Journal of Scientific & Industrial Research
Vol. 84, July 2025, pp. 799-813
DOI: 10.56042/jsir.v84i7.4849

Investigating Associative Relationships between Green Manufacturing and Sustainable Manufacturing Enablers in Context to Indian Manufacturing Industry

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Received 13 August 2023; revised 13 March 2025; accepted 20 June 2025

The mounting challenge of net zero by 2070, towards responsible and eco-friendly business practices has led corporates, industry-houses, and lawmakers to increasingly adopt Green Manufacturing (GM) and Sustainable Manufacturing (SM). Typically, these terms are employed interchangeably, but in reality, terms are distinct but are closely associated. The associative relationships between GM and SM need to be demystified by addressing applicable enablers in context of developing economies like India. Existing research does not adequately deal with the associations between GM and SM, creating a critical gap. By methodically recognizing and assessing the enablers and establishing the connection between the two, this study aims to bridge this gap in the context of the Indian manufacturing sector. By developing a structured model cum roadmap and offering meaningful comparisons, this research provides strategic insights to help researchers, corporates, and policymakers to address relationships between the two. The research findings are expected to facilitate navigational requirements for the GM and SM implementation. It is expected that the study will facilitate scholars and business experts opening the door for new applications in line with SDG7 (affordable and clean energy) and SDG13 (climate action).

Keywords: Business impact, Enablers, Green and sustainable manufacturing, ISM, Societal impact

Overview and Pre-Requisites for Research

With over one fifth of global population and its position as a strong sourcing hub, India's manufacturing sector is significantly important. After agriculture, it is the second-largest direct employment provider influencing economic growth, and supporting 16% to India's Gross Domestic Product (GDP).[1,2] For a fast-growing economy like India, leveraging the manufacturing sector's full potential is critical for fostering inclusive and sustainable development, India has been facing environmental challenges imposed by regulatory frameworks like International Energy Agency (IEA) and World Trade Organization (WTO). These encounters are being created in different manners like by imposing carbon taxes, emission-tariffs, net zero by 2070, circular economy and carbon border adjustment mechanisms, for energy intensive manufacturing like cement, steel and other similar industries.

To remain responsible and competitive, manufacturing needs to deal with above challenges for greener and sustainable production with management policies alignment. Naturally, these requirements will influence global engagement. The situation has been knocking doors for Indian executives, academicians, business leaders, and legislators to capitalize on the expanding opportunities for manufacturing, considering the changes in it.

New trends like sustainable operations, green and clean driven manufacturing have become an urgent requirement. Unfortunately, this shift from simple manufacturing to green and sustainable manufacturing is not linear in nature but has many tangling techno-managerial considerations. Looking to these difficulties, the investigation necessitates new innovations, manufacturing enhancements and requires the use of better roadmaps, frameworks and modeling-based solutions.

It is observed that most of the developing economies including BRICS, prefer lowering manufacturing expenses and price of goods, over higher order societal needs like resources consumption, wastes, air pollution, and degradation of the environment.[2,3] Manufacturing sector has initiated Green Manufacturing (GM) and Sustainable Manufacturing (SM) approaches but much more needs to be done and investigated.[4]

GM and SM encourage businesses to integrate societal and ecological factors into their actions[5] and

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not to operate in social vacuum. Thus, to deal with regulatory and compliance related challenges regarding reduction of environmental damages while maintaining profitability and upholding social obligations, businesses all over the world, including those in India, have either initiated or are about to embrace GM and SM both as programs and as strategies.[6] These initiatives, however, are still in nascent stages and need guidance. At present there is no systematic roadmap and modeling attempt covering associative relationships between GM and SM for industry captains and policy makers to navigate their journeys.[7,3]

The future of manufacturing will be shaped by encounters like cleaner production, legal obligations, and green processes, for responsible business. Thus, GM and SM must be strategically adopted, with careful considerations after critically mapping associative relationships between their enablers.

Research studies[8,9] have highlighted that manufacturers throughout the world have become more conscious about the sustainable effects of industrial operations. But still, there are many gap areas and knowledge deficits. Literature is full of green and sustainability related researches, however the associative relationships between enablers in context to an important developing country are not fully understood. As mentioned earlier, this research attempts to plug in this gap. Industry captains wish to extend their journeys from GM to SM. The inadequate research support about extending 3Rs (reduce, reuse, recycle) to 6Rs (reduce, reuse, recycle, refuse, repair and redesign/reimagine) in the Indian milieu, is another important gap, which is being addressed.

Scholars struggle, as there are no frameworks, or models to address associative relationships between the two. Despite just putting GM into practice, the industry has been expanding it to meet SM along with other societal needs. Both researchers and executive communities wish to establish responsible choices, and need new methods to be developed.[4,10,11] Understanding the connections between GM and SM is of interest to many disciplines. This problem affects other emerging nations also. The absence of modeling-based guidance and enabler-based understanding of relationships is noticed as a significant research gap. This study attempts to plug in gap using a novel methodology addressing associative relationships.

Manufacturing requires thorough research into GM and SM-related enhancements due to the intricate nature of enablers and execution difficulty. Exploring GM and SM view points, and pertinent enablers will therefore be helpful.

Background of Green & Sustainable Manufacturing

With its roots in Germany, GM tackles important issues in resource conservation and environmental management. Its adoption has been largely fueled by growing worries about harmful emissions, depletion of natural resources, and rising energy costs. As GM implementation is complicated, it is expected that the authorities must provide guidance in the form of directives, incentives and enabler-driven policies.[1] GM reduces environmental damage and promotes an eco-conscious industrial model that incorporates green technologies and sustainable design principles by prioritizing efficient resource usage.[12] It guarantees that products are manufactured using environmentally-friendly, efficient techniques that strike a balance between economic viability and a small environmental impact.[13,14] One finds that, GM offers a comprehensive strategy that improves financial standing through waste reduction, cleaner manufacturing, and reduced emissions. SM is broader than GM.

SM is a collection of ideas, procedures, and technological advancements that make it possible to manufacture products and services in an economically viable, ethical, and environmentally conscious manner.[4] SM aims to minimize harm to society while optimizing the utilization of resources. Please refer studies like Ching *et al*.[16], Malek & Desai[17], Hariyani & Mishra[10] for SM details. SM creates societal benefits, improves operational efficiency, and cultivates green knowledge. Thus, SM is organized around a closed-loop model that incorporates methods, regulations, protocols, and sustainable practices into an enterprise's long-term goals.[18]

Study's Structure and Objective:

1. To investigate GM and SM enablers with a view to examine their associative relationships and to model for facilitating implementation, expansion, and evaluation smoother.

For conceptual diagram, please refer to Fig. 1. In terms of organization, the study covers literature review, research methodology, results assessment & contrasts ISM models, discussion, findings and conversation followed by conclusion, constraints or limitations, future extensions.

Literature Review

There are two subsections within this section covering GM and SM enablers. The authors very

humbly would like to mention about the use of select studies for both GM and SM. Many Indian and global studies are available on GM enablers, and it is impractical to include all. As the objective of the literature review is to offer a concise academic basis for Indian contextual research, based on pertinent and appropriate enabler-based studies. Accordingly, it is not meant for an exhaustive review on GM and SM.

Review of GM Enablers

Some studies[1,2] argue that commitment from top, development of green process-driven technologies, green laws, and green corporate image are key for GM in India. It includes reduction in waste, water, energy, product returns, encourages new opportunities, assists in improving profit, revamping supply chain, and improving employee morale.[18] Scholars like Sarkis,[19] argue that manufacturers should be familiar with appropriate GM strategies for competitive advantages while complying regulatory requirements. Consumers are prepared to pay more for green initiatives.[20] Government encourages manufacturers for GM through incentives and investment schemes, to reduce resources consumption and to reduce environmental deterioration.[21] Reducing material utilization, releasing pollutants, power usage, and corporate social responsibility can be accomplished by using sustainable supplies and environmentally friendly designs.[22,23]

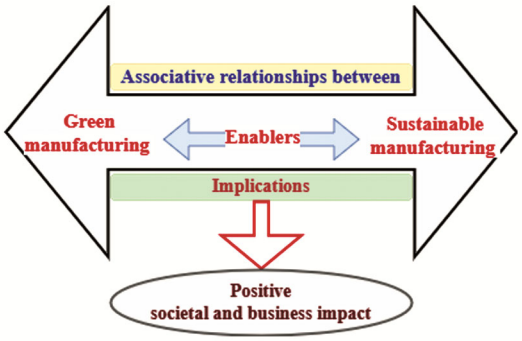

Fig. 1 — Conceptual diagram capturing associative relationships between GM and SM enablers

Indian manufacturing enterprises should include GM training to promote green products with regulations. Roy & Khastagir[24] emphasize on the green innovations, and recycled products.[3,6] Singh *et al.*[25] argue that cost-reduction is not considered important for GM in small and medium industries, and state about GM acceptance in large industries. Whereas, the reality is, GM leads to improved relations, compliance, and lower costs.

GSCM (green supply chain management) has been identified as a critical component in reducing negative environmental impacts in developing countries, as well as a contributor to achieving comprehensive environmental performance improvement.[3]

According to Agi & Nishant[9], employee education and GM training impact on GSCM practices in Gulf countries. In Indian context compliance with commitment, is critical.[6] Following GM enablers as given in Table 1 are identified based on the literature along with involvement of experts.

Determination of SM Enablers

SM has many definitions and interpretations. Its premise is based on triple bottom line of the industrial system emphasizing social, environmental, and economical aspects for sustainable production. According to Enyoghasi & Badurdeen[37] SM is subset of overall sustainable development. SM is eco and society friendly and has a potential of paying good dividends.[3–5]

Caiado *et al.*[37] recognize strategic planning, reduce energy, green image, customers and suppliers satisfaction to achieve SM. Reduction in transportation, SM processes and technologies, sustainable supportive innovation create larger impact in this domain. Similarly green marketing, is also a major proponent for SM. Scholars[38,39] identified various enablers of SM like environmental (reduction in emission, waste, material usage, energy), economic (use of products leveraging

Table 1 — GM Enablers

S. r	Abr.	Description
1	REG	Regulatory enforcement and Compliance with rigorous implementation from Governments[21,25–27]
2	GPR	Government, Civic, and Market Pressures to become green[3,6,21]
3	GCO	Government cooperation and support in the form of incentives, subsidies, financial aid, and technical support[18,20,21]
4	RUE	Resource utilization efficiency promoting green design, waste minimization and green packaging[8,24,26,28–32]
5	TLC	Top Leadership dedication with a definite goal and tenacity[6,7,33]
6	GSCM	Green Supply Chain Management with reverse logistics for GM[12,27,32–34]
7	SIP	Participation of all stakeholders with significant, observable contributions[6,13,20,35]
8	GTU	Innovative green technological advancement with improved performance analysis and control methods[6,8,25,33]
9	EAP	Promoting ecological awareness via green education and skill enhancement[7,18,21]
10	GCM	Green competitiveness in the market through brand positioning along with price minimization[6,14,18,20,25]
11	GOC	Green transformation in organizations that promotes productivity, strategy, and fidelity[3,7,36]

Table 2 — Sustainable manufacturing enablers

Sr	Abr.	Description
1	GRT	Plan of action from government to help move toward sustainable activities[7,44,45]
2	GER	Governments must enforce regulations and comply with their rigorous execution to ensure sustainable manufacturing[6,19,38,46]
3	GSM	Attempts from the government, society, and market for being sustainable[3,11,20,21]
4	GFS	Government involvement and assistance for sustainable manufacturing in the form of funding, aid, rewards, and support for technology[6,18,47]
5	RUE	Efficiency in using resources, encouraging waste reduction, recyclable packaging, and sustainable design[8,24,26,31,38,39]
6	RTA	Recent technology is being used for manufacturing to create sustainable value[8,18,24,42,48]
7	TLC	Top Leadership commitment with an explicit objective and perseverance for sustainability[3,6,45,49]
8	SSCM	Sustainable supply chain management with reverse logistics, ensuring sustainable supplier[5,19,27,34,36,38,40,50]
9	STD	Sustainable technical development with enhanced control and operation techniques[8,25,33]
10	SEA	Promoting ecological awareness via sustainability instruction and learning[18,21,51]
11	SBM	Maintaining Sustainable Business Competence through customer delighted and Brand positioning[14,18,33]
12	SOC	Sustainable organizational change that nurtures tactics, dedication, and profitability[20,25,29]
13	ESM	Encouragement and support for sustainable production among employees[13,38,45]
14	SPM	Sustainable Procurement & Material Management balancing factors of sustainability[36,38,47]
15	CWP	Consumers' willingness and ability to pay more for sustainable stuffs[36,39,52]
16	EFA	Environmental Footprint based awareness among the stakeholders[3,8,37,52]
17	CRI	The impact of corporate responsibility on stakeholder perception and organizational image[38,45]

3Rs, energy-efficiency, lower cost) and societal (use of products ensuring ergonomics, employee safety, customer satisfaction and social needs). Practice of the 6Rs strategy leads to closed loop manufacturing and drives SM. Scholars highlight the significance of technology and its leading role for SM.

According to Samad *et al.*[40] GSCM positively influences the firms' sustainable enactments. Study by Zhang *et al.*[41] proposes use of big data analytics and artificial intelligence (BDA-AI) to ensure GSCM.

Manufacturing industries must shift to Industry 4.0 to achieve SM for organizational synergy[42], whereas green planning for SM could be another strategy.[43]

Asian countries like, Japan and South Korea have stepped forward to deploy SM. India and China have been slow to adapt this concept. Customer needs, regulation, manager roles, and cost reductions vary depending on the cultural milieu in which a firm operates.[11] For industrial organisations, Barletta *et al.*[4] developed an organizational sustainability readiness model and identified capability in terms of product modularity, refurbishment, easy maintenance, continuous improvement, new technology, resource efficiency.

The enablers for SM (Table 2) have been identified in Indian context based on literature & expert opinions.

Research Methodology (ISM Selection, Rationale, and Model Creation for GM and SM)

This section covers both—methodology and working of the chosen approach. The key requirements of research are-chosen approach should facilitate prioritization, modelling to handle tangling nature of enablers and offer detailed comparisons to ensure demystification and extensions. Authors attempted this through Interpretive Structural Modelling (ISM) as suggested by scholars (Seth *et al.*[2], Bhanot *et al.*[53] and Govindan *et al.*[54]) inclusive research methodology as shown in Fig. 2.

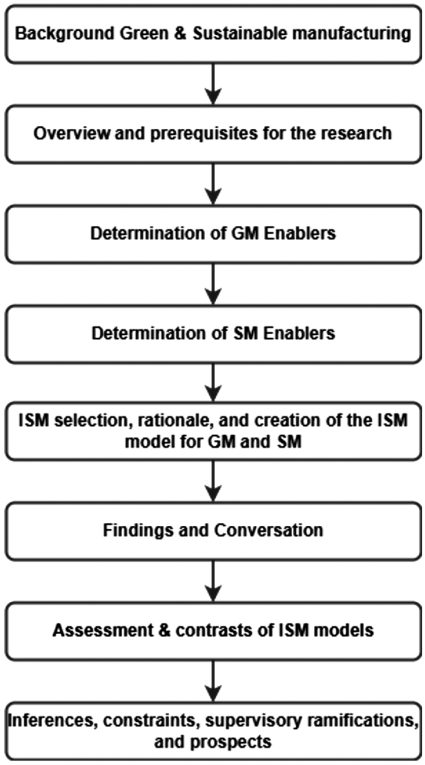

Fig. 2 — Inclusive research methodology

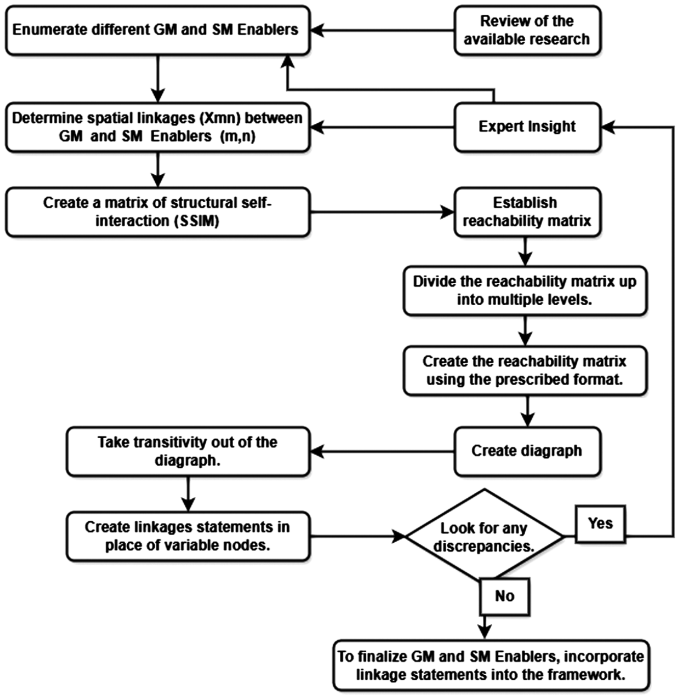

Fig. 3 — Working of ISM (modified from[3,54])

Table 3 — Structural self-interaction matrix(SSIM) for GM enablers

	Enabler	11	10	9	8	7	6	5	4	3	2
1	REG	E	E	G	E	E	E	E	E	G	F
2	GPR	E	E	G	E	E	E	E	E	G	
3	GCO	E	E	E	E	F	G	E	E		
4	RUE	E	E	F	E	F	E	E			
5	TLC	E	F	E	F	F	E				
6	GSCM	E	F	E	F	F					
7	SIP	E	E	G	E						
8	GTU	E	G	E							
9	EAP	E	E								
10	GCM	G									
11	GOC	G									

Working of ISM

Few investigations using ISM in this domain, are available in Indian context, like Govindan *et al*.[55] for analyzing enablers in the reverse logistic providers. Seth *et al*.[2] used ISM for small & medium industries along with large industries for GM enablers. Various enablers in the Indian oil and gas sectors were highlighted by Raut *et al*.[33] The working of ISM is presented in Fig. 3.

The following are various phases involved in creating an ISM model.

Structural Self-Interaction Matrix (SSIM) Preparation Involving Experts

Experts from related fields (industries, consultants, and academicians) were involved in establishing the Structural Self-Interaction Matrix (SSIM) based relationships among enablers. The listed SM and GM enablers are discussed with experts for their consensus regarding placement and to finalize relative relationships between enablers.

Table 4 — Structural self-interaction matrix(SSIM) for SM enablers

	Enabler	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2
1	GRT	E	F	G	E	E	E	E	E	E	G	E	E	G	G	G	G
2	GER	G	F	G	E	E	E	E	E	E	F	E	E	F	F	F	
3	GSM	E	G	G	E	E	E	E	E	E	E	E	E	G	E		
4	GFS	E	G	G	E	E	E	E	E	E	E	E	E	G			
5	RUE	E	E	G	E	E	E	E	E	E	F	G	E				
6	RTA	E	G	G	E	E	F	E	F	F	F	E					
7	TLC	E	G	G	E	E	F	E	F	F	F						
8	SSCM	E	E	G	E	E	E	E	E	E							
9	STD	E	E	G	F	E	F	E	G								
10	SEA	G	G	G	F	G	F	G									
11	SBM	G	G	G	F	F	F										
12	SOC	E	E	G	E	E											
13	ESM	E	E	G	F												
14	SPM	E	E	G													
15	CWP	E	G														
16	EFA	G															
17	CRI																

Tables 3 and 4 indicate SSIM representation in context to GM and SM enablers. As recommended by Govindan *et al*.[55], following ISM methodology and guidelines about transitivity, this study also uses four

notations to represent the relationships between GM and SM enablers (y and z).[54,55]

E-Enabler y will aid in attaining enabler z; F-Enabler z will aid in attaining enabler y;

G-Enablers y and z will aid mutually; H-Enablers y and z are unrelated

Preparation of Reachability Matrices (Initial & Final for Both Set of Enablers)

For the next stage also, following Govindan *et al*.[55] experts are involved and reach ability matrices are prepared. The major steps are as under.

The initial reach ability matrix is developed using a binary structure, substituting 1 and 0 for E, F, G, and H as indicated.

If (y, z) admittance in SSIM is E, then (z, y) entry becomes 0 and (y, z) entry turns 1 in the initial reachability matrix;

If (y, z) admittance in SSIM is F, then (z, y) entry turns 1 and (y, z) entry turns 0 in the matrix;

If (y, z) admittance in SSIM is G, then (z, y) entry turns 1 and(y, z) entry also turns 1 in matrix; If (y, z) admittance in SSIM is H, then (z, y) entry turns 0 and (y, z) entry also turns 0 in initial reachability matrix; Tables 5 and 6 respectively capture both, driving and dependence powers for GM & SM. These powers indicate the impact of one enabler over other. The core of ISM is made of driving and reliance power elements, which represent how one enabler influences another. An enabler's driving power is the total number of enablers—including oneself—that it can help achieve. The dependence is the total number of enablers that could help it be accomplished. Tables 5 and 6 represent GM and SM final reachability matrices with driving and dependence powers of applicable enablers.

Table 5 — Final reachability matrix for GM

No	Enablers	1	2	3	4	5	6	7	8	9	10	11	Driving power
1	REG	1	0	1	1	1	1	1	1	1	1	1	10
2	GPR	1	1	1	1	1	1	1	1	1	1	1	11
3	GCO	1	1	1	1	1	1	0	1	1	1	1	10
4	RUE	0	0	0	1	1	1	0	1	0	1	1	6
5	TLC	0	0	0	0	1	1	0	0	1	0	1	4
6	GSCM	0	0	1	0	0	1	0	0	1	0	1	4
7	SIP	0	0	1	1	1	1	1	1	1	1	1	9
8	GTU	0	0	0	0	1	1	0	1	1	1	1	6
9	EAP	1	1	1	1	0	1	1	0	1	1	1	9
10	GCM	0	0	0	0	1	1	0	1	0	1	1	5
11	GOC	0	0	0	0	0	0	0	0	0	1	1	2
	Dependence power	4	3	6	6	8	11	4	7	8	9	11	

Table 6 — Final reachability matrix for SM

No	Enablers	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	Driving power
1	GRT	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	16
2	GER	1	1	0	0	0	1	1	0	1	1	1	1	1	1	1	0	1	12
3	GSM	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	17
4	GFS	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	16
5	RUE	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	16
6	RTA	0	0	0	0	0	1	1	0	0	0	1	0	1	1	1	1	1	8
7	TLC	1	0	0	0	1	0	1	0	0	0	1	0	1	1	1	1	1	9
8	SSCM	1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	15
9	STD	0	0	0	0	0	1	1	0	1	1	1	0	1	0	1	1	1	9
10	SEA	0	0	0	0	0	1	1	0	1	1	1	0	1	0	1	1	1	9
11	SBM	0	0	0	0	0	0	0	0	0	1	1	0	0	0	1	1	1	5
12	SOC	0	0	0	0	0	1	1	0	1	1	1	1	1	1	1	1	1	11
13	ESM	0	0	0	0	0	0	0	0	0	1	1	0	1	0	1	1	1	6
14	SPM	0	0	0	0	0	0	0	0	1	1	1	0	1	1	1	1	1	8
15	CWP	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	17
16	EFA	1	1	1	1	0	1	1	0	0	1	1	0	0	0	1	1	1	11
17	CRI	0	1	0	0	0	0	0	0	0	1	1	0	0	0	0	1	1	5
	Dependence power	9	9	5	6	7	12	13	5	11	15	17	8	14	11	16	15	17	

Level Partitions along with Iterations

Each enabler's reachability and precursor group are determined by the final reachability matrix.

Level partitioning is the process of dividing this matrix of reachability into several levels using repetitions based on every variable's reachability and antecedent sets. A graph with directions is prepared by forming a canonical matrix based on the reachability matrix and level partitioning. At the peak of the ISM-structure, are enablers with identical intersection set and reachability, nonetheless they don't assist in achieving another component atop their own particular level.[54] The study presents iterations or cycles for the initial reachability, antecedent, and intersection sets of GM and SM enablers. The ISM structure can be built by separating the top-level variables from the remaining ones and repeating the process for every stage until all enablers have identical tiers (refer sample workings shown in Table 7 for GM, it also capture final levels for GM and SM).

Table 7 — GM & SM enablers' initial reachability, antecedent, and intersection sets

	Enablers	Reachability Set	Antecedent Set	Intersection Set	Level
GM Enablers	1	1,3,4,5,6,7,8,9,10,11	1,2,3,9	1,3,9	I
	2	1,2,3,4,5,6,7,8,9,10,11	2,3,9	2,3,9	
Iteration 1	3	1,2,3,4,5,6,8,9,10,11	1,2,3,6,7,9	1,2,3,6,9	
	4	4,5,6,8,10,11	1,2,3,4,7,9	4	
	5	5,6,9,11	1,2,3,4,5,7,8,10	5	
	6	3,6,9,11	1,2,3,4,5,6,7,8,9,10	3,6,9	
	7	3,4,5,6,7,8,9,10,11	1,2,7,9	7,9	
	8	5,6,8,9,10,11	1,2,3,4,7,8,10	8,10	
	9	1,2,3,4,6,7,9,10,11	1,2,3,5,6,7,8,9	1,2,3,6,7,9	
	10	5,6,8,10,11	1,2,3,4,7,8,9,10,11	8,10,11	
	11	10,11	1,2,3,4,5,6,7,8,9,10,11	10,11	
GM Enablers	1	1,3,4,5,6,7,8,9,10,11	1,2,3,9	1,3,9	II
	2	1,2,3,4,5,6,7,8,9,10,11	2,3,9	2,3,9	
Iteration 2	3	1,2,3,4,5,6,8,9,10,11	1,2,3,6,7,9	1,2,3,6,9	
	4	4,5,6,8,10,11	1,2,3,4,7,9	4	
	5	5,6,9,11	1,2,3,4,5,7,8,10	5	
	6	3,6,9,11	1,2,3,4,5,6,7,8,9,10	3,6,9	
	7	3,4,5,6,7,8,9,10,11	1,2,7,9	7,9	
	8	5,6,8,9,10,11	1,2,3,4,7,8,10	8,10	
	9	1,2,3,4,6,7,9,10,11	1,2,3,5,6,7,8,9	1,2,3,6,7,9	
	11	10,11	1,2,3,4,5,6,7,8,9,10,11	10,11	
GM Enablers	1	1,3,4,5,6,7,8,9,10,11	1,2,3,9	1,3,9	III
	2	1,2,3,4,5,6,7,8,9,10,11	2,3,9	2,3,9	
Iteration 3	3	1,2,3,4,5,6,8,9,10,11	1,2,3,6,7,9	1,2,3,6,9	
	4	4,5,6,8,10,11	1,2,3,4,7,9	4	
	5	5,6,9,11	1,2,3,4,5,7,8,10	5	
	6	3,6,9,11	1,2,3,4,5,6,7,8,9,10	3,6,9	
	7	3,4,5,6,7,8,9,10,11	1,2,7,9	7,9	
	9	1,2,3,4,6,7,9,10,11	1,2,3,5,6,7,8,9	1,2,3,6,7,9	
	11	10,11	1,2,3,4,5,6,7,8,9,10,11	10,11	
Level of GM enablers	1	1,3,4,5,6,7,8,9,10,11	1,2,3,9	1,3,9	**VII**
	2	1,2,3,4,5,6,7,8,9,10,11	2,3,9	2,3,9	**VIII**
	3	1,2,3,4,5,6,8,9,10,11	1,2,3,6,7,9	1,2,3,6,9	**VII**
	4	4,5,6,8,10,11	1,2,3,4,7,9	4	**IV**
	5	5,6,9,11	1,2,3,4,5,7,8,10	5	**VI**
	6	3,6,9,11	1,2,3,4,5,6,7,8,9,10	3,6,9	**IV**
	7	3,4,5,6,7,8,9,10,11	1,2,7,9	7,9	**V**
	8	5,6,8,9,10,11	1,2,3,4,7,8,10	8,10	**II**
	9	1,2,3,4,6,7,9,10,11	1,2,3,5,6,7,8,9	1,2,3,6,7,9	**VI**
	10	5,6,8,10,11	1,2,3,4,7,8,9,10,11	8,10,11	**I**
	11	10,11	1,2,3,4,5,6,7,8,9,10,11	10,11	**III**

(*Contd.*)

Table 7 — GM & SM enablers' initial reachability, antecedent, and intersection sets — (*Contd*.)

	Enablers	Reachability Set	Antecedent Set	Intersection Set	Level
Level of SM enablers	1	1,2,3,4,5,6,7,8,9,10,11,12,13,14, 15,17	1,2,3,4,5,7,8,15,16	1,2,3,4,5,7,8,15	**VI**
	2	1,2,6,7,9,10,11,12,13,14,15,17	1,2,3,4,5,8,15,16,17	1,2,15,17	**X**
	3	1,2,3,4,5,6,7,8,9,10,11,12,13,14,15, 16,17	1,3,5,15,16	1,3,5,15,16	**VIII**
	4	1,2,4,5,6,7,8,9,10,11,12,13,14,15, 16,17	1,3,4,5,15,16	1,4,5,15,16	**IX**
	5	1,2,4,5,6,7,9,10,11,12,13,14,15,16,17	1,3,4,5,7,8,15	1,„4,5,7,15	**V**
	6	6,7,11,13,14,15,16,17	1,2,3,4,5,6,8,9,10,12,15,16	6,15,16	**IV**
	7	1,5,7,11,13,14,15,16,17	1,2,3,4,5,6,7,8,9,10,12,15,16	1,5,7,15,16	**VII**
	8	1,2,5,6,7,8,9,10,11,12,13,14,15,16,17	1,3,4,8,15	1,8,15	**V**
	9	6,7,9,10,11,13,15,16,17	1,2,3,4,5,8,9,10,12,14,15	9,10,15	**III**
	10	6,7,9,10,11,12,13,15,16,17	1,2,3,4,5,8,9,10,11,12,13,14,15, 16,17	9,10,11,12,13,15, 16,17	**VI**
	11	10,11,15,16,17	1,2,3,4,5,6,7,8,9,10,11,12,13,14, 15,16,17	10,11,15,16,17	**IV**
	12	6,7,9,10,11,12,13,14,15,16,17	1,2,3,4,5,8,12,15	12,15	**VI**
	13	10,11,13,15,16,17	1,2,3,4,5,6,7,8,9,10,12,13,14,15	10,13,15	**III**
	14	9,10,11,12,13,14,15,16,17	1,2,3,4,5,6,7,8,12,14,15,	12,14,15,	**III**
	15	1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,1 7	1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16	1,2,3,4,5,6,7,8,9,10,11 ,12,13,14,15,16	**II**
	16	1,2,3,4,6,7,10,11,15,16,17	3,4,5,6,7,8,9,10,11,12,13,14,15,16,17	3,4,6,7,10,11,15,16,17	**II**
	17	2,10,11,16,17	1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,2,10,11,16,17 17		**I**

MICMAC Analysis of GM and SM Enablers

MICMAC analysis, often used in tandem with ISM offers classification of enablers in four broad categories. It does so utilizing their powers of driving and dependence. It offers meaningful insights based on the positioning of enablers which in turn decide the influence and role and subsequent treatments. Enablers can be grouped as autonomous, dependent, linkage, and independent enablers and accordingly the matrix has four quadrants[6,55] as shown in Fig. 4 and 5 respectively.

Here, sum of rows represents driving power, while column represents dependence power. It is revealed in Table 5 and Table 6 respectively. Enablers 3 and 4 (driving power 10 & 6, dependence power 6) are placed grounded as per their driving and dependence power as shown in Fig. 4 and 5 respectively.

There are no autonomous enablers in Cluster I in context to GM enablers. Four dependent enablers (5, 6, 10, and 11) that have weak driving power but substantial reliant power are part of Cluster II. The four linkage enablers (3, 4, 8, and 9) that form Cluster III have substantial driving and dependency powers. Three independent enablers (1, 2, and 7) that exhibit strong driving power and low reliance power make up Cluster IV.

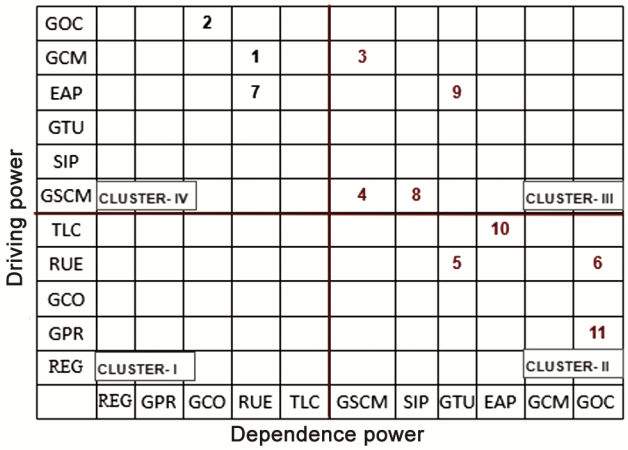

Fig. 4 — Clusters of GM enablers for strategic positioning

No autonomous enablers are noticed in Cluster I for SM enablers. Five dependent enablers (6, 11, 13, 14, and 17) form Cluster II due to high reliance power but low driving power. Seven linking enablers (numbers 1, 2, 7, 9, 10, 15, and 16) in Cluster III have substantial driving and reliance powers, demonstrating their crucial role in SM adoption. Five independent enablers 3, 4, 5, 8 and 12 are highlighted in Cluster IV. Each of these enablers exhibits considerable driving power and little dependence, indicating their impact as shown in Fig. 5

ISM Digraphs Development for GM and SM

Employing initial reachability matrix, the framework is created referring Govindan *et al*.[55] The first digraph is prepared by using arrows pointing from element y to z to highlight the relationships between enablers. The final digraph, is then converted into ISM and is created by refining previous digraph by removing transitive relationships. Digraph relationships between enablers could be understood from Fig. 6.

Results Assessment & Contrasts of Models

From the appropriate GM and SM enablers, using ISM modelling and subsequently MICMAC analysis, this research models to address the tangling relationships and offers meaningful clustering to comprehend deeper aspects of enablers about their strengths, dependencies, and interdependencies, to ensure better treatment. Both ISM modelling and MICMAC analysis reinforce each other and therefore, are used in tandem.

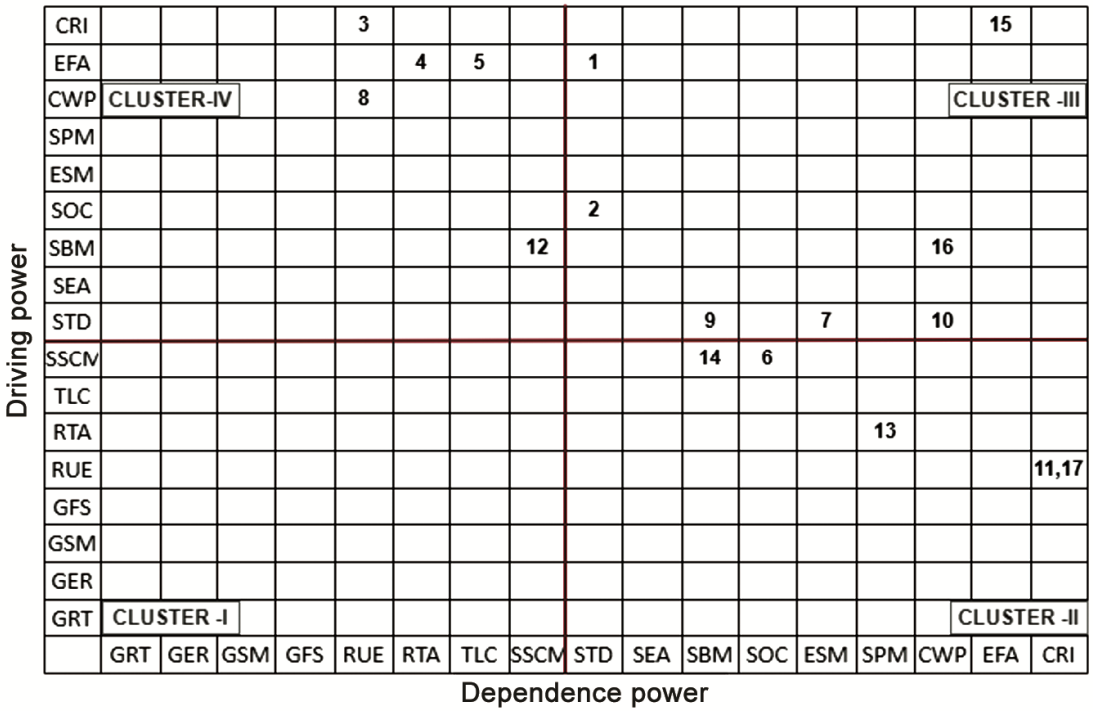

Fig. 5 — Cluster of SM enablers for strategic positioning

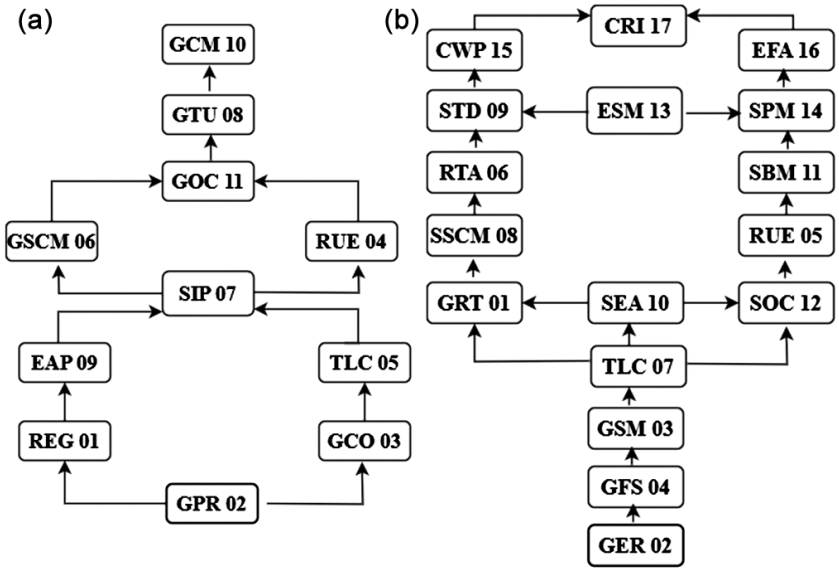

Fig. 6 — Digraph relationships between: (a) GM enablers, (b) SM enablers

Based on modelling and clustering of enablers, one develops deeper understandings and enlarged depiction, the findings are:

Cluster I (Autonomous enablers): -Cluster I of autonomous enablers offers a kind of check for the chosen enablers, its appropriateness and its treatment. Presence of no enablers in cluster I, clearly indicates that chosen GM and SM enablers are suitable and important for the study.

Cluster II (Dependent enablers): -Please refer to Figs 4 and 5 respectively, this cluster of enablers indicate weak driving power but strong dependence power.

For GM four dependent enablers (5, 6, 10, 11) like resource utilization efficiency promoting green design, waste minimization and green packaging, top leadership dedication with a definite goal and tenacity, green competitiveness in the market through brand positioning along with price minimization and green transformation in organizations that promotes productivity, strategy, and fidelity are the ones which belong to this category.

Whereas, for SM Five dependent enablers (6, 11, 13, 14, 17) like Recent technology for manufacturing to create sustainable value, maintaining sustainable business competence through customer, brand-positioning, encouragement and support for sustainable production among employees are important ones. This category includes the effects of corporate responsibility on stakeholder perception, organizational image, and sustainable procurement and material management.

Upon delving deep, one finds that enablers are similar in terms of leadership commitment, both focuses on leadership commitment with perseverance for green and sustainability (TLC).

Cluster III (Linkage enablers):-One finds from the Fig. 4 and 5, that enablers with strong driving and dependence powers are treated as cluster III enablers, which have compounding and feedback capabilities for actions. For GM four and for SM seven enablers form this category. For GM Linkage enablers (3, 4, 8, 9) belong to this cluster. These are Government cooperation and support in the form of incentives, subsidies, financial aid, and technical support, resource utilization efficiency promoting green design, waste minimization and green packaging, innovative green technological advancement with improved performance analysis and control methods, promoting ecological awareness via green education and skill enhancement.

Whereas, for SM (1, 2, 7, 9, 10, 15, 16) form this cluster. These are Government plan of action for sustainable activities. Government must enforce regulations and ensure rigorous execution for SM, top leadership commitment with an explicit objective and perseverance for sustainability, sustainable technical development with enhanced control and operation techniques, promoting ecological awareness via sustainability instruction and learning, consumers' willingness and ability to pay more for sustainable stuffs, environmental footprint-based awareness among the stakeholders.

Cluster IV (Independent enablers): As mentioned earlier enablers with strong driving and weak dependence powers are treated as independent. For GM three and for SM eight enablers form this cluster. For GM these three independent enablers (1, 2, 7) are regulatory enforcement and compliance with rigorous implementation from Government, civil society, and market pressures to become green, participation of all stakeholders with significant, observable contributions.

For SM independent enablers (3, 4, 5, 8, 12) are-attempts from the government, society, and market for being sustainable, Government involvement and assistance in the form of funding, aid, rewards, and support for technology, efficiency in using resources, encouraging waste reduction, recyclable packaging, and sustainable design, sustainable supply chain management with reverse logistics, ensuring sustainable supplier sustainable organizational change that nurtures tactics, dedication, and profitability

The ISM models for both GM and SM represented in Fig. 7 (a) and (b) respectively to indicate positioning of enablers based on intensity. Grouping of enablers facilitates the comparison as one notices lot of similarities and dissimilarities between them. This comparison becomes meaningful from treatment point of view when one compares cluster specific situation. For both GM and SM among all identified enablers, environmental regulation from State and strict implementation supported by legislation and pressures for greening from Government, markets, communities and supply chain needs, financial assistance and technology-based supports are the key common enablers. One also notices that because of high driving and low dependence strengths these enablers are observed at the bottom of model. A comparison of GM and SM enables is given in Table 8 and a cluster based summarization is presented in Fig. 8.

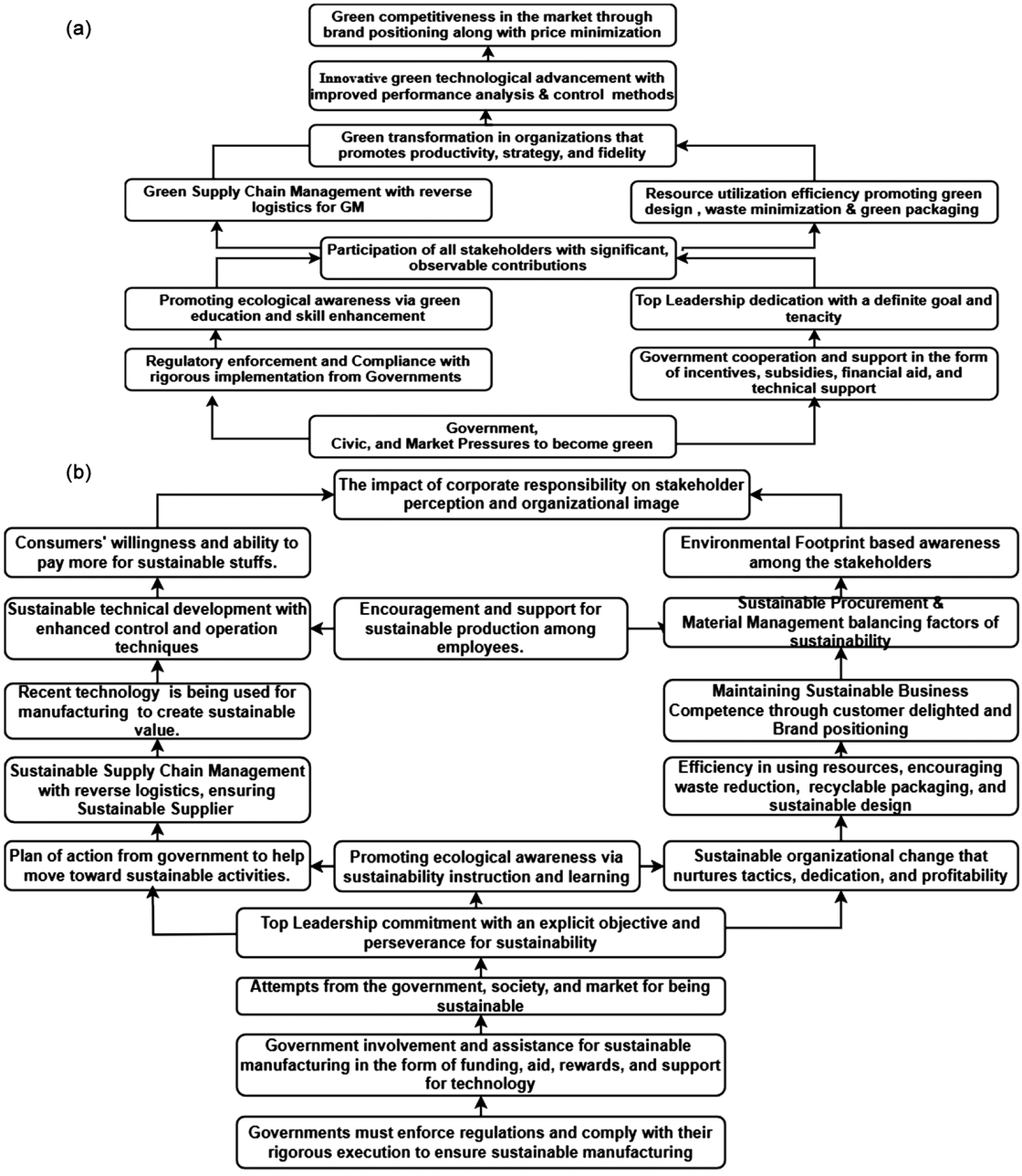

Fig. 7 —ISM models: (a) GM enablers-based, (b) SM enablers-based

Table 8 — Cluster wise comparison between GM and SM enablers

Cluster	GM	SM
I-autonomous enablers	None	None
II-dependent enablers	Four (TLC,GSCM,GCM,GOC)	Five (RTA,SBM,ESM,SPM, CRI)
III-Linkage enablers	Four (GCO,RUE,GTU,EAP)	Seven- GRT,GER ,TLC, STD,SEA, CWP,EFA)
IV-Independent enablers	Three (REG,GPR,SIP)	Five (GSM,GFS,RUE,SSCM,SOC)

Discussion, Major-Findings and Outcomes

It is expected developed ISM model should be discussed, with executives and policy makers. One notices infancy in context to Indian manufacturing sector in context to GM and SM associative relationship and much more needs to be done. Industries have understood the significance and benefits of GM and SM deployment, and the green

image.[8] Similarly, government assistance and initiatives are important determinants in the adoption of GM and SM infrastructure.[56]

Establishing cutting-edge R&D hubs through partnerships with research universities, energy providers, and investors call for a concerted effort from the government and business captains. Contemporary solutions that are in line with societal demands and environmental objectives, like high-efficiency solar materials, cutting-edge battery technologies, recycling systems, smart grids, and green hydrogen for storage and transportation, should be given priority. Industries in developing countries like India, can accelerate their green manufacturing progress by addressing key enablers such as REG, GPR, GCO, TLC, and EAP, as outlined in the established ISM model. Once these are effectively implemented and integrated into the system, the remaining enablers can be gradually addressed.

Authorities and business executives can use the study's insightful analysis as a strategic roadmap to improve manufacturing regulations and speed-up GM and SM initiatives. With interventions like tax breaks, financial assistance, technology support, focused training, it will facilitate Indian firms to embrace eco-friendly practices by plugging knowledge gaps. By embracing green energy, waste reduction, green design, and efficient resource usage, the findings endorse associative relationship toward more sustainable operations. The strength and social benefits are highlighted in Fig. 9

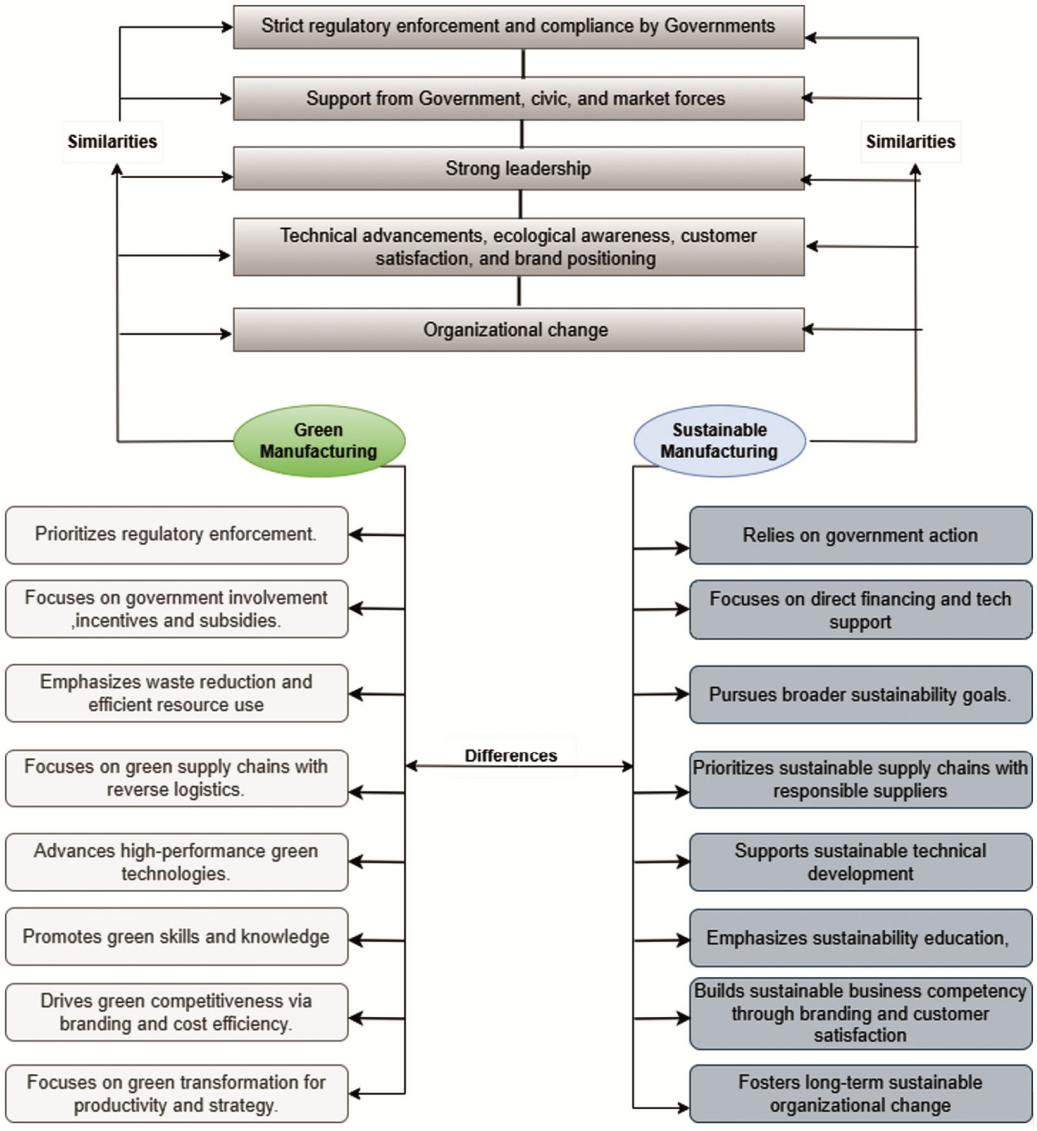

Fig. 8 — Key similarities and differences between GM and SM

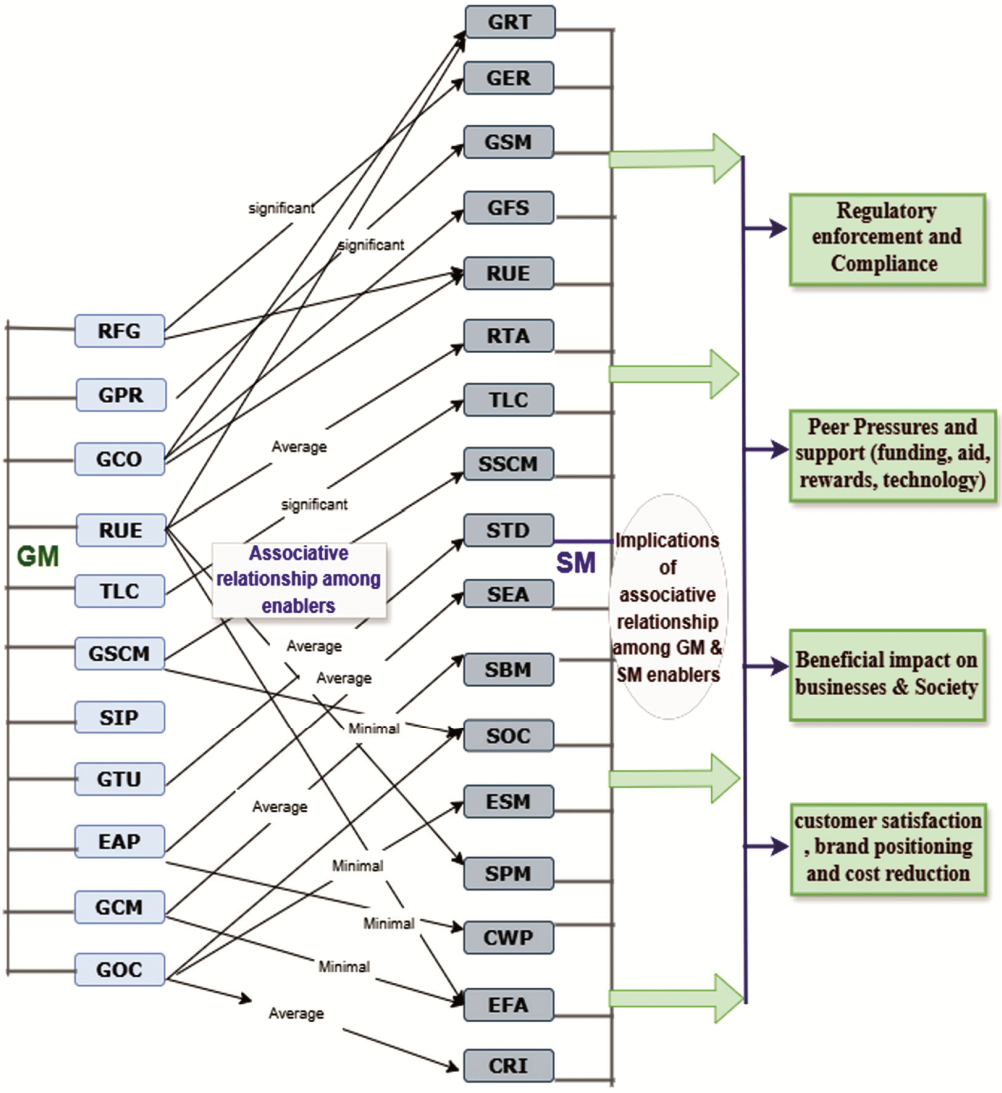

Fig. 9 — Implications of associative relationship among GM and SM enablers

Conclusions

In line with research objective raised, the study addresses enablers based associative relationship between GM and SM, using ISM modelling with MICMAC analysis. The research offers replicable roadmap for developing countries to lessen negative effects of manufacturing. Thus, it is immensely useful for researchers, managers and executives in comprehending an overall picture and will catalyze in accelerating the GM-SM implementation. One may find that associative relationship is more applicable in developing country rather than developed one. Other challenge, is due to lack of quantitative insight and restricted enablers. Researchers may extend this approach encompassing GM and SM on the upstream and downstream side of manufacturing and may include impacts of electrical vehicle. According to the placement in ISM models, the Government, businesses, and other stakeholders may work together to promote new researches in this domain. Comparative studies covering both developing and developed nations, will further add value to the body of knowledge.

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