & Fujii, H. (2022). Trend and priority change of climate change mitigation technology in the global mining sector. *Resources Policy*, *78*, 102870.

Zahan, I., & Chuanmin, S. (2021). Towards a green economic policy framework in China: role of green investment in fostering clean energy consumption and environmental sustainability. *Environmental Science and Pollution Research*, 28(32), 43618-43628.

Zhao, L. T., He, L. Y., Cheng, L., Zeng, G. R., & Huang, Z. (2018). The effect of gasoline consumption tax on consumption and carbon emissions during a period of low oil prices. *Journal of Cleaner Production*, *171*, 1429-1436.

Zheng, H., & Ge, L. (2022). Carbon emissions reduction effects of sustainable development policy in resource-based cities from the perspective of resource dependence: Theory and Chinese experience. *Resources Policy*, *78*, 102799.

Zhou, Q., Cui, X., Ni, H., & Gong, L. (2022). The impact of environmental regulation policy on firms' energy-saving behavior: A quasi-natural experiment based on China's low-carbon pilot city policy. *Resources Policy*, *76*, 102538.

Zhu, Q., & Geng, Y. (2013). Drivers and barriers of extended supply chain practices for energy saving and emission reduction among Chinese manufacturers. *Journal of Cleaner Production*, 40, 6-12.

Zimmer, A., Jakob, M., & Steckel, J. C. (2015). What motivates Vietnam to strive for a low-carbon economy?—On the drivers of climate policy in a developing country. *Energy for Sustainable Development*, 24, 19-32.

**Appendix-A**

# Phase 1 - Questionnaire

This research is about evaluating the barriers in adopting LCO practices in Indian automobile industry. We identified the barriers through literature and experts’ inputs. Please respond to confirm the barriers using five-point Likert scale (5 = Strongly Agree to 1 = Strongly Disagree).

 Please tick (√) in appropriate box

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Barriers** | **Strongly Agree****5** | **Agree****4** | **Natural****3** | **Disagree****2** | **Strongly Disagree****1** |
| Cost effectiveness  |  |  |  |  |  |
| High set up cost  |  |  |  |  |  |
| Low credit rating  |  |  |  |  |  |
| Lack of market gain  |  |  |  |  |  |
| Lack of low carbon competitiveness |  |  |  |  |  |
| Commercialization  |  |  |  |  |  |
| Lack of motivation for low carbon focused procurement  |  |  |  |  |  |
| Lack of awareness  |  |  |  |  |  |
| Lack of supporting finance by financial Institutions  |  |  |  |  |  |
| Less mobilized private fund for LCO related activities  |  |  |  |  |  |
| Information asymmetry  |  |  |  |  |  |
| Environmental regulations  |  |  |  |  |  |
| Resources unavailability  |  |  |  |  |  |
| Air quality  |  |  |  |  |  |
| Issues related to energy transition from fossil fuels  |  |  |  |  |  |
| Lack of renewable energy options |  |  |  |  |  |
| Lack of political commitment  |  |  |  |  |  |
| Lack of resources to electrify renewable energy  |  |  |  |  |  |
| Lack of specific laws  |  |  |  |  |  |
| Lack of low carbon supply chain management  |  |  |  |  |  |
| Lack of testing nodes in LCO practices |  |  |  |  |  |
| Lack of proper policy mechanism |  |  |  |  |  |
| Lack of potential vendors |  |  |  |  |  |
| Slow vehicle electrification |  |  |  |  |  |
| Lack of capacity building and green training  |  |  |  |  |  |
| Scarcity of energy sources |  |  |  |  |  |
| Lack of low carbon technology  |  |  |  |  |  |
| Lack of operational efficiency  |  |  |  |  |  |
| Carbon risk assessment  |  |  |  |  |  |
| Lack of carbon governance  |  |  |  |  |  |
| Lack of performance assessment  |  |  |  |  |  |
| Lack of top management commitment  |  |  |  |  |  |
| Lack of green motivation  |  |  |  |  |  |

Phase 2 - Evaluating the barriers using BWM-DEMATEL

***Priority rank of main barriers using BWM***

We attempt to distinguish the priority of barriers in LCO practices in Indian automobile industry. In this sense, please provide themost significantbarrier from the seven barriers as mentioned in table below. For this, it is suggested to use number between1 and 9 for providing their response.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **The Most Important Barrier** | Economic | Market | Environmental/Resources  | Policy/regulatory | Infrastructure | Operational | Organizational Governance |
|  |  |  |  |  |  |  |  |

Next to this, please provide theleast significantbarrier from the seven barriers as mentioned in table below. For this, it is suggested to use number between1 and 9 for providing their response.

|  |  |
| --- | --- |
| **The Least Important Barrier** |  |
| Economic |  |
| Market  |  |
| Environmental/resources  |  |
| Policy/regulatory  |  |
| Infrastructure |  |
| Operational |  |
| Organizational Governance |  |

# Causal relationships among barriers using DEMATEL

We also attempts to define the causal relationships among barriers in LCO adoption. Thus, please provide your response evaluating the causal relationship among the barriers using the following scale: 4 = Very high influence, 3 = High influence, 2 = Low influence, 1 = Very low influence, 0 = No influence.

 Please mark your response in a suitable box

|  |  |
| --- | --- |
|  | **Compare the influence of one barrier over another** |
| *Main barriers**Main barriers* | Economic | Market  | Environmental/resources | Policy/regulatory  | Infrastructure  | Operational | Organizational Governance |
| 4 | 3 | 2 | 1 | 0 | 4 | 3 | 2 | 1 | 0 | 4 | 3 | 2 | 1 | 0 | 4 | 3 | 2 | 1 | 0 | 4 | 3 | 2 | 1 | 0 | 4 | 3 | 2 | 1 | 0 | 4 | 3 | 2 | 1 | 0 |
| Economic | 0 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Market  |  |  |  |  |  | 0 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Environmental/resources |  |  |  |  |  |  |  |  |  |  | 0 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Policy/regulatory  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 0 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Infrastructure |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 0 |  |  |  |  |  |  |  |  |  |  |
| Operational |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 0 |  |  |  |  |  |
| Organizational Governance |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 0 |

**Appendix-B**

**Appendix B1.** Consistency Index (CI)

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| ***aBW*** | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| ***Consistency index (max ξ)*** | 0 | 0.44 | 1 | 1.63 | 2.3 | 3 | 3.73 | 4.47 | 5.32 |

Appendix B2: Consistency ratio and ξ\* for each expert

|  |  |  |  |
| --- | --- | --- | --- |
| **Experts**  | **Abw** | **ξ\*** | **CR** |
| DM1 | 9 | 0.09 | 0.019 |
| DM2 | 8 | 0.08 | 0.029 |
| DM3 | 6 | 0.12 | 0.025 |
| DM4 | 7 | 0.13 | 0.032 |
| DM5 | 8 | 0.10 | 0.048 |
| DM6 | 9 | 0.08 | 0.034 |
| DM7 | 9 | 0.09 | 0.035 |
| DM8 | 8 | 0.11 | 0.023 |
| DM9 | 7 | 0.13 | 0.029 |
| DM10 | 6 | 0.16 | 0.023 |
| DM11 | 8 | 0.12 | 0.036 |
| DM12 | 9 | 0.11 | 0.021 |
| DM13 | 8 | 0.10 | 0.045 |
| DM14 | 8 | 0.15 | 0.046 |
| DM15 | 6 | 0.11 | 0.032 |