Lunaz Design

BUSINESS REPORT

ECOMOTIVE

Aniruddha Bhalsing
Faisal Firoz
George Raptis
Nattaporn Rubngam
Nishit Gaur
Prae Nandavisai
Xianglin Zheng

CONSULTANCY PROJECT
ME50369

4255 words

Abstract

This paper proposes Lunaz, a company working in the vehicle electrification field toward sustainability, with a developed practice framework for sustainable product development and life cycle management. This paper covers product lifecycle steps: Product Definition and Specification, Design and Development, Procurement and Production, Testing, Delivery, Maintenance, End of Life and Implementation. The framework's development started by researching vehicle components and materials used in building each component, and further researching carbon emissions from each component. This examination reveals that the primary source of carbon emission is the battery. Therefore, this paper focuses on reducing carbon emissions from battery as it will significantly reduce carbon emissions from vehicles overall. Furthermore, with consideration that Lunaz is involved in interior upholstery modification, this area has been taken into the scope of this paper. The proposed approach consists in selecting eco-friendly materials and suppliers considering both total value and cost, introducing a sustainable manufacturing strategy to enhance energy efficiency and reduce material waste, performing sustainable practices in testing, delivery, and maintenance, and taking an end-of-life route that minimises carbon emission. On top of that, the implementation plan includes McKinsey Horizon Strategy to plan initiatives based on short term, medium term and long-term time horizon, along with the risk assessment of the overall framework.

Table of Contents

Introduction

In an era defined by the urgent need to address climate change, organizations are challenged to re-evaluate their approach to product development with a focus on sustainability and lifecycle management. Lunaz, a visionary player in vehicle electrification based in Silverstone, is aware of this necessity and has embarked on a mission to provide sustainable solutions, ensuring a harmonious synergy between innovation and sustainability.

The purpose of this project is to establish a holistic sustainable product lifecycle framework that specifically addresses vehicle electrification processes. By quantifying the environmental impact at every stage of the retrofitting journey, this framework will serve as a compass, guiding stakeholders towards more sustainable choices, thereby contributing to reducing the carbon footprint of products.

The scope of this project extends beyond the immediate realm of vehicle electrification. While Lunaz's primary focus is on electrifying vehicles, the developed framework will provide insights applicable to a diverse range of industries and products. The scope encompasses the entire product lifecycle, encapsulating critical stages such as Product Definition and Specification, Design and Development, Procurement, Testing, Delivery and Maintenance, and finally, the End-of-Life phase.

There are two main objectives of this project: developing a framework that will seamlessly assess carbon emissions throughout the product lifecycle and offering a quantitative understanding of environmental impact. Additionally, the framework will harmoniously merge with existing product Life Cycle Assessments (LCAs) for distinct components, such as batteries and interiors, thus amplifying the synergy between sustainable practices and cutting-edge innovation.

Background Research

The automotive industry undeniably holds a position of immense magnitude and influence on a global scale (Orsato & Wells, 2007; Mathivathanan & Haq, 2017). As the industry continues to expand, an escalating number of automobiles populate road networks, facilitating efficient and comfortable transportation. Nevertheless, this upsurge has resulted in a significant escalation of air pollution levels within urban areas, presenting a notable downside. Furthermore, as outlined in a report published by the European Union (Directorate-General for Mobility and Transport, European Commission, 2011) the transport sector is responsible for nearly 28% of the total carbon dioxide emissions. Remarkably, road transport alone is accountable for over 70% of the transport sector emissions (Sanguesa et al., 2021). As a result, governments have suggested several policy measures to encourage the use of EVs as they emit zero tailpipe emissions. Although the overall environmental performance of EVs is still debatable, particularly in terms of battery production (Romare & Dahllöf, 2017), electrification of the transportation industry is already a focus of investment and research (Guo et al., 2020).

Advancements in the automobile industry, such as zero-emission vehicles and carbon-neutral production, illustrate the growing importance of sustainability. These developments are being pushed not only by the implementation of stronger emissions rules, but also by rising societal awareness of environmental issues, as well as a growing customer demand in sustainable vehicles (Jursch, 2021). Big and small firms in the automobile industry are under increased pressure to reevaluate their business strategies. They have to reconsider everything, all the way from the design and engineering phase of the vehicles to their end of life. Some significant ways the industry is addressing these ongoing difficulties include fostering more cross-industry collaboration and utilising modern technologies to improve supply chain visibility (Pohl, 2021).

The conversion of internal combustion engine (ICE) vehicles to electric vehicles (EVs) stands as a promising intermediary measure aimed at expediting the widespread adoption of EVs and drive towards sustainability. This retrofitting process holds the potential to accelerate the uptake of EVs, bolster societal acceptance of this technology, and expedite the development of EV infrastructure. The advantages extend to consumers, who can enjoy reduced operational expenses, quieter vehicle operation, and a cleaner environmental footprint (Hoeft, 2021). However, EV retrofitting can be a complex and challenging process that requires careful planning and execution. Some of the challenges faced in the process are lack of data, resistance to change, high initial costs supply chain disruptions (Anon, 2023). To address some of the challenges in EV retrofitting and to enhance the overall sustainability of the process, this report presents a framework that emphasises the life cycle assessment (LCA) of the most polluting components in the whole retrofitting procedure.

Organisational Framework

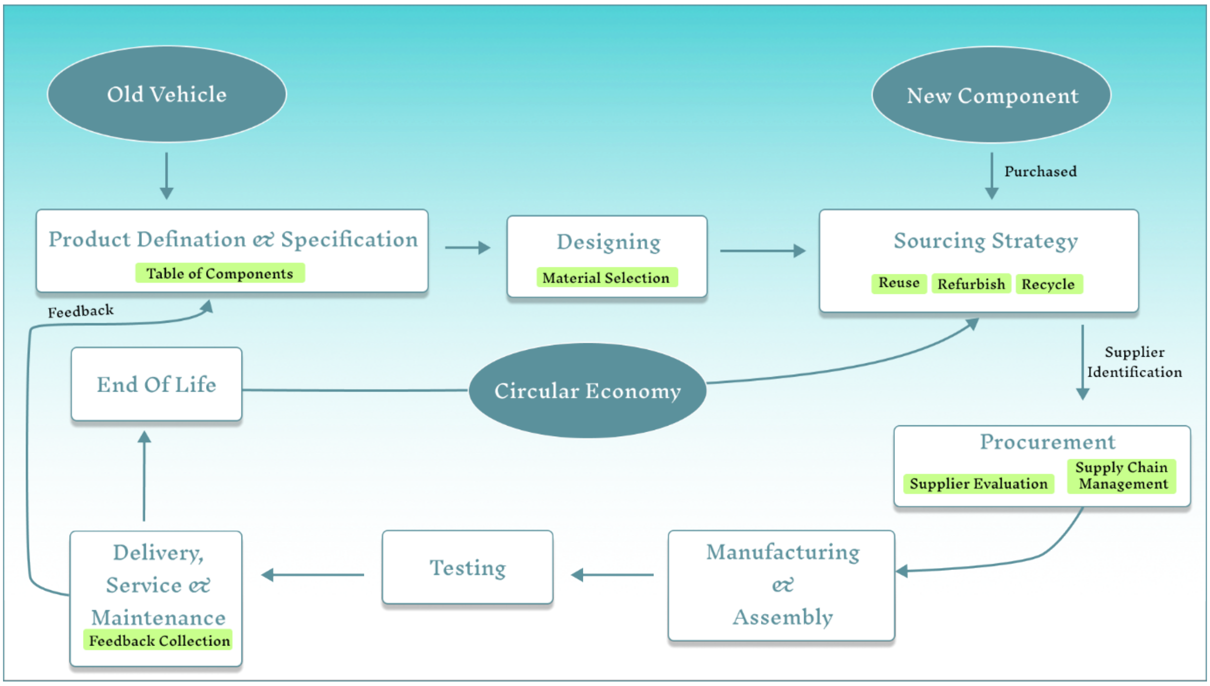


Figure 1: Organizational Framework

The presented framework outlines the sequential procedure for conducting the retrofitting process. Commencing with the Product Definition and Specification phase, this stage involves a thorough examination of the vehicle and the selection of appropriate materials for its various components. Based on the Table of Components, sourcing strategy for the components is determined. This approach will mainly focus on the circular economy in which products or components are reused, refurbished, and recycled or new components can be ordered if needed. In the case of procurement of new components, supplier evaluation will be carried out based on the parameters of sustainability. The required components will be procured by establishing a supply chain that will focus on mitigating negative environmental impacts, reducing resource consumption, and promoting long-term sustainability (Khan et al., 2023; Roehrich, Hoejmose and Overland, 2017). The manufacturing and assembly stage will focus on streamlining the process with help of methodologies such as Six Sigma (Lakshmi, 2022). Innovative methods such as virtual simulation and integration with public transportation can be employed for vehicle testing phase. In the final stage of delivery, service, and maintenance, focus will be on stakeholder engagement and customer education to gather feedback aimed at refining the framework based on sustainability.

Product Definition and Specification

The Table of components and materials (Table 1) is a structured way to methodically categorise the many constituent parts and substances inside a complex system, allowing for more complete analysis and decision-making (Lodha, 2023). This method is especially useful in engineering and manufacturing industries, where it facilitates efficient design, production, and maintenance operations by giving a comprehensive perspective of the materials utilised in each component (Component materials Definition | Law Insider, n.d.).

The figures shown in the table have been derived from a combination of scholarly research papers and represent the average expected value. The table provides a comprehensive overview of the materials used in the manufacturing of an EV, together with their corresponding components and the quantities necessary for assembly. Subsequently, the emissions produced by the materials are illustrated, and these emissions are multiplied by the quantities of the components to calculate the final carbon dioxide emissions per vehicle. This results in the identification of materials with the highest pollution levels per metric tonne of material, as well as emissions per vehicle. The three highest-ranking entries in each column have been emphasised. The production of the large lithium-ion batteries employed in powering EVs contributes roughly around 40 to 60 percent of the comprehensive emissions generated during EV production (Linder et al., 2023). Additionally, given that Lunaz engages in extensive in-house activities related to interior upholstery (IU) modification, these two components have been chosen for further research and development efforts in the pursuit of sustainability.

Materials	Components	Quantity (Mt)	Price (£/Mt or £/L or £/m)	Average Emissions(CO2) / Material(mt)	Emissions/car (Mt)
Aluminium	Body	0.35	1,400 to 1,950/Mt	14	4.9
Iron & Steel	Chassis, Body	1.7	675 to 900	2	3.4
Glass	Glass	0.05	375 to 750	0.65	0.0325
Plastics & Fibre	Battery, IU	0.25	600 to 1,500	3	0.75
Fabrics	IU	0.02	5 to 30 per meter	3.5	0.07
Rubber	Brake Pads, IU	0.02	1,125 to 1,875	3.5	0.07
Cathode (NMC)	Battery	0.007	15,000 to 22,500	10	0.07
Anode (Graphite)	Battery	0.003	3,750 to 7,500	7.5	0.0225
Lithium	Battery	0.0007	6,000 to 11,250	2	0.0014
Zinc	EM	0.003	1,875 to 2,625	2	0.006
Copper	Battery, EM	0.015	6,000 to 7,500	2	0.03
Paint	IU, EM	0.0003	10 to 40 per litre	0.3	0.00009

IU = Interior Upholstery
EM = Electric Motor

Metric tons = Kilograms / 1000

Table 1: Table of Components

Sustainable Design and Development

This section explores the importance of sustainable design and material choices in the context of environmentally conscious automotive retrofitting. Following are the sustainable material selections for battery chemistry, battery enclosure and interior upholstery.

Battery chemistry selection

Electric vehicles (EVs) offer the potential to decrease emissions, but their operational reliance on lithium-ion batteries introduces a distinctive challenge to sustainability. Various types of EV batteries differ significantly in terms of their materials, manufacturing processes, production methods, and approaches to recycling or disposal, resulting in varying environmental consequences (Shu et al., 2021). Therefore, for a company prioritising sustainability, selecting an appropriate battery chemistry that is both feasible to integrate into the business and ecologically beneficial in comparison to other battery chemistries available in the market is a critical task.

In the process of choosing the suitable battery for EVs, one of the practical approaches is to use the Simple Multi-Attribute Rating Technique (SMART). SMART serves as a tool for performing Multi-Criteria Decision Analysis (MCDA), where the evaluation and choice of the most suitable option from a range of alternatives is determined by a set of pertinent criteria (Patel et al., 2017; Vasilakis, 2022). In this analysis, commercially available EV batteries, such as Li-NMC, Li-LFP, and NiMH, alongside emerging battery chemistries like Li-S and Solid-State batteries, have been subjected to comparative evaluation. A range of criteria that influence battery performance, such as energy density and range, along with those affecting the environment, such as carbon emissions over the battery's lifecycle and battery weight, have been selected for comparison.

Subsequently, numeric values have been assigned to each battery under each criterion to populate Table 2. To simplify computations, a linear approximation technique has been employed, scaling each value in each column to a uniform 0-100 range (Appendix 4). To demonstrate the influence of varying criteria, different weights have been applied to them (Table 3), offering flexibility for customisation in accordance with different corporate priorities. The summation of values for each battery, factoring in the assigned weights, results in a final total value. To facilitate comparison, a graphical representation of total value against cost has been plotted (Graph 1). Many conclusions can be made from the graph such as the Solid-State battery emerges as the most favourable option, albeit accompanied by the highest cost. Notably, transitioning from a Li-NMC to a Li-LFP battery can be a prudent choice for the company, as a mere $20 per kWh increase in cost translates to a notable 10-point enhancement in the total value.

Battery Type	Energy Density (Wh/kg)	Range (miles)	Lifetime and Degradation	Relative safety rating	Carbon Emission LCA (kg CO2eq)	Weight (Kg)	Relative Availability and Production Scalability	Cost ($/kWh)
Li-NMC	160-200	150-300	500-1500 Cycles	80	240	250-350	High (95)	150-200
Li-LFP	90-120	100-250	2000-5000 Cycles	100	166	250-400	Good (85)	170-220
Li-NCA	200-240	200-350	500-1500 Cycles	70	230	200-300	Moderate (75)	200-250
Li-S	300-500	250-300	500-1000 Cycles	60	146	200-300	Low (55)	300-400
Solid State Battery	400-500	300-400	2000-7000 Cycles	70	122	150-250	Low (55)	400-800
NiMH	60-120	80-150	500-1000 Cycles	70	300	300-400	Moderate (65)	140-150

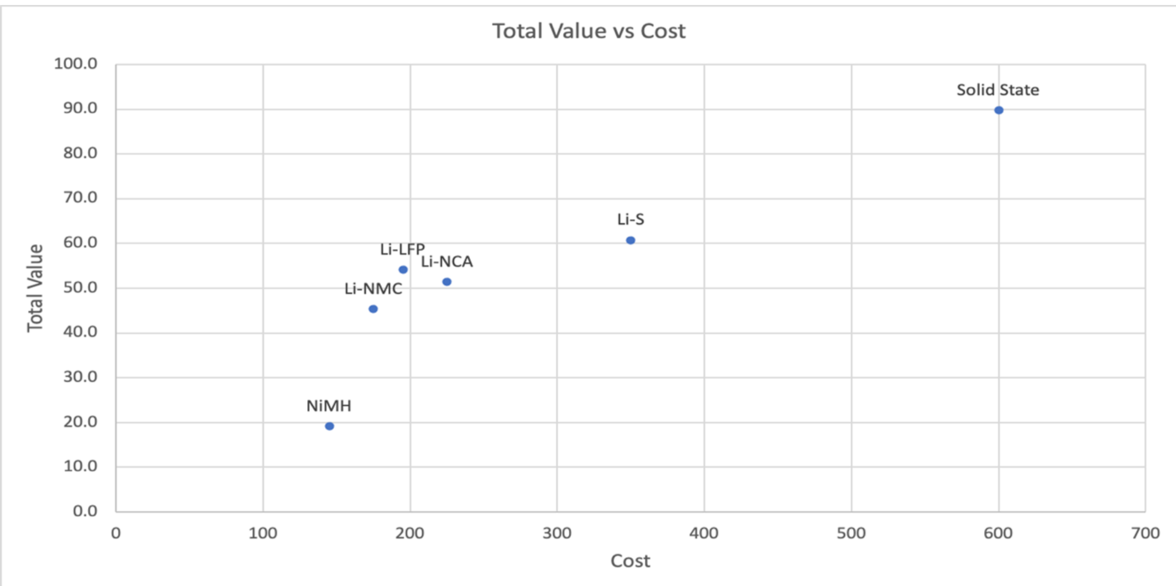
Table 2: Selection Criteria

Criteria	Swing weights	Normalised weight
Energy density	70	0.1522
Range	70	0.1522
Lifetime and degradation	65	0.1413
Relative safety rating	75	0.1630
Carbon emission LCA	65	0.1413
Weight	60	0.1304
Relative availability	55	0.1196
Total Weight	460	1.0000

Table 3: Assigned weights for the criteria.

Battery Type	Energy Density	Range	Lifetime and Degradation	Relative safety rating	Carbon Emission LCA	Weight	Relative Availability and Production Scalability	Cost	Total Value
Li-NMC	25	46.8	6.7	80	33.7	33.32	95	175	45.4
Li-LFP	4.169	25.52	73.45	100	75.28	16.65	85	195	54.2
Li-NCA	36.116	68.07	6.7	70	39.32	66.65	75	225	51.4
Li-S	86.12	68.07	0	60	86.51	66.65	55	350	60.7
Solid State Battery	100	100	100	70	100	100	55	600	89.7
NiMH	0	0	0	70	0	0	65	145	19.2

Table 4: Normalized Value



Graph 1: Total Value vs Cost (Battery Chemistry)

Interior Upholstery Material selection

The SMART-Multi-criteria decision-making method, as used previously, is also applied to offer significant insights into the selection of materials for car interior upholstery. This involves assessing conventional and alternate materials that have the potential to enhance sustainability within the company.

Traditional materials like PVC, PU, PP, PC, ABS, and PMMA have long been used, but advancements in sustainable alternatives like Bio-PET, BioPP, PLA, and PHA have offered more environmentally friendly options. When assessing these materials, six key criteria were considered: longevity, acidification, relative human toxicity potential, global warming potential, water consumption, and energy consumption.

Prioritising global warming potential, human toxicity potential, and energy consumption as the top criteria, the Value vs Cost graph presents a comprehensive evaluation. The results indicate that while alternative materials come at slightly higher costs, they boast significantly higher total value scores when compared to traditional materials.

	Materials		Life cycle assessments						Cost ($/kg)
		Longevity (years)	Acidification potential (kg SO2-eq)	Relative Human toxicity potential (0-most hazardous, 100-least hazardous)	Global warming potential (kg CO2-eq)	Relative Water Consumption (0-highest consumption, 100-lowest consumption)	Energy consumption (MJ)	Biodegradability	
Traditional Materials	PVC (Polyvinyl Chloride)	100	0.0062	0	1.9	90	55.5	NO	1
	PU (Polyurethane)	15	0.00885	20	3.084	60	101.5	NO	2.5
	PP (Polypropylene)	20	0.0043	30	1.6	80	73	NO	1
	PC (Polycarbonate)	10	0	35	5.6	50	112.95	NO	3
	ABS (Acrylonitrile Butadiene Styrene)	70	0.00658	40	2.354	70	95.34	NO	2
	PMMA (Polymethyl Methacrylate)	25	0.02935	45	8.21	75	116.14	NO	5
Sustainable Alternatives	Bio-PET (Bio-based Polyethylene)	35	0.013	60	2.1	5	60	NO	3.5
	Bio-PP (Bio-based Polypropylene)	15	0	65	2.4	0	42	NO	4
	PLA (Polylactic Acid)	15	0.0073	80	0.6	10	35	YES	3
	PHA (Polyhydroxyalkanoates)	3	0.016811	85	3.491	15	23.33	YES	3.5

Table 5: Selection Criteria (References in Appendix 3)

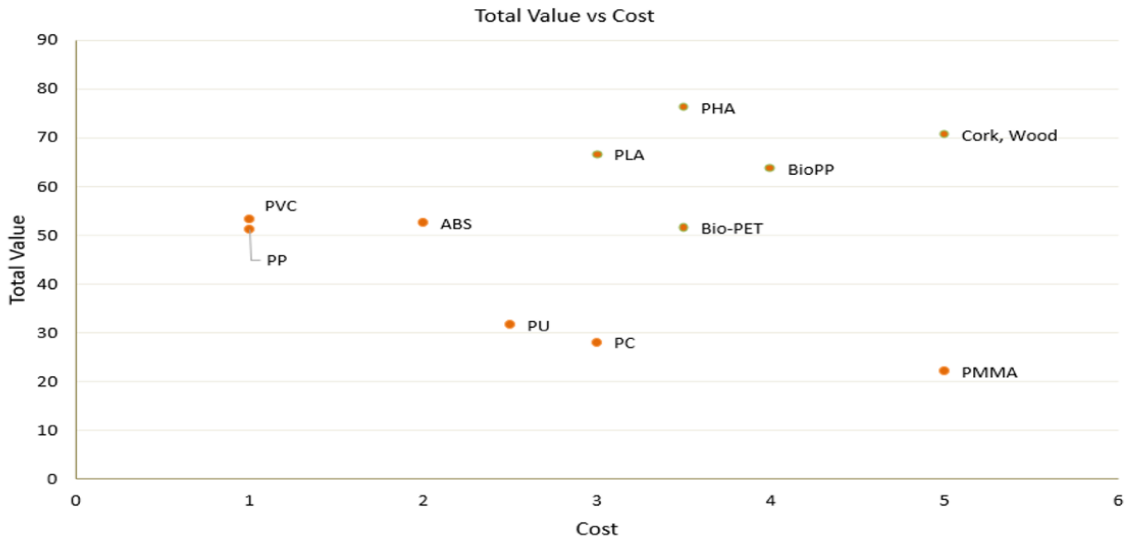
Attribute	Swing weights	Normalized Weights
Longevity	5	0.05
Acidification	5	0.05
HTP	20	0.18
GWM	30	0.27
Water	10	0.09
Energy	25	0.23
Biodegradability	15	0.14
Total Weight	110	1

Table 6: Assigned weights for the criteria

This data-driven approach guides decision-making. For instance, seat padding materials like PLA and PHA emerge as superior alternatives to PU, demonstrating double the total value. The graph empowers the company to optimize their choice within budget constraints, promoting sustainability without compromising affordability (Graph 2).

	Alternatives	Longevity (years)	Acidification	HTP	GWM	Water Consumption	Energy Consumption	Biodegradability	Total value	Cost
Traditional Materials	PVC	100	99.52485	0	74.1481	100	65.3	0	53.2	1
	PU	12.3707	99.22075	22.22	47.1208	66.66	15.8	0	31.6	2.5
	PP	17.5252	99.52485	33.33	77.6734	88.88	46.5	0	51.2	1
	PC	7.1262	100	38.85	37.72	55.55	3.4	0	28.0	3
	ABS	69.0702	99.27291	44.44	90.32	77.77	22.4	0	52.5	2
	PMMA	22.6797	96.756825	49.95	0	83.33	0	0	22.1	5
Alternative Materials	Bio-PET	32.9887	98.5635	66.66	70.035	5.55	60.5	0	51.5	3.5
	Bio-PP	12.3707	100	72.22	100	0	79.9	0	63.7	4
	PLA	12.3707	99.19335	88.88	89.4244	11.11	87.4	0	66.5	3
	PHA	0	98.1436	94.44	61.22	16.65	100	100	76.2	3.5
	Cork,Wood	48.4522	0	100	91.751	22.22	41.8	100	70.6	5

Table 7: Normalized Value



Graph 2: Total Value vs Cost (Interior Upholstery)

Material selection for Battery enclosure

The selection of sustainable and lightweight materials for battery enclosures has significant importance as it contributes to the improvement of efficiency and ecological accountability. The reduction in system weight contributes to the enhancement of energy efficiency in EVs (Dhoke and Dalavi, 2021). Using SMART as used previously, this research will provide a range of materials that show promise as feasible substitutes for traditional steel and aluminium. In this study, weight and CO_2 emissions surface as the pivotal variables, accompanied by considerations such as durability and lifespan. The outcome of the study is a graphical representation illustrating the ultimate values of the materials in correlation with their respective costs, facilitating a straightforward comparison among them (Graph 3). The findings may be summarised as follows: Aluminium has better characteristics compared to steel, while maintaining a relatively affordable price point. Furthermore, it should be noted that materials such as wood, basalt fibre, and mycelium possess a greater overall value compared to aluminium and steel. However, it is important to acknowledge that these materials also incur higher costs.

Nevertheless, these battery enclosure boxes exhibit superior performance in terms of both CO_2 emissions and weight, which are considered crucial factors.

BATTERY ENCLOSURE BOX MATERIALS	Weight (kg/m^3)	CO2 (kg/kg material)	Durability	Longevity (years)	Cost (£/kg)
Hemp-based	650	1	3	7.5	2.625
Mycelium	300	0.3	2	10	7.5
Algae-based	300	0.35	1	3	15
Bio-derived Polyurethanes	600	1.75	3	12.5	4.875
Recycled Carbon Fiber Reinforced Plastics	1750	3	4	17.5	20.625
Wood	600	0.3	2	35	3.75
Bio-based Polyethylene Terephthalate (PET)	2500	1.5	4	15	1.5
Bio-based Polyamides	1200	1.5	4	17.5	3
Basalt Fiber	2850	0.5	4	40	6
Recycled Plastic	1000	1	2	27.5	1.25
Biodegradable Bioplastics	1000	0.5	1	2.5	3.5
Banana Fiber	600	1	3	10	9.375
Steel	7850	1.5	4	50	0.8
Aluminum	2700	1.75	3	50	2

Table 8: Selection Criteria

Figure 2: Battery Enclosure box

Durability
Low = 1
Moderate = 2
Moderate to High = 3
High = 4

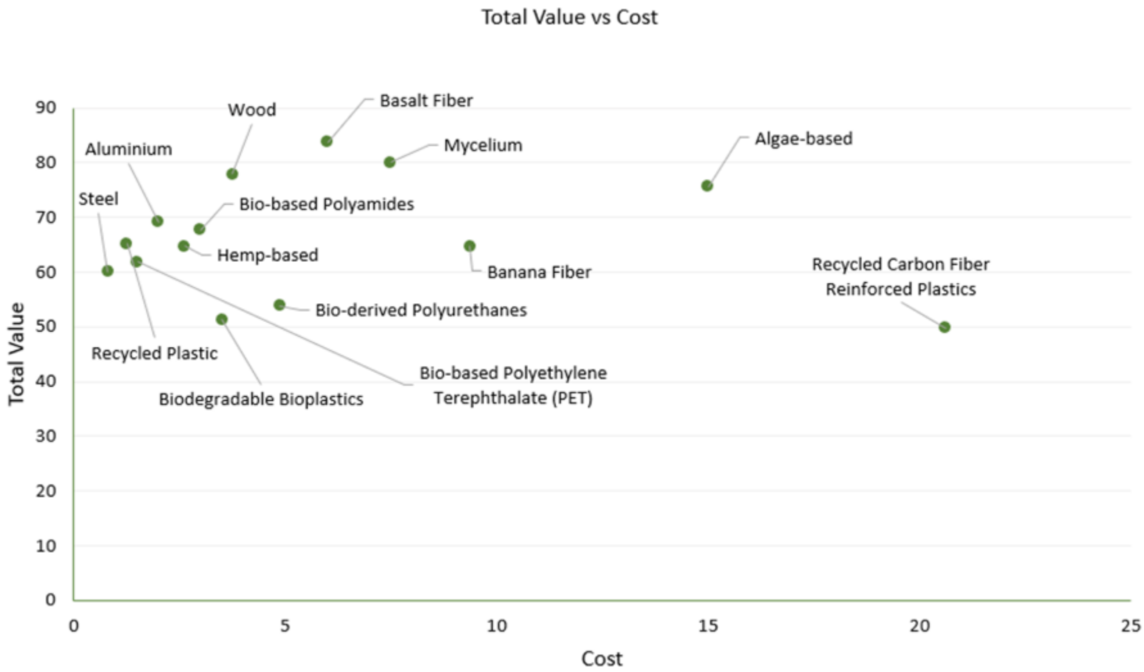
Table 9: Durability

Attribute	Swing weights	Normalized Weights
Weight (kg/m^3)	80	0.2712
CO2 (kg/kg material)	85	0.2881
Durability	60	0.2034
Longevity (years)	70	0.2373
Total Weight:	295	1

Table 10: Assigned weights for the criteria

Alternatives	Weight	CO2	Durability	Longevity	Total value	Cost (£/kg)
Hemp-based	95.39	74.07	74.07	10.53	64.8	2.625
Mycelium	100	100	100	15.79	80.0	7.5
Algae-based	100	98.15	98.15	1.05	75.6	15
Bio-derived Polyurethanes	96.05	46.3	46.3	21.05	53.8	4.875
Recycled Carbon Fiber Reinforced Plastics	80.87	0	100	31.58	49.8	20.625
Wood	96.05	100	33.33	68.42	77.9	3.75
Bio-based Polyethylene Terephthalate (PET)	70.97	55.55	100	26.32	61.8	1.5
Bio-based Polyamides	88.13	55.55	100	31.58	67.7	3
Basalt Fiber	66.35	92.59	100	78.95	83.7	6
Recycled Plastic	90.77	74.07	33.33	52.63	65.2	1.25
Biodegradable Bioplastics	90.77	92.59	0	0	51.3	3.5
Banana Fiber	96.05	74.07	66.67	15.79	64.7	9.375
Steel	0	55.55	100	100	60.1	0.8
Aluminum	68.33	46.3	66.67	100	69.2	2

Table 11: Normalized Value



Graph 3: Total Value vs Cost (Battery Enclosure Box)

Procurement and Production

The procurement and production processes play a crucial role in nearly every business, especially in an industry as substantial as the automotive sector (Jenkins, 2022). While EVs reduce greenhouse gas emissions during the use phase, the sourcing and manufacturing processes account for a substantial part of the environmental impact (Freitas, n.d.). Focusing on two main areas - Supply Chain Management and Process Optimization - this section will provide feasible strategies to increase sustainability at these key stages, applicable across various organizations within the industry.

Supply Chain Management

Evaluating the most sustainable supplier is paramount in constructing a green supply chain (Roehrich, Hoejmose and Overland, 2017). SMART analysis may be used to help the company make an informed choice by considering multiple factors, as indicated in the hypothetical scenario below.

Suppliers	Transportation Emission (tCO2e)	Waste generation (metric tonnes)	Water Usage (gallons)	Carbon footprint (tCO2e)	Certifications (ISO 9001, ISO 14001, etc.)	Sustainability reporting	Transparency (%)	Cost ($)
Supplier 1	70	22000	200,000	200000	Yes	Yes	57	200000
Supplier 2	80	24000	250000	210000	No	No	60	320000
Supplier 3	200	23809	300000	215000	Yes	No	65	210000
Supplier 4	500	12998	350000	320000	Yes	Yes	30	340000
Supplier 5	180	31783	400000	280000	No	No	35	220000
Supplier 6	150	12000	210000	300000	No	Yes	89	230000
Supplier 7	100	21000	220000	190000	Yes	No	90	150000

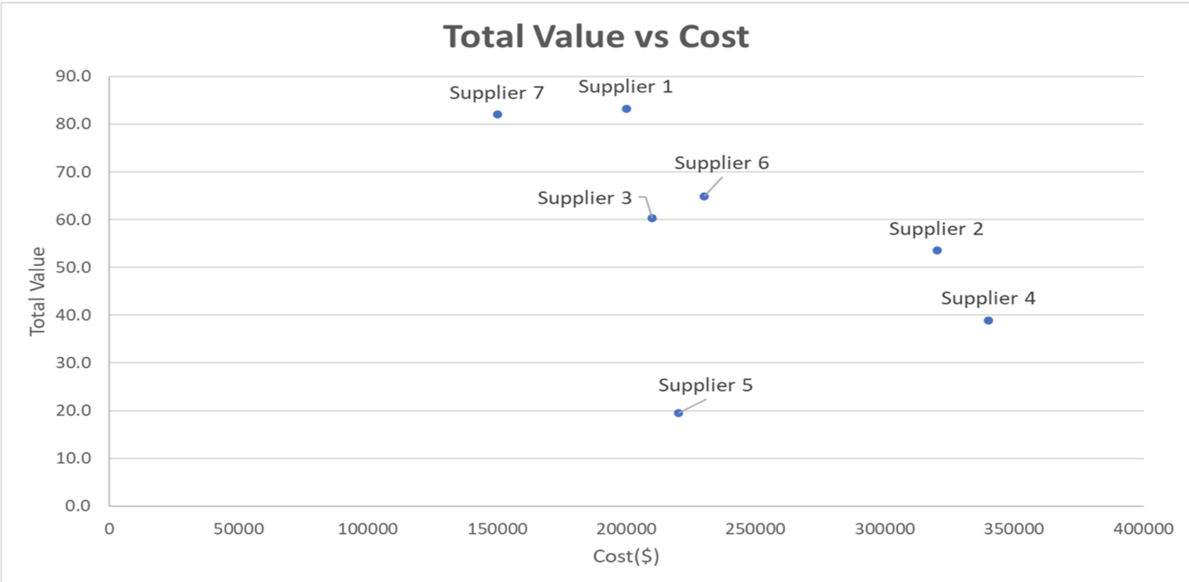
Table 12: Selection Criteria

Attribute	Swing weights	Normalised weights
Transportation Emission	80	0.20
Waste generation	50	0.12
Water Usage	50	0.12
Carbon footprint	70	0.17
Certifications (ISO 9001, ISO 14001, etc.)	60	0.15
Sustainability reporting	40	0.10
Transparency	60	0.15
Total weight:	410	1.00

Table 13: Swing Weights

Suppliers	Transportation Emission	Waste generation	Water Usage	Carbon footprint	Certifications (ISO 9001, ISO 14001, etc.)	Sustainability reporting	Transparency	Cost ($)	Total value
Supplier 1	100	48.46	100	86.15	100	100	45	200000	83.3
Supplier 2	97.672	38.26	75	78.15	0	0	50	320000	53.5
Supplier 3	69.76	39.23	50	74.15	100	0	58.33	210000	60.3
Supplier 4	0	94.37	25	0	100	100	0	340000	38.9
Supplier 5	74.412	0	0	22.15	0	0	8.33	220000	19.5
Supplier 6	81.39	100	95	6.15	0	100	98.33	230000	64.9
Supplier 7	93.02	53.56	90	100	100	0	100	150000	82.0

Table 14: Normalised Value



Graph 4: Total Value vs Cost (Supplier Evaluation)

Based on the report published by the United Nations Environmental Programme, a range of criteria encompassing environmental, social, and economic aspects have been selected to evaluate supplier sustainability (UNEP, 2020) (Table 12). These criteria are adaptable and dependent on the actual situation and the product procured. Company can also add more criteria into the analysis from not just sustainability but other aspects as well to get a comprehensive result.

Upon identifying sustainable suppliers, the focus is on fostering collaboration strategies based on the supplier's bargaining power. Building stable relationships with suppliers possessing significant leverage and incorporating their sustainability practices could enhance company operations. Conversely, the company may actively guide sustainability efforts with smaller suppliers, choosing those consistent with its vision. Training and reward systems can further enhance commitment to sustainability across the supply chain (Gutierrez et al., 2020).

Other initiatives that have been successfully implemented within the automotive industry to increase supply chain sustainability include utilizing technology and establishing collaborative frameworks. For instance, a blockchain-based traceability system has been adopted by Volvo Cars to track the origin and authenticity of cobalt used in electric vehicle batteries (Volvo Car, 2019). Additionally, initiatives such as Volkswagen's Sustainability Council, comprising representatives from various stakeholders, demonstrate a strategic approach to enhance collaboration and transparency within the supply chain (Volkswagen, 2020).

Sustainable Manufacturing

Sustainable manufacturing is the integration of processes and systems that prioritize using sustainable resources to produce high-quality products and services (Machado, Winroth and Ribeiro da Silva, 2019). For companies like Lunaz, the focus on increasing energy efficiency and reducing material waste is key to achieving this goal.

Companies can enhance sustainability by utilising Six Sigma, a method used for improving business processes. Through the structured DMAIC approach (Define, Measure, Analyze, Improve, Control), Six Sigma aimed to achieve a level of quality that is nearly perfect (Pankaj Kumar, 2023). An example of Six Sigma applied on abrasive blasting process has been demonstrated below. Detailed process is mentioned in Appendix 1.

Figure 3: Six Sigma Application

In addition to implementing Six Sigma methodologies, embracing advanced technologies such as digital twins and Intelligent Immune System (I2S) in manufacturing is a key trend in the Industry 4.0 era as these technologies can not only enhance sustainability but can also foster a superior working environment in the company (Rüßmann, Lorenz and Gerbert, 2015). Lunaz could consider integrating these technologies in the production process. Leveraging a digital twin approach, akin to the services provided by Siemens, can enable process optimization, continuous improvement, predictive maintenance, and superior worker training (Siemens, n.d.). I2S is an innovative approach that utilizes Big Data analytics and adaptive mechanisms to enhance energy efficiency in manufacturing. Through industrial case studies, it has been validated to achieve around 30% energy savings and over 50% productivity enhancement in factories (Wang et al., 2018). A detailed explanation of how I2S works can be found in Appendix 2. Though the upfront investment might be considerable for these technologies, the long-term gains for companies like Lunaz can be profound.

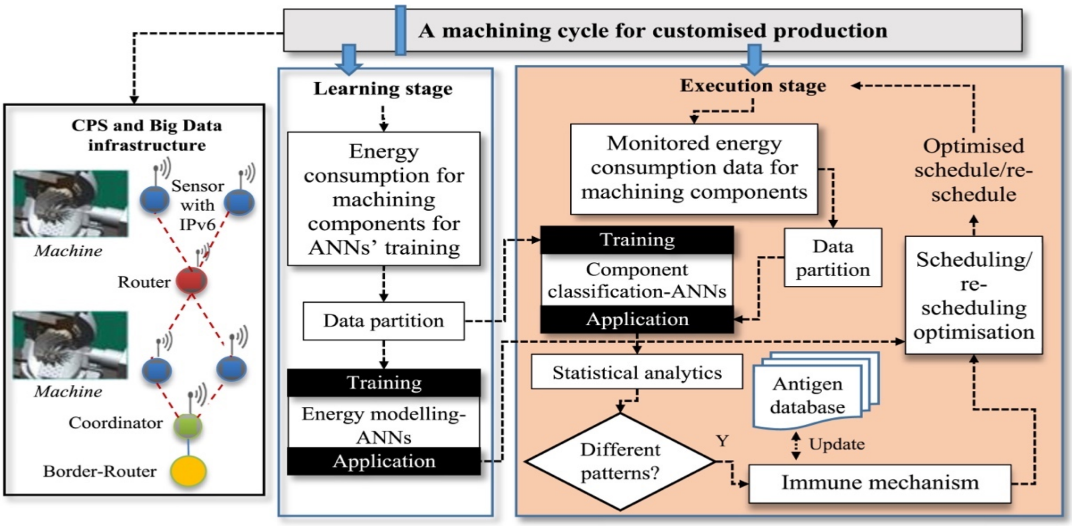


Figure 4: I2S for monitoring, analysing and optimising manufacturing for energy efficiency [9]

Testing, Delivery and Maintenance

Amidst technological advancements, new sustainable practices have been identified for the testing, delivery, and maintenance of vehicles. This section highlights some potential methods.

For the domain of testing, Virtual Simulation stands out as a noteworthy contender. This method employs simulations to replicate diverse driving conditions, various load scenarios, and a range of environmental factors (Springer India, 2017). This practice notably amplifies the efficiency and precision of testing procedures, leading to accurate evaluations of vehicle performance and safety attributes (Vaccaro, Brusoni, & Veloso, 2010). In the realm of integration with public transport, a promising avenue involves the assimilation of technologies such as electric vehicle (EV) batteries and electric motors into the existing infrastructure of public transport networks, encompassing buses, service trucks, and related services. This integration not only enhances operational efficiency but also contributes to sustainability goals while yielding potential cost savings for the company (Shen, Zhang, & Zhao, 2018).

Another significant facet pertains to Battery Life Optimization, a process that entails a comprehensive evaluation of electric vehicles to extend their battery lifespan and overall performance. This optimization procedure encompasses the analysis of charge-discharge cycles, management of thermal conditions, and the distribution of power—aligning with sustainability objectives and fostering the long-term viability of the industry (You, Krage, & Jalics, 2005).

During the delivery phase, integrating product handover with customers and stakeholders develops a sense of ownership to encourage responsible usage, leading to longer product lifespans and decreased service requirements.

In the maintenance stage, remote diagnostics and troubleshooting allow for the monitoring of various parameters of vehicles in real time (Yang, Huang, and Lin, 2022). Accurate information enables predictive issue identification, enhancing maintenance efficiency (Carr, 2005).

End of Life

End of Life refers to the final stage in the Life Cycle Analysis (LCA) of a product (Eger and Drukker, 2010). This stage becomes relevant once the initial purpose of the product is no longer viable. This phase encompasses activities such as Reuse, Remanufacture, Repurpose, and Recycle, as outlined by Srisruthi (2017).

Battery

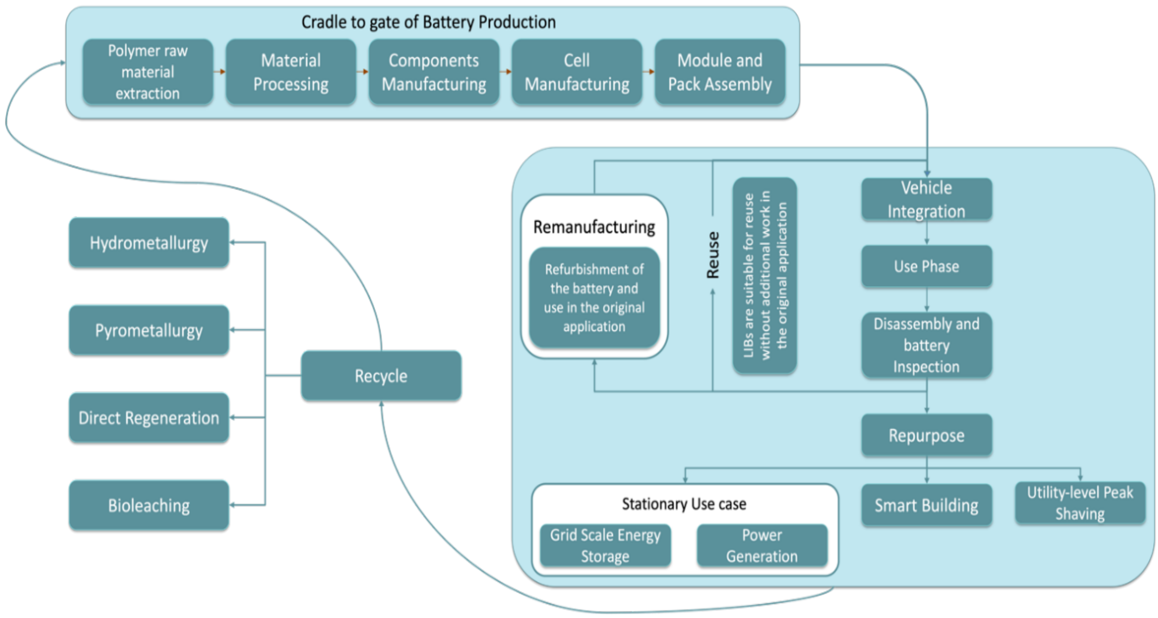


Figure 5: Battery Framework

When a battery is assembled and integrated into a vehicle, it's use phase comes into play. Use phase is the only phase where the EV battery can offset the emissions generated by it during the manufacturing process. The initial use phase of the EV battery approximately lasts for 10-15 years (Xia and Li, 2022). At the end of the initial phase, the battery retains 80% of the power storage capacity (Yang, Huang and Lin, 2022). The remaining capacity makes the battery unfit for the application in a vehicle.

Once the battery is disassembled and inspected, the next steps are determined in the table below:

	Description	Benefits
Reuse	Using the battery without modifications in its initial application reduces resource demand.	Battery can be reused in other EVs after an accident, saving resources.
Repurpose	After the first EV cycle, batteries can be repurposed for energy storage, power generation, or buildings.	Enables power generation, utility peak shaving, and efficient building power control.
Remanufacture	Refurbishing batteries for reintegration into EVs maximize battery utilization.	Optimizes battery lifespan and performance in the original application.
Recycle	Following Reuse, Repurpose, and Remanufacture, batteries are recycled for new battery components.	Extracts valuable materials through various recycling methods: hydrometallurgy, pyrometallurgy, direct regeneration, and bioleaching.

Table 15: EOL phases of the battery

Considering the cost-benefit analysis of recycling NMC and LFP batteries, reuse and repurposing appear to offer greater financial benefits than recycling. However, the potential benefits of battery recycling may be enhanced by future economic and legal frameworks, particularly within the EU (Achim Kampker et al., 2023).

Interior Upholstery

Interior upholsteries typically comprise a plastic layer (backing) with an upper mat (Correnti et al., 2005). Considering moving from traditional materials used in building interior upholstery to alternative materials suggestions to improve sustainability, the plastic is still the primary material used. Thus, the end-of-life framework conducted for interior upholstery is based on plastic. Figure below shows the interior upholstery life cycle, starting from cradle-to gate, integration, use phase, to end-of-life.

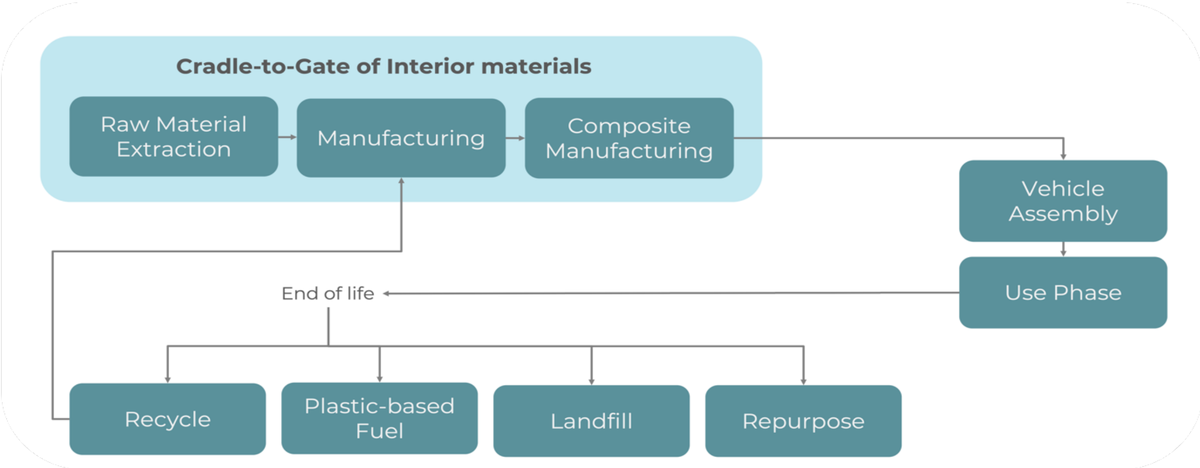


Figure 6: Interior Upholstery Framework (Hermansson, Janssen

Once the interior upholstery ends up in the end-of-life stage, materials can take various routes, including repurposing, recycling, conversion into plastic-based fuel, or ultimately landfill.

End-of-Life stages	Description
Repurpose	Repurposing interior upholstery into furniture will require few chemical processes that release toxic emissions such as carbon monoxide and chlorine, along with preventing problems in landfill operations (Kumar Jha and Kannan, 2020).
Recycle	This process is to put waste plastic through the process to produce granulate and create new plastic products (Jeswani et al., 2021). However, recycling can degrade the mechanical properties. Therefore, plastic can only be recycled 2 to 3 times (Sedaghat, 2018).
Plastic-based fuel	This approach converts plastic into oil using methods such as pyrolysis (Li et al., 2022). According to Kundan Kumar Jha and T.T.M Kannan (2020), waste plastic has a better synergistic effect than pure heavy oil cracking. Traditional materials used in interior upholstery, such as polyvinyl chloride (PVC) and polypropylene (PP), can be converted into liquid oil (Li et al., 2022).
Landfill	Landfill is the least preferrable plastic waste management (Jeswani et al., 2021). However, 75.8% of plastic waste was landfilled, according to John D. Chea, Kirti M. Yenki, Joseph F. Stanzione III, Gerardo J. Ruiz-Mercado (2022). Comparing the effect from conventional plastic with bioplastic going to landfill, bioplastic is worth substituting to reduce environmental impact since it is either biodegradable or made from biological material or feedstock (Atiwesh et al., 2021). However, an effective end-of-life strategy is still needed to minimise the environmental impact (Fredi and Dorigato, 2021).

Table 16: Table showing interior upholstery end-of-life framework

Implementation

Phased Rollout

The rollout and adaptation process requires strategic planning, coordination of systems and resources, employee and customer training, and efficient communication (Experts, 2023). Here's a more detailed breakdown of the process:

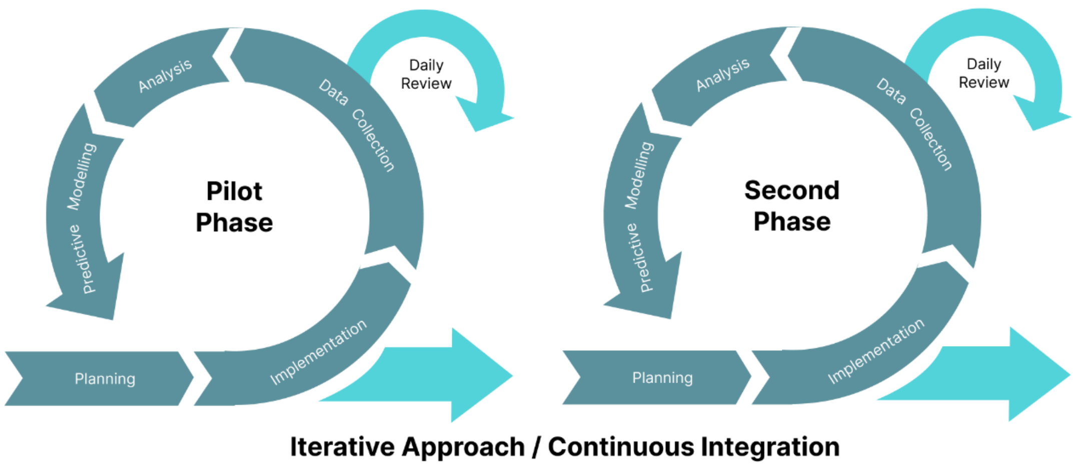


Figure 7: Phased Rollout Iterative Approach

Pilot: The framework is initially to be introduced in a few departments of the organization to understand any issues or challenges on a small scale before a full-scale rollout. Closely monitoring the performance, recording data, building a dataset, and collecting feedback are done in this stage.

Iterative Approach: Gradually expanding the framework by collecting and analysing the inputs and completing the research and development needed for the next rollout will help in seamless implementation. It will also help in addressing issues promptly and reducing risks.

The McKinsey Horizon Strategy (McKinsey & Company, 2009) has been applied to plan initiatives based on time horizon.

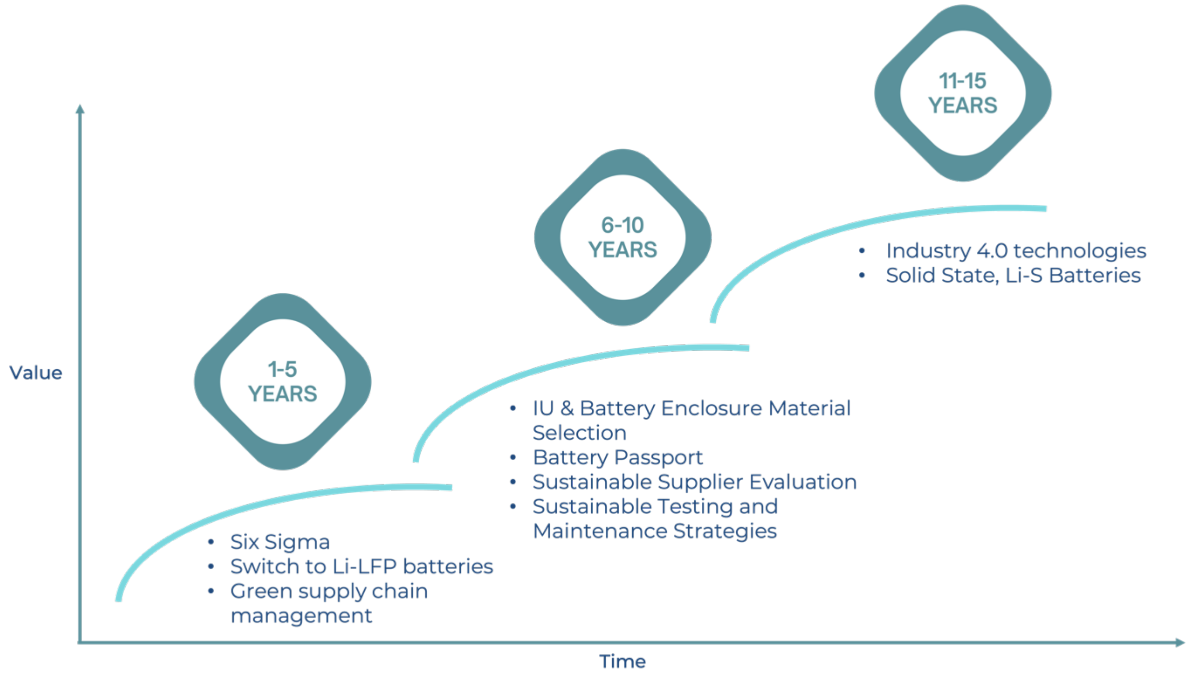


Figure 8: McKinsey Horizon Strategy applied on proposed framework

Short Term 1-5 Years:

The focus is on optimizing operational efficiency and quality through initiatives like implementing Six Sigma methodologies. A transition to Lithium Iron Phosphate (LFP) battery chemistry enhances charging speed, battery lifespan, and safety.

Medium Term 6-10 Years:

Post pilot phase years, efforts shift towards innovation. Investigating suitable materials for Battery Enclosures and Interior Upholstery (IU), and Battery Passport aims to improve sustainable traceability. Evaluating suppliers based on sustainability criteria align with responsible business practices.

Long Term 11-15 Years:

The long-term horizon focuses on transformative changes. Integrating Industry 4.0 technologies revolutionizes manufacturing and management. Predictive modelling allows accurate forecasting of different components. The exploration of Solid State and Lithium-Sulphur (LIS) batteries demonstrates a commitment to pushing the boundaries of energy density and performance.

Risk Analysis

Risk Analysis in an organizational framework is a structured approach to recognizing, analysing, and prioritizing potential risks that might hinder an organization's goals. It aids in comprehending threats and devising strategies to control or alleviate them. (Eichler, 2019; Kenton, 2020). Certain risks associated with the above framework has been highlighted on the risk register below:

Risk No.	Risk Name	Risk Description	Low	Medium	High	Mitigation Action
1	SMART Analysis Decision-Making Tool	Accurate SMART Analysis relies on relevant criteria; incorrect data can lead to inaccurate predictions.			✓	• Validate data sources for analysis • Evolve data collection methods consistently
2	Supplier Data Collection	Aligning operations and measuring impacts for small-scale suppliers without standardised metrics is challenging, time-consuming, and costly		✓		• Partnering for standardised sustainability metrics Boost supplier education and training Optimise data collection and tracking.
3	Supply Chain Disruptions	Adopting sustainable materials or suppliers may disrupt the supply chain, impacting production schedules.		✓		• Conduct thorough risk assessment before making supply chain changes. • Develop contingency plans for potential disruptions.
4	Regulatory Compliance	Evolving environmental regulations may affect framework effectiveness, requiring time-consuming and costly adjustments.	✓			• Monitor and adapt to regulatory shifts Design framework with future regulations in mind.
5	Technical Challenges	Introducing sustainable methods (E.g.- Digital Twins, Battery EoL) faces technical hurdles. Compatibility with existing systems and maintaining quality is demanding.	✓			• Perform feasibility studies and pilots Partner with experts to conquer technical barriers Gradually integrate methods for quality assurance.

Table 17: Risk Analysis

Conclusion

In a world focused on combating climate change, retrofitting organizations like Lunaz are leading the way in reimagining product development by integrating innovation with sustainability. Companies aim to adopt a holistic framework for the entire lifecycle of sustainable products, hence, the proposed framework will quantify environmental impacts at every stage, guiding choices and reducing carbon footprint.

Importantly, the project's purview extends beyond the immediate realm of vehicle electrification. While Lunaz's central focus remains on electrifying vehicles, the evolved framework offers insights applicable to a diverse spectrum of industries and products encompassing the complete product lifecycle. The framework outlines a comprehensive journey toward operational excellence, sustainability, and technological advancement. Refining operational efficiency through Six Sigma methodologies, pioneering battery chemistry transitions, material selection, and supplier evaluations, the vision extends to integrating cutting-edge Industry 4.0 technologies, predictive modelling, and innovative battery exploration.

The project's twin objectives come into sharper focus: first, the creation of a seamlessly integrated framework for evaluating carbon emissions throughout the product lifecycle; and offering a quantitative comprehension of environmental impact. Secondly, the framework will seamlessly dovetail with prevailing product Life Cycle Assessments (LCAs) for distinct components, like batteries and interiors, further fortifying the symbiosis between sustainable practices and cutting-edge innovation.

In the wake of these trends, the automobile industry finds itself at a crossroads, compelled to re-evaluate its strategies and practices. The paradigm shift spans design to end-of-life considerations and necessitates cross-industry collaboration and technological integration (Pohl, 2021). The goal is for organizations to adopt the proposed framework and utilize its specified measurement method to generate data, revealing carbon emissions at various product life-cycle stages. These customized datasets, based on vehicle models and specifications, can then drive predictive modelling to estimate emissions during Product Definition and Design stages. The data-driven structure helps identify inefficiencies, bottlenecks, and opportunities for improvement, leading to informed decision-making.

References

Achim Kampker, Heiner Hans Heimes, Offermanns, C., Frieges, M.H., Graaf, M., Natalia Soldan Cattani and Benedikt Späth, 2023. Cost-Benefit Analysis of Downstream Applications for Retired Electric Vehicle Batteries [Online]. *World Electric Vehicle Journal* [Online], 14(4), pp.110–110. Available from: https://doi.org/10.3390/wevj14040110 [Accessed 10 August 2023].

Atiwesh, G., Mikhael, A., Parrish, C.C., Banoub, J. and Le, T.-A.T., 2021. Environmental impact of bioplastic use: A review. *Heliyon*, [online] 7(9).

Carr, B.J., 2005. Practical Application of Remote Diagnostics [Online]. *SAE Transactions* [Online], 114, pp.376–382. Available from: https://www.jstor.org/stable/44682443 [Accessed 14 August 2023].

Chea, J.D., Yenkie, K.M., Stanzione, J.F. and Ruiz-Mercado, G.J., 2023. A generic scenario analysis of end-of-life plastic management: Chemical additives. *Journal of Hazardous Materials*, 441, pp.129902–129902.

Correnti, A., Bocchino, M., Filippi, S., Pier Luigi Magagnini, Polacco, G. and F.P. La Mantia, 2005. Recycling of inside upholstery of end-of-life cars. *Journal of Applied Polymer Science*, 96(5), pp.1716–1728.

Dhoke, A. and Dalavi, A., 2021. A Critical Review on Lightweight Design of Battery Pack Enclosure for Electric Vehicles [Online]. *International Journal of Sustainable Transportation Technology* [Online], 4(2), pp.53–62. Available from: https://doi.org/10.31427/ijstt.2021.4.2.2 [Accessed 10 May 2022].

Eger, A.O. and Drukker, J.W., 2010. Phases of Product Development: a Qualitative Complement to the Product Life Cycle [Online]. *Design Issues* [Online], 26(2), pp.47–58. Available from: https://doi.org/10.1162/desi_a_00004.

Eichler, R., 2019. *Risk Management Framework (RMF): An Overview* [Online]. *Investopedia*. Available from: https://www.investopedia.com/articles/professionals/021915/risk-management-framework-rmf-overview.asp [Accessed 15 August 2023].

Experts, D., 2023. *Phased Implementation* [Online]. *DealHub*. Available from: https://dealhub.io/glossary/phased-implementation/ [Accessed 15 August 2023].

Fredi, G. and Dorigato, A., 2021. Recycling of bioplastic waste: A review. *Advanced Industrial and Engineering Polymer Research*, 4(3).

Freitas, C., n.d. *What is the environmental impact of lithium batteries?* [Online]. *changeit.app*. Available from: https://changeit.app/blog/2021-03-26-environmental-impact-of-lithium-batteries/.

Gutierrez, A., Kothari, A., Mazuera, C. and Schoenherr, T., 2020. *Taking supplier collaboration to the next level | McKinsey* [Online]. *www.mckinsey.com*. Available from: https://www.mckinsey.com/capabilities/operations/our-insights/taking-supplier-collaboration-to-the-next-level.

Hermansson, F., Janssen, M. and Gellerstedt, F. (2013). Environmental evaluation of bio-composites using LCA - Comparison of two different applications.

Jeswani, H., Krüger, C., Russ, M., Horlacher, M., Antony, F., Hann, S. and Azapagic, A., 2021. Life cycle environmental impacts of chemical recycling via pyrolysis of mixed plastic waste in comparison with mechanical recycling and energy recovery. *Science of The Total Environment*, 769, p.144483.

Kenton, W., 2020. *Business Risk* [Online]. *Investopedia*. Available from: https://www.investopedia.com/terms/b/businessrisk.asp [Accessed 15 August 2023].

Khan, M.R., Khan, N.R., Muhammad, T. and Ali, L., 2023. A Path towards a Greener Future: Fostering green supply chain, green marketing and environmental sustainability [Online]. *Scientific Journal of Logistics* [Online], 19(1), pp.1–14. Available from: https://doi.org/10.17270/j.log.2023.815 [Accessed 15 May 2023].

Koroma, M.S., Costa, D., Philippot, M., Cardellini, G., Hosen, M.S., Coosemans, T. and Messagie, M., 2022. Life cycle assessment of battery electric vehicles: Implications of future electricity mix and different battery end-of-life management [Online]. *Science of The Total Environment* [Online], 831, p.154859. Available from: https://doi.org/10.1016/j.scitotenv.2022.154859.

Kumar Jha, K. and Kannan, T.T.M., 2020. Recycling of plastic waste into fuel by pyrolysis - a review. *Materials Today: Proceedings*.

Lakshmi, S., 2022. A Study On Six-Sigma Practice And Implementation In Small And Medium Enterprises (SME) [Online]. *Aweshkar Research Journal* [Online], 29(1), pp.16–25. Available from:

https://web.s.ebscohost.com/ehost/pdfviewer/pdfviewer?vid=0&sid=cf567977-4668-4b71-bc1d-5ae068c9aeb6%40redis [Accessed 10 August 2023].

Law Insider, n.d. *Component materials Definition* [Online]. Available from: https://www.lawinsider.com/dictionary/component-materials [Accessed 20 August 2023].

Lean Six Sigma Groep, n.d. *DMAIC* [Online]. *Lean Six Sigma Groep*. Available from: https://leansixsigmagroep.nl/en/lean-agile-and-six-sigma/dmaic/.

Li, N., Liu, H., Cheng, Z., Yan, B., Chen, G. and Wang, S., 2022. Conversion of plastic waste into fuels: A critical review. *Journal of Hazardous Materials*, 424, p.127460.

Lodha, K., 2023. *Material Table React* [Online]. *Scaler Topics*. Available from: https://www.scaler.com/topics/react/material-table-react [Accessed 20 August 2023].

Machado, C.G., Winroth, M.P. and Ribeiro da Silva, E.H.D., 2019. Sustainable manufacturing in Industry 4.0: an emerging research agenda [Online]. *International Journal of Production Research* [Online], 58(5), pp.1–23. Available from: https://doi.org/10.1080/00207543.2019.1652777.

McKinsey & Company, 2009. *Enduring Ideas: The three horizons of growth | McKinsey* [Online]. *www.mckinsey.com*. Available from: https://www.mckinsey.com/capabilities/strategy-and-corporate-finance/our-insights/enduring-ideas-the-three-horizons-of-growth [Accessed 15 August 2023].

Pankaj Kumar, 2023. *What is Six Sigma: A Complete Overview* [Online]. *Simplilearn.com*. Simplilearn. Available from: https://www.simplilearn.com/what-is-six-sigma-a-complete-overview-article.

Roehrich, J.K., Hoejmose, S.U. and Overland, V., 2017. Driving Green Supply Chain Management Performance through Supplier Selection and Value Internalisation [Online]. *International Journal of Operations & Production Management* [Online], 37(4), pp.489–509. Available from: https://doi.org/10.1108/ijopm-09-2015-0566.

Rüßmann, M., Lorenz, M. and Gerbert, P., 2015. *Industry 4.0: The Future of Productivity and Growth in Manufacturing Industries* [Online]. *BCG Global*. Available from: https://www.bcg.com/publications/2015/engineered_products_project_business_industry_4_future_productivity_growth_manufacturing_industries.

Sedaghat, L., 2018. *7 Things You Didn't Know About Plastic (and Recycling)* [Online]. National Geographic Society Newsroom. Available from: https://blog.nationalgeographic.org/2018/04/04/7-things-you-didnt-know-about-plastic-and-recycling/ [Accessed 4 April 2018]

Shen, Y., Zhang, H. and Zhao, J., 2018. Integrating shared autonomous vehicle in public transportation system: A supply-side simulation of the first-mile service in Singapore [Online]. *Transportation Research Part A: Policy and Practice* [Online], 113, pp.125–136. Available from: https://doi.org/10.1016/j.tra.2018.04.004 [Accessed 14 October 2019].

Siemens, n.d. *Smart Path to Vehicle Electrification* [Online]. *Siemens Resource Center*. Available from: https://resources.sw.siemens.com/en-US/solution-brief-vehicle-electrification-brief [Accessed 9 August 2023].

Springer India, 2017. Simulation, virtual prototyping for automotive applications [Online]. *Auto Tech Review* [Online], 6(1), pp.68–71. Available from: https://doi.org/10.1365/s40112-017-1283-3 [Accessed 16 March 2020].

Srisruthi, K.M., 2017. Circular Economy [Online]. *International Journal of Trend in Scientific Research and Development* [Online], Volume-1(Issue-6), pp.566–569. Available from: https://doi.org/10.31142/ijtsrd4610.

UNEP, 2020. *Sustainable Public Procurement How to 'Wake the Sleeping Giant' Second Edition* [Online]. Available from: https://wedocs.unep.org/bitstream/handle/20.500.11822/37045/SPPWSG.pdf [Accessed 9 August 2023].

Vaccaro, A., Brusoni, S. and Veloso, F.M., 2010. Virtual Design, Problem Framing, and Innovation: An Empirical Study in the Automotive Industry [Online]. *Journal of Management Studies* [Online], 48(1), pp.99–122. Available from: https://doi.org/10.1111/j.1467-6486.2010.00939.x [Accessed 11 December 2019].

Volkswagen, 2020. *Volkswagen Konzern - AR 20 - Sustainability* [Online]. *annualreport2020.volkswagenag.com*. Available from: https://annualreport2020.volkswagenag.com/group-management-report/sustainable-value-enhancement/sustainability.html.

Volvo Car, 2019. *Volvo Cars to implement blockchain traceability of cobalt used in electric car batteries* [Online]. *www.media.volvocars.com*. Available from:

https://www.media.volvocars.com/global/en-gb/media/pressreleases/260242/volvo-cars-to-implement-blockchain-traceability-of-cobalt-used-in-electric-car-batteries.

Wang, C., Xu, S. and Si, C., 2010. *Study on vehicle remote test and diagnosis technology* [Online]. *IEEE Xplore*. pp.116–119. Available from: https://doi.org/10.1109/ICCSE.2010.5593682 [Accessed 14 August 2023].

Wang, S., Liang, Y.C., Li, W.D. and Cai, X.T., 2018. Big Data enabled Intelligent Immune System for energy efficient manufacturing management [Online]. *Journal of Cleaner Production* [Online], 195, pp.507–520. Available from: https://doi.org/10.1016/j.jclepro.2018.05.203 [Accessed 18 January 2021].

Xia, X. and Li, P., 2022. A review of the life cycle assessment of electric vehicles: Considering the influence of batteries [Online]. *Science of The Total Environment* [Online], 814, p.152870. Available from: https://doi.org/10.1016/j.scitotenv.2021.152870.

Yang, Z., Huang, H. and Lin, F., 2022. Sustainable Electric Vehicle Batteries for a Sustainable World: Perspectives on Battery Cathodes, Environment, Supply Chain, Manufacturing, Life Cycle, and Policy [Online]. *Advanced Energy Materials* [Online], 12(26), p.2200383. Available from: https://doi.org/10.1002/aenm.202200383.

You, S., Krage, M.K. and Jalics, L., 2005. Overview of Remote Diagnosis and Maintenance for Automotive Systems [Online]. *SAE technical paper series* [Online], (2005-01-1428). Available from: https://doi.org/10.4271/2005-01-1428 [Accessed 14 August 2023].

Yusof, M.S., Toha, S.F., Kamisan, N.A., Hashim, N.N.W.N. and Abdullah, M.A., 2017. Battery Cell Balancing Optimisation for Battery Management System [Online]. *IOP Conference Series: Materials Science and Engineering* [Online], 184(184), p.012021. Available from: https://doi.org/10.1088/1757-899x/184/1/012021 [Accessed 30 August 2020].

Zulkarnain, I., Mohamad Kassim, N., Syakir, M., Abdul Rahman, A., Md Yusuff, M., Mohd Yusop, R. and Keat, N., 2021. Sustainability-Based Characteristics of Abrasives in Blasting Industry [Online]. *Sustainability* [Online], 13(15), p.8130. Available from: https://doi.org/10.3390/su13158130 [Accessed 22 April 2022].

Appendix 1

Example use of Six Sigma on Abrasive Blasting Process:

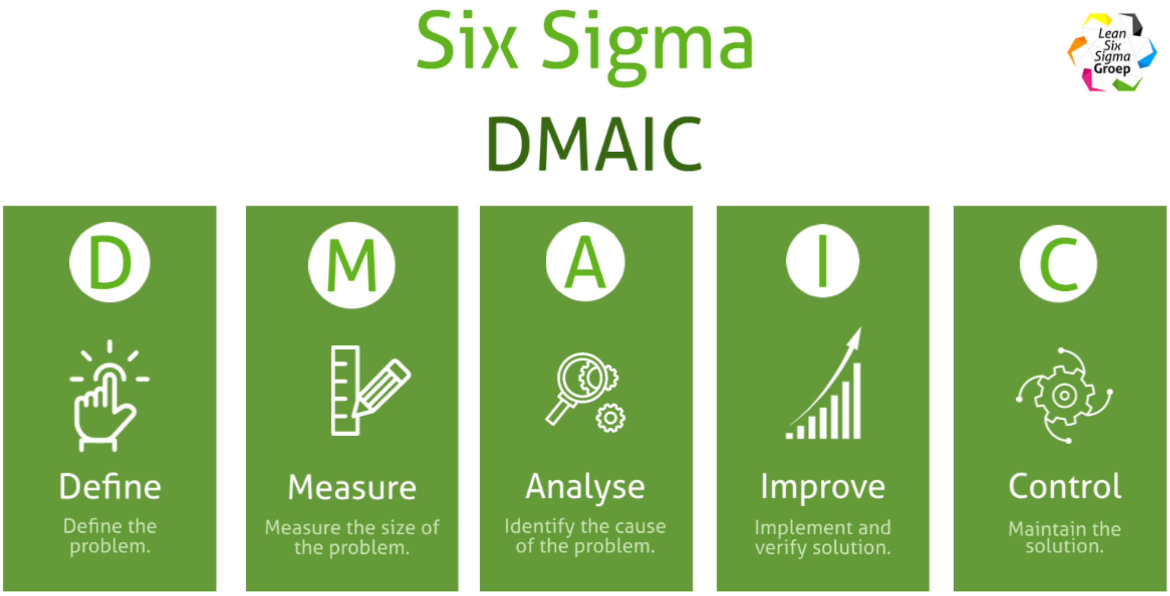


Figure: Structured DMAIC approach (Lean Six Sigma Groep, n.d.)

1. Define: The goal is to enhance the sustainability of the vehicle cleansing process.
2. Measure: Relative measurements including the PM emissions, material waste, noise pollution, and energy consumption should be taken.
3. Analyse: Initial analysis reveals relatively high levels of air and noise pollution in the current abrasive blasting method used by Lunaz.
4. Improvement: Research indicates that bead blasting is more sustainable compared to the currently used shot blasting method, considering factors such as noise, PM emission, durability, environmental and health impact (Zulkarnain et al., 2021). The recommendation is to transition to bead blasting.
5. Control: Continuous monitoring should be implemented to ensure that improved results meet expectations.

Appendix 2

The Intelligent Immune System (I2S) is an advanced system to manage and optimize machining processes across production cycles, accommodating energy efficiency and manufacturing performance. It integrates two main functions: Machine Condition Monitoring and a re-scheduling algorithm.

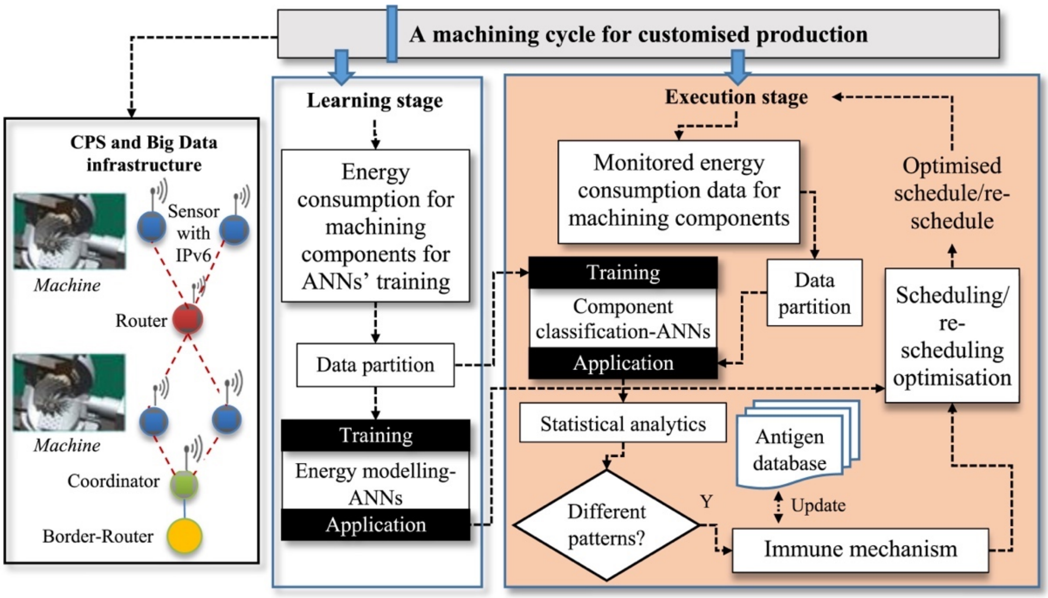


Figure:

1. Machine Condition Monitoring:

Utilizing electricity sensors-based Wireless Sensor Network (WSN), I2S can measure the energy consumption of machines. Unlike traditional vibration or acoustic sensors, this configuration offers more flexibility in deployment, allowing for better reflection of machine and tooling conditions. This Big Data infrastructure facilitates real-time energy monitoring and optimization.

2. Re-scheduling algorithm:

I2S divides a machining cycle into two stages, learning and execution:

Learning Stage: Two Artificial Neural Networks (ANNs): energy modelling-ANNs and component classification-ANNs are trained. The energy modeling-ANN is utilized for scheduling optimization and setting up an optimized plan to support the decision at the execution stage.

Execution Stage: The component classification-ANNs is being used to analyze monitored energy data, adapting to dynamic conditions during the machining execution lifecycles. If significant energy pattern changes are detected, a re-scheduling optimization generates an optimized plan to adjust current manufacturing plans.

Appendix 3

References for IU Material Selection Table

	Materials		Life cycle assessments									Cost ($/kg)
		Longevity (years)	Acidification potential ((kg SO2-eq)	Reference	Relative Human toxicity potential (0-most hazardous, 100-least hazardous)	Global warming potential (kg CO2-eq)	Reference	Relative Water Consumption (0-highest consumption, 100-lowest consumption)	Energy consumption (MJ)	Relative Biodegradability (0-least biodegradable, 100-most biodegradable)		
Traditional Materials	**PVC** (Polyvinyl Chloride)	100	0.0062	(Spierling et al., 2018)	0	1.9	(Spierling et al., 2018)	90	55.5	0		1
	PU (Polyurethane)	15	0.00885	(Franklin, 2022)	20	3.084	(Franklin, 2022)	60	101.5	45		2.5
	PP (Polypropylene)	20	0.0043	(Spierling et al., 2018)	30	1.6	(Spierling et al., 2018)	80	73	40		1
	PC (Polycarbonate)	10	0	(Kua and Lu, 2016)	35	5.6	(Kua and Lu, 2016)	50	112.95	55		3
	ABS (Acrylonitrile Butadiene Styrene)	70	0.00658	(Franklin, 2022)	40	2.354	(Franklin, 2022)	70	95.34	50		2
	PMMA (Polymethyl Methacrylate)	25	0.02935	(Mahmud and Farjana, 2020)	45	8.21	(Mahmud and Farjana, 2020)	75	116.14	60		5
Sustainable Alternatives	**Bio-PET** (Bio-based Polyethylene)	35	0	(Spierling et al., 2018)	60	2.1	(Spierling et al., 2018)	5	60	85		3.5
	Bio-PP (Bio-based Polypropylene)	15	0	(Spierling et al., 2018)	65	2.4	(Spierling et al., 2018)	0	42	80		4
	PLA (Polylactic Acid)	15	0.0073	(Spierling et al., 2018)	80	0.6	(Spierling et al., 2018)	10	35	100		3
	PHA (Polyhydroxyalkanoates)	3	0.016811	(Qiang et al., 2013)	85	3.491	(Qiang et al., 2013	15	23.33	95		3.5
	Cork and wood composites	50	0.905	(Silestre et al., 2016)	90	0.402	(Silestre et al., 2016)	20	77.3	90		5

Appendix 4

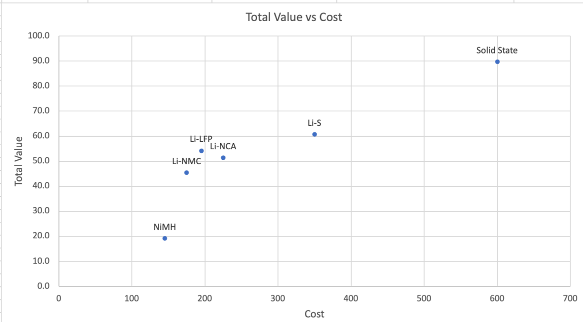
Calculation of Total Value for SMART Analysis

Battery Comparison

Battery Type	Energy Density (Wh/kg)	Range (miles)	Lifetime and Degradation	Relative safety rating	Carbon Emission LCA (kg CO2eq)	Weight (Kg)	Relative Availability and Production Scalability	Cost ($/kWh)
Li-NMC	160-200	150-300	500-1500 Cycles	80	240	250-350	High (95)	150-200
Li-LFP	90-120	100-250	2000-5000 Cycles	100	166	250-400	Good (85)	170-220
Li-NCA	200-240	200-350	500-1500 Cycles	70	230	200-300	Moderate (75)	200-250
Li-S	300-500	250-300	500-1000 Cycles	60	146	200-300	Low (55)	300-400
Solid State Battery	400-500	300-400	2000-7000 Cycles	70	122	150-250	Low (55)	400-800
NiMH	60-120	80-150	500-1000 Cycles	70	300	300-400	Moderate (65)	140-150

Battery Type	Energy Density	Range	Lifetime and Degradation	Relative safety rating	Carbon Emission LCA	Weight	Relative Availability and Production Scalability	Cost	Total Value
Li-NMC	25	46.8	6.7	80	33.7	33.32	95	175	45.4
Li-LFP	4.169	25.52	73.45	100	75.28	16.65	85	195	54.2
Li-NCA	36.116	68.07	6.7	70	39.32	66.65	75	225	51.4
Li-S	86.12	68.07	0	60	86.51	66.65	55	350	60.7
Solid State Battery	100	100	100	70	100	100	55	600	89.7
NiMH	0	0	0	70	0	0	65	145	19.2

Criteria	Swing weights	Normalised weight
Energy density	70	0.1522
Range	70	0.1522
Lifetime and degradation	65	0.1413
Relative safety rating	75	0.1630
Carbon emission LCA	65	0.1413
Weight	60	0.1304
Relative availability	55	0.1196
Total Weight:	**460**	1.0000



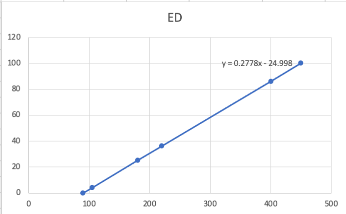
Total Value for Li-NMC = (Values of different criteria * Respective normalised weights)

(B15*C25+C15*C26+D15*C27+E15*C28+F15*C29+G15*C30+H15*C31)

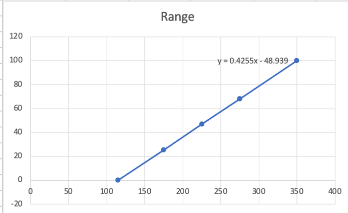
= 45.4

Linear Value Functions for different Criteria

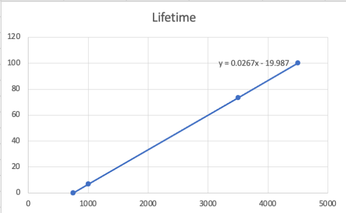
Energy Density	Rating
90	0
105	4.169
180	25.004
220	36.116
400	86.12
450	100



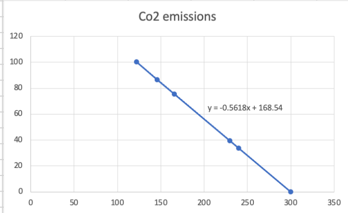
Range	Rating
115	0
175	25.5265
225	46.8015
275	68.0765
275	68.0765
350	100



Lifetime	Rating
750	0
750	0
1000	6.7
1000	6.7
3500	73.45
4500	100



CO2	Rating
122	100
146	86.5172
166	75.2812
230	39.326
240	33.708
300	0



Weight	Rating
200	100
250	66.655
250	66.655
300	33.32
325	16.6525
350	0