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A Novel Approach towards Sustainability Assessment in Manufacturing and Stakeholder's Role

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Abstract: With increasing consumer awareness about sustainability and governmental policies to address environmental challenges and social responsibility, the manufacturing sector is under continuous pressure to adopt more sustainable practices. Trends show that factories of the future (FOF) will need to adapt to market demands, growing economic and ecological efficiency requirements, and corporate social responsibility; such versatility is vital to address consumer disquiet and sustainability expectations. Various approaches have been proposed to assess sustainability over the last few decades. Most of these approaches have limitations in that they are of marginal relevance to the manufacturing environment, tend to focus on only one aspect of sustainability, or are too complicated for most organisations to implement. Moreover, numerous studies have demonstrated a gap in sustainability expectations among various stakeholders, and no active mechanisms exist to prioritise sustainability in manufacturing. This paper introduced a novel approach to address both the manufacturer and multiple stakeholders' expectations about sustainability prioritisations in manufacturing practices. It achieved this using a modified quality function deployment (QFD) tool along with AHP and normalisation techniques. A set of system boundaries was adopted to evaluate sustainability in the manufacturing context; this research was a 'Gate to Gate' border. These indicators and a score-based approach will help organisations better grasp how manufacturing operations interact with sustainability and decision-making. They will help lead to improvements in the allocation of corporate resources used to manage and improve sustainability performance in manufacturing.

Keywords: sustainability; FOF; QFD; AHP; manufacturing

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1. Introduction

The article introduces a new sustainability assessment approach in manufacturing using the modified QFD tool and accounts for stakeholders' roles. The approach manages multiple stakeholders' expectations and influence in manufacturing. Sustainability assessment is a means that can help decisions and policymakers what actions they should take and should not take to make society more prosperous and ecological [1]. Defining and assessing sustainability is vital to track performance and set critical goals [2]. Sustainability has different dimensions, addressing environmental challenges, economic growth, social aspects, best practices in manufacturing, and performance management [3]. Different studies point to a split between the manufacturer's and stakeholders' preferences [4].

Sustainability is firmly on the agenda for manufacturing companies, and trends show that consumer interest and loyalty will be higher for the companies managing sustainability issues [5]. The impact of stakeholders in corporate sustainability performance keeps increasing, and governments reflect on these aspects of new taxation and legislation in the manufacturing sector [5,6]. Numerous studies have demonstrated that companies ignoring the sustainability issues and stakeholders' concerns in manufacturing practices will distance themselves from consumers [5,7].

There is a split between manufacturer and consumer expectations about sustainability elements [4]. Consumers and manufacturers have a diverse set of expectations about the sustainability elements. Consumers expect the manufacturer to give more attention to social sustainability, better utilise available resources, and value the money. In addition, manufacturers pay less attention to resource utilisation in contrast to consumer preferences; consumers almost give double the weightage to best utilisation of the resources and keep less dependency on the virgin materials. This provides a gap among multiple sustainability stakeholders and the need for an improved sustainability performance assessment methodology that accounts for stakeholder concerns and ranks in manufacturer agenda to deal with them.

There is the realisation that multiple stakeholders, mainly manufacturers and consumers, prioritise sustainability elements differently, such as Consumers want societal issues on the top of the agenda and 22.9% weightage whereas manufacturers consider 8% in their prioritisation list; similarly, a split exist on the environmental and resource utilisation elements [4]. This argument advocates that a holistic approach should adopt manufacturers to gauge multiple stakeholders' prioritisation and use organisation resources inaccurately.

This split argument about the different stakeholders' prioritisation demands a robust and custom approach in the manufacturing sector to address the multiple stakeholder's preferences and their role in designing and managing sustainability in the manufacturing sector.

Research question: How can sustainability be assessed in the manufacturing sector more robust, flexible, and precise while still incorporating stakeholders' expectations?

The research question demands an improved sustainability assessment approach explained in the paper within the manufacturing context. The contributions in this work are given as:

1. A number of benefits, limitations, and gaps in available sustainability assessment approaches in the manufacturing context are highlighted.
2. A robust and accurate sustainability assessment framework is proposed.
3. This research underlines the sustainability performance assessment and identifies manufacturing operations that require attention.
4. Validation of the sustainability approach in the manufacturing sector.

The sustainability score system in the manufacturing (3SM) approach has been proposed and developed after examining the different practice approaches and understanding the gaps in sustainability evaluation practices. After development, the '3SM' approach was validated through a pilot study using current manufacturing data in a manufacturing environment using a 'gate-to-gate' system boundary. The '3SM' approach was presented to a manufacturing company during the development phase and was updated using company appraisal and recommendations. It was then used for validation through a cross-functional team by collating relevant stakeholders' feedback and gathering sustainability data used in manufacturing. The approach appraisal was made with researchers, industry experts, and senior management in a manufacturing company regarding the applicability, usefulness, and relevance to the manufacturing environment.

2. Literature Review

Traditionally, sustainability is based on three essential aspects: environmental, economic growth, and social aspects. For this research, these were termed sustainability dimensions or pillars. The concept is studied in many environmental sciences, particularly business and management. The environmental factor is one of the elements in the supply chain. It plays an essential role in determining its impact on firms and its bearing on supply chain operations [8]. These societal forces are concerned with sustainability performance, which protects the environment and biodiversity and creates a better workplace and social life for employees and people involved in the supply chain. However, firms are typically more interested in profit and focus on the business's economic performance. There is a lack of understanding of the relationship between organisational responsibilities and stakeholder relationships. The stakeholder's and society's expectations are often not present in organisation sustainability actions [9].

In the manufacturing context, there are five critical aspects of sustainability, i.e., sustainability dimensions, as shown in Figure 1. A comparative study of different sustainability approaches found that most were environment-focused and did not address sustainability's other critical aspects, such as social, research and development, and performance management. It was also identified through literature review and analysis of different sustainability assessment approaches in the manufacturing context lacking in sustainability elements and not considering multiple stakeholders' roles. This leads to a split and broader gap between manufacturers' efforts and stakeholders and customers' expectations about manufacturing [4].

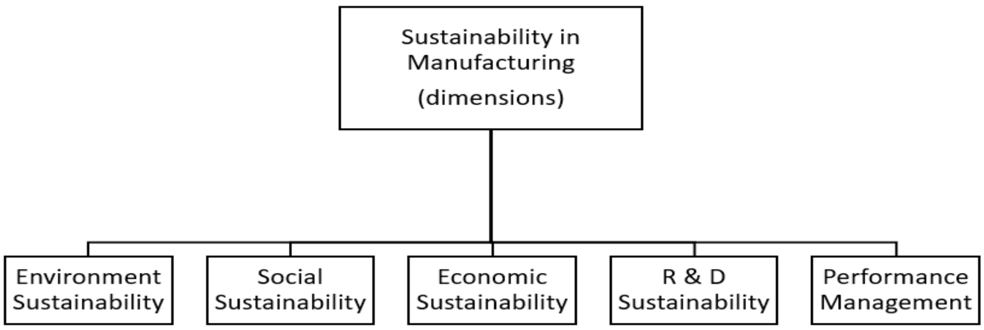

Figure 1. Five sustainability dimensions for sustainable manufacturing [3].

The most common guidelines for evaluating sustainability in the industry are GRI 4.0, which over twelve thousand organisations adopted to assess and report sustainability performance [10]. However, it does not consider relevant stakeholders' expectations and the manufacturing dynamics of organisations. In practice, this gap exists in most sustainability approaches, not just ones about manufacturing.

Researchers and experts agree that sustainability, including production and people's consumption patterns, is crucial for securing a prosperous future. Various approaches are practised and published in academic literature, but most are generic or applied to specific scenarios. What is needed is a flexible approach that can be customised to meet any organisation's needs in the manufacturing sector. Manufacturing needs to measure better, monitor, control, and deliver sustainable manufacturing technologies. Organisations must analyse feedback from stakeholders, meet consumer demands, and cope with the changing trends in modern industry.

2.1. Sustainability Assessment Approaches and Frameworks

Stakeholders' expectations management about multiple stakeholders and accounting in sustainability element appreciation and prioritisation is essential to bridge the split of multiple stakeholder preferences. In this section, different sustainability assessment approaches appreciate five sustainability pillars outlined by the NIST (2015) [3] study, including the stakeholder's role in sustainability prioritisations. There is an argument that stakeholders have a crucial position in developing an organisation's sustainability program [11], and it appears that existing approaches have tended to neglect this. Most available approaches are general and do not consider the relevant stakeholders' expectations in sustainability elements or pillar prioritisations.

EN ~ Environmental sustainability indicators.
S.C. ~ Social sustainability indicators.
E.C. ~ Economic sustainability indicators.
R.D. ~ Research and development indicators.
P.F. ~ Performance management.
S.T. ~ Stakeholders' concerns (internal and external).

Most sustainability approaches listed in Table 1 are limited to one or two sustainability dimensions and focus on one dimension. For example, life cycle analysis (LCA) is a renowned approach but is limited to environmental only. Life cycle sustainability analysis is a comprehensive approach to sustainability assessment. It combines life cycle analysis, life cycle costing, and social life cycle costing (LCSA = LCA + LCC + SLCA), covering all key sustainability dimensions [12]. It still does not account for stakeholder concerns [13], such as their expectations about manufacturing. Few companies consider customer and stakeholder expectations in a sustainability matrix. Different studies and surveys have demonstrated that customers' loyalty to and satisfaction with a brand increase when their sustainability concerns are addressed [14].

Table 1. Comparison of different sustainability assessment approaches.

Sustainability Approaches	EN	SC	EC	RD	PF	ST	Sources
Life cycle analysis (LCA)	√						[15]
Life cycle sustainability analysis (LCSA=LCA+LCC+SLCA)	√	√	√				[12]
SAM*i* (Sustainability model indicator-BP)	√	√	√				[16]
Integrated environment assessment (IEA)	√						[17]
Lowell Sustainability for Sustainable Manufacturing (LCSP)	√	√	√				[2]
Material intensity analysis	√						[18]
Dow Jones Sustainability Index	√	√	√				[19]
Ford Product Sustainability Index (Ford PSI)	√	√	√				[20]
International Organization for Standardization (ISO) Environment Performance Evaluation (EPE) standard (ISO 14031)	√	√			√		[21]
Japan National Institute of Science and Technology Policy (NIS-TEP)		√	√	√			[22]
S-loop sustainability model	√	√	√				[23]
The Institute of Chemical Engineers (IChemE)	√	√	√				[24]

Another approach, the Global Reporting Initiatives (GRI) guidelines, is most commonly and widely used to report on corporate social responsibility (CSR), and over 12,000 organisations use the GRI guidelines to do so [10]. However, GRI guidelines do not address stakeholders' expectations regarding selecting and assessing sustainability elements and prioritising the organisation. GRI guidelines have become a default way to select sustainability elements and report performance. However, they do not provide a basis to reflect stakeholders' expectations in prioritising sustainability elements.

2.2. Stakeholder's Engagement in Sustainability Assessment

It has been identified that the split of multiple stakeholders' preferences in sustainability assessment approaches demands the new approach to account for stakeholders' prioritisation in manufacturing. Another reason for corporate sustainability reports (CSR's) is to address stakeholder concerns about the environment and social subjects in the organisation [25,26]. The manufacturing sector should address social responsibility, business challenges, and initiatives to handle those [6]. Different studies demonstrate that with increasing awareness of sustainability, climate changes, and global warming, customers and stakeholders pay more attention to organisation efforts to deal with them [27].

A scoring system for sustainability assessment in manufacturing can help manufacturers and policymakers understand the sustainability of operations [28]. Dedicated efforts and teamwork require addressing and managing stakeholders' expectations and influence sustainability [29].

Research of 2500 companies listed in the Dow Jones Index was surveyed to establish the relationship between stakeholders' engagement in sustainability performance [11]. These companies included all sectors and strengthened the sustainability innovation and stakeholder engagement relationship. This work demonstrated that for sustainability innovation, it is essential to involve internal stakeholders (H1) and external (H2) stakeholders and knowledge management [11]. There are different tools, including interviews, surveys, public opinions, social media, Facebook, and Twitter, to understand the local and global sustainability trends to develop corporate social responsibility strategy and align company efforts to satisfy stakeholders, including consumers [30]. Active stakeholders' engagement in selecting and weighting sustainability indicators is vital for sustainability performance and loyalty to the company [11]. This discussion highlights the importance of the sustainability assessment, which captures the stakeholder's interest and influence at stage-II.

Figure 2 validated that internal and external stakeholders' feedback is directly related to sustainability innovation in manufacturing. The stakeholders' impact can be assessed by understanding their expectations and influence on business sustainability, including evaluating a similar approach to risk assessments [31]. In risk management, two factors involved in the assessment are severity and chances of occurrence [32]. Similarly, we can assess stakeholder impact by considering expectations and influence as the two main factors [31,33]. The stakeholder's impact can assess by understanding their expectation and influence, as shown in Figures 3 and 4.

Stakeholder impact = stakeholder expectations × stakeholder influence.

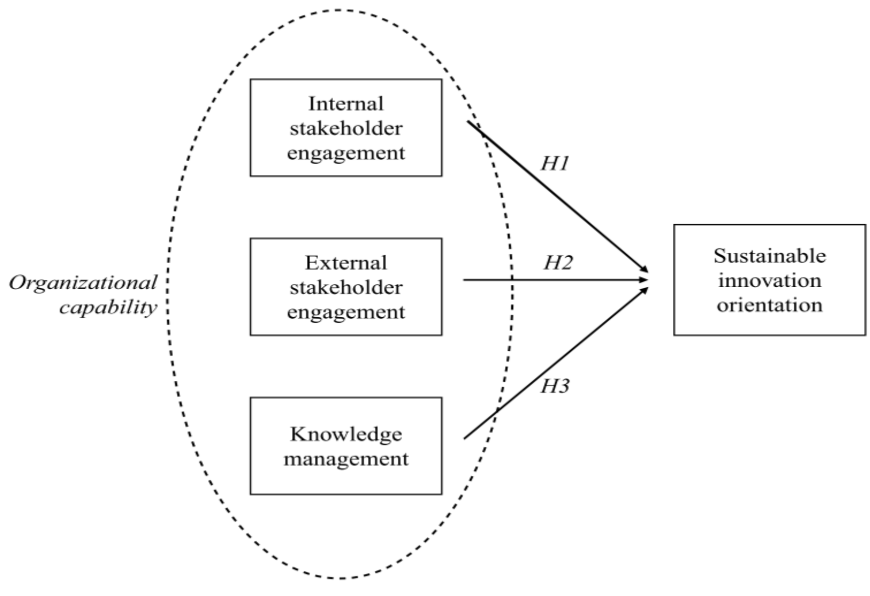

Figure 2. Stakeholder's relationship for sustainability innovation [11].

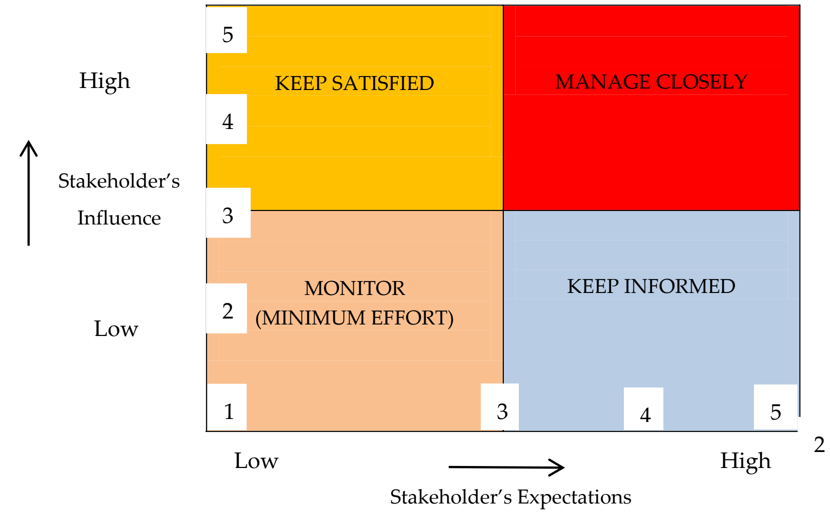

Figure 3. Stakeholder grid over influence and interest.

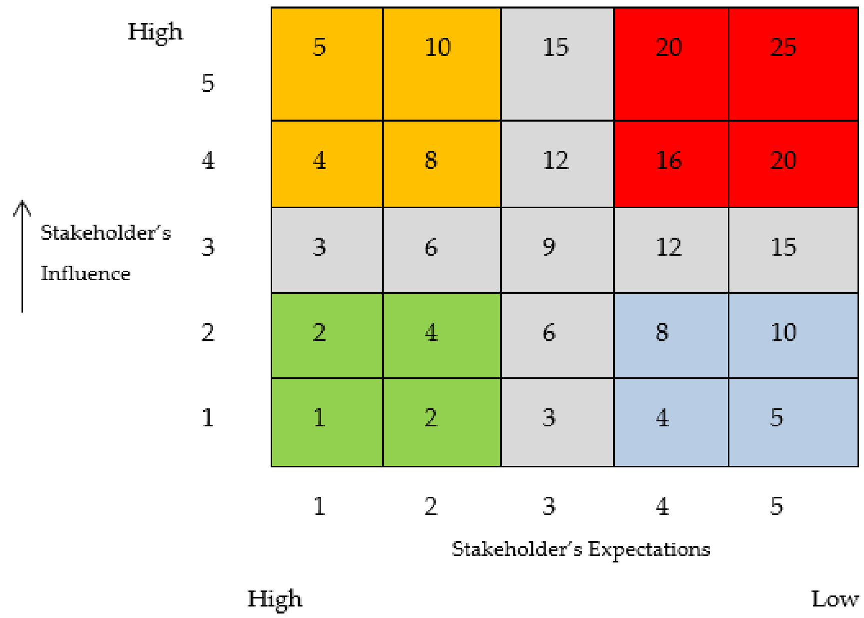

Figure 4. Stakeholder's power grid.

Figure 3 shows the stakeholder's power grid matrix that provides the potential impact of stakeholders on the projects and requires handling according to a matrix based on assessment score. The red colour indicates high influence and high expectations of stakeholders and must be addressed accordingly. The colours indicate the weightage of stakeholders having a role in prioritising sustainability and should manage accordingly.

The matrix is helpful to gauge the power of stakeholders. It provides the ground for categorising stakeholders according to their strengths and weight in sustainability reporting, managing stakeholders according to their strengths and weight in sustainability reporting, managing jointly, and addressing their concerns in initiatives.

3. A Framework about New' Sustainability Score System in Manufacturing' (3SM)

This section explains the new sustainability approach framework description, justification, structure, how it works, and prerequisites, including the sustainability data and multiple stakeholders' prioritisations. The sustainability assessment framework outlined provides the four steps of the manufacturing's sustainability scoring system. The four steps framework explains the information process flow from one step to the next. These steps include a sustainability charter, selecting a cross-functional team in the organisation who may name a sustainability team, selecting manufacturing boundaries (system boundaries), and sustainability indicators representing S.E (sustainability elements).

Figure 5 shows the concept and outline of the framework developed for manufacturing. Its purpose is to ascertain stakeholders' and manufacturer aspirations regarding sustainability performance and integrate them into manufacturing sustainability targets and goals. It is an overview of how the sustainability framework guides stakeholders' expectations alongside relevant information in the team's manufacturing process to score the sustainability performance.

A coceptual framework of 'Sustainability score system in manufacturing' (3SM)			
	Description	Tools	
Plan	Sustainability charter Sustainability team System boundaries	Delphi techniques Group discussion	Step-I
Integrate & Measure	Sustainability pillars & elements selection Multiple stakeholders role Manufacturing functions	Delphi techniques Surveys Pairwise relationship QFD modified tool	Step-II
Measure & Control	Sustainability indicators selection Sustainability targets	Group discussion pairwise relationship & AHP Normalisation method	Step-III
Organise	Sustainability reporting	CSR's GRI guidelines	Step-IV

Figure 5. Four steps framework of carrying the sustainability approach.

In following figure 6 outlined the plan, integrate, measure, control and organise strategy in the sustainability performance assessment framework.

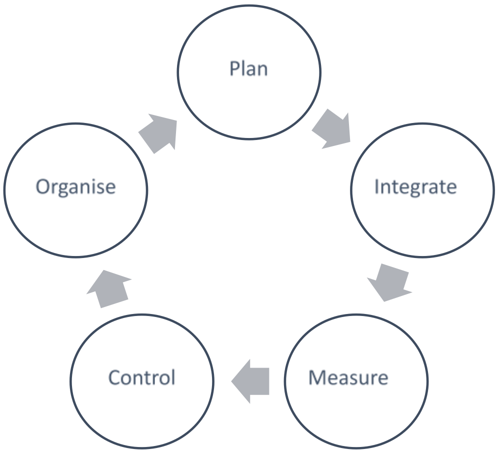

Figure 6. An approach adopted from [34] of the indicator-based approach.

The framework was developed based on the researcher's experience managing sustainability issues in manufacturing over the past 16 years. This further investigation of the approaches practised in published literature and industry; the framework also accounted for the discussion made by Permatasari [34] and Boulanger [35] on converting a conceptual model into an indicator-based approach. The framework and approach have steps that follow the sustainability charter's development, selecting the system boundaries identified in the literature review consolidating various industry standards, targets and organisation ambitions [36,37]. The approach also guides why and how to select sustainability pillars (out of five pillars); Nist [3], S.E. selection from Global reporting initiative standards by GRI [10], as it is now an industry-wide practice. It is also emphasised that the most effective way for sustainability evaluation in manufacturing is to link the sustainability process and operations to indicators (providing an indicators data bank for sustainable manufacturing). Then, by controlling indicators, manufacturing performance will help manage sustainability [38,39] in the manufacturing sector.

The framework is designed to allow an organisation to integrate all the sustainability-related systems and initiatives to merge in the same framework [36,40,41] through the sustainability team and Delphi technique, to use S.E. and indicator selection in manufacturing. This is a bottom upward approach [42], which involves relevant people making decisions about manufacturing sustainability targets. The sustainability framework was developed regarding the above discussion, considering the shortcomings and gaps identified in current approaches. The framework's basis focuses on how a conceptual approach shall link to a qualitative subject, which can further be transformed into measurable parameters defined with legitimate criteria to record those manufacturing parameters.

Boulanger [35] also informed the aim of quantifying qualitative data by splitting sustainability assessment into secondary and tertiary levels and then into measurable sustainability indicators, which is the key basis of the sustainability framework outlined. The summary of the gaps identified in the literature review regarding sustainability assessment approaches and practices, especially the lack of multiple stakeholders' preferences, are incorporated in the framework. An innovative method of gauging multiple stakeholders' impact will capture the preferences and influence in manufacturing and inform the manufacturer of what to do and where to allocate resources. For this, a modified QFD approach was adopted, as it works well to prioritise the relationships among different S.E. and their subsequent reinforcement of other sustainability indicators [40,43,44]. Some other tools that have effects, such as pairwise relationship and normalisation methods, were used in some steps and provided justification and benefits later in the chapter.

Figure 7 outlines the steps involved in developing the sustainability concept in manufacturing and then selecting S.E., multiple stakeholders' priorities, and sustainability indicators and assessing each sustainability indicator's contribution to manufacturing. More details about the structure and assessment approaches are discussed in the following sections of the chapter. The four steps' sustainability approach, framework and steps are appraised by sustainability practitioners and validated using actual sustainability data

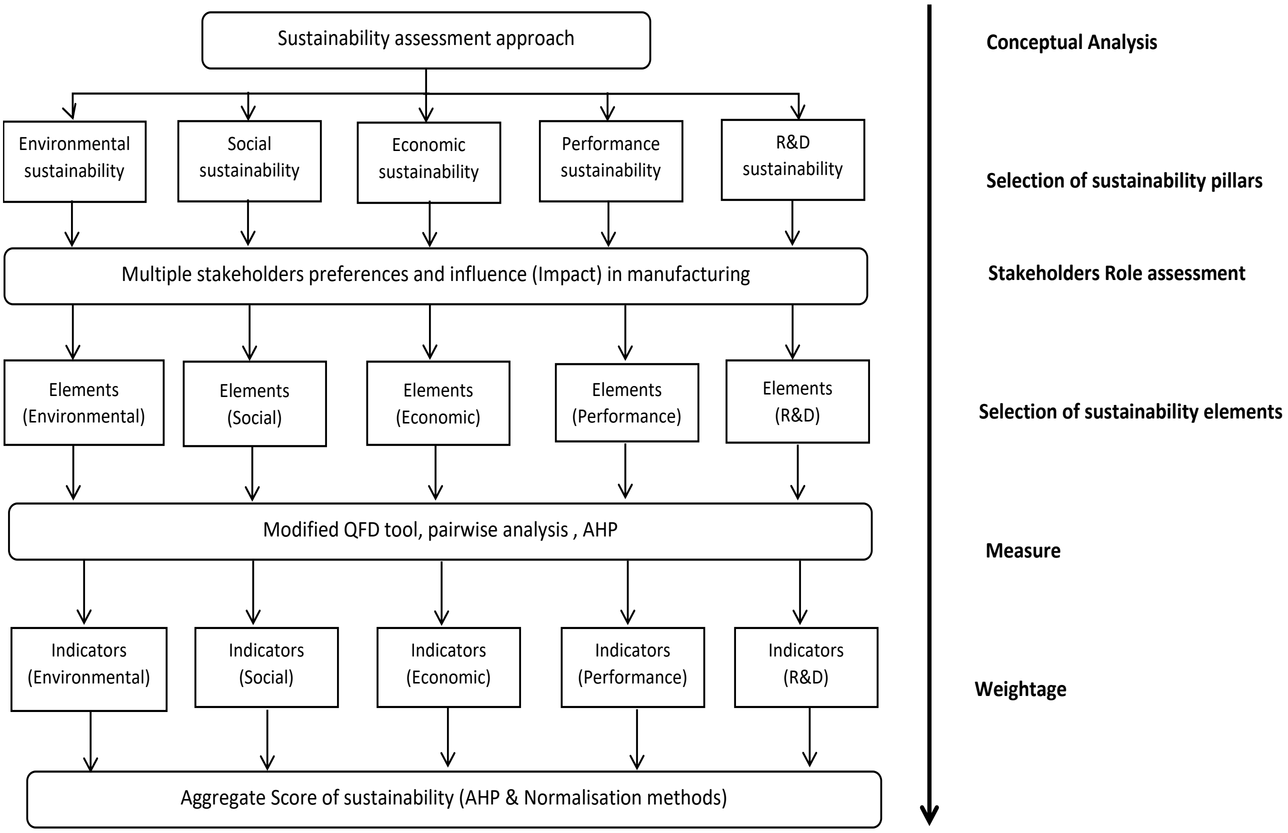

Figure 7. Objective tree showing the steps involved in sustainability evaluation—modified and adopted by Boulanger (2008) [35] and Oecd (2008, 2009) [38,39].

3.1. Sustainability Approach at Step-I

The first step includes a formal write-up of a sustainability charter by senior management, including an outline of objectives. This charter will explain the sustainability assessment purposes, the context of assessment within the organisation and system boundaries in manufacturing. It includes the organisations' ambitions to be responsible producers of goods while benefitting from natural resources and resource allocation to assess sustainability [37]. The sustainability charter shall guide the cross-functional sustainability team (made up of employees based on sustainability and manufacturing). The sustainability charter should identify and authorise a sustainability team in an organisation responsible for evaluating sustainability and reporting. The sustainability team shall further lead the sustainability assessment and define the sustainability charter.

Furthermore, the team is accountable for seeking expert advice when necessary, using the Delphi technique. Additionally, the sustainability team's responsibility is to extract measurable objectives and deliverable tasks from the sustainability charter, highlight the sustainability drivers (such as legislative and compliance aspirations), and refer to multiple relevant stakeholders in the supply chain. The sustainability team then identifies system boundaries in the manufacturing context, sustainability dimensions, elements, and indicators. It also identifies the resources required for sustainability evaluation in the organisation. The sustainability charter at step-I also highlights sustainability dimensions, such as the environment, the economy, social factors, R and D, and performance, which senior management should consider while drawing up the sustainability charter.

Figure 8 shows the sequential flow of information at step I, selecting a sustainability team identified in the sustainability charter and system boundaries in the manufacturing sustainability evaluation. The five system boundaries are identified with preferences. The sustainability team should also investigate the multiple stakeholders' roles in a supply chain that holds interest and influence in sustainable manufacturing. Multiple stakeholders' internal and external stakeholders have an interest or preference and influence their sustainability performance. As discussed in the literature review, it includes the customers and consumers. The internal stakeholders, including the organisation's employees, have influence and direct involvement in manufacturing functions and decision making. The external stakeholders, including consumers and end-users, as well as NGOs, local and international legislative authorities, manufacturing sector, contractors, suppliers, and groups of people, have expectations and influence on manufacturing. The information collated at step-I included the sustainability charter, which further helps select the sustainability team, select appropriate system boundaries in sustainability assessment and performance, and identify the multiple stakeholders to account for while prioritising sustainability pillars, elements, indicators, and performance.

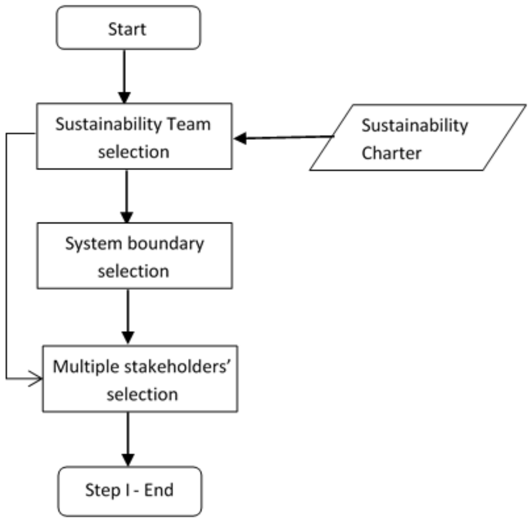

Figure 8. Sustainability approach at step-I.

3.2. Sustainability Approach at Step-II

The information gathered by the sustainability team in step I, such as the list of multiple stakeholders and system boundary selection, was used to measure sustainability in manufacturing in step II. In step II, the sustainability team identifies sustainability pillars out of five [3] and their representation with S.E. in manufacturing. The sustainability team understands the manufacturing operations and S.E. involved. The team then assess the hierarchy of the sustainability pillars and elements in conjunction with multiple stakeholders' preferences and influence in manufacturing. A QFD modified matrix will also be used to the manufacturing function to identify hotspots, assign resources, and manage them in the organisation's best interest to satisfy multiple stakeholders. This assessment will provide high performing S.E. and manufacturing functions in the organisation.

Figure 9 outlines the information flow process and the sustainability team's selection of the sustainability pillars, elements, and system boundaries. The sustainability team shall survey multiple stakeholders (internal and external) relevant to the organisation to use their aspirations to rank the selected sustainability pillars listed by Nist [3] and S.E. in the database of GRI [10]. It is a well-known fact that various business stakeholders have varying expectations and influence over the organisation [4]. Thus, it is important to value their contribution to sustainability prioritisation in manufacturing.

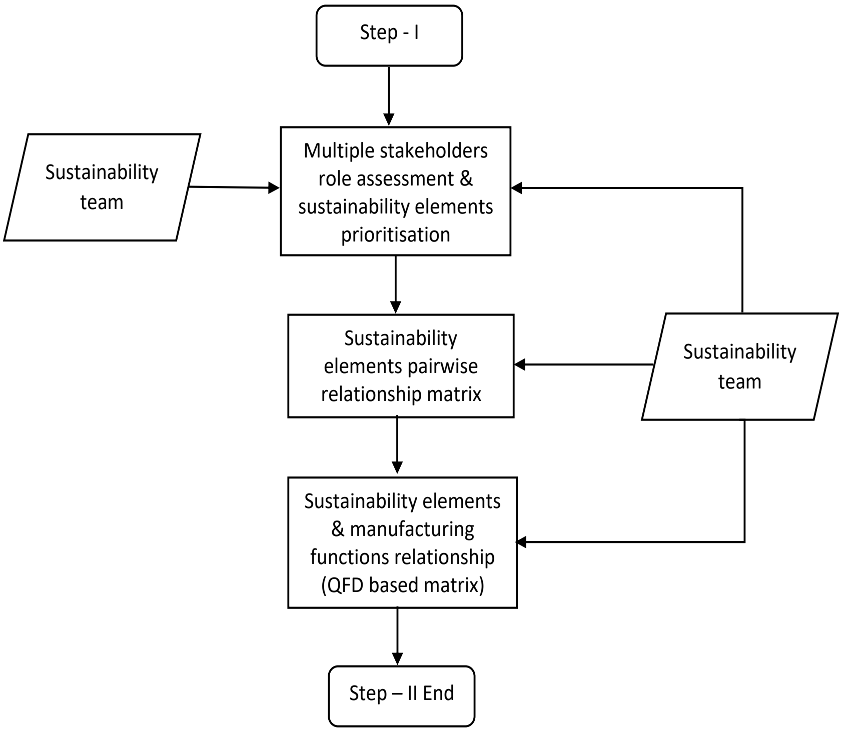

Figure 9. Sustainability approach at step II.

Abbreviations used in the paper:

- S.E.: Sustainability elements in manufacturing
- E(X): Average of external stakeholders' expectations in manufacturing
- E (I): Average of internal stakeholders influence in manufacturing
- ESI: external stakeholders impact, ESI= E(X)xE(I)
- I (X): Average of internal stakeholders' expectations in manufacturing
- I (I) Average of internal stakeholders influence in manufacturing
- ISI: Internal stakeholders impact, ISI= I(X)xI(I)
- Tech: Research and development (sustainability pillar)
- PM: Performance management

The matrix shown in Figure 10 lists the five sustainability pillars with different subsets of S.E. in manufacturing. After selecting the S.E., the sustainability team shall survey multiple stakeholders (internal and external stakeholders) to understand their preferences. The sample survey form used to collate multiple stakeholders' prioritisations is added in the appendix. The matrix shown in Figure 10 considers two internal and two external stakeholders, but the sustainability team should decide how many internal and external stakeholders to survey.

Stakeholders role assessment in manufacturing			External stakeholders expectations		E(X) - Average of external stakeholders expectations	E (I) - External stakeholders Influence	**External stakeholders Impact = E(X) x E(I) = ESI**	Internal stakeholders expectations		I(X) - Average of internal stakeholders expectations	I (I) - Internal stakeholders Influence	**Internal stakeholders Impact = I(X) x I(I) = ISI**
Primary level	Sustainability pillars	Tertiary level - Sustainability elements (SE j)	1	2				1	2			
Sustainability score system in manufacturing	Environment	Sustainability element 1										
		Sustainability element 2										
		Sustainability element 3										
	Social	Sustainability element 4										
		Sustainability element 5										
	Economic	Sustainability element 6										
		Sustainability element 7										
	Tech	Sustainability element 8										
		Sustainability element 9										
	PM	Sustainability element 10										
		Sustainability element 11										

Figure 10. Internal and external stakeholders' role impact (expectations × influence) in manufacturing.

Figure 10 shows two columns for the sustainability stakeholders' expectations and the influence of S.E. The survey form suggests rating stakeholders' expectations on a scale of 1 to 5, where 5 indicates the maximum rating for that sustainability factor, and 1 indicates the minimum weighting. This scale rating gives a more accurate hierarchy of S.E., considering multiple stakeholders' preferences and influences. The sustainability team should discuss and assess different stakeholders' influence and rate them according to their expectations to gauge S.E.'s impact. The impact is calculated by multiplying stakeholders' preferences by their influence on manufacturing. These calculations are explained and justified in the literature review. The external stakeholders' impact (ESI) and internal stakeholders' impact (ISI), assessed in the matrix shown in Figure 10, provide the S.E.' weightage in the eyes of multiple stakeholders. The following matrix will be used to determine pairwise relationships. These matrices are interlinked, and their data are used to achieve meaningful information for the manufacturer.

Figure 11 shows the pairwise relationship matrix of S.E. developed by the sustainability team using their operational knowledge and the Delphi technique. Figure 11 shows ESI and ISI scores of 1 for each sustainability element. These scores should be replaced with the scores calculated from matrix Figure 11. The sustainability team should decide the relationship between S.E. in the matrix. The pairwise relationship among SE is shown using the following signs: ● = 9, ○= 3, ∇= 1, and no relation value = 0.

Internal and external sustainability stakeholders' preferences are used to prioritise the S.E. and complete a pairwise relationship. The S.E. in Figure 11 are listed horizontally (SEi) and vertically (S.E. j) pairwise. The pairwise relationship provides the rank of key S.E. in manufacturing. The sustainability ranking will help manufacturers and decision-makers to focus their attention and resources accordingly.

Pairwise relationships	PR
Strong	●
Moderate	○
Weak	▽

Column #					1	2	3	4	5	6	7	8	9	10	11
Relationship Matrix					Pairwise relationship /comparison among sustainability										
Strategic Requirements			ISI	ESI	Sustainability elements (SE i)										
					Environment			Social		Economic		TECH		PM	
Primary level	Sustainability pillars	Tertiary level - Sustainability elements (SE j)	Internal Stakeholders Impact	External Stakeholders Impact	Sustainability element 1	Sustainability element 2	Sustainability element 3	Sustainability element 4	Sustainability element 5	Sustainability element 6	Sustainability element 7	Sustainability element 8	Sustainability element 9	Sustainability element 10	Sustainability element 11
Sustainability score system in manufacturing	Environment	Sustainability element 1	1	1	●										
		Sustainability element 2	1	1		●									
		Sustainability element 3	1	1			●								
	Social	Sustainability element 4	1	1				●							
		Sustainability element 5	1	1					●						
	Economic	Sustainability element 6	1	1						●					
		Sustainability element 7	1	1							●				
	Tech	Sustainability element 8	1	1								●			
		Sustainability element 9	1	1									●		
	PM	Sustainability element 10	1	1										●	
		Sustainability element 11	1	1											●
Pairwise relationship		Pairwise elements relationship score (			909	909	909	909	909	909	909	909	909	909	909
		Relative percentage score			9.1%	9.1%	9.1%	9.1%	9.1%	9.1%	9.1%	9.1%	9.1%	9.1%	9.1%
		Weight chart													

Figure 11. Sustainability element prioritisation by having a pairwise relationship.

The following formula calculates the pairwise relationship score:

$$PR - E = \sum_{j=1}^{n} \left[\left(SE_i \, \epsilon \, SE_j \right) . ISI + \left(SE_i \, \epsilon \, SE_j \right) . ESI \right]$$

With a further simplified form:

$$PR - E = \sum_{j=1}^{n} \left[\left(SE_i \, \epsilon \, SE_j \right) \left(ISI + ESI \right] \right. \quad (1)$$

Where $PR - E$ is the pairwise relationship among S.E., considering internal and external stakeholders' impact; symbol'$\in$' represents the pairwise relation between SE *I*, the S.E. in rows, and 'S.E. *j*', the S.E. in columns (as shown in Figure 11) Where $i \,\&\, j = 1$ (starts from 1) and 'm' and 'n' are the total number of S.E. in rows and columns, respectively (selected by the sustainability team).

Figure 11 also provides the key S.E. that have an impact on manufacturing. The sustainability team will input these figures into Figure 12 to complete S.E.'s relationship with the manufacturing function. The pairwise relationship score, as a percentage, will be used in the following QFD modified matrix to prioritise manufacturing functions in manufacturing.

Column #				1	2	3	4	5	6	7	8	9	10	11
Relationship Matrix				Manufacturing Functions in Supply chain										
QFD modified Matrix				MF i										
Primary level	Sustainability pillars	Tertiary level - Sustainability elements (SE j)	Pairwise relationship score (PR-E) in %	Manufacturing Function 1	Manufacturing Function 2	Manufacturing Function 3	Manufacturing Function 4	Manufacturing Function 5	Manufacturing Function 6	Manufacturing Function 7	Manufacturing Function 8	Manufacturing Function 9	Manufacturing Function 10	Manufacturing Function 11
Sustainability score system in manufacturing	Environment	Sustainability element 1	9%	o										
		Sustainability element 2	9%		o									
		Sustainability element 3	9%			o								
	Social	Sustainability element 4	9%				o							
		Sustainability element 5	9%					o						
	Economic	Sustainability element 6	9%						o					
		Sustainability element 7	9%							o				
	Tech	Sustainability element 8	9%								o			
		Sustainability element 9	9%									o		
	PM	Sustainability element 10	9%										o	
		Sustainability element 11	9%											o
MF relative contribution		Manufacturing functions rating (MF)		0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
		Manufacturing functions rating in %		9.1%	9.1%	9.1%	9.1%	9.1%	9.1%	9.1%	9.1%	9.1%	9.1%	9.1%
		Weight chart - MF												

Figure 12. The weighting of different manufacturing functions in sustainability performance.

The matrix is shown in Figure 12 the relationship between S.E. and manufacturing functions within the prioritisation of the manufacturing functions that significantly impact sustainability. This matrix is based on the QFD tool to prioritise manufacturing functions to understand the hotspots in manufacturing. Here, the multiple stakeholders' prioritisations and influence in manufacturing contribute to identifying hotspots in manufacturing functions. The matrix identifies the hotspots and manufacturing functions with higher manufacturing and sustainability roles by accounting for multiple stakeholders' impact. The relative weight of S.E. is calculated in the following mathematical equations:

$$RW = \sum_{i=1}^{n} \left[\left(MF_i \in SE_j \right) x \left(PR - E \right) \right] \quad (2)$$

The symbol'$\in$ ' represents the pairwise relation among '*S.E.*' and '*M.F.*'. In addition, i &$j = 1$ (starts from 1) and 'n' are the total numbers of *S.E.* and *M.F.* in the list. The hot spots identification in Figure 12 identifies key manufacturing functions influencing sustainability. The percentage demonstrates the role of each *S.E.* in manufacturing. This percentage score enables manufacturers and decision-makers to take informed action and initiative for sustainability performance. The output of the calculations performed in step II will be used in step III.

3.3. Sustainability Approach at Step III

In step III of the approach, S.E. is further split into the sustainability indicators represented in manufacturing. The benefits of using an indicator-based methodology for representing sustainability in manufacturing operations were discussed in the literature review (chapter 2). A sustainability indicators data bank formulated for sustainable manufacturing was collected from most of the published and available indicators in the appendix. The sustainability team, who has a functional knowledge of manufacturing and supply chains, can select appropriate sustainability indicators representing S.E. and manufacturing.

Figure 13 outlines the steps in selecting sustainability indicators and sustainability in manufacturing. Cross-functional knowledge of manufacturing operations can help use a Delphi technique to select the most relevant, applicable manufacturing indicators. The Delphi method is a forecasting approach based on the results of multiple rounds of questionnaires sent to a group of experts. The selection of indicators must be represented in manufacturing operations, manufacturing sector priorities and interests, stakeholders' expectations, legal obligations, and international and local sustainability trends regarding manufacturing expectations [38,39,45].

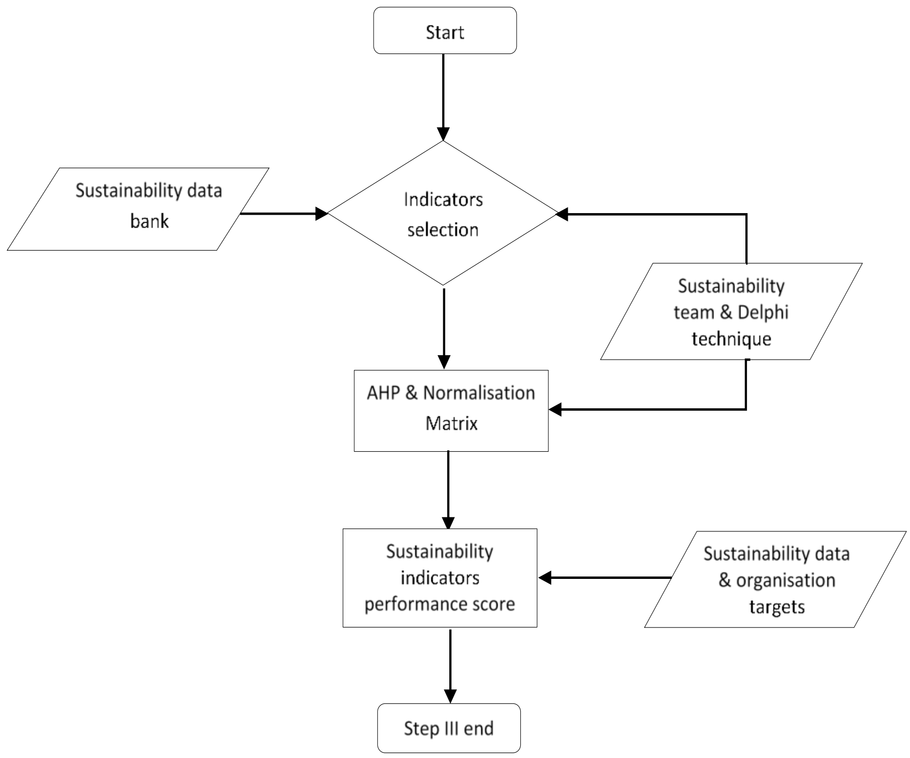

Figure 13. Sustainability evaluation approach at step III.

Following this, the sustainability team prioritise indicators using the analytic hierarchy process (AHP) technique, which allows them to understand the most important ones in manufacturing. The matrix shown in Figure 14 explains the S.E. selected by the sustainability team and the relationships between them using multi-criteria decision making (MCDM) and normalisation approaches in evaluating indicators within the organisation [35,39,46].

Sustainability indicators role accounting stakeholders role

Relationships
1= the row is equally important as the column
3= slightly more important
5= more important
7= much more important
9= very much more important
0.33 = slightly less important
0.20 = less important
0.14 much less important
0.11 = very much less important

Elements representing the status of sustainability		Indicators from Data Bank	Indicator 1	Indicator 2	Indicator 3	Indicator 4	Indicator 5	Indicator 6	Indicator 7	Indicator 8	Indicator 9	Indicator 10	Indicator 11	Indicator 12	Indicator 13	Indicator 14	Indicator 15	Indicator 16	Indicator 17	Indicator 18	Indicator 19	Normalised Assessment																			Absolute Weigh	Elements relationship score in %	Relative function AHP Priority (%)
Environment	Sustainability element 1	Indicator 1	1																			1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1	9%	3%
		Indicator 2		1																		0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1		3%
		Indicator 3			1																	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1		3%
	Sustainability element 2	Indicator 4				1																0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1	9%	5%
		Indicator 5					1															0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1		5%
	Sustainability element 3	Indicator 6						1														0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1	9%	5%
		Indicator 7							1													0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1		5%
Social	Sustainability element 4	Indicator 8								1												0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1	9%	5%
		Indicator 9									1											0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1		5%
	Sustainability element 5	Indicator 10										1										0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1	9%	5%
		Indicator 11											1									0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1		5%
Economic	Sustainability element 6	Indicator 12												1								0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1	9%	5%
		Indicator 13													1							0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	1		5%
	Sustainability element 7	Indicator 14														1						0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	1	9%	5%
		Indicator 15															1					0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	1		5%
Tech	Sustainability element 8	Indicator 16																1				0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	1	9%	9%
	Sustainability element 9	Indicator 17																	1			0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	1	9%	9%
PM	Sustainability element 10	Indicator 18																		1		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	1	9%	9%
	Sustainability element 11	Indicator 19																			1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	1	9%	9%
	Total		1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	19	100%	100%

Figure 14. Sustainability indicators' role in performance, accounting for multiple stakeholders' roles.

The matrix in Figure 14 shows the sustainability pillars and S.E. split into sustainability indicators and their pairwise relationship and normalisation in manufacturing. S.E. selected from the GRI 4.0 aspect register [10](GRI, 2018) is split further into measurable indicators selected from the sustainability indicators databank listed in the appendix. Figure 14 also shows MCDM and normalisation techniques to assess the contribution and role of sustainability indicators in manufacturing [47]. The MCDM method weights each sustainability indicator and uses the same methodology employed by the European Commission [48] to evaluate environmental footprints. An in-process case study also uses it to prioritise indicators [47].

AHP, MCDM, and normalisation approaches are successful techniques for prioritising indicators in a given set [46]. They also analyse how different indicators affect each element's net contribution and weight in the assessment. The normalisation approach describes how each indicator and element plays a role in manufacturing. It is based on the understanding that each indicator has a different function and contribution. Sustainability indicators also create a ripple effect on sustainability performance and reinforce sustainability indicators. For instance, emissions and energy consumption have a strong relationship, as many emissions come from energy use [46,47].

The matrix aims to prioritise the most critical sustainability indicators in manufacturing. AHP uses a pairwise approach to evaluate S.E.'s impact; the normalisation method's matrix is the first step in the decision-making process and involves averaging the various weights into other different indicators. It is helpful for comparison purposes [47]. Figure 14 shows the normalisation technique N1 (linear: max) combined with N3 (linear sum) to ensure the sum is '1'.

The indicators' contribution assessment was then used to establish each indicator's value by understanding and accounting for multiple stakeholders using pairwise relationships and QFD-based methodology to rank manufacturing indicators. The sustainability indicators' values in manufacturing and targets can then be set. The assessment also indicates how each sustainability indicator contributes to sustainability in manufacturing. The S.E. and indicators with performance scores are listed in the matrix shown in Figure 15 alongside manufacturing data and each contribution to sustainability, calculated earlier.

Sustainability Performance Assessment				Sustainability weightage in Manufacturing			Manufacturing Data (Target)	Manufacturing sector (Target)	Sustainability data in manufacturing (actual)	Factor (actual/target)	Indicator contribution	Sustainability performance Score in Manufacturing	
Elements representing the status of sustainability		Sustainability elements	Sustainability Indicators	Pillars	Elements	Indicators	Manufacturing unit	Manufacturing unit	Manufacturing unit	Ratio	Indicator Contribution	Elements	Pillars
	Environment	Sustainability element 1	Indicator 1	27%	9%	3%	1	1	1	1.00	3%	100%	100%
			Indicator 2			3%	1	1	1	1.00	3%		
			Indicator 3			3%	1	1	1	1.00	3%		
		Sustainability element 2	Indicator 4		9%	5%	1	1	1	1.00	5%	100%	
			Indicator 5			5%	1	1	1	1.00	5%		
		Sustainability element 3	Indicator 6		9%	5%	1	1	1	1.00	5%	100%	
			Indicator 7			5%	1	1	1	1.00	5%		
	Social	Sustainability element 4	Indicator 8	18%	9%	5%	1	1	1	1.00	5%	100%	100%
			Indicator 9			5%	1	1	1	1.00	5%		
		Sustainability element 5	Indicator 10		9%	5%	1	1	1	1.00	5%	100%	
			Indicator 11			5%	1	1	1	1.00	5%		
	Economic	Sustainability element 6	Indicator 12	18%	9%	5%	1	1	1	1.00	5%	100%	100%
			Indicator 13			5%	1	1	1	1.00	5%		
		Sustainability element 7	Indicator 14		9%	5%	1	1	1	1.00	5%	100%	
			Indicator 15			5%	1	1	1	1.00	5%		
	Tech	Sustainability element 8	Indicator 16	18%	9%	9%	1	1	1	1.00	9%	100%	100%
		Sustainability element 9	Indicator 17		9%	9%	1	1	1	1.00	9%	100%	
	PM	Sustainability element 10	Indicator 18	18%	9%	9%	1	1	1	1.00	9%	100%	100%
		Sustainability element 11	Indicator 19		9%	9%	1	1	1	1.00	9%	100%	
	Total			**100%**	100%	100%					**100%**	100%	

Figure 15. Sustainability indicators' performance scores in manufacturing.

Figure 15 shows the organisation's sustainability performance scores after assessing an operational efficiency-based indicator against the targets. The sustainability performance score is calculated using the following equations:

The performance of indicator = weight contribution (%) × (actual sustainability data/company target SET).

The indicator performance score is based on the actual sustainability indicator performance and the actual and target value ratio, accounting for the multiple stakeholders' preferences and influence in manufacturing. Figure 15 shows that not all S.E. in manufacturing has the same weight: each one makes a different contribution to sustainability performance. This scoring system provides a better representation of sustainability performance in the organisation. It also considers the multiple stakeholders' roles, thus bridging the gap within current sustainability practices. The manufacturing frequently revisits their stakeholders' expectations to check for any material change, new stakeholders, or revised sector targets.

This performance indication score will allow manufacturing to directly understand sustainability indicators' performance in manufacturing and the hotspots that require more attention than others. It will also provide grounds for the manufacturer to allocate resources appropriately.

3.4. Sustainability Approach at Step IV

Step IV is about communicating sustainability performance to multiple stakeholders, and it is up to manufacturing organisations to select one or multiple ways to communicate with their stakeholders. The paper did not provide any particular approach; although GRI 4.0 guidelines are becoming the default global standard of communication, over 12,000 worldwide organisations are now using them [10]. However, other communication approaches exist besides publishing environmental, social, and economic advances via a corporate sustainability report using GRI 4.0 guidelines. After the sustainability team evaluates sustainability in manufacturing, it is up to the organisation which approach they should use in step IV. The novelty of the approach exists at steps I, II, and III, and step IV is about the communication of sustainability performance and initiatives for multiple stakeholders and organisations that can use suitable means.

3.5. Appraisal of the Sustainability Approach

After developing the sustainability approach, it was presented to and discussed with industry experts within a manufacturing organisation and researchers at the University of Strathclyde. This appraisal was carried out through three different sessions, and appraisals made are added in the appendix. The sustainability approach was reviewed and critically analysed during the appraisal using a similar pattern adopted by Hay's (2015) sustainability work and approach validation [23]. The critical analysis steps were based on an approach developed by Young and Solomon [23,49].

These groups were asked to provide feedback using the appraisal form developed by the researcher. This feedback about the improvement was used to further develop the approach before presenting it for the pilot study and validation in the manufacturing organisation. The appraisal included questions covering how the approach would work, applicability in the manufacturing environment, flexibility, and features to understand multiple stakeholders. Tables 1,2 and Figure 5 gives a summary of the feedback. During the discussion and presentation, different suggestions and recommendations were made, some of which were accepted through team discussion and used to improve the approach further and increase the likelihood of being accepted by manufacturers.

Table 2. Summary of the sustainability approach validation.

Sustainability approach appraisal					
Groups	**Attributes & Experience**	**Applicability of approach**	**Understanding stakeholders expectations**	**Utility of the approach**	**Feedback & improvement about the approach**
1. Industry experts providing consultancy to the manufacturing sector					
Industry expert -1	26 years	Excellent	Excellent	Good	Differentiate about internal and external stakeholders
Industry expert -2	20 years	Good	Excellent	Excellent	
2. Manufacturing company employees (Technical Manager, Quality Manager & Supply chain manager)					
Manager 1	22 years	Excellent	Excellent	Good	Training elements should consider for the validation in manufacturing
Manager 2	12 years	Excellent	Excellent	Excellent	
Manager 3	20 years	Excellent	Good	Excellent	
3. Academic researchers at the University of Strathclyde					
Researcher 1	2nd year in PhD	Excellent	Excellent	Good	Suggested full validation in the manufacturing environment
Researcher 2	3rd year in PhD	Excellent	Excellent	Good	
Researcher 3	3rd year in PhD	Excellent	Good	Excellent	
Researcher 4	4th year in PhD	Excellent	Excellent	Excellent	
Researcher 5	4th year in PhD	Excellent	Excellent	Excellent	

The sustainability approach's applicability: Most current sustainability practices and methods are too generic and fail to target manufacturing sustainability. The advantage of the 3SM approach lies in the fact that it was developed for and underwent validation in the manufacturing context; it is ideal for the industry.

Understanding the multiple stakeholders' expectations: incorporating: a QFD-based approach into sustainability evaluation criteria is the unique feature of the tool. It is different from other approaches and provides a customised and tailored solution for manufacturers to compare general sustainability approaches. All panel experts appreciated this part of understanding the relevant stakeholders' expectations. After the initial discussion, stakeholder influence was incorporated into the approach. It was observed that different stakeholders have different degrees of influence on manufacturing; it is not just their expectations that need to be considered.

The sustainability approach's utility: the experts also wanted to understand and rate the sustainability approach based on how well it can be utilised in manufacturing and how useful it is to manufacturers.

After collating all the appraisals from different experts, changes were made to 'version-I' of the sustainability approach; it was updated to include stakeholders' influence and categorise stakeholders as either internal or external. Manufacturing functions were prioritised and added to the approach to understand those areas where sustainability issues were most pressing in the manufacturing process. This will also help manufacturers allocate resources more effectively to improve the sustainability score.

Overall, sustainability experts rated each aspect of the sustainability approach as either 'excellent' or 'good' and recommended its use in the manufacturing environment. Industry experts also recommended digitalising the 3SM sustainability approach to make it easier to use. One group also recommended applying for a grant to develop software for the 3SM QFD-based approach and patent it. These recommendations and feedback were added to version-I's sustainability approach, and the changes and additions formed version II.

4. Discussion and Conclusion

Academics and industry leaders are now more concerned about sustainability and sustainable manufacturing. However, there is still no consensus about the fundamental issues in manufacturing a sustainability assessment. In traditional sustainability approaches, three pillars are recognised: environmental, social, and economic, representing sustainability in general [50]. Some approaches added new pillars, namely research and development and performance management [3]. The justification for these two additional pillars is that understanding sustainability will be limited. The paper provides an approach that allows manufacturing organisations to select a custom approach by selecting their relevant stakeholders in the supply chain and setting sustainability element appreciation, considering manufacturing dynamics. Unlike some other approaches, selecting pre-decided sustainability pillars and indicators may or may not be relevant in the supply chain.

However, there are limitations to this research, particularly concerning its scope, boundary setting, stakeholder selection, materials, and information about resource consumption. The validation of the approach was limited to one organisation and with its four manufacturing sites data. Thus, the findings cannot be for utilisation in other sectors; however, the approach's flexibility and consultation of relevant stakeholders, sustainability, and boundary selection provide an educated guess that it can still perform a meaningful sustainability assessment sector.

The proposed 3SM approach is novel, contributes to the knowledge, and has managerial implications in the manufacturing sector. The approach was developed with the researcher's interest and experience on the topic and then presented in the manufacturing sector. The sustainability data of four manufacturing business sites from different geographical locations were gathered and fed into the sustainability assessment approach.

The sustainability approach and outcome were discussed with the manufacturer, industry experts, academic researchers, and practitioners' sustainability team. The different aspects of the approach, such as the relevance of approach in manufacturing, suitability, and fit for the purpose, were gauged in the separate appraisal. The proposed 3SM approach was further improved with feedback and affirmed the manufacturing environment's suitability.

The manufacturing shows interest and plans to use the same approach for the following financial year. It addresses all their concerns, meets expectations, and accounts for multiple stakeholders in the business. Moreover, it also highlighted the hotspots in the manufacturing where further improvements can be made and benefit from allocated organisation resources that the organisation finds relevant and suitable to estimate and request the budget.

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