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Study and Structural Modeling of Barriers in Green Lean Implementation

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Abstract
Purpose: Green Lean is a new approach that helps organizations improve both their operations and their environmental performance at the same time. Interest in Green Lean has grown quickly in both academic and business communities. However, even though many people are talking about it, very little research has been done on how to put Green Lean into practice, and no studies have looked at the challenges that make it difficult to succeed. This research aims to fill that gap by focusing on two main goals: first, to find out what barriers companies face when trying to implement Green Lean; and second, to create a model that explains how these barriers interact and how they can be overcome. This model will help companies successfully adopt Green Lean practices. The need for Green Lean Manufacturing has grown because of issues like product defects, pollution, and high energy use. Green Lean (GL) is seen as an important strategy for reducing costs, improving efficiency, and supporting sustainability.
Design/methodology/approach: This paper explains how an ISM (Interpretive Structural Model) was developed to find and understand the connections between Lean and Green practices. It also helps in evaluating how Green Lean can be implemented. Using this model, a survey was conducted, and a review of past research on Green and Lean practices was carried out to find the barriers to their implementation.
Findings: Lean management helps improve the environmental performance of production systems. This is especially true when it comes to creating a culture of continuous improvement and reducing waste. Studies show that lean and eco-friendly production systems bring very good results, proving that lean practices do help the environment. However, the results also show that many companies have not properly applied or formalized lean and green practices.
Originality/value: The purpose of this research paper is to add the environmental point of view to the long-term planning and strategies of companies. To achieve this, the ISM (Interpretive Structural Modeling) method was suggested. Using ISM helps to better understand how lean and green practices are connected and how they can lead to sustainable benefits.

Keywords: Green practices, Lean management, Interpretive Structural Modeling (ISM), MICMAC Analysis, and Barriers.

1. Introduction

The Green and Lean management paradigms play a significant role in the automotive industry. A key focus of Green Lean manufacturing systems is to minimize waste and enhance operational efficiency.

Lean manufacturing prioritises the optimisation of workflows by implementing strategic procedures aimed at reducing waste and increasing adaptability. On the other hand, Green manufacturing involves rethinking and renewing production processes to promote environmentally sustainable practices. It represents the “greening” of manufacturing, where natural resource consumption is minimised, pollution and waste are reduced, materials are recycled and reused, and emissions are controlled throughout the production cycle. Green (Environmental) Production, In recent decades, accelerated population growth, industrial development, reliance on fossil fuels, and sustained economic expansion have collectively contributed to the excessive exploitation of natural resources, frequently surpassing sustainable thresholds. This unsustainable consumption pattern has been a significant driver of environmental degradation, manifesting in widespread pollution arising from both end-use products and the processes involved in their production. Lean started in the early 1950s at Toyota, Japan. Originally a textile company, Toyota began making cars in 1937 under the name *Toyota Motor Company*. During wartime, they shifted to truck production for the military, but after the war, they returned to car manufacturing and became globally competitive. Toyota’s 8 Types of Waste: (1) Overproduction: Producing more than what is needed. (2) Waiting: Lost time when work is delayed. (3) Transportation: Unnecessary movement of materials or products. (4) Overprocessing: Doing extra work that isn’t needed or correcting mistakes. (5) Inventory: Having too much raw material or finished goods. (6) Motion: Unnecessary movements by workers. (7) Defects: Products with mistakes that need fixing. (8) Unused Talent: Not making full use of employees’ skills and ideas.

2. Methodology

2.1 Questionnaire development

To achieve the research objective, a literature review on Green and Lean initiatives was conducted. Eighteen barriers were identified, and ten industry experts were contacted via email and visits. After follow-ups, only four agreed to participate. Similarly, six academic experts were approached, and two joined the study. A decision team of five was formed, including three industry professionals (operations, improvement, and environmental managers) and two Lean Six Sigma university professors. All had experience with Green Lean implementation. One key challenge was convincing experts to participate, making the process lengthy and difficult.

2.2 Data collection

The ISM method relies on expert opinions to determine the relationships among the 18 identified barriers. Experts were consulted in meetings and asked to rate each barrier's impact on a Low, Moderate, High scale. High indicates that the impact of barriers in either green or lean would be maximum. If one barrier leads to high in green implies barrier would directly contribute in environment safety. It helps reduce the environmental impact of production by lowering energy use and pollution during the product's life, and by promoting recycling after the product is no longer used. On the other hand, if a barrier strongly affects lean practices, it can still help bring major benefits by cutting waste, reducing cycle time, and keeping risks low. Moderate indicates that impact of barriers in green and lean respectively would be optimum. Low indicates that dominate factor or impact of respective barriers in green and lean would be minimum. If some barrier is low in green it simply indicates that it contribution in environment has very low and same as in lean.

3. Interpretive Structural Modeling (ISM) Model

ISM is a well-known method used to find and understand the relationships between specific items that are part of a problem or issue. Figure 1 illustrates the flow diagram of the ISM model and helps people better understand and clearly recognize these connections. It turns unclear and confusing ideas about systems into clear and easy-to-see models. ISM can be used for both high-level planning and detailed problem-solving, such as process design, strategic planning, engineering, finance, HR, and more. It creates a clear, structured model of complex issues, improving communication and understanding among team members. ISM helps focus on one issue at a time, encourages deeper analysis, supports learning, and guides policy or action decisions by highlighting key areas with the most impact.

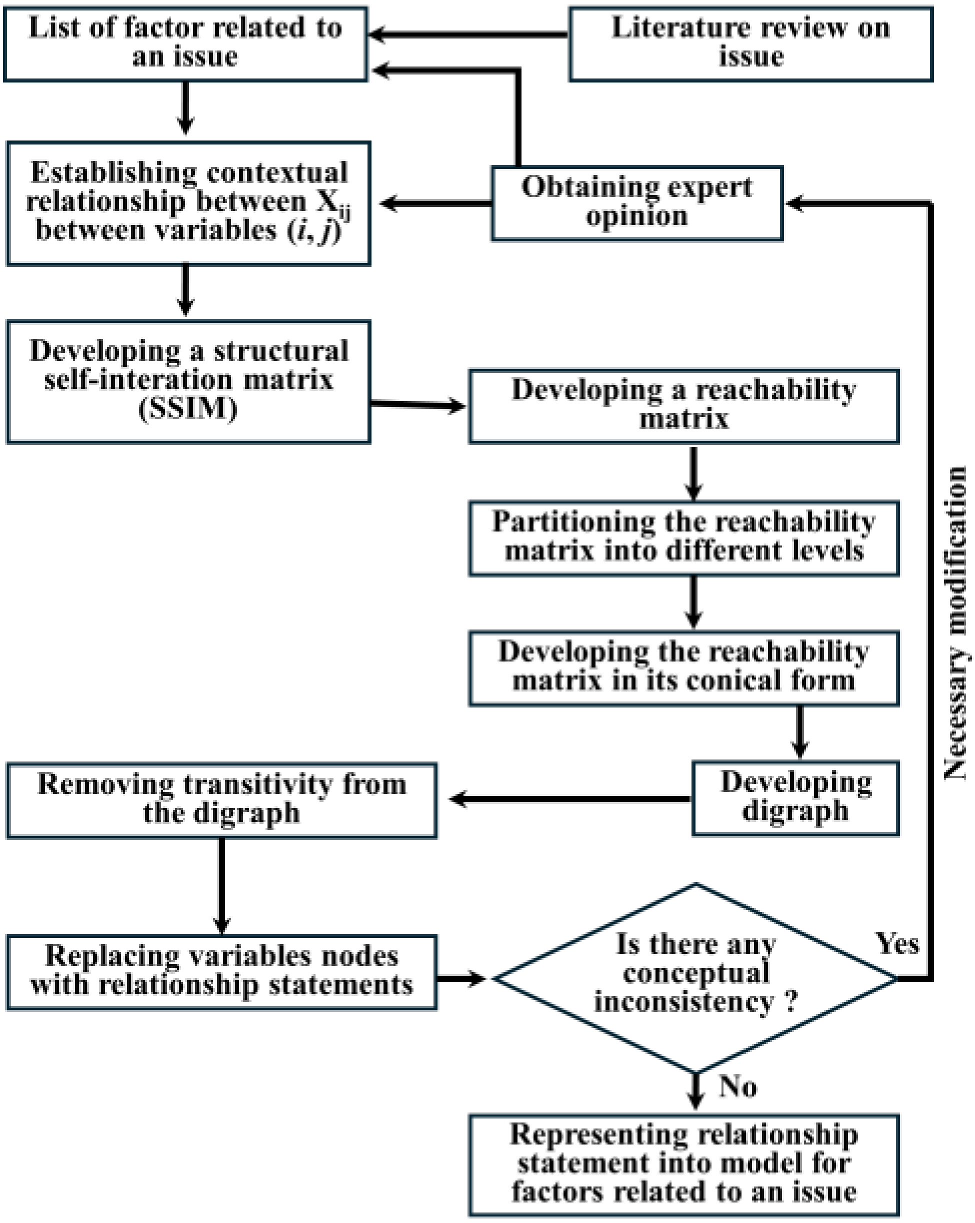

Figure 1: Flow Diagram for preparing ISM Model

4. Model development

4.1 Barriers selection

A systematic review of existing studies was used to find out these barriers because it is a clear, repeatable, and careful way to meet research goals. Feedback from industry experts and scholars helped adjust the barriers to make them more relevant and suitable for Green Lean. Barriers in implementing Green Lean Practices:

1. Lack of top management support for Green Lean initiatives
2. Customers not involved in Green Lean awareness programs
3. Resistance to organizational change
4. Fear of failure in implementing new practices
5. Outdated technology and inefficient manufacturing facilities
6. Lack of proper training and education programs
7. Absence of statistical, Lean, and Green thinking
8. Limited funding or financial constraints
9. High implementation costs
10. Lack of understanding of Green Lean benefits
11. Poor communication and collaboration across departments
12. Low environmental awareness
13. Inadequate quality of human resources
14. Market competition and uncertainty
15. Low quality of raw materials
16. Poor time management
17. Insufficient government support for green practices
18. Lack of a continuous improvement (Kaizen) culture

4.2 Development Of Structural Self-Interaction Matrix (SSIM)

The ISM method relies on expert opinions to explore how different factors are connected. These experts, from both industry and academia, should have a strong understanding of the issue being studied. Methods like brainstorming or the nominal group technique are commonly used to collect their insights. A specific type of relationship, such as "leads to" or "influences", is chosen to show how one factor affects another. Using this approach, the relationships between the identified factors are then established. Considering the contextual relationship between each pair of factors (*i* and *j*), the direction of the relationship is examined. Four symbols are used to represent how the two factors are connected: V - Factor *i* helps to achieve factor *j*, A - Factor *j* helps to achieve factor *i*, X - Both factors *i* and *j* help to achieve each other, O - Factors *i* and *j* are not related.

The SSIM is constructed based on the contextual relationships identified among the barriers to Green Lean implementation. Table 1 presents the developed SSIM. To ensure its validity and reliability, expert consensus is necessary. Therefore, the matrix should be finalized through deliberation with a panel of subject matter experts who can collectively assess and agree upon the contextual relationships. Once the SSIM is finalized, it is converted into a binary form known as the *Initial Reachability Matrix*. This transformation is carried out by replacing the qualitative symbols (*V*, *A*, *X*, and *O*) in the SSIM with binary values (0 or 1) according to the following standardized rules: If the SSIM entry at position (i, j) is V (i influences j), then the reachability matrix will have a 1 at (i, j) and a 0 at (j, i). For instance, for entry (1,18), the matrix has 1 at (1,18) and 0 at (18,1). If the SSIM entry is A (j influences i), then (i, j) is assigned 0 and (j, i) is assigned 1. For example, an A at (1,17) results in a 0 at (1,17) and 1 at (17,1). If the SSIM entry is X (i and j influence each other), both (i, j) and (j, i) are assigned 1. For example, for X at (1,13), both (1,13) and (13,1) are 1. If the SSIM entry is O (no influence), both (i, j) and (j, i) are assigned **0**. For example, O at (3,13) results in 0 at both (3,13) and (13,3).

Table 1: Structural Self Interaction Matrix (SSIM)

Variables	**18**	**17**	**16**	**15**	**14**	**13**	**12**	**11**	**10**	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**
1	V	A	V	V	V	X	X	V	V	V	X	V	V	V	V	V	V
2	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	
3	V	A	X	A	A	O	O	V	A	V	A	V	A	A	X		
4	V	A	V	A	A	A	A	V	A	V	A	V	A	A			
5	V	A	V	O	V	A	A	V	V	V	A	V	V				
6	V	A	V	O	O	A	O	V	V	V	A	V					
7	A	A	A	A	A	A	A	V	A	A	A						
8	V	A	V	V	V	X	X	V	V	V							
9	V	A	A	A	A	O	O	V	A								
10	V	A	V	A	A	A	A	V									
11	A	A	A	A	A	A	A										
12	O	A	V	V	V	X											
13	V	A	V	V	V												
14	V	A	V	O													
15	V	A	V														
16	V	A															
17	V																

4.3 Development of reachability matrix

The next step in the ISM approach is to construct the initial reachability matrix using the Structural Self-Interaction Matrix (SSIM)**.** This involves converting the SSIM into a matrix of 1s and 0s by replacing the four symbols (V**,** A**,** X**,** and O) according to specific rules: (a) If the (i, j) entry in the SSIM is V, then *(i, j) = 1* and *(j, i) = 0*. (b) If the (i, j) entry in the SSIM is A, then *(i, j) = 0* and *(j, i) = 1*. (c) If the (i, j) entry in the SSIM is X, then *(i, j) = 1* and *(j, i) = 1*. (d) If the (i, j) entry in the SSIM is O, then *(i, j) = 0* and *(j, i) = 0*. These substitution rules are applied to generate the initial reachability matrix, as shown in Table 2, which forms the basis for further analysis in the ISM process. Hence, the final reachability matrix for Green Lean implementation barriers was developed, as shown in Table 3.

Table 2: Initial reachability matrix of barriers in green lean implementation

S. No.	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**
1.	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1
2.	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3.	0	1	1	1	0	0	1	0	1	0	1	0	0	0	0	1	0	1
4.	0	1	1	1	0	0	1	0	1	0	1	0	0	0	0	1	0	1
5.	0	1	1	1	1	1	1	0	1	1	1	0	0	1	0	1	0	1

6.	0	1	1	1	0	1	1	0	1	1	1	0	0	0	0	1	0	1
7.	0	1	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0
8.	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1
9.	0	1	0	0	0	0	1	0	1	0	1	0	0	0	0	0	0	1
10	0	1	1	1	0	0	1	0	1	1	1	0	0	0	0	1	0	1
11	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
12	1	1	0	1	1	0	1	1	0	1	1	1	1	1	1	1	0	0
13	1	1	0	1	1	1	1	1	0	1	1	1	1	1	1	1	0	1
14	0	1	1	1	0	0	1	0	1	1	1	0	0	1	0	1	0	1
15	0	1	1	1	0	0	1	0	1	1	1	0	0	0	1	1	0	1
16	0	1	1	0	0	0	1	0	1	0	1	0	0	0	0	1	0	1
17	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
18	0	1	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	1

Table 3: Final reachability matrix (1st iteration) for barriers

S. No.	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**DVR**
1.	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	**17**
2.	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**1**
3.	0	1	1	1	0	0	1	0	1	0	1	0	0	0	0	1	0	1	**8**
4.	0	1	1	1	0	0	1	0	1	0	1	0	0	0	0	1	0	1	**8**
5.	0	1	1	1	1	1	1	0	1	1	1	0	0	1	0	1	0	1	**12**
6.	0	1	1	1	0	1	1	0	1	1	1	0	0	0	0	1	0	1	**10**
7.	0	1	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	**3**
8.	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	**17**
9.	0	1	0	0	0	0	1	0	1	0	1	0	0	0	0	0	0	1	**5**
10	0	1	1	1	0	0	1	0	1	1	1	0	0	0	0	1	0	1	**9**
11	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	**2**
12	1	1	1*	1	1	1*	1	1	1*	1	1	1	1	1	1	1	0	1*	**17**
13	1	1	1*	1	1	1	1	1	1*	1	1	1	1	1	1	1	0	1*	**17**
14	0	1	1	1	0	0	1	0	1	1	1	0	0	1	0	1	0	1	**10**
15	0	1	1	1	0	0	1	0	1	1	1	0	0	0	1	1	0	1	**10**
16	0	1	1	1*	0	0	1	0	1	0	1	0	0	0	0	1	0	1	**8**
17	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	**18**
18	0	1	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	1	**4**
Dependence	**5**	**18**	**13**	**13**	**6**	**7**	**16**	**5**	**14**	**10**	**17**	**5**	**5**	**7**	**6**	**13**	**1**	**15**	**176**

4.4 Partitioning the reachability matrix level partitions

Using the final reachability matrix (see Table 3), we identified which factors influence others and which are influenced. This was done using the method introduced by Warfield (1974). The reachability set for each factor includes that factor itself and any others it can influence. The antecedent set includes the factor and those that can influence it. By comparing these two sets, we found which level each factor belongs to in the hierarchy. If a factor's reachability set is the same as its intersection with the antecedent set, it means that factor is at the top level; it doesn't influence any other factor above its level. After identifying top-level factors, we removed them and repeated the process to find the next levels. This continued until all factors were assigned a level. Tables 4 to 24 show this step-by-step process. These levels helped to build a digraph and the final ISM model.

Table 4: Partitioning of levels (1st iteration) for barriers

S. No.	**Reachability Set**	**Antecedent Set**	**Intersection**	**Level**
1.	1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,18	1,8,12,13,17	1,8,12,13	
2.	2	1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17	2	**I**
3.	2,3,4,7,9,11,16,18	1,3,4,5,6,8,10,12,13,14,15,16,17	3,4,16	
4.	2,3,4,7,9,11,16,18	1,3,4,5,6,8,10,12,13,14,15,16,17	3,4,16	
5.	2,3,4,5,6,7,9,10,11,14,16,18	1,5,8,12,13,17	5	
6.	2,3,4,6,7,9,10,11,16,18	1,5,6,8,12,13,17	6	
7.	2,7,11	1,3,4,5,6,7,8,9,10,12,13,14,15,16,17,18	7	
8.	1,2,3,4,5,7,8,9,10,11,12,13,14,15,16,18	1,8,12,13,17	1,8,12,13	
9.	2,7,9,11,18	1,3,4,5,6,8,9,10,12,13,14,15,16,17	9	
10.	2,3,4,7,9,10,11,16,18	1,5,6,8,10,12,13,14,15, 17	10	
11.	2,11	1,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18	11	
12.	1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,18	1,8,12,13,17	1,8,12,13	
13.	1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,18	1,8,12,13,17	1,8,12,13	
14.	2,3,4,7,9,10,11,14,16,18	1,5,8,12,13,14,17	14	
15.	2,3,4,7,9,10,11,15,16,18	1,8,12,13,15,17	15	
16.	2,3,4,7,9,11,16,18	1,3,4,5,6,8,10,12,13,14,16,17	3,4,16	
17.	1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18	17	17	
18.	2,7,11,18	1,3,4,5,6,8,9,10,12,13,14,15,16,17,18	18	

Table 5: Final reachability matrix (2nd iteration) for barriers

S. No.	1	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	DVR
1.	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	**16**
3.	0	1	1	0	0	1	0	1	0	1	0	0	0	0	1	0	1	**7**
4.	0	1	1	0	0	1	0	1	0	1	0	0	0	0	1	0	1	**7**
5.	0	1	1	1	1	1	0	1	1	1	0	0	1	0	1	0	1	**11**
6.	0	1	1	0	1	1	0	1	1	1	0	0	0	0	1	0	1	**9**
7.	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	**2**
8.	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	**16**
9.	0	0	0	0	0	1	0	1	0	1	0	0	0	0	0	0	1	**4**
10	0	1	1	0	0	1	0	1	1	1	0	0	0	0	1	0	1	**8**
11	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	**1**
12	1	1*	1	1	1*	1	1	1*	1	1	1	1	1	1	1	0	1*	**16**
13	1	1*	1	1	1	1	1	1*	1	1	1	1	1	1	1	0	1*	**16**
14	0	1	1	0	0	1	0	1	1	1	0	0	1	0	1	0	1	**9**
15	0	1	1	0	0	1	0	1	1	1	0	0	0	1	1	0	1	**9**
16	0	1	1*	0	0	1	0	1	0	1	0	0	0	0	1	0	1	**7**
17	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	**17**
18	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	1	**3**
Dependence	**5**	**13**	**13**	**6**	**7**	**16**	**5**	**14**	**10**	**17**	**5**	**5**	**7**	**6**	**13**	**1**	**15**	**158**

Table 6: Partitioning of levels (2nd iteration) for barriers

S. No.	**Reachability Set**	**Antecedent Set**	**Intersection**	**Level**
1.	1,3,4,5,6,7,8,9,10,11,12,13,14,15,16,18	1,8,12,13,17	1,8,12,13	
3.	3,4,7,9,11,16,18	1,3,4,5,6,8,10,12,13,14,15,16,17	3,4,16	
4.	3,4,7,9,11,16,18	1,3,4,5,6,8,10,12,13,14,15,16,17	3,4,16	
5.	3,4,5,6,7,9,10,11,14,16,18	1,5,8,12,13,17	5	
6.	3,4,6,7,9,10,11,16,18	1,5,6,8,12,13,17	6	
7.	7,11	1,3,4,5,6,7,8,9,10,12,13,14,15,16,17,18	7	
8.	1,3,4,5,7,8,9,10,11,12,13,14,15,16,18	1,8,12,13,17	1,8,12,13	
9.	7,9,11,18	1,3,4,5,6,8,9,10,12,13,14,15,16,17	9	
10.	3,4,7,9,10,11,16,18	1,5,6,8,10,12,13,14,15, 17	10	
11.	11	1,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18	11	**II**
12.	1,3,4,5,6,7,8,9,10,11,12,13,14,15,16,18	1,8,12,13,17	1,8,12,13	
13.	1,3,4,5,6,7,8,9,10,11,12,13,14,15,16,18	1,8,12,13,17	1,8,12,13	

14.	3,4,7,9,10,11,14,16,18	1,5,8,12,13,14,17	14	
15.	3,4,7,9,10,11,15,16,18	1,8,12,13,15,17	15	
16.	3,4,7,9,11,16,18	1,3,4,5,6,8,10,12,13,14,16,17	3,4,16	
17.	1,3,4,5,6,7,8,9,10,11,12,13,14,15,16, 17,18	17	17	
18.	7,11,18	1,3,4,5,6,8,9,10,12,13,14,15,16,17,18	18	

Table 7: Final reachability matrix (3rd iteration) for barriers

S. No.	**1**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**DVR**
1.	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	**15**
3.	0	1	1	0	0	1	0	1	0	0	0	0	0	1	0	1	**6**
4.	0	1	1	0	0	1	0	1	0	0	0	0	0	1	0	1	**6**
5.	0	1	1	1	1	1	0	1	1	0	0	1	0	1	0	1	**10**
6.	0	1	1	0	1	1	0	1	1	0	0	0	0	1	0	1	**8**
7.	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	**1**
8.	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	**15**
9.	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	1	**3**
10	0	1	1	0	0	1	0	1	1	0	0	0	0	1	0	1	**7**
12	1	1*	1	1	1*	1	1	1*	1	1	1	1	1	1	0	1*	**15**
13	1	1*	1	1	1	1	1	1*	1	1	1	1	1	1	0	1*	**15**
14	0	1	1	0	0	1	0	1	1	0	0	1	0	1	0	1	**8**
15	0	1	1	0	0	1	0	1	1	0	0	0	1	1	0	1	**8**
16	0	1	1*	0	0	1	0	1	0	0	0	0	0	1	0	1	**6**
17	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	**16**
18	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	**2**
Dependence	**5**	**13**	**13**	**6**	**7**	**16**	**5**	**14**	**10**	**5**	**5**	**7**	**6**	**13**	**1**	**15**	**141**

Table 8: Partitioning of levels (3rd iteration) for barriers

S. No.	**Reachability Set**	**Antecedent Set**	**Intersection**	**Level**
1.	1,3,4,5,6,7,8,9,10,12,13,14,15,16,18	1,8,12,13,17	1,8,12,13	
3.	3,4,7,9,16,18	1,3,4,5,6,8,10,12,13,14,15,16,17	3,4,16	
4.	3,4,7,9,16,18	1,3,4,5,6,8,10,12,13,14,15,16,17	3,4,16	
5.	3,4,5,6,7,9,10,14,16,18	1,5,8,12,13,17	5	
6.	3,4,6,7,9,10,16,18	1,5,6,8,12,13,17	6	
7.	7	1,3,4,5,6,7,8,9,10,12,13,14,15,16,17, 18	7	**III**
8.	1,3,4,5,7,8,9,10,12,13,14,15,16,18	1,8,12,13,17	1,8,12,13	
9.	7,9,18	1,3,4,5,6,8,9,10,12,13,14,15,16,17	9	
10.	3,4,7,9,10,16,18	1,5,6,8,10,12,13,14,15, 17	10	

12.	1,3,4,5,6,7,8,9,10,12,13,14,15,16,18	1,8,12,13,17	1,8,12,13	
13.	1,3,4,5,6,7,8,9,10,12,13,14,15,16,18	1,8,12,13,17	1,8,12,13	
14.	3,4,7,9,10,14,16,18	1,5,8,12,13,14,17	14	
15.	3,4,7,9,10,15,16,18	1,8,12,13,15,17	15	
16.	3,4,7,9,16,18	1,3,4,5,6,8,10,12,13,14,16,17	3,4,16	
17.	1,3,4,5,6,7,8,9,10,12,13,14,15,16,17,18	17	17	
18.	7,18	1,3,4,5,6,8,9,10,12,13,14,15,16,17,18	18	

Table 9: Final reachability matrix (4th iteration) for barriers

S. No.	**1**	**3**	**4**	**5**	**6**	**8**	**9**	**10**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**DVR**
1.	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	**14**
3.	0	1	1	0	0	0	1	0	0	0	0	0	1	0	1	**5**
4.	0	1	1	0	0	0	1	0	0	0	0	0	1	0	1	**5**
5.	0	1	1	1	1	0	1	1	0	0	1	0	1	0	1	**9**
6.	0	1	1	0	1	0	1	1	0	0	0	0	1	0	1	**7**
8.	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	**14**
9.	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	**2**
10	0	1	1	0	0	0	1	1	0	0	0	0	1	0	1	**6**
12	1	1*	1	1	1*	1	1*	1	1	1	1	1	1	0	1*	**14**
13	1	1*	1	1	1	1	1*	1	1	1	1	1	1	0	1*	**14**
14	0	1	1	0	0	0	1	1	0	0	1	0	1	0	1	**7**
15	0	1	1	0	0	0	1	1	0	0	0	1	1	0	1	**7**
16	0	1	1*	0	0	0	1	0	0	0	0	0	1	0	1	**5**
17	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	**15**
18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	**1**
Dependence	5	13	13	6	7	5	14	10	5	5	7	6	13	1	15	**125**

Table 10: Partitioning of levels (4th iteration) for barriers

S. No.	**Reachability Set**	**Antecedent Set**	**Intersection**	**Level**
1.	1,3,4,5,6,8,9,10,12,13,14,15,16,18	1,8,12,13,17	1,8,12,13	
3.	3,4,9,16,18	1,3,4,5,6,8,10,12,13,14,15,16,17	3,4,16	
4.	3,4,9,16,18	1,3,4,5,6,8,10,12,13,14,15,16,17	3,4,16	
5.	3,4,5,6,9,10,14,16,18	1,5,8,12,13,17	5	
6.	3,4,6,9,10,16,18	1,5,6,8,12,13,17	6	
8.	1,3,4,5,8,9,10,12,13,14,15,16,18	1,8,12,13,17	1,8,12,13	
9.	9,18	1,3,4,5,6,8,9,10,12,13,14,15,16,17	9	
10.	3,4,9,10,16,18	1,5,6,8,10,12,13,14,15, 17	10	

12.	1,3,4,5,6,8,9,10,12,13,14,15,16,18	1,8,12,13,17	1,8,12,13	
13.	1,3,4,5,6,8,9,10,12,13,14,15,16,18	1,8,12,13,17	1,8,12,13	
14.	3,4,9,10,14,16,18	1,5,8,12,13,14,17	14	
15.	3,4,9,10,15,16,18	1,8,12,13,15,17	15	
16.	3,4,9,16,18	1,3,4,5,6,8,10,12,13,14,16,17	3,4,16	
17.	1,3,4,5,6,8,9,10,12,13,14,15,16,17,18	17	17	
18.	18	1,3,4,5,6,8,9,10,12,13,14,15,16,17,18	18	**IV**

Table 11: Final reachability matrix (5th iteration) for barriers

S. No.	**1**	**3**	**4**	**5**	**6**	**8**	**9**	**10**	**12**	**13**	**14**	**15**	**16**	**17**	**DVR**
1.	1	1	1	1	1	1	1	1	1	1	1	1	1	0	**13**
3.	0	1	1	0	0	0	1	0	0	0	0	0	1	0	**4**
4.	0	1	1	0	0	0	1	0	0	0	0	0	1	0	**4**
5.	0	1	1	1	1	0	1	1	0	0	1	0	1	0	**8**
6.	0	1	1	0	1	0	1	1	0	0	0	0	1	0	**6**
8.	1	1	1	1	1	1	1	1	1	1	1	1	1	0	**13**
9.	0	0	0	0	0	0	1	0	0	0	0	0	0	0	**1**
10	0	1	1	0	0	0	1	1	0	0	0	0	1	0	**5**
12	1	1*	1	1	1*	1	1*	1	1	1	1	1	1	0	**13**
13	1	1*	1	1	1	1	1*	1	1	1	1	1	1	0	**13**
14	0	1	1	0	0	0	1	1	0	0	1	0	1	0	**6**
15	0	1	1	0	0	0	1	1	0	0	0	1	1	0	**6**
16	0	1	1*	0	0	0	1	0	0	0	0	0	1	0	**4**
17	1	1	1	1	1	1	1	1	1	1	1	1	1	1	**14**
Dependence	5	13	13	6	7	5	14	10	5	5	7	6	13	1	**110**

Table 12: Partitioning of levels (5th iteration) for barriers

S. No.	**Reachability Set**	**Antecedent Set**	**Intersection**	**Level**
1.	1,3,4,5,6,8,9,10,12,13,14,15,16	1,8,12,13,17	1,8,12,13	
3.	3,4,9,16	1,3,4,5,6,8,10,12,13,14,15,16,17	3,4,16	
4.	3,4,9,16	1,3,4,5,6,8,10,12,13,14,15,16,17	3,4,16	
5.	3,4,5,6,9,10,14,16	1,5,8,12,13,17	5	
6.	3,4,6,9,10,16	1,5,6,8,12,13,17	6	
8.	1,3,4,5,8,9,10,12,13,14,15,16	1,8,12,13,17	1,8,12,13	
9.	9	1,3,4,5,6,8,9,10,12,13,14,15,16,17	9	**V**
10.	3,4,9,10,16	1,5,6,8,10,12,13,14,15, 17	10	
12.	1,3,4,5,6,8,9,10,12,13,14,15,16	1,8,12,13,17	1,8,12,13	

13.	1,3,4,5,6,8,9,10,12,13,14,15,16	1,8,12,13,17	1,8,12,13	
14.	3,4,9,10,14,16	1,5,8,12,13,14,17	14	
15.	3,4,9,10,15,16	1,8,12,13,15,17	15	
16.	3,4,9,16	1,3,4,5,6,8,10,12,13,14,16,17	3,4,16	
17.	1,3,4,5,6,8,9,10,12,13,14,15,16,17	17	17	

Table 13: Final reachability matrix (6th iteration) for barriers

S. No.	**1**	**3**	**4**	**5**	**6**	**8**	**10**	**12**	**13**	**14**	**15**	**16**	**17**	**DVR**
1.	1	1	1	1	1	1	1	1	1	1	1	1	0	**12**
3.	0	1	1	0	0	0	0	0	0	0	0	1	0	**3**
4.	0	1	1	0	0	0	0	0	0	0	0	1	0	**3**
5.	0	1	1	1	1	0	1	0	0	1	0	1	0	**7**
6.	0	1	1	0	1	0	1	0	0	0	0	1	0	**5**
8.	1	1	1	1	1	1	1	1	1	1	1	1	0	**12**
10	0	1	1	0	0	0	1	0	0	0	0	1	0	**4**
12	1	1*	1	1	1*	1	1	1	1	1	1	1	0	**12**
13	1	1*	1	1	1	1	1	1	1	1	1	1	0	**12**
14	0	1	1	0	0	0	1	0	0	1	0	1	0	**5**
15	0	1	1	0	0	0	1	0	0	0	1	1	0	**5**
16	0	1	1*	0	0	0	0	0	0	0	0	1	0	**3**
17	1	1	1	1	1	1	1	1	1	1	1	1	1	**13**
Dependence	5	13	13	6	7	5	10	5	5	7	6	13	1	**96**

Table 14: Partitioning of levels (6th iteration) for barriers

S. No.	**Reachability Set**	**Antecedent Set**	**Intersection**	**Level**
1.	1,3,4,5,6,8,10,12,13,14,15,16	1,8,12,13,17	1,8,12,13	
3.	3,4,16	1,3,4,5,6,8,10,12,13,14,15,16,17	3,4,16	**VI**
4.	3,4,16	1,3,4,5,6,8,10,12,13,14,15,16,17	3,4,16	**VI**
5.	3,4,5,6,10,14,16	1,5,8,12,13,17	5	
6.	3,4,6,10,16	1,5,6,8,12,13,17	6	
8.	1,3,4,5,8,10,12,13,14,15,16	1,8,12,13,17	1,8,12,13	
10.	3,4,10,16	1,5,6,8,10,12,13,14,15, 17	10	
12.	1,3,4,5,6,8,10,12,13,14,15,16	1,8,12,13,17	1,8,12,13	
13.	1,3,4,5,6,8,10,12,13,14,15,16	1,8,12,13,17	1,8,12,13	
14.	3,4,10,14,16	1,5,8,12,13,14,17	14	
15.	3,4,10,15,16	1,8,12,13,15,17	15	
16.	3,4,16	1,3,4,5,6,8,10,12,13,14,16,17	3,4,16	**VI**
17.	1,3,4,5,6,8,10,12,13,14,15,16,17	17	17	

Table 15: Final reachability matrix (7th iteration) for barriers

S. No.	**1**	**5**	**6**	**8**	**10**	**12**	**13**	**14**	**15**	**17**	**DVR**
1.	1	1	1	1	1	1	1	1	1	0	**9**
5.	0	1	1	0	1	0	0	1	0	0	**4**
6.	0	0	1	0	1	0	0	0	0	0	**2**
8.	1	1	1	1	1	1	1	1	1	0	**9**
10	0	0	0	0	1	0	0	0	0	0	**1**
12	1	1	1*	1	1	1	1	1	1	0	**9**
13	1	1	1	1	1	1	1	1	1	0	**9**
14	0	0	0	0	1	0	0	1	0	0	**2**
15	0	0	0	0	1	0	0	0	1	0	**2**
17	1	1	1	1	1	1	1	1	1	1	**10**
Dependence	**5**	**6**	**7**	**5**	**10**	**5**	**5**	**7**	**6**	**1**	**57**

Table 16: Partitioning of levels (7th iteration) for barriers

S. No.	**Reachability Set**	**Antecedent Set**	**Intersection**	**Level**
1.	1,5,6,8,10,12,13,14,15	1,8,12,13,17	1,8,12,13	
5.	5,6,10,14	1,5,8,12,13,17	5	
6.	6,10	1,5,6,8,12,13,17	6	
8.	1,5,8,10,12,13,14,15	1,8,12,13,17	1,8,12,13	
10.	10	1,5,6,8,10,12,13,14,15, 17	10	**VII**
12.	1,5,6,8,10,12,13,14,15	1,8,12,13,17	1,8,12,13	
13.	1,5,6,8,10,12,13,14,15	1,8,12,13,17	1,8,12,13	
14.	10,14	1,5,8,12,13,14,17	14	
15.	10,15	1,8,12,13,15,17	15	
17.	1,5,6,8,10,12,13,14,15,17	17	17	

Table 17: Final reachability matrix (8th iteration) for barriers

S. No.	**1**	**5**	**6**	**8**	**12**	**13**	**14**	**15**	**17**	**DVR**
1.	1	1	1	1	1	1	1	1	0	**8**
5.	0	1	1	0	0	0	1	0	0	**3**
6.	0	0	1	0	0	0	0	0	0	**1**
8.	1	1	1	1	1	1	1	1	0	**8**
12	1	1	1*	1	1	1	1	1	0	**8**
13	1	1	1	1	1	1	1	1	0	**8**
14	0	0	0	0	0	0	1	0	0	**1**
15	0	0	0	0	0	0	0	1	0	**1**
17	1	1	1	1	1	1	1	1	1	**9**
Dependence	**5**	**6**	**7**	**5**	**5**	**7**	**6**	**1**	**5**	**47**

Table 18: Partitioning of levels (8th iteration) for barriers

S. No.	Reachability Set	Antecedent Set	Intersection	Level
1.	1,5,6,8,12,13,14,15	1,8,12,13,17	1,8,12,13	
5.	5,6,14	1,5,8,12,13,17	5	
6.	6	1,5,6,8,12,13,17	6	**VIII**
8.	1,5,8,12,13,14,15	1,8,12,13,17	1,8,12,13	
12.	1,5,6,8,12,13,14,15	1,8,12,13,17	1,8,12,13	
13.	1,5,6,8,12,13,14,15	1,8,12,13,17	1,8,12,13	
14.	14	1,5,8,12,13,14,17	14	**VIII**
15.	15	1,8,12,13,15,17	15	**VIII**
17.	1,5,6,8,12,13,14,15,17	17	17	

Table 19: Final reachability matrix (9th iteration) for barriers

S. No.	**1**	**5**	**8**	**12**	**13**	**17**	**DVR**
1.	1	1	1	1	1	0	**5**
5.	0	1	0	0	0	0	**1**
8.	1	1	1	1	1	0	**5**
12	1	1	1	1	1	0	**5**
13	1	1	1	1	1	0	**5**
17	1	1	1	1	1	1	**6**
Dependence	**5**	**6**	**5**	**5**	**5**	**1**	**27**

Table 20: Partitioning of levels (9th iteration) for barriers

S. No.	Reachability Set	Antecedent Set	Intersection	Level
1.	1,5,8,12,13	1,8,12,13,17	1,8,12,13	
5.	5	1,5,8,12,13,17	5	**IX**
8.	1,5,8,12,13	1,8,12,13,17	1,8,12,13	
12.	1,5,8,12,13	1,8,12,13,17	1,8,12,13	
13.	1,5,8,12,13	1,8,12,13,17	1,8,12,13	
17.	1,5,8,12,13,17	17	17	

Table 21: Final reachability matrix (10th iteration) for barriers

S. No.	**1**	**8**	**12**	**13**	**17**	**DVR**
1.	1	1	1	1	0	**4**
8.	1	1	1	1	0	**4**
12	1	1	1	1	0	**4**
13	1	1	1	1	0	**4**

17	1	1	1	1	1	**5**
Dependence	**5**	**5**	**5**	**5**	**1**	**21**

Table 22: Partitioning of levels (10th iteration) for barriers

S. No.	Reachability Set	Antecedent Set	Intersection	Level
1.	1,8,12,13	1,8,12,13,17	1,8,12,13	**X**
8.	1,8,12,13	1,8,12,13,17	1,8,12,13	**X**
12.	1,8,12,13	1,8,12,13,17	1,8,12,13	**X**
13.	1,8,12,13	1,8,12,13,17	1,8,12,13	**X**
17.	1,8,12,13,17	17	17	

Table 23: Final reachability matrix (11th iteration) for barriers

S. No.	17	DVR
17	1	**1**
Dependence	**1**	**1**

Table 24: Partitioning of levels (11th iteration) for barriers

S. No.	Reachability Set	Antecedent Set	Intersection	Level
17.	17	17	17	**XI**

Finally, a conical matrix is created by grouping factors at the same level. In this matrix, the number of ones in a row shows a factor's driving power (how much it influences others). The number of ones in a column shows a factor's dependence power (how much it is influenced by others), shown in Table 25.

Table 25: Conical Matrix

S.No.	2	11	7	18	9	3	4	16	10	6	14	15	5	1	8	12	13	17	DVR
2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
11	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2
7	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3
18	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4
9	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	5
3	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	8
4	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	8
16	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	8
10	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	9
6	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	10
14	1	1	1	1	1	1	1	1	1	0	1	0	0	0	0	0	0	0	10
15	1	1	1	1	1	1	1	1	1	0	0	1	0	0	0	0	0	0	10

5	1	1	1	1	1	1	1	1	1	1	1	0	1	0	0	0	0	0	12
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	17
8	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	17
12	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	17
13	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	17
17	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	18
	18	**17**	**16**	**15**	**14**	**13**	**13**	**13**	**10**	**7**	**7**	**6**	**6**	**5**	**5**	**5**	**5**	**1**	**176**

4.5 ISM based model formation

Based on the final reachability matrix, a structural representation was developed, as illustrated in Figure 2. In cases where a barrier *i* influenced another barrier *j*, this was depicted with a directional arrow from *i* to *j*. This form of representation is referred to as a *directed graph* or *digraph*. Following the procedure outlined in the ISM methodology by Kannan et al. (2008), transitive links were eliminated to refine the digraph, which was then transformed into the final Interpretive Structural Modelling (ISM) structure.

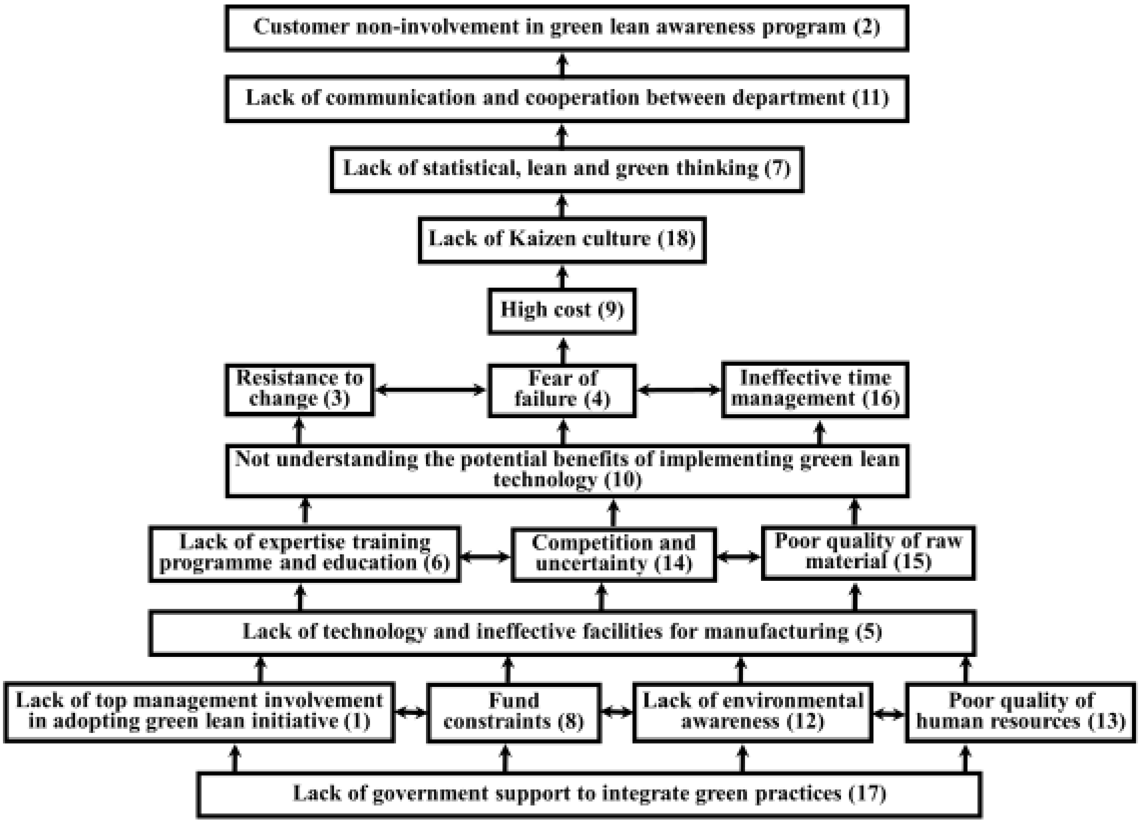

Figure 2: ISM-Based Model of barriers in Green Lean Implementation

4.6 MICMAC Analysis

The MICMAC (Matrice d'Impacts Croisés Multiplication Appliquée àn Classement) methodology, translated as *Cross-Impact Matrix Multiplication Applied to Classification*, is employed to evaluate the driving and dependence power of various factors within a system. Rooted in matrix multiplication principles, MICMAC helps to distinguish and categorize influential elements based on how strongly they affect or are affected by others. Driving power refers to the extent a factor influences others, while dependence power denotes how much a factor is influenced by others. These relationships are visually mapped in the driver-dependence diagram (see Figure 3). Factors are grouped into four distinct categories:

(1) *Autonomous factors:* These exhibit low driving and low dependence power. They tend to be isolated, with limited and often weak interactions within the system.

(2) *Linkage factors:* Characterised by both high driving and high dependence power, these elements are dynamic and sensitive; changes in these factors can significantly impact others and, in turn, influence themselves through feedback loops.

(3) *Dependent factors:* These have high dependence but low driving power, indicating they are heavily influenced by other elements but exert minimal influence themselves.

(4) *Independent factors*: Marked by strong driving power and minimal dependence, these variables are key drivers of the system. When a factor exhibits particularly high driving influence, it is often considered a *key factor*, typically falling into the linkage or independent category.

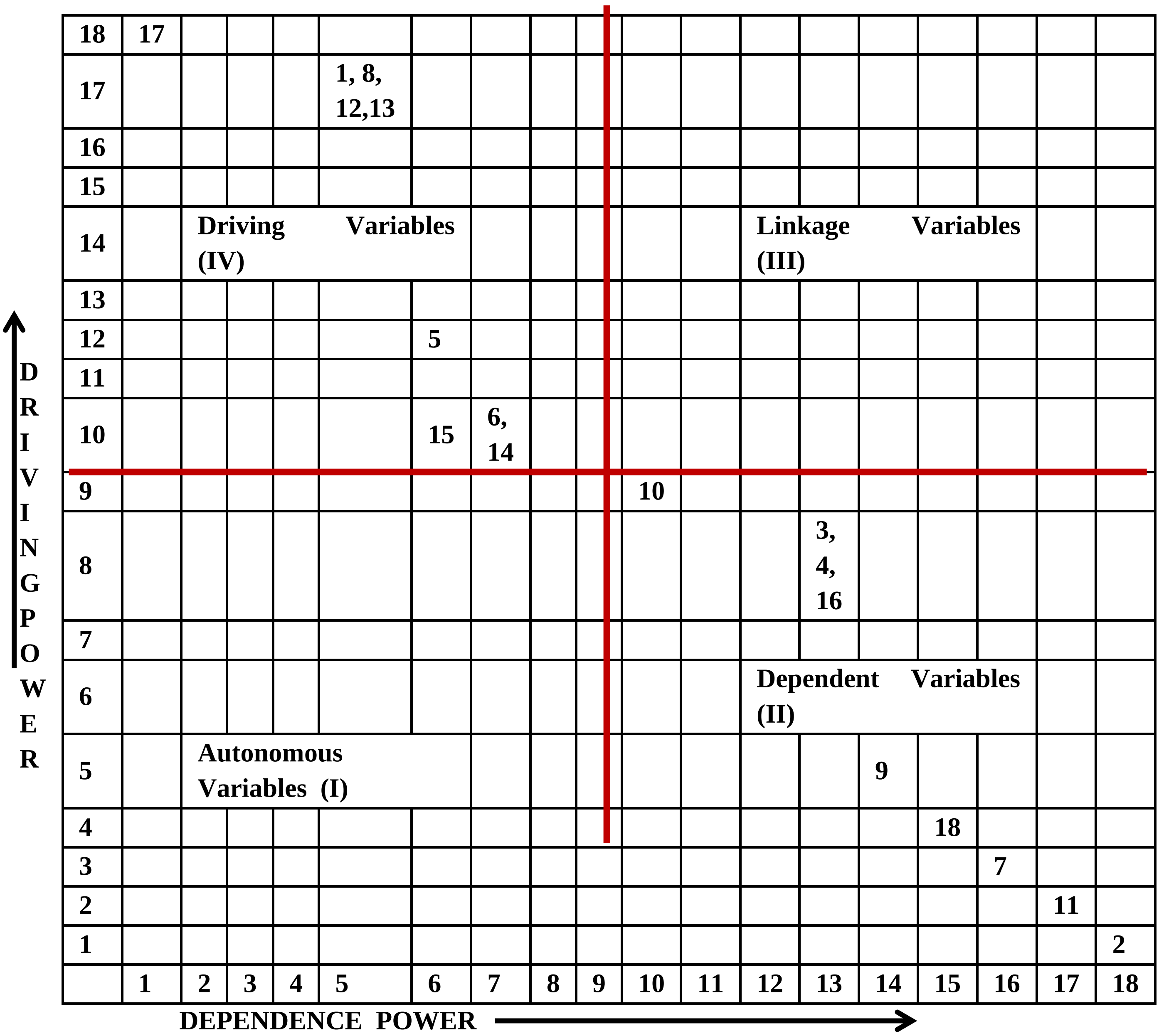

Figure 3: MICMAC Analysis

4.7 Summary of Partitioning The Reachability Matrix

The reachability matrix was divided into levels to organize the barriers based on their driving power and dependence power. As shown in Table 26, ranks were given by counting how many ones each factor had - more ones in a row meant higher driving power, and more ones in a column meant higher dependence power.

Table 26: Summary of partitioning of levels (after 11th iteration) for barriers

S.N.	Quadrant	Driving Power	Dependence Power	Net Value	Dominant Nature	Levels
1.	Driver	17	5	12	Driver	**X**
2.	Dependence	1	18	-17	Dependent	**I**
3.	Dependence	8	13	-5	Dependent	**VI**
4.	Dependence	8	13	-5	Dependent	**VI**
5.	Driver	12	6	6	Driver	**IX**
6.	Driver	10	7	3	Driver	**VIII**
7.	Dependence	3	16	-13	Dependent	**III**
8.	Driver	17	5	12	Driver	**X**
9.	Dependence	5	14	-9	Dependent	**V**
10.	Dependence	9	10	-1	Dependent	**VII**
11.	Dependence	2	17	-15	Dependent	**II**
12.	Driver	17	5	12	Driver	**X**
13.	Driver	17	5	12	Driver	**X**
14.	Driver	10	7	3	Driver	**VIII**
15.	Driver	10	6	4	Driver	**VIII**
16.	Dependence	8	13	-5	Dependent	**VI**
17.	Driver	18	1	17	Driver	**XI**
18.	Dependence	4	15	-11	Dependent	**IV**

5. Results and Discussion

Green Lean implementation is seen as a useful combination of two different methods, green (environment-friendly) and lean (efficient), to improve things like environment, time, speed, quality, consistency, and cost. The main goal of using Green Lean is to bring together the benefits of both green and lean ideas, as suggested by many researchers and professionals. To apply this system, specific knowledge and financial investment are needed. A total of 18 barriers to applying Green Lean have been identified for detailed study. The ISM (Interpretive Structural Modelling) method was used to understand how these barriers are related. A model was created using this method. In the model, "*Customer non-involvement in Green Lean awareness"* is placed at the top, while *"Lack of government support to integrate green practices"* is at the bottom. MICMAC analysis helped group the barriers into three types: driving, dependent, and linkage. This helps managers and professionals know which barriers to focus on for achieving sustainable business. Out of the 18 barriers, 9 are driving barriers and 9 are dependent barriers. No barriers were found to be linkage or autonomous barriers.

6. Limitations of Research and Future Scope

This research has some limitations. First, the model was created based on expert opinions, which might be biased. Second, the study was done in a general way. While the results may apply to many situations, more research is needed in different industries, countries, and company sizes to confirm the model. In those cases, some barriers might need to be added or removed depending on the situation. Lastly, this study identified 18 barriers to Green Lean implementation, but in the real world, the number and type of barriers may be different.

7. Theoretical Implications

This study helps to grow the use of Green Lean practices. It is especially helpful for companies, particularly in manufacturing, that want to improve their operations and become more sustainable. The study also introduced a structural model for lean and green practices. This model helps companies understand how these two practices work together, making it easier to plan effective strategies for sustainability.

8. Managerial Implications

The results of this study, especially the ISM-based model, can help managers and professionals find and rank the main problems in using Green Lean. It also helps them take the right steps to solve these problems. This study guides them to focus their efforts in the right direction to achieve sustainable growth. In this way, it supports the practical use of Green Lean by helping top management understand, manage, and handle the challenges that could stop it from being successful.

9. Social Implication

Green Lean principles can be used in many fields beyond manufacturing, like services, healthcare, logistics, and transport. These areas also feel the need to be more eco-friendly and improve their products, services, and processes. This research gives helpful guidance to support that goal. From a social point of view, lean practices help workers build their skills and grow personally. This research also supports policymakers by giving them useful tools to create better policies that help organizations move toward sustainability.

10. Conclusions and Future Work

Overall, this paper gives useful information about how to apply Green Lean and encourages its use. It also offers reliable evidence to help industry professionals understand the barriers that can make implementation difficult. Another point from this study is that, even though lean and green practices can improve business performance and help reduce negative effects on the environment, only a few companies are using them. Even with these benefits, it's clear that these practices can help companies deal with sustainability challenges. In the future, researchers should test and confirm the barriers identified and the ISM model developed in this study using real-world data. The current ISM-based model gives a practical view of the challenges faced during Green Lean implementation, but it still needs to be statistically validated. To do this, Structural Equation Modelling (SEM) is recommended. SEM is a well-known method used in lean research (as shown in Belekoukias et al., 2014). It will help to confirm if the ISM model is accurate and verify the research results with statistical evidence. In future studies, graph theory could also be used to measure and analyze the importance of each barrier. Based on case studies, we have created a model that brings together common lean and green practices, and we have suggested some ideas (propositions) that can be tested in future research.

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