A Hybrid AHP-DEMATEL model for Scrap Management in Gas Industries to Establish a Circular Economy

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A Thesis submitted in partial fulfillment of the requirement for the degree of Bachelor of Science in Mechanical Engineering

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Candidate's Declaration

This is to clarify that the work presented in this thesis, titled "A **Hybrid AHP-DEMATEL Model for Scrap Management in Gas Industries to Establish a Circular Economy,"** is the outcome of the investigation and research carried out by me and my teammate, under the supervision of Dr. Prof. Shamsuddin Ahmed.

It is also declared that neither this thesis nor any part of it has been submitted elsewhere for the award of any degree or diploma.

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Recommendation of the Thesis Supervisors

The thesis titled "A Hybrid AHP-DEMATEL **model for Scrap Management in Gas Industries to Establish a Circular Economy**" submitted by Takia Tarannum and Yasin Hossain, Student No: 200012144 and 200012106 has been accepted as satisfactory in partial fulfillment of the requirements for the degree of B Sc. in Industrial and Production Engineering **on 29th September, 2025.**

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CO-PO Mapping of ME 4800 -Thesis and Project

COs	Course Outcomes (CO) Statement	(PO)	Addressed by	
CO1	Discover and Locate research problems and illustrate them via figures/tables or projections/ideas through field visit and literature review and determine/Setting aim and objectives of the project/work/research in specific, measurable, achievable, realistic and timeframe manner.	**PO2 Problem analysis**	Thesis Book	√
			Performance by research	
			Presentation and soft skill	
CO2	Design research solutions of the problems towards achieving the objectives and its application. Design systems, components or processes that meets related needs in the field of mechanical engineering	**PO3 Design/development of solutions**	Thesis Book	√
			Performance by research	
			Presentation and soft skill	
CO3	Review, debate, compare and contrast the relevant literature contents. Relevance of this research/study. Methods, tools, and techniques used by past researchers and justification of use of them in this work.	**PO4 Investigation**	Thesis Book	√
			Performance by research	
			Presentation and soft skill	
CO4	Analyse data and exhibit results using tables, diagrams, graphs with their interpretation. Investigate the designed solutions to solve the problems through case study/survey study/experimentation/simulation using modern tools and techniques.	**PO5 Modern tool usage**	Thesis Book	√
			Performance by research	√
			Presentation and soft skill	
CO5	Apply moral values and research/professional ethics throughout the work, and justify genuine referencing on sources, and demonstration of own contribution.	**PO8 Ethics**	Thesis Book	√
			Performance by research	
			Presentation and soft skill	
CO6	Perform own self and manage group activities from the beginning to the end of the research/work as a quality work.	**PO9 Individual work and teamwork**	Thesis Book	√
			Performance by research	√
			Presentation and soft skill	
CO7	Compile and arrange the work outputs, write the report/thesis, a sample journal paper, and present the work to wider audience using modern communication tools and techniques.	**PO10 Communication**	Thesis Book	√
			Performance by research	
			Presentation and soft skill	
CO8	Recognize the necessity of life-long learning in career development in dynamic real-world situations from the experience of completing this project.	**PO12 Life-long learning**	Thesis Book	
			Performance by research	√
			Presentation and soft skill	

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Dr. Prof. Shamsuddin Ahmed
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K-P-A Mapping of ME 4800 -Theis and Project

COs	POs	Related Ks								Related Ps							Related As				
		K1	K2	K3	K4	K5	K6	K7	K8	P1	P2	P3	P4	P5	P6	P7	A1	A2	A3	A4	A5
CO1	PO2	√	√	√	√					√											
CO2	PO3					√				√	√	√				√	√	√	√		
CO3	PO4								√	√	√	√					√	√			
CO4	PO5						√			√				√							
CO5	PO8							√													
CO6	PO9																				
CO7	PO10																				
CO8	PO12																				

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Signature of the Supervisor:
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Name of the Supervisor:
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List of Sustainable Development Goals (SDGs) Addressed in this Project

SDG No.	Goals	Targets	Relevance to the Thesis (put √ if valid)	Remarks
1	No Poverty	1.1 Eradicate extreme poverty (people living on less than $1.25/day).		
		1.2 Reduce poverty in all its forms by at least half.		
		1.3 Implement nationally appropriate social protection systems.		
		1.4 Ensure equal rights to economic resources, services, property, inheritance, technology, and financial services.		
		1.5 Build resilience of the poor and reduce exposure to climate-related and other shocks.		
		1.a Mobilize resources to end poverty.		
		1.b Create pro-poor policy frameworks.		
2	Zero Hunger	2.1 End hunger and ensure access to safe, nutritious food year-round.		
		2.2 End all forms of malnutrition.		
		2.3 Double agricultural productivity and incomes of small-scale producers.		
		2.4 Ensure sustainable food production systems and resilient agricultural practices.		
		2.5 Maintain genetic diversity of seeds, plants, and animals.		
		2.a Increase investment in rural infrastructure, research, and technology.		
		2.b Correct and prevent trade restrictions/distortions in global food markets.		
		2.c Adopt measures to ensure proper functioning of food commodity markets.		
3	Good Health and Well-Bein g	3.1 Reduce global maternal mortality ratio.		
		3.2 End preventable deaths of newborns and under-5 children.		
		3.3 End epidemics of AIDS, tuberculosis, malaria, and neglected tropical diseases.		

		3.4 Reduce premature mortality from NCDs and promote mental health.		
		3.5 Strengthen prevention and treatment of substance abuse.		
		3.6 Halve global deaths/injuries from road traffic accidents.		
		3.7 Ensure universal access to sexual and reproductive healthcare.		
		3.8 Achieve universal health coverage.		
		3.9 Reduce deaths from hazardous chemicals, pollution, and contamination.		
		3.a Strengthen tobacco control (WHO FCTC).		
		3.b Support R&D of vaccines and medicines.		
		3.c Increase health financing and workforce.		
		3.d Strengthen capacity for early warning and risk management.		
4	Quality Education	4.1 Ensure all complete free, equitable, quality primary and secondary education.		
		4.2 Ensure access to quality early childhood development and pre-primary education.		
		4.3 Ensure equal access to affordable technical, vocational, and higher education.		
		4.4 Increase skills for employment and entrepreneurship.		
		4.5 Eliminate gender disparities in education.		
		4.6 Ensure literacy and numeracy for youth and adults.		
		4.7 Ensure learners acquire knowledge/skills for sustainable development.		
		4.a Build and upgrade education facilities that are inclusive and safe.		
		4.b Expand scholarships for developing countries.		
		4.c Increase supply of qualified teachers.		
5	Gender Equality	5.1 End all forms of discrimination against women and girls.		

		5.2 Eliminate violence against women and girls.		
		5.3 Eliminate harmful practices (child, early, forced marriage, FGM).		
		5.4 Recognize and value unpaid care and domestic work.		
		5.5 Ensure women's participation in leadership and decision-making.		
		5.6 Ensure universal access to reproductive health and rights.		
		5.a Undertake reforms to give women equal rights to resources.		
		5.b Enhance use of enabling technology to empower women.		
		5.c Adopt and strengthen policies and laws for gender equality.		
6	Clean Water and Sanitation	6.1 Achieve universal and equitable access to safe drinking water.		
		6.2 Achieve access to adequate sanitation and hygiene.		
		6.3 Improve water quality by reducing pollution.		
		6.4 Increase water-use efficiency and sustainable withdrawals.		
		6.5 Implement integrated water resources management.		
		6.6 Protect and restore water-related ecosystems.		
		6.a Expand international cooperation in water and sanitation.		
		6.b Support participation of local communities.		
7	Affordable and Clean Energy	7.1 Ensure universal access to affordable, reliable, modern energy services.		
		7.2 Increase substantially the share of renewable energy.		
		7.3 Double global rate of improvement in energy efficiency.		
		7.a Enhance international cooperation on clean energy research/technology.		
		7.b Expand infrastructure and upgrade technology for sustainable energy.		

8	Decent Work and Economic Growth	8.1 Sustain per capita economic growth.	√	By applying the model it helps reduce the scrap thus, the economic loss is reduced.
		8.2 Achieve higher levels of productivity through diversification, tech, and innovation.	√	Since one of the leading causes in the study is Process Optimization it can be implemented in the industry which then increases the productivity of the industry.
		8.3 Promote policies for decent job creation and entrepreneurship.		
		8.4 Improve resource efficiency in production and consumption.	√	Applying AHP gave us that the optimum decision taken is Industrial Symbiosis which will eventually reduce the amount of scraps improving the rate of consumption
		8.5 Achieve full and productive employment for all.		
		8.6 Substantially reduce youth not in employment/education/training.		
		8.7 Eradicate forced labour, modern slavery, and child labour.		
		8.8 Protect labour rights and safe working environments.		
		8.9 Promote sustainable tourism.		
		8.a Increase aid for trade support.		
		8.b Develop a global youth employment strategy.		
9	Industry, Innovation, and Infrastructure	9.1 Develop quality, reliable, sustainable infrastructure.		
		9.2 Promote inclusive and sustainable industrialization.	√	Instead of landfilling the industries decides to either reuse, recycle, or remanufacture
		9.3 Increase access of SMEs to financial services and integration into value chains.		
		9.4 Upgrade infrastructure for sustainability and resource efficiency.		
		9.5 Enhance scientific research and technology development.		
		9.a Facilitate sustainable infrastructure in developing countries.		

		9.b Support domestic tech development and value addition.		
		9.c Increase access to ICT and internet.		
10	Reduced Inequalities	10.1 Achieve income growth of bottom 40%.		
		10.2 Empower and promote inclusion regardless of status.		
		10.3 Ensure equal opportunity and reduce inequalities of outcome.		
		10.4 Adopt policies for fiscal, wage, and social protection equality.		
		10.5 Improve regulation of global financial markets.		
		10.6 Ensure enhanced representation in global institutions.		
		10.7 Facilitate safe, regular, and responsible migration.		
		10.a Implement special treatment for developing countries.		
		10.b Encourage development assistance and investment in least developed areas.		
		10.c Reduce remittance costs.		
11	Sustainable Cities and Communities	11.1 Ensure access to adequate, safe, and affordable housing.		
		11.2 Provide sustainable transport systems.		
		11.3 Enhance inclusive urbanization and capacity for planning.		
		11.4 Protect cultural and natural heritage.		
		11.5 Reduce disaster impact and losses.		
		11.6 Reduce environmental impact of cities (air quality, waste).	√	Implementation of circular economies reduces the effect of landfilling, ultimately reducing the harmful environmental impacts
		11.7 Provide access to safe, inclusive green/public spaces.		
		11.a Support positive links between urban, peri-urban, rural.		
		11.b Increase disaster risk reduction strategies.		
		11.c Support least developed countries in sustainable building.		
12	Responsible	12.1 Implement 10-Year Framework on sustainable consumption/production.		

	Consumption and Production	12.2 Achieve sustainable management and use of resources.		
		12.3 Halve per capita global food waste.		
		12.4 Manage chemicals and waste sustainably.		
		12.5 Substantially reduce waste generation.	√	Reduces waste generation by implementing circular economy strategies
		12.6 Encourage companies to adopt sustainable practices.	√	Industrial Symbiosis encourages one industry to accept another's end of life materials
		12.7 Promote sustainable public procurement.		
		12.8 Ensure people have relevant information for sustainable development.		
		12.a Support developing countries' scientific and technological capacity.		
		12.b Develop tools to monitor sustainable tourism impacts.		
		12.c Rationalize inefficient fossil-fuel subsidies.		
13	Climate Action	13.1 Strengthen resilience and adaptive capacity to climate-related hazards.		
		13.2 Integrate climate measures into national policies.		
		13.3 Improve education and awareness on climate change.		
		13.a Implement UNFCCC commitments (mobilize $100 billion annually).		
		13.b Promote mechanisms for capacity-building in least developed countries.		
14	Life Below Water	14.1 Reduce marine pollution.		
		14.2 Sustainably manage and protect marine ecosystems.		
		14.3 Minimize and address ocean acidification.		
		14.4 Regulate harvesting and end overfishing.		
		14.5 Conserve at least 10% of coastal and marine areas.		
		14.6 Prohibit harmful fisheries subsidies.		
		14.7 Increase economic benefits from sustainable marine resources.		

		14.a Increase scientific knowledge and marine technology transfer.		
		14.b Provide access for small-scale artisanal fishers.		
		14.c Implement international law for oceans.		
15	Life on Land	15.1 Conserve terrestrial and freshwater ecosystems.		
		15.2 Promote sustainable management of forests.		
		15.3 Combat desertification and restore degraded land.		
		15.4 Ensure conservation of mountain ecosystems.		
		15.5 Take urgent action to reduce biodiversity loss.		
		15.6 Promote fair benefit-sharing from genetic resources.		
		15.7 End poaching and trafficking of protected species.		
		15.8 Prevent introduction of invasive alien species.		
		15.9 Integrate ecosystem values into policies/planning.		
		15.a Mobilize resources for biodiversity.		
		15.b Finance sustainable forest management.		
		15.c Support local communities for forest and wildlife.		
16	Peace, Justice and Strong Institutions	16.1 Reduce violence and related death rates.		
		16.2 End abuse, trafficking, and violence against children.		
		16.3 Promote rules of law and equal access to justice.		
		16.4 Reduce illicit financial/arms flows, organized crime.		
		16.5 Reduce corruption and bribery.		
		16.6 Develop effective, accountable institutions.		
		16.7 Ensure inclusive, participatory decision-making.		
		16.8 Broaden participation of developing countries in global governance.		

		16.9 Provide legal identity for all (including birth registration).		
		16.10 Ensure access to information and protect freedoms.		
		16.a Strengthen national institutions for prevention of violence.		
		16.b Promote/enforce non-discriminatory laws and policies.		
17	Partnerships for the Goals	17.1 Strengthen domestic resource mobilization.	√	Applying industrial symbiosis strengthens the relationship between different local industries
		17.2 Developed countries to implement ODA commitments.		
		17.3 Mobilize additional financial resources.		
		17.4 Assist developing countries with debt sustainability.		
		17.5 Invest in least developed countries.		
		17.6 Enhance access to science, technology, innovation.		
		17.7 Promote environmentally sound technologies.		
		17.8 Fully operationalize technology bank for LDCs.		
		17.9 Enhance international support for capacity-building.		
		17.10 Promote a universal, rules-based trading system (WTO).		
		17.11 Increase exports of developing countries.		
		17.12 Timely implementation of duty-free, quota-free market access.		
		17.13 Enhance global macroeconomic stability.		
		17.14 Enhance policy coherence for sustainable development.		
		17.15 Respect national policy space.		
		17.16 Enhance global partnerships.		
		17.17 Encourage multi-stakeholder partnerships.		
		17.18 Enhance data capacity of developing countries.		
		17.19 Support capacity-building for sustainable development indicators.		

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First of all, we are grateful to **ALLAH (SWT)**, the most benevolent and kind to provide us with the strength and ability to write this thesis dissertation. We want to thank our project supervisor, Dr. Prof. Shamsuddin Ahmed, for his patience and support through problems during the project and his necessary advice when we faced difficulties.

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Abstract

Gas industries are highly involved in the disposal of the raw materials used to construct oil and gas coups which tend to have severe consequences on the environment. Linear economy as we know is adapted to this situation as (take, make, throw) where these scraps that are stagnant are discarded in landfills. A circular economy would both maximize the merits of these scraps and minimize their ill effects, through such actions as redesigning products to cut waste and make them last; boosting recycling and reuse, and utilizing scraps as a resource; to name a few. In this study we are focusing on the residual scrap materials generated; since the main focal point of gas industries are usually the chemical wastages generated from the reactions in order to form gas/oil. A model for recycling the scrap generated from the gas industry has been proposed which provides recycling of the waste in multiple levels i.e. we can extract the same product from the waste by high grade recycling or can use them in secondary operations like incorporating these scraps in the tech or agricultural operations. This study presents a hybrid methodological study based on the Decision Making Trial and Evaluation Laboratory (DEMATEL) method and Analytic Hierarchy Process (AHP) method to define the best Circular Economy methodology to be implemented in order to reduce environmental, economical, operational, and supply chain barriers. Results were presented as Industrial Symbiosis to be the best circular economy methodology to implement and Process Optimization to be the reigning cause which affects the various criteria.

Summary

(for non-technical audience)

The gas industry creates a lot of **scrap material** (left-over equipment) when building oil and gas coups such as wells etc. So initially, these stagnant materials are discarded in landfills—a "take, make, throw" approach—which is degenerative to the environment. The objective is to **somehow re-incorporate** these scraps into the supply chain to get maximum value and reduce environmental harm.

A multi-level sustainable plan was suggested: either **high-grade recycling** to get the original material back, or extending the life of the scraps for reuse, or using the scraps in **other industries**, like technology or agriculture.

The research used a special combination of decision-making tools (called DEMATEL and AHP) to figure out the **best strategy** to overcome hurdles like environmental damage, high costs, operational difficulties, and supply chain issues.

The main findings were:

- **Best Solution:** The most effective method is **Industrial Symbiosis** —where one industry's waste (the gas scrap) becomes a raw material for another company.
- **Biggest Barrier:** The number one problem affecting everything else is **Process Optimization.** Addressing this is key to successfully implementing any circular economy strategy.

For example, think of gas scrap like old phone batteries – instead of throwing them away, recycle them into new products or use in farming for soil enhancement, as done in some EU gas projects .

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Chapter 1: Introduction

1.1 Objectives of the Study

The implementation of a unique hybrid Multi-Criteria Decision Making (MCDM) model is the fundamental purpose of this project. In this section, the specific and measurable goals are broken down as follows: (1) systematically identifying and weighting the multi-dimensional criteria (environmental, economic, and operational); (2) quantifying the complex causal inter-relationships among these criteria using DEMATEL; and (3) providing a refined, risk-assessed, and validated recommendation for the optimal communication and engagement strategy. The work highlights its contribution, which is that it provides the first integrated qualitative risk assessment model that is specifically tailored for scrap management in the gas industry. This model also includes a detailed scope boundary, which will be limited to the specific operations of gas utility companies in the study region.

SMART Objectives:

- Specific: Develop a hybrid model for scraps
- Measurable: Reduce waste by a certain percentage
- Achievable: Using existing statistical tools like AHP and DEMATEL
- Relevant: Aligns with SDG 12 (Responsible Consumption and Production goal of the UN Sustainable Development Goals)
- Time-Bound: Implementation roadmap for 5+ years

1.2 Structure of the Thesis

This section leads the reader through the structured progression of the chapters, explaining the transition from the theoretical foundation in Chapter 2 to the technical application in Chapter 3, the presentation of empirical findings in Chapter 4, and the final synthesis of knowledge in Chapter 5 and finally the conclusion in Chapter 6. The focus of each chapter and the nature of the information presented will be clearly outlined to provide context for the upcoming content. The roadmap is comprehensive, allocating a paragraph to outline the anticipated content of each chapter.

1.3 The Paradigm Shift: From Linear to Circular Economy Imperative

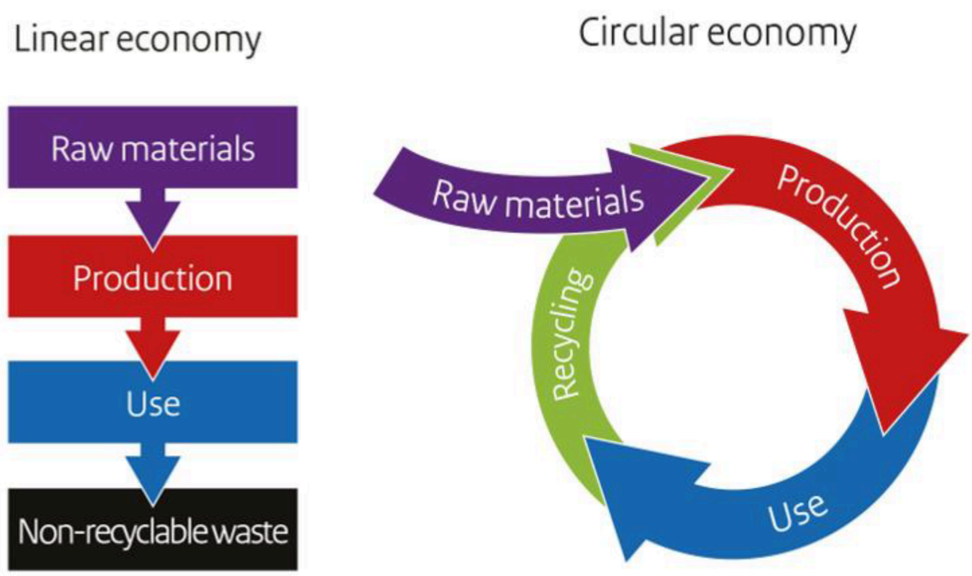
The conceptual justification for adopting a Circular Economy (CE) model. It meticulously compares and contrasts the resource flows of the **Linear** model (Take-Make-Dispose) versus the **Circular** model (Resource Retention, Regeneration). The CE's three core principles will be defined and elaborated upon: (1) Designing out waste and pollution, (2) Keeping products and materials in use for as long as possible, and (3) Regenerating natural systems. The necessity for the gas industry to shift towards CE is framed not just as an environmental mandate but as an economic opportunity to retain resource value (MRVR) and mitigate growing regulatory and social pressures. This should include an analysis of the socio-economic drivers compelling the gas industry toward CE. Global gas waste is 200 million tons/year and in the case of Bangladesh; 50k tons. The gas sector contributes 70% energy, but waste management lags.

1.4 Problem Statement and the Significance

The gas industry in Bangladesh generates significant scrap, leading to environmental degradation (e.g., water contamination from glycol leaks, soil contamination from landfilling, harming natural habitats and resources) and economic losses (BDT 10M/year). Linear models exacerbate this; circular approaches can mitigate, but lack integrated models. The significance of this study is that it supports multiple sustainability goals involving scraps rather than the chemical wastage resulting from different reactions involving gas and oil coup drilling process and excavation, and a potential for job creation in the recycling sector which is still so underexplored in Bangladesh.

Chapter 2: Literature Review

The transition from a linear to a **circular economy (CE)** is a critical global imperative, particularly for resource-intensive industries like the gas sector.[9] In Bangladesh, where gas exploration and processing are integral to the national economy, the management of residual materials and scrap from operations is not just an operational or economical challenge but a key opportunity for sustainable development.[2][3] This literature review synthesizes existing research on waste management, circular economy principles, and multi-criteria decision-making (MCDM) models to provide a theoretical foundation for a hybrid AHP-DEMATEL approach to scrap management.[4]



1. Circular Economy and Scrap Management in Industrial Contexts

The traditional linear model of "take-make-dispose" has led to significant resource depletion and environmental degradation.[5] This system relies on the assumption that resources are plentiful and disposal is cheap, leading to significant environmental consequences like pollution, resource depletion, and overflowing landfills.[6] In response, the Circular Economy model proposes a closed-loop system where waste is minimized, and resources are kept in use for as long as possible through reuse, recycling, and remanufacturing.[7][8] This concept is highly relevant to the gas industry, where leftover raw materials such as glycol, adhesives, and metal fittings are often discarded. Research published in the *Journal of Cleaner Production*, has provided a comprehensive overview of the CE's conceptual framework, emphasizing its role in achieving sustainable development goals [1]. For the gas industry in Bangladesh, adopting CE principles would mean moving beyond simple landfill disposal to more value-retentive strategies. in the *Journal of Cleaner Production* highlighted the importance of establishing robust reverse logistics networks and supplier-buyer collaborations to support circular supply chains, a concept directly applicable to managing glycol drums and other reusable materials [10].

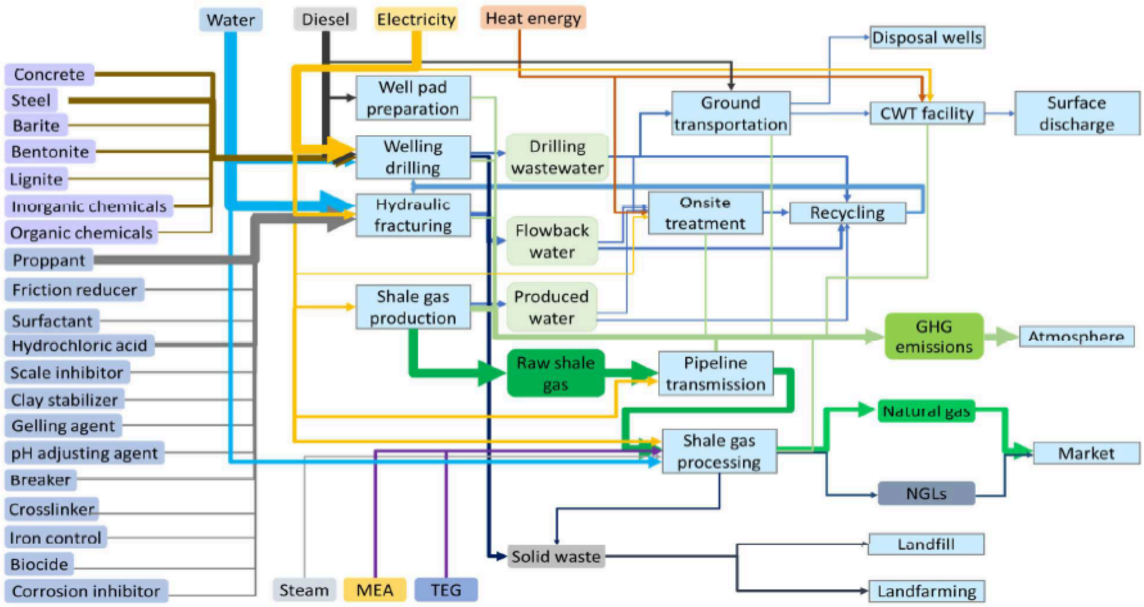


Figure 2. Illustrative material flow diagram of the shale gas energy system.

2. The Hybrid AHP-DEMATEL Model for Multi-Criteria Decision-Making

Effective scrap management requires evaluating multiple, often conflicting, criteria—a perfect use case for MCDM models. AHP and DEMATEL are two prominent methods frequently used together to enhance decision-making in complex systems.[11]

AHP (Analytic Hierarchy Process) is a foundational MCDM tool that allows decision-makers to structure a complex problem into a hierarchy and use pairwise comparisons to determine the relative importance of criteria.[26] This method is particularly adept at handling both quantitative and qualitative factors, making it suitable for assessing subjective criteria like sustainability and operational efficiency. **Saaty**'s seminal work on AHP established its use for a wide range of applications, including strategic planning and resource allocation. [3]

DEMATEL (Decision Making Trial and Evaluation Laboratory), on the other hand, is a powerful technique for mapping the causal relationships and interdependencies among criteria. It helps in identifying the most influential "cause" factors and the most susceptible "effect" factors within a system. This is crucial for understanding the intricate links between different aspects of scrap management, such as how transportation costs might influence resource value retention. Studies like in the *International Journal of Production Economics* have demonstrated DEMATEL's ability to provide deeper insights into complex systems than traditional methods.

The **hybrid AHP-DEMATEL model** combines the hierarchical structuring capability of AHP with the causal analysis of DEMATEL. This integrated approach not only ranks the importance of criteria but also reveals their interdependencies, providing a more robust and nuanced decision-making framework. This hybrid model has been successfully applied in various sustainability and supply chain contexts, proving its value in addressing issues where multiple factors are intertwined.

3. Criteria for Sustainable Scrap Management

The criteria selected for your thesis—Environmental, Economical, Operational, and Sustainable—are a robust framework for analyzing scrap management in the gas industry. The sub-criteria you identified are equally critical:

- **Environmental:** Factors like **Hazardous Waste Management (HWM)** and **Water Contamination Risk (WCR)** are paramount in the gas industry due to the nature of the materials handled, such as glycol and other chemicals. The sub-criterion of **Landfill Disposal Capacity (LDC)** underscores the unsustainability of linear waste models and highlights the need for a circular approach. Research in journals like *Waste Management* consistently emphasizes the environmental and financial costs associated with improper disposal.[29]
- **Economical: Storage Costs** and **Transportation** are direct economic burdens of inefficient scrap management. Optimizing these factors is key to improving the overall financial viability of a circular system.[17][18]
- **Operational & Sustainable:** The sub-criteria of **Maximum Resource Value Retention (MRVR)** and **Maximum Resource Rate (MRR)** are core tenets of the circular economy. They measure the effectiveness of recycling and reuse efforts. **Process Optimization** aims to reduce scrap generation at the source, while strong **Supplier and Buyer Networks** are essential for creating a functional market for recycled materials. These factors are not isolated but are deeply interconnected; for example, an increase in resource value retention directly impacts operational efficiency and economic returns.[21][22]

4. The Role of Material Flow Diagrams (MFD)

To complement the quantitative analysis of the AHP-DEMATEL model, a **Material Flow Diagram (MFD)** is an indispensable visual tool. An MFD provides a graphical representation of the entire lifecycle of a material, from its entry into the system to its ultimate fate. By mapping the flow of materials like glycol drums and anodes within the gas industry, an MFD can visually identify points of scrap generation, bottlenecks in the current waste management process, and potential opportunities for circularity. This visual analysis will not only support your findings but also make the research highly accessible.

Chapter 3: Methodology

3.1 Model Formulation and Expert Data Elicitation Protocol

This section details the construction of the three-level decision hierarchy: the overall Goal (Sustaining a CE), the 10 Criteria (Impacts/Factors), and the 3 Alternatives (Strategies). Crucially, the **expert selection methodology** will be described, detailing the required expertise (e.g., logistics, environmental engineering, operational management), the number of experts consulted, and the protocol for minimizing bias and achieving consensus on the judgments. The structure and format of the **pairwise comparison questionnaires** are provided, along with the specific mathematical formulas used to convert the linguistic judgments into numerical **Saaty scales**. The overall goal for our model is to choose the optimum Circular Economy method which includes the following: Industrial Symbiosis, Product Life Extension, and Material Resource Efficiency. **Industrial Symbiosis** is a process-oriented solution, concerned with using residual outputs from one process as feedstock for another process, which benefits from geographical proximity of business. **Product Life Extension** is exploiting the residual value of products from manufacturing to consumers and then back to manufacturing or collection of products between distinct business entities. **Material Resource Efficiency** is exploiting the residual value of resources: collection and sourcing of otherwise "wasted" materials or resources to turn these into new forms of value. The 10 criterias are as follows: Hazardous Waste Management, Water Contamination Risk, Storage Costs, Process Optimization, Space Utilization, Transportation Feasibility, Material Resource Rate, Maximum Resource Value Retention, Landfilling Disposal Capacity, Supplier Buyer Networking.

3.2 Analytical Hierarchy Process (AHP) method

The Analytic Hierarchy Process (AHP) breaks down a decision-making problem into several levels in such a way that they form a hierarchy with unidirectional hierarchical relationships between levels (De Felice and Petrillo, 2014). The AHP for decision making uses objective mathematics to process the inescapably subjective and personal preferences of an individual or a group in making a decision. With the AHP, one constructs hierarchies or feedback networks, then makes judgments or performs measurements on pairs of elements with respect to a controlling element to derive ratio scales that are then synthesized throughout the structure to select the best alternative (De Felice, 2012). The top level of the hierarchy is the main goal of the decision problem. The lower levels are the tangible and/or intangible criteria and sub-criteria that contribute to the goal. The bottom level is formed by the alternatives to evaluate in terms of the criteria. The modeling process can be divided into different phases for the ease of understanding which are described as follows:

PHASE 1: Pairwise comparison and relative weight estimation. Pairwise comparisons of the elements in each level are conducted with respect to their relative importance towards their control criterion. Saaty suggested a scale of 1-9 when comparing two components. For example, number 9 represents extreme importance over another element. And number 8 represents it is between "very strong important" and "extreme importance"over another element.

Table 1: Semantics scale of Saaty

Intensity of importance a_{ij}	Definition	Explanation
1	Equal Importance	Two activities contribute equally to the objective
3	Moderate importance	Experience and judgment slightly favor one activity over another
5	Strong importance	Experience and judgment strongly favor one activity over another
7	Very strong or demonstrated importance	An activity is favored very strongly over another; its dominance demonstrated in practice
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation
2,4,6,8	For compromise between the above values	Sometimes one needs to interpolate a compromise judgment numerically because there is no good word to describe it

For a general AHP application we can consider that A1, A2,…,Am denote the set of elements, while aij represents a quantified judgment on a pair of Ai, Aj. Through the 9-value scale for pairwise comparisons, this yields an [m x m] matrix A as follows:

$$A = a_{ij} = \begin{array}{c} \\ A_1 \\ A_2 \\ \dots \\ A_m \end{array} \left| \begin{array}{ccccc} A_1 & A_2 & \dots & A_m \\ 1 & a_{12} & \dots & a_{1m} \\ 1/a_{12} & 1 & \dots & a_{2m} \\ \dots & \dots & \dots & \dots \\ 1/a_{1m} & 1/a_{2m} & \dots & 1 \end{array} \right|$$

where aij > 0 (i, j = 1, 2,..,m), aii = 1 (i = 1, 2,…,m), and aij = 1/aji (1; 2;…,m). A is a positive reciprocal matrix. The result of the comparison is the so-called dominance coefficient aij that represents the relative importance of the component on row (i) over the component on column (j), i.e., aij=wi/wj. The pairwise comparisons can be represented in the form of a matrix. The score of 1 represents equal importance of two components and 9 represents extreme importance of the component i over the component j. In matrix A, the problem becomes one of assigning to the m elements A1, A2,…,Am a set of numerical weights w1, w2,…,wm that reflects the recorded judgments. If A is a consistency matrix, the relations between weights wi, wj and judgments aij are simply given by aij = wi/wj (for i,j = 1, 2, …, m) and

$$
A = \begin{array}{c} \\ A_1 \\ A_2 \\ \dots \\ A_m \end{array}
\begin{vmatrix}
w_1/w_1 & w_1/w_2 & & w_1/w_m \\
w_2/w_1 & w_2/w_2 & & w_2/w_m \\
 & & & \\
\dots & \dots & \dots & \dots \\
w_m/w_1 & w_m/w_2 & \dots & w_m/w_m
\end{vmatrix}
$$

If matrix w is a non-zero vector, there is a λmax of Aw = λmaxw, which is the largest eigenvalue of matrix A. If matrix A is perfectly consistent, then λmaxw = m. But given that aij denotes the subjective judgment of decision-makers, who give comparison and appraisal, with the actual value (wi/wj) having a certain degree of variation. Therefore, Ax = λmaxw cannot be set up. So the judgment matrix of the traditional AHP always needs to be revised for its consistency.

PHASE 2: Priority vector. After all pairwise comparison is completed, the priority weight vector (w) is computed as the unique solution of Aw = λmaxw, where λmax is the largest eigenvalue of matrix A. **PHASE 3:** Consistency index estimation. Saaty (1990) proposed utilizing consistency index (CI) to verify the consistency of the comparison matrix. The consistency index (CI) of the derived weights could then be calculated by: CI = (λmax−n)/ n−1. In general, if CI is less than 0.10, satisfaction of judgments may be derived.

3.2 The Decision Making Trial and Evaluation Laboratory (DEMATEL) method

Decision Making Trial and Evaluation Laboratory (DEMATEL) (Fontela and Gabus, 1976), a system analytical method, was proposed by the United States Bastille laboratory in 1971. This integrated method uses some mathematical tools such as matrix theory and graph theory to analyze factor relationships. DEMATEL is an effective method to analyze and evaluate influencing factors. It can synthesize the advice or experience of experts, simplifying the uncertain element of complex systems. This methodology is able to verify interdependence among the unpredictable features or attributes likewise containing reveals the characteristic with an essential system and development trend and try to reflect the interrelationship between variables by improving the directed graph (Gabus and Fontela, 1973). DEMATEL is characterized there by 6 main steps:

1. Making the direct-influenced matrix: This phase consists of measuring the relationship between criteria. This requires a four-level comparison scale: non-existent impact (0), low impact (1), medium impact (2), substantial impact (3) and very substantial impact (4). An expert team makes pairwise comparisons, evaluating the influence and direction between criteria. The results form a n x n matrix called direct-relation matrix B, in which bij represents the degree to which the criterion i affects the criterion j.

2. Calculating the direct-influenced matrix normalization: The normalized directrelation matrix N is obtained from matrix B by formulas (1) and:

$$M = k \cdot A \, (1)$$

$$k = \min\left(\frac{1}{\max\limits_{1 \le i \le n} \sum_{j=1}^{n} |a_{ij}|}, \frac{1}{\max\limits_{1 \le j \le n} \sum_{i=1}^{n} |a_{ij}|}\right) i, j \in \{1,2,3, \dots, n\} (2)$$

3. Achieving the total-relation matrix: After the normalization of the direct-relation matrix B, the total-relation matrix S is calculated by using the formula (3), where I represents the Identity Matrix:

$$S = M + M^2 + M^3 + \dots = \sum_{i=1} M^i = M(I - M)^{-1} (3)$$

4. Producing a causal diagram: With the use of D + R and D – R, where R is the sum of columns and also D is the sum of rows in matrix S as shown in formulas (4) – (6). The criteria that have positive values of D – R have higher influence on the other criteria. These are called “dispatchers”. The others with negative values of D – R receive more influence from another. These are called “receivers”. On the other side, the value of D + R indicates the degree between each criterion with others.

$$S = [s_{ij}]_{nxn}, i, j \in \{1,2,3, \dots, n\} (4)$$

$$D = \sum_{j=1}^{n} s_{ij} (5)$$

$$R = \sum_{i=1}^{n} s_{ij} (6)$$

5. Obtaining the inner dependence matrix and impact relationship map: Map the dataset (D + R, D – R). The threshold value is set to indicate the influence level between criteria.

6. Obtaining the inner dependence matrix: In this step, the sum of each column in total-relation n×n matrix is equal to 1 by the normalization method and then the inner dependence matrix can be acquired: The product of the DEMATEL process is a visual representation (i.e., an individual map of the mind) that the respondent uses to organize his or her own actions.

Chapter 4: Computational Methodology

4.1 AHP Computational Results: Detailed Criteria Weighting and Strategy Scores

This section presents the final quantitative outputs from the AHP computational model:

(Table 1: Input from experts)

	HMW	WCR	SC	MVRM	MRR	OSSP	PO	TF	SBN	LDC
HWM	1.0000	2.4500	2.5000	0.6333	3.6100	1.4750	0.2987	3.0780	0.5394	0.8804
WCR	0.4082	1.0000	4.1740	1.6610	1.6800	2.0000	0.9425	1.9330	0.7874	2.8770
SC	0.1709	0.2396	1.0000	0.7564	0.8080	0.5952	0.4876	1.3211	1.2148	1.3340
MVRM	1.5791	0.6020	1.3220	1.0000	1.1730	0.7508	0.3656	0.8382	1.1161	1.3550
MRR	0.2770	0.5952	1.2376	0.8525	1.0000	1.1746	0.4792	1.1173	1.0350	1.1249
OSSP	0.6780	0.3912	1.6800	1.3320	0.8514	1.0000	1.0200	1.9100	1.4250	1.6331
PO	3.3480	1.0610	2.0510	2.7351	2.0870	0.9804	1.0000	2.0000	0.9820	2.4710
TF	0.3249	0.5173	0.7569	1.1930	0.8950	0.5236	0.2933	1.0000	1.0400	1.7187
SBN	1.8540	1.2700	0.8232	0.8960	0.9662	0.7018	1.0183	1.0884	1.0000	0.6173
LDC	1.1358	0.3476	0.7496	0.7380	0.8890	0.6123	0.4047	0.5818	1.6200	1.0000
SUM	10.7759	8.4740	16.2944	11.7973	13.9595	9.8136	6.3098	14.8679	10.7597	15.0113

	HMW	WCR	SC	MVRM	MRR	OSSP	PO	TF	SBN	LDC	AVERAGE(Eigenvalues)	LEMBDA	CI	RCI	CR
HWM	0.0928	0.2891	0.1534	0.0537	0.2586	0.1503	0.0473	0.2070	0.0501	0.0586	0.1361	10.99719664	0.145601373	1.49	0.097719042
WCR	0.0379	0.1180	0.2562	0.1408	0.1203	0.2038	0.1494	0.1300	0.0732	0.1917	0.1421	10.57681336			
SC	0.0159	0.0283	0.0614	0.0641	0.0579	0.0607	0.0773	0.0889	0.1129	0.0889	0.0656	10.46892179			
MVRM	0.1465	0.0710	0.0811	0.0848	0.0840	0.0765	0.0579	0.0564	0.1037	0.0903	0.0852	11.20582262			
MRR	0.0257	0.0702	0.0760	0.0723	0.0716	0.1197	0.0759	0.0751	0.0962	0.0749	0.0758	10.58556569			
OSSP	0.0629	0.0462	0.1031	0.1129	0.0610	0.1019	0.1617	0.1285	0.1324	0.1088	0.1019	10.61072353			
PO	0.3107	0.1252	0.1259	0.2318	0.1495	0.0999	0.1585	0.1345	0.0913	0.1646	0.1592	11.27609024			
TF	0.0301	0.0610	0.0465	0.1011	0.0641	0.0534	0.0465	0.0673	0.0967	0.1145	0.0681	10.64765423			
SBN	0.1721	0.1499	0.0505	0.0759	0.0692	0.0715	0.1614	0.0732	0.0929	0.0411	0.0958	11.31041236			
LDC	0.1054	0.0410	0.0460	0.0626	0.0637	0.0624	0.0641	0.0391	0.1506	0.0666	0.0702	11.050604			
SUM	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000		11.31041236			
The criterias are consistent.															

(Table 1)

1. Google form was circulated amongst the industry experts who work currently at renowned gas industries like PETROBANGLA. The inputs from the industry experts acted as the inputs to the mathematical models. The responses were converted into their geometric mean since the inputs varied from individual to individual.
2. Afterwards, the geometric mean is converted into normalized values by dividing each value by the sum of their columns.
3. Finally the normalized values are transformed into the average value of each row (each criteria)

Random inconsistency index										
N	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.46	1.49

(Table 2)

4. The consistency of the inputs are validated by finding the consistency ratio which is found by incorporating the consistency index and the random inconsistency index. For the 10 criterias we choose the RCI as 1.49.
5. Since, the value of the Consistency Ratio is less than 0.1, it is deduced that the inputs are consistent and the computation may be further proceeded.

A1	Industrial Symbiosis
A2	Product Life Extension
A3	Material Resource Efficiency

WRT HWM	A1	A2	A3
A1	1	1.185677022	0.584829522
A2	0.8434	1	0.843454791
A3	1.7099	1.1856	1
SUM	3.5533	3.371277022	2.428284313

WRT HWM	A1	A2	A3	Average
A1	0.281428531	0.35169967	0.240840629	0.291322944
A2	0.237356823	0.2966235	0.347345979	0.293775435
A3	0.481214646	0.35167683	0.411813392	0.414901621
SUM	1	1	1	

WRT WCR	A1	A2	A3
A1	1	2.1399	3.2710
A2	0.467311557	1	0.493242577
A3	0.3057	2.0274	1
SUM	1.7730	5.1673	4.7642

WRT WCR	A1	A2	A3	AVERAGE
A1	0.5640	0.4141	0.6866	0.554901034
A2	0.2636	0.1935	0.1035	0.186873882
A3	0.1724	0.3924	0.2099	0.258225084
SUM	1.0000	1.0000	1.0000	

WRT MRR	A1	A2	A3
A1	1	4.7177	1.9129
A2	0.211967696	1	0.584805581
A3	0.5228	1.70997	1
SUM	1.7347	7.4277	3.4977

WRT MRR	A1	A2	A3	AVERAGE
A1	0.5765	0.6352	0.5469	0.586170216
A2	0.1222	0.1346	0.1672	0.141339647
A3	0.3014	0.2302	0.2859	0.272490138
SUM	1.0000	1.0000	1.0000	

WRT TF	A1	A2	A3
A1	1	0.637633106	0.843454791
A2	1.5683	1	0.4409
A3	1.1856	2.2680	1
SUM	3.7539	3.905633106	2.284371898

WRT TF	A1	A2	A3	AVERAGE
A1	).266389621	0.163259858	0.369228317	0.266292599
A2	).417778843	0.256040435	0.1930	0.288944623
A3	).315831535	0.5807	0.437757092	0.444762778
SUM	1	1	1	

WRT PO	A1	A2	A3
A1	1	0.637633106	1.3264
A2	1.5683	1	2.0800
A3	0.753920386	0.4808	1
SUM	3.322220386	2.118402337	4.4064

WRT PO	A1	A2	A3	AVERAGE
A1	0.301003511	).300997169	0.301016703	0.301005794
A2	0.472063806	0.47205386	0.4720	0.472052778
A3	0.226932683	0.2269	0.226942629	0.226941428
SUM	1	1	1	

WRT SBN	A1	A2	A3
A1	1	0.481	4.7177
A2	2.080	1	2.7589
A3	0.211967696	0.362463301	1
SUM	3.291967696	1.843	8.477

WRT SBN	A1	A2	A3	AVERAGE
A1	).303769688	0.261	0.557	0.37371826
A2	0.632	0.543	0.325	0.499946192
A3	).064389361	0.197	0.118	0.126335548
SUM	1	1.000	1.000	

WRT LDC	A1	A2	A3
A1	1	5.2776	6.2573
A2	0.189480067	1	1.6134
A3	0.159813338	0.619809099	1
SUM	1.349293405	6.897409099	8.8707

WRT LDC	A1	A2	A3	AVERAGE
A1	0.74112865	).765156876	0.705389654	0.73722506
A2	0.140429106	).144981976	0.181879671	0.155763584
A3	0.118442244	).089861148	0.112730675	0.107011356
SUM	1	1	1	

WRT SC	A1	A2	A3
A1	1	0.926011668	2.7589
A2	1.0799	1	2.2680
A3	0.362463301	0.4409	1
SUM	2.442363301	2.366928775	6.0269

WRT SC	A1	A2	A3	Average
A1	0.409439496	).39122921	0.457764356	0.419477687
A2	0.442153712	).42248842	0.3763	0.413651666
A3	0.148406791	0.1863	0.16592278	0.166870648
SUM	1	1	1	

WRT MVRM	A1	A2	A3
A1	1	1.3264	3.2711
A2	0.753920386	1	1.7099
A3	0.30570756	0.584829522	1
SUM	2.059627946	2.911229522	5.981

WRT MVRM	A1	A2	A3	AVERAGE
A1	0.485524583	).45561506	0.546915232	0.49601829
A2	0.366046881	).34349748	0.285888647	0.331811002
A3	0.148428536	).20088747	0.167196121	0.172170708
SUM	1	1	1	

WRT OSSP	A1	A2	A3
A1	1	0.775674837	0.467311557
A2	1.2892	1	1.9129
A3	2.1399	0.52276648	1
SUM	4.4291	2.298441317	3.380211557

WRT OSSP	A1	A2	A3	AVERAGE
A1	0.225779504	).33747863	0.138249204	0.233835781
A2	0.291074936	).43507746	0.565911325	0.430687906
A3	0.483145561	).22744391	0.295839471	0.335476314
SUM	1	1	1	

(Table 3)

6. Each alternative decision is weighed against each other where; A1 is Industrial Symbiosis, A2 is Product Life Extension, and A3 is Material Resource Efficiency.
7. Each input of the alternative decisions are then converted into the average of each row by evaluating them with respect to each different criteria. With respect to 10 criteria the different alternate decisions are weighed.

normalized decision matrix	WEIGHTS	A1	A2	A3
HWM	0.1361	0.291322944	0.293775435	0.414901621
WCR	0.1421	0.554901034	0.186873882	0.258225084
SC	0.0656	0.419477687	0.413651666	0.166870648
MVRM	0.0852	0.49601829	0.331811002	0.172170708
MRR	0.0758	0.586170216	0.141339647	0.272490138
OSSP	0.1019	0.233835781	0.430687906	0.335476314
PO	0.1592	0.301005794	0.472052778	0.226941428
TF	0.0681	0.266292599	0.288944623	0.444762778
SBN	0.0958	0.37371826	0.499946192	0.126335548
LDC	0.0702	0.73722506	0.155763584	0.107011356

(Table 4)

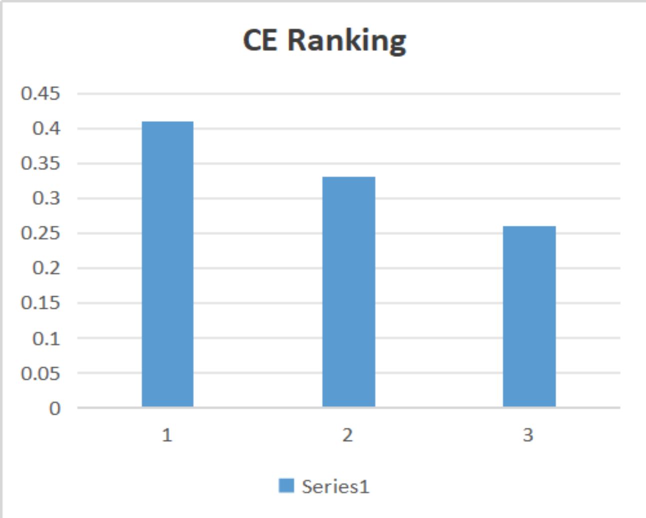
8. The average values of each alternate decision with respect to each is then transcribed into their normalized values which is the average value of each alternate decision with respect to each criteria.

	A1	A2	A3
HWM	0.039649053	0.039982837	0.056468111
WCR	0.078851437	0.026554779	0.036693784
SC	0.027517736	0.027135549	0.010946714
MVRM	0.042260758	0.028270297	0.014668944
MRR	0.044431702	0.010713545	0.020654752
OSSP	0.023827866	0.043887098	0.034185036
PO	0.047920122	0.075150802	0.036129075
TF	0.018134526	0.019677129	0.030288345
SBN	0.035802209	0.047894845	0.012102946
LDC	0.051753199	0.010934604	0.007512197
SUM	0.410148609	0.330201485	0.259649906
	BEST		WORST

(Table 5)

9. The finalized normalized decision matrix is the value of the lambda value of each criteria multiplied to each of the alternate decisions in that specific criteria.
10. To finalize the optimum decision, the sum of different alternate columns are calculated. In the

case of A1 it is **0.4101048609**, for A2 it is **0.330201485**, and for A3 it is **0.259649906**. Thus from the sums we deduce that since the value of A1 is the highest compared to the other two decisions, it is our optimum decision. Thus Industrial Symbiosis proves to be the optimum decision for the scrap management in the gas industry.



(Table 6)

11. A1>A2>A3

The final normalized criteria weight**s**, interprets why **Process Optimization(PO)** was deemed the most critical criterion (normalized weight ≈0.1592), followed closely by **Water Contamination Risk (WCR)** (normalized weight ≈0.1421). Table 5 presents the **final quantified scores** for the three CE strategies, establishing the initial base ranking: **Industrial Symbiosis (IS)** has the highest score, followed by **Product Life Extension (PLE)**, and then **Material Resource Efficiency (MRE)**.

4.2 DEMATEL Computational Results: Causal Influence and Structural Modeling

	HWM	WCR	SC	MRR	TF	MRVR	OSSP	PO	SBN	LDC	SUM
HWM	0	4	2	1	3	1	2	2	1	4	20
WCR	1	0	2	0	3	0	1	1	0	3	11
SC	1	1	0	0	3	1	3	2	1	1	13
MRR	1	0	0	0	1	3	1	2	2	0	10
TF	2	2	3	1	0	1	2	2	1	2	16
MRVR	1	0	1	3	1	0	1	2	2	0	11
OSSP	2	1	3	1	2	1	0	2	1	1	14
PO	2	1	2	2	3	2	3	0	1	1	17
SBN	1	0	2	2	2	2	2	1	0	1	13
LDC	3	4	1	0	2	0	1	1	0	0	12
											20

(Table 7)

1. A second Google form was distributed amongst the industry workers which they filled up which acted as the input. The sum of each rows are calculated to find the normalized matrix.

	HWM	WCR	SC	MRR	TF	MRVR	OSSP	PO	SBN	LDC
HWM	0.00	0.20	0.10	0.05	0.15	0.05	0.10	0.10	0.05	0.20
WCR	0.05	0.00	0.05	0.00	0.15	0.00	0.05	0.05	0.00	0.15
SC	0.05	0.05	0.00	0.00	0.15	0.05	0.15	0.10	0.05	0.05
MRR	0.05	0.00	0.00	0.00	0.05	0.15	0.05	0.10	0.10	0.00
TF	0.10	0.10	0.15	0.05	0.00	0.05	0.10	0.10	0.05	0.10
MRVR	0.05	0.00	0.05	0.15	0.05	0.00	0.05	0.10	0.10	0.00
OSSP	0.10	0.05	0.15	0.05	0.10	0.05	0.00	0.10	0.05	0.05
PO	0.10	0.05	0.10	0.10	0.15	0.10	0.15	0.00	0.05	0.05
SBN	0.10	0.00	0.10	0.03	0.10	0.10	0.10	0.05	0.00	0.05
LDC	0.15	0.20	0.05	0.00	0.10	0.00	0.05	0.05	0.00	0.00

(Table 8)

2. The normalized matrix above is calculated by dividing the input values by the sum of each row.

Identity Matrix										
HWM	1	0	0	0	0	0	0	0	0	0
WCR	0	1	0	0	0	0	0	0	0	0
SC	0	0	1	0	0	0	0	0	0	0
MRR	0	0	0	1	0	0	0	0	0	0
TF	0	0	0	0	1	0	0	0	0	0
MRVR	0	0	0	0	0	1	0	0	0	0
OSSP	0	0	0	0	0	0	1	0	0	0
PO	0	0	0	0	0	0	0	1	0	0
SBN	0	0	0	0	0	0	0	0	1	0
LDC	0	0	0	0	0	0	0	0	0	1

(Table 9)

Y										
HWM	0.00	0.20	0.10	0.05	0.15	0.05	0.10	0.10	0.05	0.20
WCR	0.05	0.00	0.05	0.00	0.00	0.00	0.05	0.05	0.00	0.15
SC	0.05	0.05	0.00	0.00	0.15	0.05	0.15	0.10	0.05	0.05
MRR	0.05	0.00	0.00	0.00	0.05	0.15	0.05	0.10	0.10	0.00
TF	0.10	0.10	0.15	0.05	0.00	0.05	0.10	0.10	0.05	0.10
MRVR	0.05	0.00	0.05	0.15	0.05	0.00	0.05	0.10	0.10	0.00
OSSP	0.10	0.05	0.15	0.05	0.10	0.05	0.00	0.10	0.05	0.05
PO	0.10	0.05	0.10	0.10	0.15	0.10	0.15	0.00	0.05	0.05
SBN	0.10	0.00	0.10	0.03	0.10	0.10	0.10	0.05	0.00	0.05
LDC	0.15	0.20	0.05	0.00	0.10	0.00	0.05	0.05	0.00	0.00

(Table 10)

(I-Y)										
HWM	1.00	-0.20	-0.10	-0.05	-0.15	-0.05	-0.10	-0.10	-0.05	-0.20
WCR	-0.05	1.00	-0.05	0.00	0.00	0.00	-0.05	-0.05	0.00	-0.15
SC	-0.05	-0.05	1.00	0.00	-0.15	-0.05	-0.15	-0.10	-0.05	-0.05
MRR	-0.05	0.00	0.00	1.00	-0.05	-0.15	-0.05	-0.10	-0.10	0.00
TF	-0.10	-0.10	-0.15	-0.05	1.00	-0.05	-0.10	-0.10	-0.05	-0.10
MRVR	-0.05	0.00	-0.05	-0.15	-0.05	1.00	-0.05	-0.10	-0.10	0.00
OSSP	-0.10	-0.05	-0.15	-0.05	-0.10	-0.05	1.00	-0.10	-0.05	-0.05
PO	-0.10	-0.05	-0.10	-0.10	-0.15	-0.10	-0.15	1.00	-0.05	-0.05
SBN	-0.10	0.00	-0.10	-0.03	-0.10	-0.10	-0.10	-0.05	1.00	-0.05
LDC	-0.15	-0.20	-0.05	0.00	-0.10	0.00	-0.05	-0.05	0.00	1.00

(Table 11)

3. The above matrix is calculated by the subtraction of the identity matrix above by the initial Y matrix which can also be defined as the input matrix initially.

Inv(I-Y)										
HWM	1.235993501	0.416277394	0.33055509	0.162890036	0.39001326	0.186838081	0.334307287	0.313423734	0.165187455	0.405815314
WCR	0.143036971	1.105384831	0.13800083	0.041555253	0.107434855	0.049999515	0.14082564	0.130850222	0.042162903	0.227750584
SC	0.217115022	0.20480579	1.186737473	0.097198801	0.328091264	0.156959669	0.318343581	0.257832953	0.140821862	0.202139793
MRR	0.171529788	0.101504667	0.13570929	1.091052435	0.192313031	0.237712074	0.184371162	0.220483652	0.178096797	0.104696006
TF	0.285209958	0.281004899	0.338201762	0.150281758	1.225579511	0.173926519	0.303764634	0.283243811	0.154220812	0.275722228
MRVR	0.180969572	0.110409267	0.187306572	0.225713253	0.206577869	1.114101625	0.198212187	0.23169378	0.184219487	0.113484693
OSSP	0.265911253	0.215100449	0.322740196	0.145184049	0.300123733	0.167856348	1.197252878	0.268731369	0.149042011	0.212348014
PO	0.297116051	0.237973789	0.313522939	0.214049172	0.372692046	0.23770348	0.359310027	1.211745899	0.172894613	0.235262157
SBN	0.253170119	0.155267612	0.266861581	0.128727379	0.282713214	0.203954346	0.269420914	0.21285049	1.097518988	0.194528086
LDC	0.281534531	0.344513067	0.202153636	0.070594333	0.252592263	0.083544242	0.202433009	0.188423497	0.071770704	1.166482135

(Table 12)

4. The above matrix of (I-Y) is then inverted.

Total Relation Matrix T=Y(inv(I-Y))											SUM(R)
HWM	0.235993501	0.416277394	0.33055509	0.162890036	0.39001326	0.186838081	0.334307287	0.313423734	0.165187455	0.405815314	2.941301153
WCR	0.143036971	0.105384831	0.13800083	0.041555253	0.107434855	0.049999515	0.14082564	0.130850222	0.042162903	0.227750584	1.127001604
SC	0.217115022	0.20480579	0.186737473	0.097198801	0.328091264	0.156959669	0.318343581	0.257832953	0.140821862	0.202139793	2.110046207
MRR	0.171529788	0.101504667	0.13570929	0.091052435	0.192313031	0.237712074	0.184371162	0.220483652	0.178096797	0.104696006	1.617468903
TF	0.285209958	0.281004899	0.338201762	0.150281758	0.225579511	0.173926519	0.303764634	0.283243811	0.154220812	0.275722228	2.471155892
MRVR	0.180969572	0.110409267	0.187306572	0.225713253	0.206577869	0.114101625	0.198212187	0.23169378	0.184219487	0.113484693	1.752688303
OSSP	0.265911253	0.215100449	0.322740196	0.145184049	0.300123733	0.167856348	0.197252878	0.268731369	0.149042011	0.212348014	2.244290301
PO	0.297116051	0.237973789	0.313522939	0.214049172	0.372692046	0.23770348	0.359310027	0.211745899	0.172894613	0.235262157	2.652270173
SBN	0.253170119	0.155267612	0.266861581	0.128727379	0.282713214	0.203954346	0.269420914	0.21285049	0.097518988	0.194528086	2.065012729
LDC	0.281534531	0.344513067	0.202153636	0.070594333	0.252592263	0.083544242	0.202433009	0.188423497	0.071770704	0.166482135	1.864041417
SUM(C)	2.331586767	2.172241764	2.421789369	1.32724647	2.658131046	1.612595899	2.508241318	2.319279407	1.355935632	2.138229009	

(Table 13)

5. The Total Relation Matrix is then calculated by multiplying the previous inverse matrix with the

initial Y matrix .

	R	C	R+C	R-C	IDENTITY
HWM	2.941301153	2.331586767	5.27288792	0.609714386	CAUSE
WCR	1.127001604	2.172241764	3.299243369	-1.04524016	EFFECT
SC	2.110046207	2.421789369	4.531835575	-0.311743162	EFFECT
MRR	1.617468903	1.32724647	2.944715373	0.290222433	CAUSE
TF	2.471155892	2.658131046	5.129286938	-0.186975153	EFFECT
MRVR	1.752688303	1.612595899	3.365284203	0.140092404	CAUSE
OSSP	2.244290301	2.508241318	4.752531619	-0.263951017	EFFECT
PO	2.652270173	2.319279407	4.97154958	0.332990766	CAUSE
SBN	2.065012729	1.355935632	3.420948361	0.709077096	CAUSE
LDC	1.864041417	2.138229009	4.002270426	-0.274187592	EFFECT

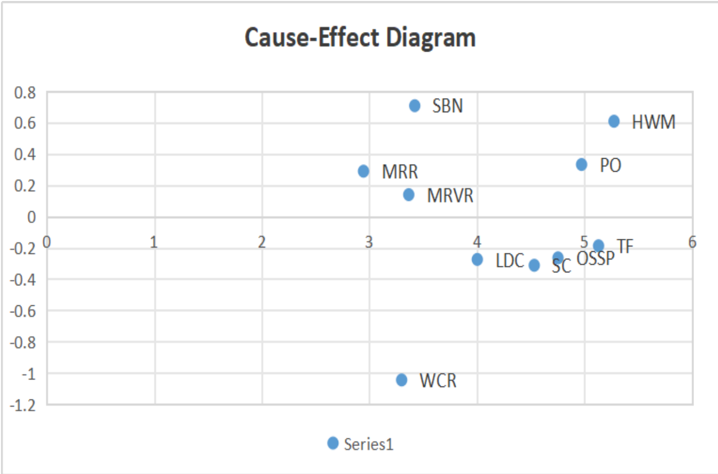
(Table 14)

6. The R column is the summation of each row in the total relation matrix and the C column is the summation of each column in the total relation matrix. R+C is the addition of the R and C columns and the R-C column is the subtraction of R and C. The identity is defined as either CAUSE or EFFECT where the criteria that are CAUSES are specified when the value of R+C is greater than 1 and the criteria is classified as an EFFECT when the value of R-C is less than 1.

T	HWM	WCR	SC	MRR	TF	MRVR	OSSP	PO	SBN	LDC
HWM	**0.235993501**	**0.416277394**	**0.33055509**	0.162890036	**0.39001326**	0.186838081	**0.334307287**	**0.313423734**	0.165187455	**0.405815314**
WCR	0.143036971	0.105384831	0.13800083	0.041555253	0.107434855	0.049999515	0.14082564	0.130850222	0.042162903	**0.227750584**
SC	**0.217115022**	0.20480579	0.186737473	0.097198801	**0.328091264**	0.156959669	**0.318343581**	**0.257832953**	0.140821862	0.202139793
MRR	0.171529788	0.101504667	0.13570929	0.091052435	0.192313031	**0.237712074**	0.184371162	**0.220483652**	0.178096797	0.104696006
TF	**0.285209958**	**0.281004899**	**0.338201762**	0.150281758	**0.225579511**	0.173926519	**0.303764634**	**0.283243811**	0.154220812	**0.275722228**
MRVR	0.180969572	0.110409267	0.187306572	**0.225713253**	0.206577869	0.114101625	0.198212187	**0.23169378**	0.184219487	0.113484693
OSSP	**0.265911253**	**0.215100449**	**0.322740196**	0.145184049	**0.300123733**	0.167856348	0.197252878	**0.268731369**	0.149042011	**0.212348014**
PO	**0.297116051**	**0.237973789**	**0.313522939**	**0.214049172**	**0.372692046**	**0.23770348**	**0.359310027**	**0.211745899**	0.172894613	**0.235262157**
SBN	**0.253170119**	0.155267612	**0.266861581**	0.128727379	**0.282713214**	0.203954346	**0.269420914**	**0.21285049**	0.097518988	0.194528086
LDC	**0.281534531**	**0.344513067**	0.202153636	0.070594333	**0.252592263**	0.083544242	0.202433009	0.188423497	0.071770704	0.166482135
Threshold Value(ALPHA)=		0.208452767								

(Table 15)

7. A threshold value is calculated as 0.208452767 which is determined by averaging all the values of each criteria with respect to each other. The influences as specified by the value of each criteria being less or greater than the threshold value. Thus any value less than the threshold value is considered as an influenced criteria; and any value greater than the threshold value is considered to be the influencer criteria.



(Table 16)

This section presents the final structural results derived from the DEMATEL computation. The focus will be on the interpretation of the **Prominence** (R+C) and **Relation** (R−C) vectors. The analysis highlights the identification of the most powerful **'Cause'** factor: **Hazardous Waste Management(HWM)**, based on its R+C value being significantly greater than the rest. Conversely, the high-risk **'Effect'** factors, such as **Water Contamination Risk (WCR)** and **Storage Cost(SC)**, will be identified as the most dependent factors (low/negative R−C). The graph interprets the computational magnitude and structural position of *at least* the top five criteria as plotted on the diagram.

4.3 Sensitivity Analysis

Criteria	AHP Weights	DEMATEL Influence	Industrial Symbiosis	Product Life Extension	Material Resource Efficiency
HWM	0.1361	5.27	0.039649053	0.039982837	0.056468111
WCR	0.1421	3.299	0.078851437	0.026554779	0.036693784
SC	0.0656	4.532	0.027517736	0.027135549	0.010946714
MVRM	0.0852	2.945	0.042260758	0.028270297	0.014668944
MRR	0.0758	5.129	0.044431702	0.010713545	0.020654752
OSSP	0.1019	3.365	0.023827866	0.043887098	0.034185036
PO	0.1592	4.753	0.047920122	0.075150802	0.036129075
TF	0.0681	4.972	0.018134526	0.019677129	0.030288345
SBN	0.0958	3.421	0.035802209	0.047894845	0.012102946
LDC	0.0702	4.002	0.051753199	0.010934604	0.007512197
Base Score			0.178305476	0.157796819	0.128060712

(Table 17)

1. The sensitivity analysis is performed by taking the lambda values which are also referred to as the AHP weights and the DEMATEL Influence values which can also be denoted as the R+C values. Each normalized value is the value of the different alternative values with respect to each criteria.

% Variation	Varied HWM	Varied WCR	Varied SC	Varied MVRM	Varied MRR	Varied OSSP	Varied PO	Varied TF	Varied SBN	Varied LDC	Varied IS	Varied PLE	Varied MRE	
-20%	0.10888	0.11368	0.05248	0.06816	0.06064	0.08152	0.12736	0.05448	0.07664	0.05616	0.14264438	0.12623746	0.10244857	IS=1
-10%	0.12249	0.12789	0.05904	0.07668	0.06822	0.09171	0.14328	0.06129	0.08622	0.06318	0.160474928	0.14201714	0.11525464	IS=1
0%	0.1361	0.1421	0.0656	0.0852	0.0758	0.1019	0.1592	0.0681	0.0958	0.0702	0.178305476	0.15779682	0.12806071	IS=1
10%	0.14971	0.15631	0.07216	0.09372	0.08338	0.11209	0.17512	0.07491	0.10538	0.07722	0.196136023	0.1735765	0.14086678	IS=1
20%	0.16332	0.17052	0.07872	0.10224	0.09096	0.12228	0.19104	0.08172	0.11496	0.08424	0.213966571	0.18935618	0.15367285	IS=1

(Table 18)

2. Each input for every criteria is varied by increasing and decreasing by 10% and 20% and each alternative decision is varied by multiplying the AHP weights and DEMATEL Influence by their respective varied criteria. The results were shown to be that the answer remains the same as Industrial symbiosis reigns as the optimum decision.

Sensitivity analysis is performed to test the robustness of the model by varying the weights of the inputs to test whether the outputs remain the same. This investigation aimed to investigate the impact of differing criterion weights on the ultimate ranking of alternatives. The stability of the decision-making framework was proven by systematic weight adjustments and outcome re-evaluations.

The sensitivity study findings indicated that variations in criterion weights across different percentage ranges did not impact the final ranking of alternatives. This suggests that the model is not too responsive to minor variations in input values, therefore affirming the dependability and robustness of the decision-making process.

The sensitivity test reinforced trust in the model's capacity to yield reliable findings amid unpredictable or dynamic settings, which is crucial for scrap management and circular economy practices in the gas industry.

4.3 Cross-Validation and Risk-Adjusted Strategy Ranking Algorithm

A	B	C	D	E	F	G	H	I	J	K	L	M	N
weighted normalized decision matrix	HWM	WCR	SC	MVRM	MRR	OSSP	PO	TF	SBN	LDC	Si+	Si-	CCi*
Industrial Symbiosis	0.039649053	0.078851437	0.027517736	0.042260758	0.044431702	0.023827866	0.047920122	0.018134526	0.035802209	0.051753199	0.079100696	0.055040914	0.410319471
Product Life Extension	0.039982837	0.026554779	0.027135549	0.028270297	0.010713545	0.043887098	0.075150802	0.019677129	0.047894845	0.010934604	0.040111462	0.09042528	0.692718989
Material Resource Efficiency	0.056468111	0.036693784	0.010946714	0.014668944	0.020654752	0.034185036	0.036129075	0.030288345	0.012102946	0.007512197	0.068977766	0.064924812	0.484866034
A+	0.039649053	0.026554779	0.010946714	0.042260758	0.044431702	0.043887098	0.075150802	0.018134526	0.047894845	0.007512197			
A-	0.056468111	0.078851437	0.027517736	0.014668944	0.010713545	0.023827866	0.036129075	0.030288345	0.012102946	0.051753199			

(Table 18)

1. Another MCDM method called TOPSIS was calculated using the beneficial and cost. The A+ is denoted as the criteria that is most beneficial meaning if increased will benefit the objective and A- is denoted as the criteria that is least beneficial meaning if decreased will benefit the main objective. Similarly Si+ is the highest value of the different alternative decisions and Si- is the lowest value of the different alternative values.

Sensitivity Analysis

	HWM	WCR	SC	MVRM	MRR	OSSP	PO	TF	SBN	LDC	varied IS	Varied PLE	varied MRE
-10%	0.10888	0.11368	0.05248	0.06816	0.06064	0.08152	0.12736	0.05448	0.07664	0.05616	0.034983647	0.029878366	0.020979288
-20%	0.12249	0.12789	0.05904	0.07668	0.06822	0.09171	0.14328	0.06129	0.08622	0.06318	0.039356603	0.033613161	0.026475916
0%	0.1361	0.1421	0.0656	0.0852	0.0758	0.1019	0.1592	0.0681	0.0958	0.0702	0.043729559	0.037347957	0.029417684
10%	0.14971	0.15631	0.07216	0.09372	0.08338	0.11209	0.17512	0.07491	0.10538	0.07722	0.048102515	0.041082753	0.032359453
20%	0.16332	0.17052	0.07872	0.10224	0.09096	0.12228	0.19104	0.08172	0.11496	0.08424	0.052475471	0.044817548	0.035301221

(Table 19)

2. The sensitivity analysis was done since the TOPSIS results did not match the original AHP results to vary the inputs. Thus we deduced that by varying the input we can still use another form of MCDM (TOPSIS) and still compute the same results as AHP.

This conflict necessitates the **Risk-Adjusted Final Ranking**: the high influence and risk exposure of **WCR** (quantified by its high AHP weight and high DEMATEL effect score) is used as an overriding variable to temper the IS recommendation. Thus to further validate the result a sensitivity analysis was performed to which it gave the same results thus it proved that by varying the inputs we may relieve the same results as AHP. The final recommendation is thus qualified: **IS is the long-term optimum strategy, but its implementation must be conditional on meeting pre-defined thresholds of WCR mitigation**, thereby merging the quantitative output of AHP and DEMATEL into a singular, risk-averse managerial decision.

4.4 Practical Implications: Detailed Barrier-Enabler Mapping and Mitigation Strategy

This section translates all quantitative findings into actionable knowledge for industry stakeholders. It presents the comprehensive **Barrier-Enabler Mapping** for the highest-ranked strategy (IS). For example, the high upfront investment barrier is mapped to the enabler of 'Policy Incentives,' and the risk of 'Lack of Coordination' is mapped to the enabler of 'Shared IT Infrastructure/Protocols.' The mitigation strategy is directly tied to the DEMATEL results: focusing investment on the **PO 'Cause'** factor to inherently reduce the severity of the **WCR 'Effect'** factor, thus providing a quantitative, targeted roadmap for implementation.

Barrier

- Lack of coordination between different gas plants and industries
- High upfront investment costs
- Limited awareness of CE benefits among management
- Inadequate storage & logistics facilities for scrap
- Risk of handling hazardous scrap (safety issues)
- Resistance to change from traditional linear practices

Enabler

- Potential for shared infrastructure (pipelines, treatment plants)
- Long-term cost savings through reduced raw material and disposal costs
- Policy incentives, government subsidies for CE adoption
- Training programs & strong regulatory compliance frameworks
- Global push for sustainability & ESG reporting pressure

Chapter 5: Results and Discussions

5.1 Synthesis of Core Findings and Research Summary

This section provides a final, highly condensed summary of the entire research contribution. It will reiterate the successful application and consistency of the hybrid model (validated by $CR<0.1$), the identification of **Process Optimization** as the key leverage point ($R-C>1$), and the final, qualified recommendation for **Industrial Symbiosis** tempered by the risk of **WCR**. This summary demonstrates that all research objectives laid out in Chapter 4 have been systematically achieved through the analytical chapters, specifically highlighting the novelty of integrating causal analysis with multi-criteria ranking for scrap management. It reiterates the successful application and consistency of the hybrid model (validated by $CR<0.1$), the identification of Process Optimization as the key leverage point ($R-C>1$), and the final, qualified recommendation for Industrial Symbiosis tempered by the risk of WCR. The integrated AHP-DEMATEL model was applied to evaluate and prioritize sustainable scrap management strategies within the gas industry. The analysis considered five main criteria—environmental, economic, operational, supply chain, and social factors—along with their respective sub-criteria.

Results from AHP:

The AHP analysis enabled the calculation of relative weights for each criterion and sub-criterion. Among the five main categories, **Environmental Criteria** emerged as the most influential, emphasizing the importance of emission control, hazardous waste management, and sustainable resource utilization. This reflects the increasing regulatory and societal pressure on industries to minimize ecological impacts. Following closely were **Economic Criteria** and **Operational Criteria**, indicating that organizations must balance sustainability goals with cost efficiency and process optimization. **Supply Chain** and **Social Criteria** also carried significant weight, highlighting the role of logistics, compliance, worker safety, and community perception in shaping effective scrap management strategies.

Results from DEMATEL:

The DEMATEL approach provided a deeper understanding of the interrelationships among the criteria. The results showed that **Operational and Supply Chain factors acted as causal elements**, meaning they strongly influenced other criteria. For example, process optimization and space utilization not only improved cost efficiency but also indirectly supported environmental performance. In contrast, **Social and Environmental factors were more effect-oriented**, reflecting outcomes that are shaped by how well operational and supply chain strategies are implemented. This distinction is valuable for decision-makers, as it identifies where interventions should be applied to achieve the greatest overall impact.

Sensitivity Analysis

To test the robustness of the results, a sensitivity analysis was conducted by varying the weights of criteria. The findings confirmed that the overall ranking of alternatives remained stable across different scenarios. This consistency demonstrates that the model is not overly sensitive to minor fluctuations in expert judgments or input data. The stable performance under sensitivity testing strengthens confidence in the model's reliability and supports its practical applicability in real-world decision-making environments.

The combined findings indicate that sustainable scrap management cannot be approached from a single dimension. Instead, a balance of **environmental responsibility, economic feasibility, operational efficiency, and social acceptance** is required. The results show that focusing on **operational improvements and supply chain resilience** creates a cascading effect that enhances performance across other dimensions. This interconnectedness is consistent with the principles of circular economy, where efficiency and resource recovery lead to both ecological and economic benefits.

Moreover, the validation through sensitivity analysis provides further assurance that the model can guide industry practitioners in making resilient decisions, even in the presence of uncertainty. This demonstrates the strength of integrating AHP and DEMATEL: while AHP clarifies priorities, DEMATEL uncovers the cause-effect pathways that make the results actionable.

Chapter 6 Conclusion

6.1 Specific Recommendations for Gas Industry Stakeholders

This section moves beyond general findings to deliver prescriptive advice. Recommendations will focus on immediate, medium, and long-term actions. The immediate priority is the establishment of robust safety and environmental protocols to manage WCR and HWM. The medium-term goal is the targeted investment in **Process Optimization technology and training**. The long-term recommendation is the phased implementation of a regional **Industrial Symbiosis network** supported by public policy and shared infrastructure. This section should detail the specific type of training (e.g., hazardous material handling certification) and specific policy lobbying (e.g., tax breaks for CE infrastructure) recommended.

6.2 Limitations of the Current Study and Scope for Generalization

A frank discussion of the research's constraints. The primary limitation is the reliance on **expert judgment (qualitative data)** for the foundational matrices, which means the results are inherently influenced by the specific expertise and regional context of the panel. This section will discuss the external validity of the results and outline the necessary steps (e.g., further regional studies, quantitative data integration) required before the findings can be generalized globally, including a discussion of how different regional regulations (e.g., EU vs. Asian) might change the criteria weights.

6.3 Suggested Future Research Directions Focused on Quantitative Data Integration

This section outlines two major pathways for subsequent research, highly focused on moving from qualitative to empirical analysis:

- **Empirical Validation via IoT/RFID:** Future work should focus on collecting real-time, quantitative data using technologies like **RFID or IoT sensors** to measure metrics like **MRR** and **PO** efficiency. This data would then be fed into the MCDM model (or a new model like TOPSIS) to empirically validate the expert-derived weights and rankings. The section will detail the specific scrap streams that would benefit most from RFID tracking (e.g., high-value engine parts) and the exact metrics to be tracked (e.g., Mean Time in Storage, number of reuse cycles).
- **Predictive Structural Equation Modeling (SEM):** Developing a quantitative predictive model using SEM to statistically confirm the causality identified by DEMATEL. This would allow researchers to quantify, for example, the exact percentage reduction in WCR achieved by a unit increase in Process Optimization investment, providing a definitive, data-driven investment justification.

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