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A comprehensive circular design framework for graphene-enhanced industrial systems: cross-sectoral methodology and multi-criteria evaluation

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ABSTRACT

This study introduces a novel integrated circular design framework that embeds different methodologies, including eco-design strategies, material selection strategies, design for assembly/disassembly, design for recycling, and multi-parameter engineering optimisation, into the earliest stages of development across 11 industrial use cases (UCs). By linking functional lightweighting, design and advanced graphene-related material (GRM)-based multifunctional (GRM-bM) solutions in a unified assessment approach, a demonstration is presented of how qualitative and cross-sector convergence can deliver high-performance products with enhanced recyclability and reduced environmental burden without relying on post hoc LCA. The novelty of this work lies not only in the conceptual advancement of a circular design framework but also in its practical implementation within operational and industrial environments involving complex graphene and GRM-bM systems. This work presents a scalable approach for integrating sustainability into material-intensive systems, from concept to pre-production. Technical and environmental specifications of the UCs, encompassing the automotive, aerospace, water treatment, hydrogen storage, and energy generation sectors, have been considered. A conceptual study has provided a realistic manufacturing scenario and cost analysis, ensuring the feasibility and practicality of the proposed solutions. Furthermore, eco-design concepts are presented to optimise advanced graphene and GRM-bM, feasibility, manufacturing technologies, and recyclability. In alignment with the United Nations Sustainable Development Goals (UN-SDG), this work contributes to delivering graphene-enabled components that maintain mechanical integrity, cut mass by up to 22 %, and achieve projected recyclability above 90 %. In comparison, conceptual manufacturing studies indicate a 20 % energy-saving and 10 % cost reduction. Collectively, these

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results demonstrate a transferable, scale-ready pathway to high-performance materials that meet the EU Green Deal and UN-SDG ambitions.

1. Introduction

Circular design involves creating products or services with the aim of minimizing waste and pollution while also maximising the reuse and recycling of materials. This approach contributes to a closed-loop system within the economy, where resources are shared, repaired, reused, or recycled rather than discarded (Ellen McArthur Foundation, 2024). The far-reaching goal is zero waste and a real reduction in environmental impact due to circular design. On the other hand, it is hard to find any universal approach to designing products or services that avoid waste and pollution, nor find a single model for products to prolong their life cycles. It opens the gate to many strategies and also innovative solutions, giving a wide possibility for research and creative adaptation.

Numerous authors have categorised and identified strategies, methodologies, and tools that support product design to facilitate the shift toward eco-design. These analyses have highlighted the extensive and varied array of supportive methods and the criteria for determining the most suitable eco-design approach, including the type of waste targeted for recovery, the product responsible for generating the waste, and the intended strategy. Bearing this in mind, Fig. 1 illustrates design methodologies that serve the dual purpose of achieving eco-design and fostering circular design principles.

Design for X (DFX) encompasses a series of methodologies aimed at enhancing a product's design to achieve particular objectives, including manufacturing, assembly, maintenance, reliability, safety, and sustainability (Mesa, 2023; Tranquillo et al., 2023; Sekhar and Maheswari, 2021). Through the application of DFX strategies to ecodesign, businesses can develop environmentally- friendly products, leading to cost reduction and enhancement of overall sustainability performance.

Ecodesign, also known as Design for Environment, is associated with the Design for X (DfX) paradigm (Biswas and John, 2022; Jaegler and Roques, 2023; Cornely et al., 2024). This paradigm entails a design methodology based on specific external requirements, such as manufacturing, quality, or variety. These requirements are prioritised and must be fulfilled by the new product design. While Design for X was not initially conceived with an eco-system perspective, the evolution of eco-design methodologies can be viewed as an extension of this DfX paradigm.

1.1. Related work on circular design frameworks and DfX strategies

A growing body of literature explores how design can accelerate the transition to a circular economy. Moreno et al. developed a conceptual framework for circular design by synthesising design-for-sustainability principles with circular business models; they argued that most prior studies focus on business models and provide little guidance for

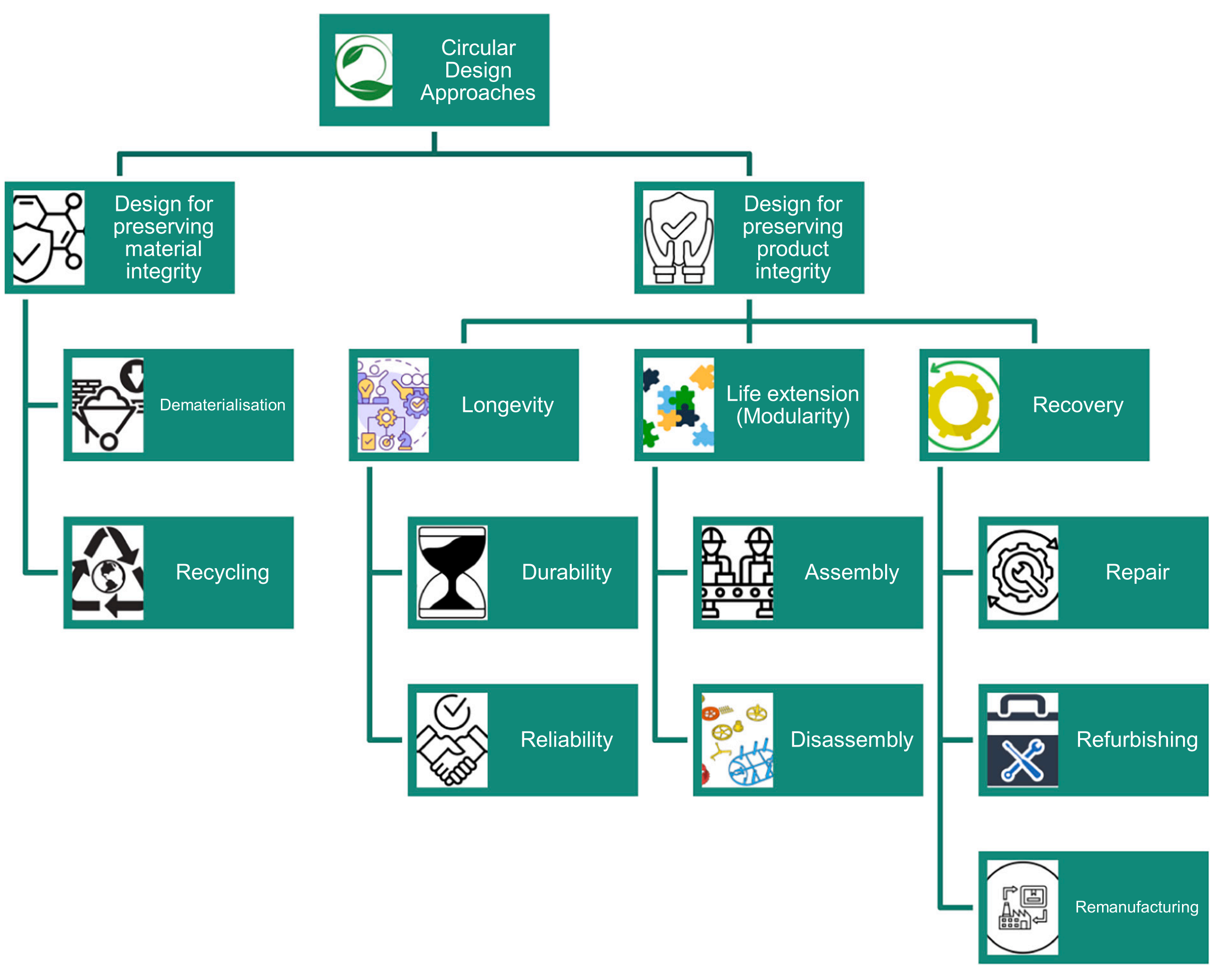

Fig. 1. A classification of circular design and associated DFX (Design for X) strategies applicable for implementation.

designers (Moreno et al., 2016). Their framework maps design strategies (e.g., resource conservation, slowing loops) against circular business models and recommends that designers consider closed-loop value creation throughout product development (Moreno et al., 2016). Medkova and Fifield highlighted that circular design requires a system-based approach; they emphasised the need to move away from take-make-dispose and to design products for reuse, repair, remanufacture and recycling (Medkova and Fifield, 2016).

Zeb and Kortelainen provided a technical design perspective, noting that circular products must be designed for maintain/prolong, reuse, refurbish, remanufacture and recycle, and that material purity and product structures must enable disassembly and reassembly (Zeb and Kortelainen, 2021). They also observed that circular design literature often neglects detailed technical design processes and blurs the boundaries between product design and business planning (Zeb and Kortelainen, 2021).

Recent research has increasingly focused on specific strategies such as design-for-disassembly. Formentini and Ramanujan proposed a Design for circular disassembly approach that models the impact of a product's end-of-life status on disassembly effort and circularity, arguing that conventional DfD methods assume ideal product conditions and therefore underestimate real-world disassembly challenges (Formentini and Ramanujan, 2023). They introduced the parent-action-child model to account for damage, corrosion or fastener failure and showed that ignoring end-of-life conditions leads to suboptimal circularity recommendations (Formentini and Ramanujan, 2023). Other works have presented practical guides; the Circular Design Basics manual summarises the three principles of circular economy—designing out waste, keeping products and materials in use, and regenerating natural systems (Martynenko, 2021)—and discusses strategies such as designing for inner loops (reuse, sharing, remanufacture) and product-as-a-service models (Martynenko, 2021). The manual also outlines four stages of circular design—Understand, Define, Make, Launch—and emphasises iterative development, user-focused research and feedback loops (Martynenko, 2021). Hanes-Gadd et al. reviewed the evolution of design for sustainability (green design, eco-design, sustainable design) and argued that circular design requires systems-level thinking and integration of lifetime extension strategies with business models (Haines-Gadd et al., 2023). Their eight "levers for change" derived from industry interviews underscore the need for organisational commitment and cross-functional collaboration. Reslan et al. examined circular economy from a product life-cycle perspective; they highlighted gaps in metrics and standardized terminology and proposed a systems-level framework to integrate circular activities across life-cycle stages (Reslan et al., 2022). In the domain of packaging, a recent design framework integrates early-stage sustainability assessments and iterative design strategies; it addresses gaps such as costly assessments, limited circularity indicators and lack of actionable implementation plans (Pathan and Aurisicchio, 2025). This framework emphasises the importance of considering conflicting functional and sustainability requirements and proposes five process stages with predefined methods and tools (Pathan and Aurisicchio, 2025).

The literature also includes numerous domain-specific frameworks and toolkits. Examples include the Ellen MacArthur Foundation's Circular Design Guide (with IDEO), which provides step-by-step methods and case studies (Ellen MacArthur Foundation and IDEO, 2016; Atta, 2023), and the Circular Design Toolkit from Delft University, which offers product teardown–based design guidance (Schoden et al., 2022; Stijn and Gruis, 2020). In addition to these, Bakker et al. (2014a) and Bocken et al.'s (2016) study on product design and business models for circularity emphasise integrating product design with circular business models. Research by Geissdoerfer et al. (n.d.) and Bakker et al. (2014b) discusses the broader circular economy paradigm and strategies for extending product life cycles. Sumter et al.'s (2021) work on key competencies for design in a circular economy, along with Cayzer et al.'s (2017) indicators for measuring product performance, highlights the nine key competencies for design in a circular economy and the increasing need for measurable design strategies. Foundational works such as Bhamra and Lofthouse's (2008) Design for Sustainability and ISO/TR 14062:2002 lay out early eco-design principles. Sonego et al. (2018) explore how modular design contributes to sustainable products across the entire life cycle, and Ceschin and Gaziulusoy's (2019) Design for Sustainability offers a multi-level perspective on sustainable design. Researchers have also proposed frameworks for circular and sustainable packaging (Rajendran and Ranjitharamasamy, 2024), circular design of natural fibre-reinforced composites (Narganes-Pineda et al., 2025), and digital knowledge bases for circular design examples (Wang et al., 2022a).

Across these studies, common themes emerge: the need to consider multiple "R-strategies" (reduce, reuse, recycle, remanufacture, refurbish), the integration of design heuristics with business models, and the importance of early design decisions. However, existing frameworks typically focus on generic product categories, lack quantitative metrics for weight reduction, recyclability and energy efficiency, and rarely account for the unique processing and end-of-life challenges of advanced materials such as graphene composites. Compared with the literature, our Circular Design for X framework makes several novel contributions:

1. Integration of DfX heuristics with circularity objectives. While DfX approaches, e.g., design-for-assembly, disassembly, modularity, maintenance, recycling and safety, are well established in the mechanical design literature (Formentini and Ramanujan, 2023), they are seldom explicitly linked to circular economy objectives. Our framework couples traditional DfX heuristics with circular design goals such as mass reduction, recyclability and energy efficiency, enabling designers to make holistic trade-offs.
2. Multi-criteria quantitative evaluation. Existing frameworks often provide qualitative guidance (Pathan and Aurisicchio, 2025). Our CDfX framework includes quantitative metrics and weighting schemes for weight saving, recyclability, assembly/disassembly, lifespan and energy efficiency. The scoring scales and weightings were informed by domain standards and refined through expert elicitation. This allows the impact of design interventions to be compared across use cases.
3. Advanced-material focus. Most reviewed frameworks target conventional products or packaging and do not address the unique properties of graphene-enhanced components. We extend circular design to advanced materials by incorporating considerations such as graphene dispersion, nano-safety protocols, and processability constraints. Our framework, therefore, bridges a gap between circular design theory and emerging nanomaterial applications.
4. Comprehensive cross-sector application. Unlike frameworks validated with one or two case studies, we apply the CDfX methodology to eleven heterogeneous industrial use cases across automotive, aerospace, water treatment and hydrogen storage sectors. This demonstrates its versatility and enables identification of commonalities and transferable solutions.
5. Holistic integration of design, manufacturing and business aspects. The CDfX framework links technical design decisions to end-of-life strategies, manufacturing challenges and cost drivers. This holistic view is rarely found in existing literature but is essential for industrial adoption.

1.2. Aims and objectives of the work

The work aims to cover the necessary procedures in the initial design phase, material selection, performance analysis, manufacturing feasibility, cost implications, and eco-design optimisation of real-life industrial applications. Eleven use cases (UCs) were selected to cover a broad spectrum of sectors: automotive, aerospace, water treatment, hydrogen storage, and energy generation, each with varying technology readiness levels and manufacturing routes. This diversity allows the Circular

Design for X framework to be tested under different functional priorities: for example, mass reduction and structural integrity in transport (UC1–UC6), chemical and material circularity in filtration and energy applications (UC3–UC11). Comparing these cases reveals both universal principles, such as the importance of reversible joining, material purity and end-of-life strategies, and sector-specific insights, informing designers how to balance circularity and performance across contexts. The cross-sector analysis thus demonstrates the framework's adaptability and offers readers transferable lessons on how circular design can drive innovation and cost efficiency across industries. Objectives considered are as follows: application of circular design principles in the development of the 11 UCs, optimisation of design and material selection through multi-parameter strategies, carrying out conceptual studies for realistic manufacturing and cost analysis, providing lightweight solutions without compromising performance, improvement of eco-design concepts with advanced materials and technologies and finally to provide insights on feasibility, manufacturing technology and recyclability for all UCs.

1.3. Workflow and structure

This paper is structured in four main sections to reflect the progression from conceptual methodology to applied outcomes. The Methodology and Theoretical Framework introduces the foundational principles of the study, presenting a series of flowcharts that define the circular design logic applied across all use cases. This includes integrating end-of-life strategies, functional lightweighting, conceptual manufacturing scenarios, and incorporating graphene-related materials (GRMs) into eco-design. The Methodology and Use-Case Analysis section outlines the specific evaluation criteria, design procedures, and metrics used to assess each use case (UC). It also details the second-stage analysis, in which individual UCs are evaluated for compatibility with the proposed circular design strategy. The Results and Discussion section presents the outcomes of applying the developed framework, interpreting key trends and trade-offs related to feasibility, material performance, and sustainability objectives. The Integrated Discussion and Decision Support section synthesises the results of case studies to identify common trends, such as recyclability gains from reversible joints, weight reductions through graphene reinforcement, and energy-efficiency improvements, and uses them to explain the iterative CDfX workflow and its role in guiding design decisions. Finally, the Conclusion summarises the findings and offers forward-looking insights for the scalable development of high-performance, circular material systems.

2. Methodology and theoretical framework

2.1. Circular design approach

The circular design approach is considered to emphasise minimizing waste and maximising product lifecycle. Integrating technical and EOL requirements ensures that products are sustainable from inception through disposal. The objective of ecodesign is to minimise the environmental impact of a product. This typically involves applying common guidelines, although the specific criteria chosen depend on the particular case under study. The diverse array of environmental and technical issues that influence the design of a product could lead to a number of “X” methodologies, which are perplexing for a new product design. The selection and implementation of these methodologies are not a single approach. It is also unrealistic to meet all the requirements simultaneously because these criteria can be in conflict with each other. For example, composite materials usually complicate the recycling steps because of their degradation in mechanical properties during the process, or it is difficult to separate the materials. On the other hand, they present several advantages in the use of material, such as low density and high mechanical performance. Under the current work, circular and recycling solutions have been developed to retain the highest possible value of the original material or its source components. Therefore, at the beginning of the design process, it is very important to prioritise the environmental requirements and find the best compromise among them; thus, Design for X (DfX) strategies can facilitate this process, as depicted in Fig. 2. Accordingly, Circular Design for X (CDfX) is a methodological extension of the classical Design for X methodology in which each attribute-specific heuristic, e.g., manufacturability, assembly, maintenance, disassembly, or up/downgradeability, is reformulated to maximise closed-loop value retention across the product life cycle, rather than optimising components solely for efficiency in a single phase, CDfX couples those heuristics with circular-economy objectives such as material purity, reversible joining, functional modularity, and end-of-life recoverability. The adopted framework is illustrated in Fig. 3.

2.2. Multi-parameter optimization

The work related to multi-parameter optimisation is vital in fine-tuning the design and development within the UCs to achieve the best performance of the products, with a focus on sustainability and cost-effectiveness.

2.2.1. Refining geometry – shape and form

Fine-tuning dimensions and the shape of components is perhaps the most powerful way to improve performance with fewer materials (Rothwell, 2017; Tang et al., 2024). The optimization of physical form allows for the enhancement of efficiency and conservation of resources while maintaining the strength and structural integrity of the product without waste.

2.2.2. Leveraging structural features

Design features such as ribs, grooves, and fillets reduce the areas of a component where stress concentration could occur, hence strengthening components (Fusano et al., 2011; Morris, 2009; Han et al., 2018). Small but essential features that will make the product perform better with minimal material usage create a benefit for efficiency and sustainability.

2.2.3. Improving manufacturing processes

The proper selection of manufacturing methods for each material is important in the making of quality products (Mital et al., 2014; Souza et al., 2017). This streamlining of processes decreases energy consumption and saves time, minimizing defects to facilitate the production of goods in an efficient, cost-effective manner with sustainability.

2.2.4. Simplifying assembly

Designing for easy assembly saves time and reduces labour costs

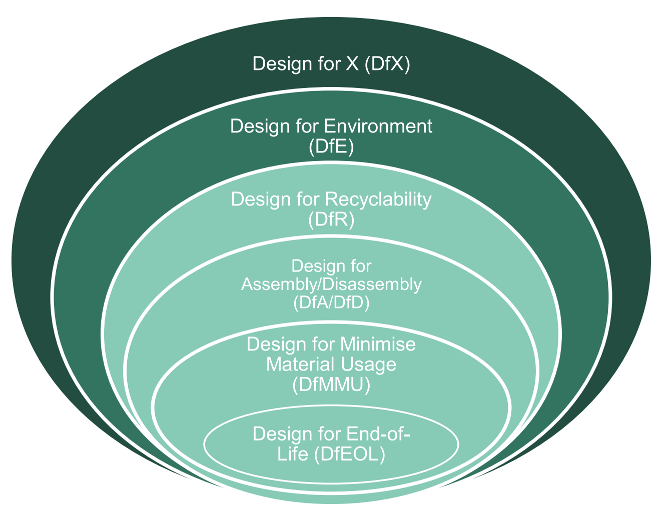

Fig. 2. Design for X structure.

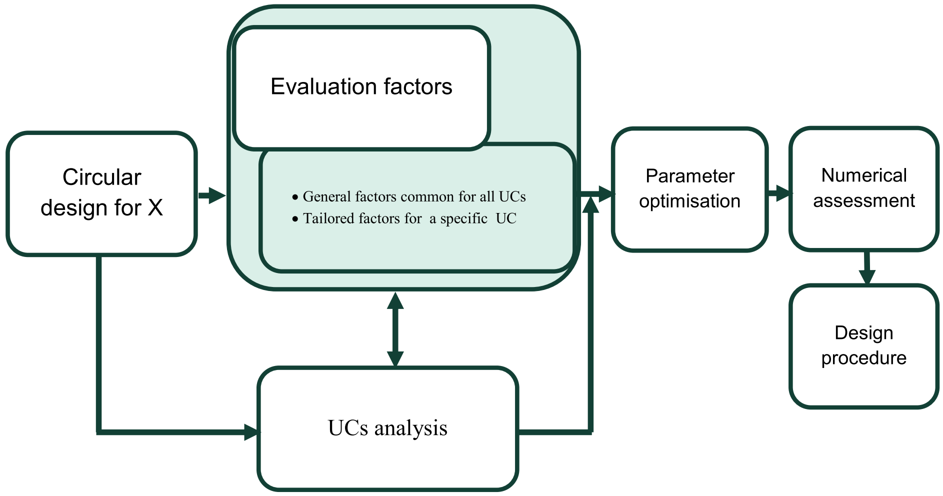

Fig. 3. Circular-design principles and multi-parameter approach.

(Prasad et al., 2022; Zhai et al., 2023). Since the components and connectors employed are standardized, assembly and maintenance are smooth, resulting in a smoother production process and an improved overall workflow.

2.2.5. *Disassembly and recycling*

The vital step toward sustainability is the design for easy disassembly at the end of life, reusing components or materials with minimal recyclable waste. If materials can be separated out without contamination, it reduces the cost of recycling and furthers a circular economy.

2.2.6. *Improving performance characteristics*

Enhancing the mechanical properties, including strength, stiffness, and durability, guarantees that parts will be reliable and long-lasting. Multifunctional integration simplifies the design because many parts can be replaced with one, reducing components and enhancing efficiency in a product.

2.2.7. *Balancing costs*

It involves shaping and sizing materials in efficient ways so that no materials are wasted (Ehrlenspiel et al., 2007). Simplistic designs also make for less complicated, faster manufacturing methods that help keep the general cost of production down without compromising on quality.

2.2.8. *Reducing environmental impact*

Designing while considering energy efficiency during both the manufacture and use of a product is important to minimise environmental footprints. Additionally, minimizing waste at both the production stage and the product's end-of-life aligns with sustainability goals.

2.3. *Conceptual study framework to deliver realistic manufacturing scenarios and cost analysis based on eco-design*

A realistic manufacturing scenario needs to be developed based on current technological capabilities, resource availability, and production timelines. For the current work, integrating graphene and GRM-based multifunctional (GRM-bM) requires significant advances in manufacturing processes for large-scale graphene and GRMs, and each new method has its specific challenges. Understanding these challenges is essential for successful implementation and further optimisation. The following methodology, illustrated in Fig. 4, presents a comprehensive analysis of diverse sources to identify challenges for manufacturing

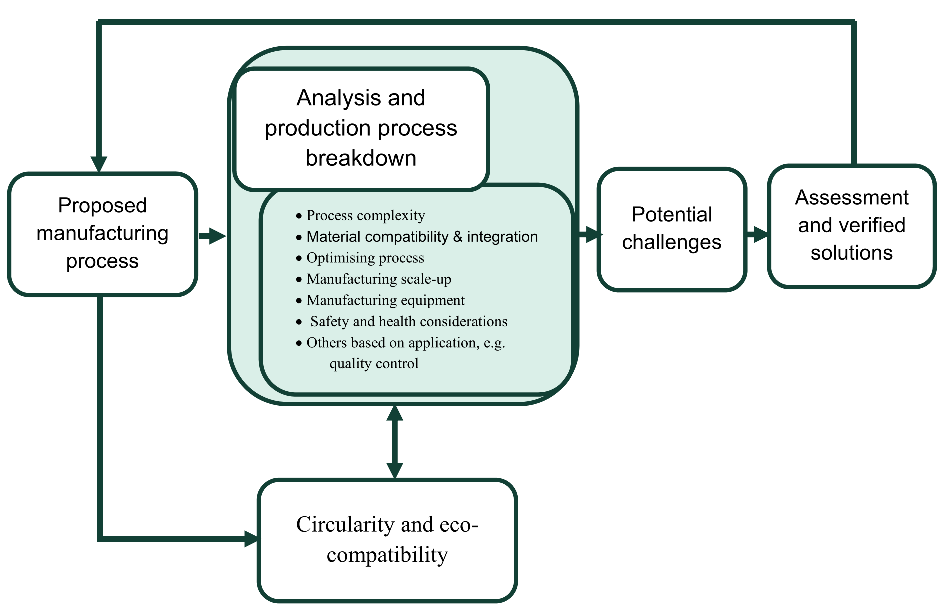

Fig. 4. Realistic manufacturing scenario framework.

technologies and application processes.

This assessment methodology ensures that the challenges identified are closely aligned with the realistic conditions and constraints of each use case. The evaluation process concentrates on understanding the practical implications of these challenges when applied to manufacturing scenarios, thus bridging the gap between theoretical projections and operational realities. Solutions addressing those challenges are integrated into the overall analytical framework. Such inputs are important references, providing key insights into the potential pathways that exist to overcome the identified challenges and are necessary for feasibility at various implementation stages. Each proposed solution has been further iteratively assessed and refined, taking into account not only feasibility but also considerations of sustainability and efficiency to enable successful implementation for each application.

An overall cost analysis considering the current feasibility of manufacturing methods and investigates their potential for scalability. Labour and energy costs are considered based on economic zones (EU-specific metrics in this study), including industrial electricity prices and labour rates, adjusted according to task complexity and sector-specific requirements, as illustrated in Fig. 5.

2.4. Functional lightweight design

By prioritising weight reduction from the early design stages, selected materials and component geometries lead to effective eco-design applications and more efficient manufacturing processes, such as lower energy input, reduced material usage, and faster cycle times. These benefits are evaluated within conceptual manufacturing scenarios, where lightweight solutions are assessed for feasibility and their ability to overcome challenges like structural integrity at reduced thickness or compatibility with existing production lines. Moreover, lightweight supports scalability by enabling simpler, more cost-effective manufacturing routes adaptable to high-volume production.

2.5. Analysis of the UCs requirements and performance to support the material selection process for new solutions and perform eco-design optimisations

Fig. 6 presents the evaluative method that links the analysis of each UC requirement with the corresponding material selection process and eco-design optimisation strategy. The process begins with extracting key functional requirements drawn from the UC specifications. These requirements feed a material selection evaluation step; in the current study, graphene and graphene-related composites, coatings, foams, or membranes are screened and ranked. Short-listed materials are subjected to a multi-parameter performance assessment that targets structural integrity, recyclability potential, energy demand, and cost against predefined indicators. The resulting data contributes to a recommendation step that issues design rules (e.g., reversible joints, mono-material layers) and processing adjustments (e.g., solvent-free curing, low-temperature consolidation). Iterative feedback links the performance stage to material selection, ensuring only solutions meeting circularity thresholds progress to prototyping and scale-up.

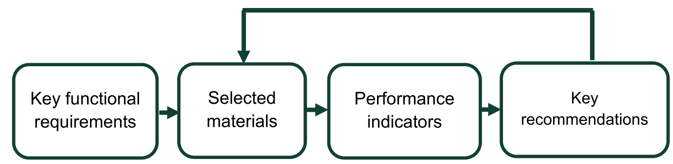

Fig. 6. Integrated workflow of functional requirements to eco-design recommendations.

2.6. Eco-design concepts with respect to optimisation of advanced GRM-bM

In the context of the development of the GRM-bM in the current work, it is necessary to analyse the eco-design considerations to identify recommendations and improvements toward a more circular design of the GRM-bM. Fig. 7 presents the general strategy for the evaluation, identifying the different phases of the study. It is important to underline that the improvement potential was analysed in two steps. The evaluation method was based on a scope identification (Step 1) and providing recommendations and improvement in Step 2.

2.7. Concepts according to feasibility, manufacturing technologies and recyclability

The steps illustrated in Fig. 8 outline a structured approach for assessing design concepts based on four sequential criteria. It begins with a feasibility assessment, where each concept is evaluated for its technical viability, resource availability, and alignment with functional requirements. The next stage examines key manufacturing technologies, focusing on process efficiency, scalability, and environmental impact. Following this, recyclability strategies are considered to ensure that materials and components support end-of-life recovery and align with circularity goals. Finally, the process concludes with key

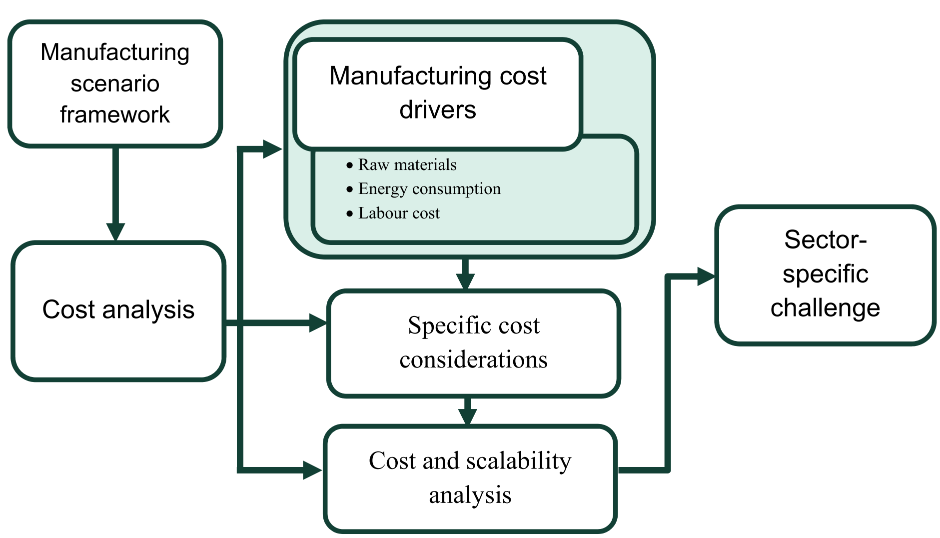

Fig. 5. Cost analysis framework.

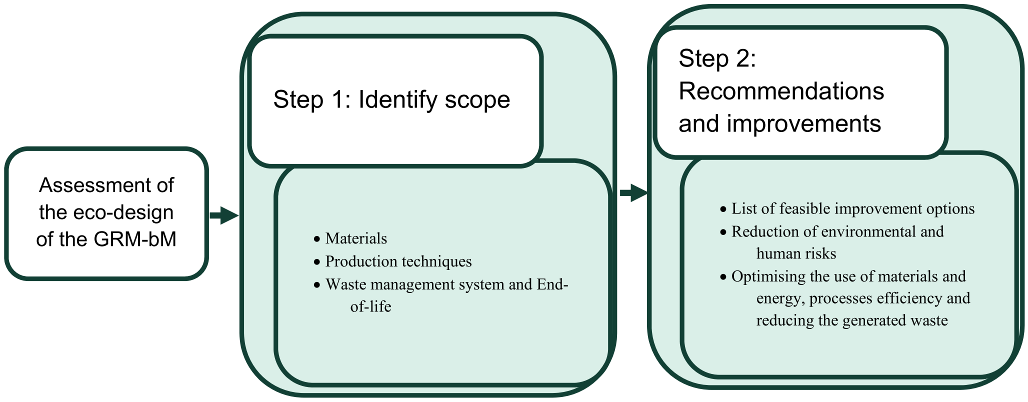

Fig. 7. Eco-design assessment with respect to the optimisation of GRM-bM.

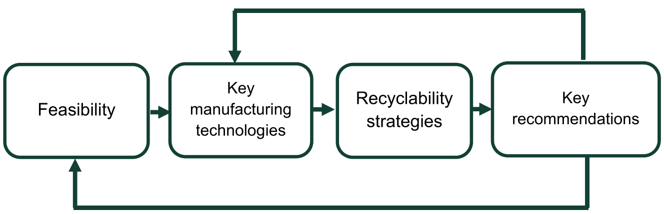

Fig. 8. Manufacturing feasibility assessment.

recommendations that integrate all prior evaluations, guiding the selection of practically feasible and environmentally sustainable concepts.

2.8. Integrated circular design framework

The overall flowchart in Fig. 9 presents an integrated view of the previously detailed subset flowcharts, capturing the whole progression from initial use-case requirements to final eco-design recommendations. It combines key stages such as requirement analysis, multi-parameter material selection, performance evaluation, lightweighting considerations, conceptual manufacturing scenarios, and recyclability strategies.

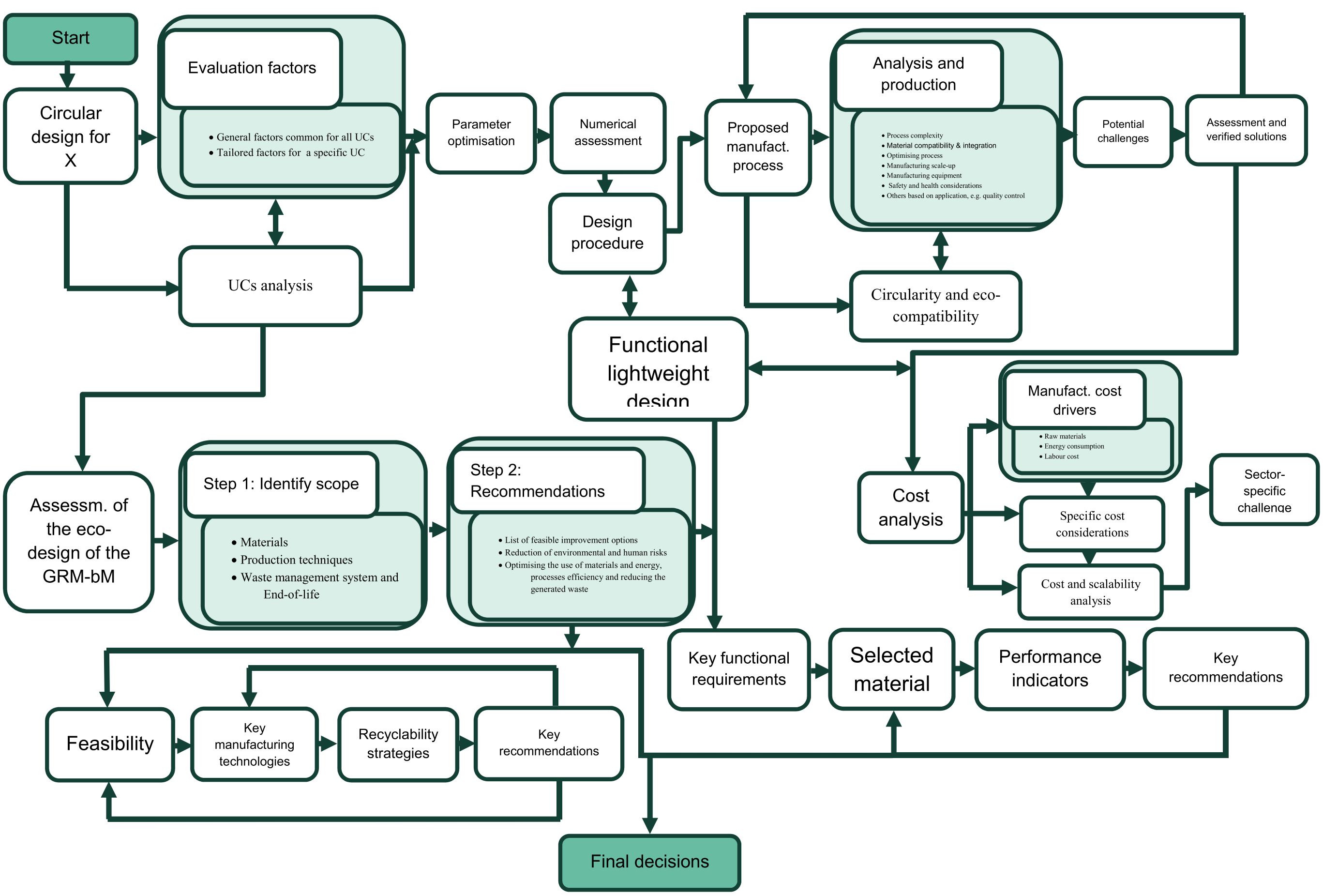

Fig. 9. Consolidated circular design flow.

By linking these elements into a unified framework, the diagram highlights how each decision point—technical feasibility, manufacturing constraints, and end-of-life potential—contributes to developing scalable, sustainable solutions. This holistic structure ensures that circularity principles consistently guide design decisions across all stages of development.

To enhance the readability of the methodology, a high-level hierarchical diagram is illustrated in Fig. 10 as an integrated, layered flow linking conceptual design logic to operational decision stages, integrating the key methodological layers, ranging from Design-for-X principles to Circular Design-for-X (CDfX), multi-parameter optimisation, manufacturing feasibility, and EoL analysis, into a unified structure. It visually demonstrates how each flowchart (Figs. 2–9) contributes to the overall circular design framework.

2.9. *Unified procedure of the CDfX framework*

Figs. 9 and 10 illustrate the sequential, yet iterative, steps of the CDfX methodology:

- Baseline characterisation. For each UC, the reference design's geometry, material composition, manufacturing process and end-of-life (EoL) pathway were established. This step provided the benchmark for evaluating improvements.
- Selection of applicable DfX heuristics. Design-for-assembly, disassembly, modularity, maintenance, recycling and safety strategies were screened to address the weaknesses of the baseline. Selection was guided by the type of component and sector requirements.
- Application of circular design strategies. Graphene-enhanced materials and geometry optimisations were introduced alongside modular

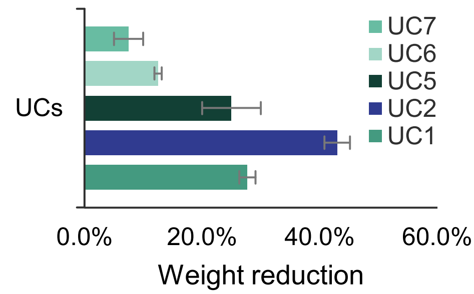

Fig. 11. Expected weight reduction KPIs for relative UCs.

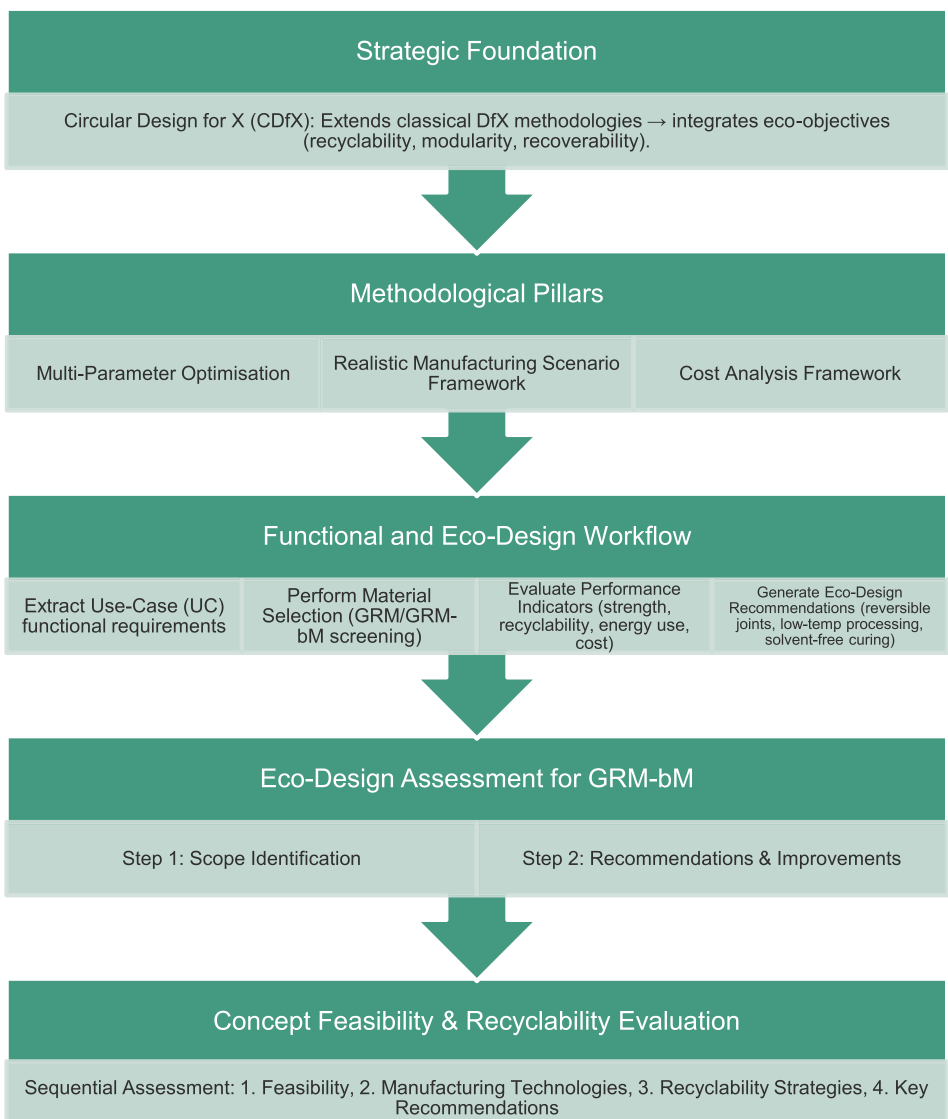

Fig. 10. Higher-level hierarchical integrated circular design framework.

interfaces, reversible joints and surface treatments to improve recyclability and lifespan.

- Multi-criteria evaluation. Each design alternative was assessed using the five metrics (weight saving, recyclability, assembly/disassembly, lifespan, energy efficiency). Weights were assigned based on stakeholder priorities and sectoral guidelines. Weighted scores were computed to rank alternatives.
- Decision support. The option with the highest weighted score was selected, subject to manufacturing feasibility and cost considerations. If manufacturing challenges or cost drivers were prohibitive, the design was iterated and re-evaluated.
- Manufacturing and cost analysis. Identified manufacturing challenges and cost drivers (raw materials, energy, labour) were analysed to ensure industrial viability. Recommendations were integrated back into the design process.

This workflow is iterative: feedback from manufacturing and cost analysis can trigger modifications in material selection or joining strategies, illustrating that the CDfX framework is a cohesive design and evaluation loop rather than a linear checklist.

3. Methodology and use-case analysis

3.1. Metrics based on UCs aspects

3.1.1. Evaluation factors

Some requirements can be proposed as a first approach to the analysis. However, each UC user's expertise can help define the most relevant factors for the evaluation. Consequently, two categories of evaluation factors can be distinguished. Every factor will undergo a numerical assessment, typically on a scale of 1 to 5. These assessments will be weighted based on their significance to the UC (Jiang et al., 2024; Hassan et al., 2015). Subsequently, this process will yield a final numerical outcome for each proposed alternative.

3.1.1.1. General factors common for all UCs. The main goal of is to carry out an assessment that is as uniform as possible for all the UCs. Given the various fields involved, the same analysis is not suitable for all the study cases. Nevertheless, three main factors have been defined as general requirements for the analysis: recyclability, weight saving, and assembly/disassembly.

3.1.1.2. Specific factors related to each single UC. In each UC, additional factors are evaluated to determine the optimal solution, which encompasses not only environmental considerations, such as material savings and lifespan, but also technical factors. For example, compatibility with the assembly line can be a critical factor that requires assessment in the automotive industry.

3.1.2. Factor numerical assessment scale

An eco-design assessment matrix, originally developed by CTAG (Fundacion Para La Promocion De La Innovacion, Investigacion Y Desarrollo Tecnologico En La Industria De Automocion De Galicia) is presented in Table 1 to establish a more stringent evaluation framework where assessments were derived based on quantitative values corresponding with key performance indicators (KPIs). Thus, the evaluation parameters and the considerations behind each have been specified, and a scoring method has been formulated following Eq. (1). It is very important that a clear and well-defined criterion be established so as to support the analysis and enhance the reliability of both the initial design and any subsequent redesign phases.

Table 1
Matrix assessment proposal.

Factors	Common factors			Specific factors	
	Weight saving	Recyclability	Assembly/ Disassembly	Lifespan	Energy efficiency
Factor weighting	X_1%	X_2%	X_3%	X_4%	X_5%
Reference design score	Ref.	Ref.	Ref.	Ref.	Ref.
Modified design score	1:5	1:5	1:5	1:5	1:5

$$\text{Weighted Score} = X_1\%{*}\text{weight saving score} + X_2\%{*}\text{recyclability score} + X_3\%{*}\text{Assembly/Disassembly score} + X_4\%{*}\text{Lifespan score} + X_5\%{*}\text{Energy efficiency score} \quad (1)$$

In each case, the weighting factors X_1–X_5 are expressed as percentages and sum to 100 % (with a dash indicating a factor not applicable and hence a zero weighting), ensuring comparability across use cases. These weighting factors were derived through an internal consensus exercise among the authors and industrial partners. Each factor's percentage reflects its perceived importance relative to the functional priorities and sustainability goals of the specific use case, as discussed in the subsequent Section 4.1. Thus, weightings are tailored to each UC and sum to 100 %, ensuring comparability across applications.

The five core metrics—weight saving, recyclability, assembly/disassembly, lifespan and energy efficiency—were selected because they capture the primary goals of circular product design: reducing material intensity, ensuring high recoverability at end-of-life, enabling non-destructive disassembly and repair, maximising the service life of components, and lowering energy consumption during use. These factors draw on established eco-design frameworks and design-for-X literature, which recommend focusing on material reduction, reuse, remanufacturing, and efficiency to achieve circularity.

The indicator scale numbers are presented in Table 2, providing an overall perspective on the entire concept. As indicated in Table 2, the uncertainty range of 5 % for the weight-saving estimations aligns with the industry standard during advanced design phases in several sectors, such as automotive and aerospace, where uncertainty margins due to material development and refined techniques for manufacturing are reduced as low as 5 % to 10 % (Horvath and Wells, 2018; Donus et al., 2010; Reis, 2020; Stegmiller et al., 2018). This estimation also accounts for material and process variabilities of composite material and advanced manufacturing techniques, where variability in properties such as graphene nanoparticle dispersion and resin adhesion can be effectively managed within a 5 % tolerance (Jazaa, 2024; Ghaleb et al., 2017; Franz et al., 2021). Additionally, advanced simulation and modelling frameworks using finite element methods (FEM) and AI-integrated digital twin technologies have demonstrated predictive accuracies of 3 %–5 % in estimating the structural behaviours, stiffness, and weight of advanced lightweight materials (Saren et al., 2024; Bolandi et al., 2022; Murray-Smith, 2015). Although digital-twin simulations are not directly implemented here, the same level of predictive reliability, commonly achieved by validated FEM-based design workflows, serves as the reference for interpreting the quantitative evaluation of structural and lightweighting performance. Thus, this uncertainty range is representative of a balanced and realistic measure in the context of innovative lightweight material development. For emerging or less industrially mature technologies, such as graphene-enhanced foams and hybrid hydrogen storage systems (e.g., UC11), the 5 % uncertainty range should be interpreted as a relative tolerance window reflecting expected material and process variability during scale-up rather than an

Table 2
Indicator scale for eco-design assessment criteria.

Metrics	1	2	3	4	5
Weight saving	>5 % heavier than the reference	In between the reference and 5 % heavier	In between reference & the KPI (Fig. 11)	KPI value to 5 % lighter than the KPI itself	>5 % lighter than the KPI
Recyclability	Landfilling/incineration	Partial recovery	Total recovery	Reprocessing/remanufacturing[a]	Reuse
Assembly/ disassembly	Permanent joining	–	Detachable/debondable	–	Reversible
Lifespan	Decreased	Additional maintenance	Reference	Optimization maintenance	Increased
Energy efficiency	Additional processes	Added complexity	Reference	Enhanced efficiency	Elimination of processes

[a] Note: Score 4 (reprocessing/remanufacturing) refers to recovery processes where materials undergo transformation to restore performance (e.g., mechanical recycling, solvolysis, pyrolysis). Score 5 (reuse) refers to direct reapplication or remanent function of components without structural alteration, maintaining product integrity.

experimental deviation. This approach prioritises comparability across different technology readiness levels (TRLs) while maintaining methodological coherence.

The weight-saving metrics are scaled relative to each use case's reference design and target KPI. Metrics 2 and 4 are defined by ±5 % bands around the reference and KPI, while metric 3 spans the range between these points. Because the baseline weight and the targeted reduction vary across use cases, this middle range may represent absolute differences from about 10 % to over 40 %; using a relative rather than fixed step provides a consistent and adaptable scoring scale.

3.2. Design procedure

At a mature development stage, an eco-design stage is presented, in which a detailed comparative assessment of the environmental-related properties of new material solutions is conducted, using the original designs as a reference. The effect of the introduction of the graphene-based material solutions is evaluated in terms of weight, the potential modification of the joining technologies to be employed, and energy consumption during the whole life cycle of the products, as well as the recyclability of such complex material solutions must be evaluated as a step before the industrialisation. The redesign steps shown in Fig. 12 of the UCs consequently result in local geometrical modifications in most cases, especially when constrained by the necessity of fitting the redesign components into complex structures, thereby adapting to the constraints already required for the original parts.

3.3. Use cases (UCs) analysis

Given that the eleven UCs originate from different industrial domains, including automotive, aerospace, water treatment, hydrogen generation, and energy storage, their descriptions inherently vary in depth and focus. This diversity reflects the unique technical and sustainability challenges of each sector. The intention is not to standardise their presentation but to establish a consistent analytical framework that enables comparative assessment across these fields in Section 4.

3.3.1. UC1: automotive aerodynamic shield

UC1 focuses on the development of a next-generation aerodynamic shield for the Maserati Levante, led by Centro Ricerche FIAT SCPA (CRF) in collaboration with Crossfire Srl. This underbody component, originally made from carbon fibre sheet moulding compound (SMC), is being redesigned to integrate graphene-enhanced hybrid composites and innovative sandwich structures, which significantly improve both environmental and technical performance. The proposed solution replaces traditional thermoset matrices with a Crosspreg® hybrid thermoplastic/epoxy resin system reinforced with carbon, glass, or hemp fibres and potentially featuring a recycled polyethylene terephthalate (PET) foam core. This new design achieves a substantial 27.7 % weight reduction, resulting in improved energy efficiency during both manufacturing and vehicle operations. The redesign also incorporates a graphene nanoplatelet (GNP)-based coating to enhance surface hardness and stone chipping resistance, which are crucial for protecting underbody components—particularly in electric vehicles, where battery integrity is paramount. From a circular design standpoint, UC1

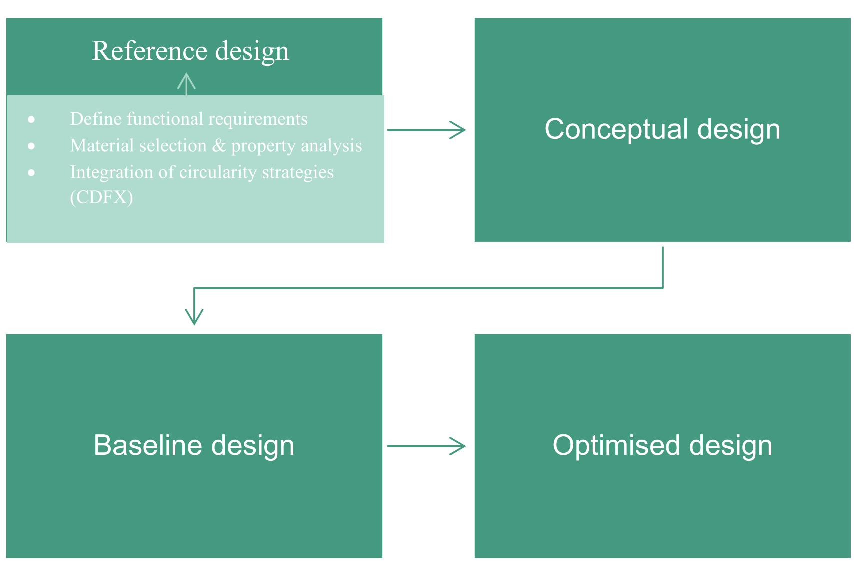

Fig. 12. Design procedure.

demonstrates remarkable advancements in recyclability, repairability, and end-of-life (EoL) management. The hybrid resin system enables thermoforming and reshaping at elevated temperatures (∼200 °C), allowing for mechanical reprocessing and the reuse of the part. Moreover, solvolysis offers a viable pathway for recovering both fibres and monomeric matrix materials, contributing to a closed-loop material cycle. The preservation of mechanical joints ensures compatibility with existing vehicle architectures and facilitates easy disassembly and replacement. Maintenance and lifespan are further extended by the capacity to apply Crosspreg® patches to damaged areas, enabling functional recovery without full replacement. Additionally, the manufacturing approach—a short-cycle, low-pressure isothermal process—minimizes energy demand while enabling automation and avoids the cold storage requirements typical of thermoset systems.

3.3.2. UC2: automotive spare wheel well

UC2 addresses the redesign of the spare wheel well of the Jeep Renegade, transitioning from a conventional stamped steel structure to an advanced graphene-enhanced glass fibre composite. Developed collaboratively by CRF and Crossfire Srl, this redesigned component leverages a GO-modified hybrid matrix (reactive thermoplastic polyester/epoxy) to meet critical performance demands—thermal resistance, crashworthiness, and corrosion protection—while also enabling significant weight reduction and full recyclability. Through the integration of tailored reinforcement patterns and the use of thermocompression manufacturing, the new composite structure provides enhanced stiffness and vibration damping, which are crucial for maintaining comfort and safety in modern vehicles. A PET-aluminium laminated thermal barrier ensures the component's resilience against high exhaust-proximal temperatures. From a circular economy perspective, UC2 exemplifies how sustainability can be embedded in material design without compromising technical performance. While reshaping the complex bathtub-like geometry at end-of-life poses challenges due to potential fibre misalignment, mechanical recycling via grinding and compounding offers a viable path forward—particularly for overmoulding or injection applications. Alternatively, solvolysis provides high-value material recovery of both fibres and monomers, though with greater cost implications. The use of reversible bolted joints preserves modularity and supports reuse or easy disassembly. Although the new thermocompression process requires a higher energy input than traditional cold stamping, the estimated weight savings directly translate into improved vehicle efficiency, reduced operational energy demand, and an extended driving range—particularly vital for electric vehicles.

3.3.3. UC3: water desalination by nanofiltration and pulse discharge plasma

UC3 presents a dual-system redesign aimed at enhancing the efficiency and lifespan of advanced water treatment processes by combining an oxidant-resistant nanofiltration (NF) membrane and a high-performance catalyst for a pulsed discharge plasma (PDP) reactor. Developed collaboratively by Lenntech BV (Netherlands) and IRIS SRL (Italy), the NF system incorporates a graphene-enhanced graphene oxide (GO) membrane on a polymeric substrate chosen for its scalability and resistance to oxidative agents. This upgrade reduces membrane fouling, decreases the frequency of cleaning operations, and extends the lifespan of components, contributing indirectly to lower chemical use and operational downtime. Assembly and modular integration are preserved through adherence to commercial membrane 1812 model geometries, allowing for easy replacement without requiring additional structural modifications. Simultaneously, the PDP reactor has been optimised to house a cylindrical cordierite support coated with a GO/Fe_3O_4 catalyst. This redesign enhances catalytic surface area while maintaining compatibility with the original PMMA housing and fluid-handling interfaces. The new catalyst enhances energy efficiency by 15–20 % through improved regeneration of reactive species in the Fenton reaction cycle and superior pollutant-radical interactions, thanks to the high surface area of graphene. Although catalyst recycling presents technical challenges due to the need for energy-intensive separation, reuse in downstream processes or re-coating offers promising end-of-life strategies. Notably, both the membrane and catalyst components are expected to exhibit substantial improvements in service life, modularity, and environmental performance. However, weight and manufacturing energy savings remain secondary in this use case.

3.3.4. UC4: oil/water separation by ultrafiltration and PDP

UC4 enhances the performance and circularity of industrial oil/water separation systems by integrating an oxidant-resistant ultrafiltration (UF) membrane with a photocatalytic pulsed discharge plasma (PDP-PC) reactor. Developed by Lenntech BV (Netherlands) and IRIS SRL (Italy), the UF membrane incorporates thermally induced phase separation (TIPS) graphene on a PVDF substrate, with graphene oxide (GO) used to enhance lipophobicity, thereby mitigating oil fouling and extending service life. Maintaining the commercial 1812 membrane spiral-wound format ensures modular integration and ease of disassembly. Although current end-of-life pathways are limited to incineration or landfill disposal, the potential for upcycling via interfacial polymerisation is being considered, contingent upon technical and economic feasibility. The PDP catalyst component, based on a TiO_2/GO composite deposited on a PTFE substrate, is optimally positioned around the plasma arc to optimise the catalytic performance in the reaction chamber. This architecture eliminates the need for complex reactor redesigns while significantly improving energy efficiency by 15–20 % through enhanced charge separation and improved utilisation of reactive oxygen species (ROS). While catalyst recycling remains a technical challenge, downcycling into a secondary chamber or redeposition of active layers on the original support offers a promising extension of service life.

3.3.5. UC5:aeroplane leading edge of supersonic aircraft

UC5 addresses the redesign of the leading edge of the vertical stabiliser for the Dawn Aerospace Mk-II Aurora supersonic aircraft by replacing the baseline carbon fibre-reinforced epoxy with a graphene-modified thermoset polyimide composite. Developed to eliminate the need for single-use thermal protection coatings, this new semi-preg solution enhances thermal oxidative resistance and simplifies the component architecture. While maintaining aerodynamic geometry, this substitution enables projected weight savings of 20–30 %, critical for aerospace performance and fuel efficiency. Despite higher energy demands during production—stemming from polyimide's elevated processing temperature (375 °C) and pressure (15 bar) over a 17-hour cycle—the shift eliminates the recurring material and energy inputs associated with the protective coating, resulting in improved lifecycle energy performance. The thermoset nature of polyimide constrains the component's recyclability, but fibre recovery via pyrolysis and post-treatment is viable, supporting circularity through reuse in secondary applications. The assembly remains unchanged, relying on structural adhesives to meet aerodynamic requirements. Significantly, the new material solution extends maintenance intervals from every flight to every 100 cycles, reducing operational costs and downtime.

3.3.6. UC6: aeroplane lightning strike protection for trailing edge of aircraft

UC6 targets the redesign of a trailing edge section of an aircraft, a critical structural and aerodynamic component frequently exposed to lightning strikes. Traditionally protected with metallic mesh integrated into fibreglass or hybrid composite panels, the baseline design poses significant recyclability and weight penalties. Boeing Turkey and partners are exploring alternative materials to replace the metallic lightning protection layer. Preliminary investigations have focused on a carbon fibre-reinforced low-melt PAEK thermoplastic composite material, enhanced with a graphene nanoplatelet-based coating (G-coating). Initial results indicate that this thermoplastic matrix offers improved recyclability through thermomechanical, pyrolytic, or solvolytic recovery methods, potentially overcoming previous challenges related to metal-polymer hybrid disassembly. From a circular design perspective, the reapplicability of the G-coating supports surface-level repair strategies, thereby extending the lifespan of components and reducing maintenance cycles. Additional benefits of this approach include enhanced energy efficiency throughout the part's lifecycle; for example, cold storage is no longer necessary, raw materials have an extended shelf life, and processes such as priming and filling are eliminated. While it is acknowledged that the transition from thermoset to thermoplastic requires higher manufacturing temperatures and pressures, the advantages of streamlined assembly and material circularity appear to outweigh the associated risks and costs.

3.3.7. UC7: H_2 storage physical tank (Type IV)

UC7 focuses on the redesign of a high-pressure hydrogen storage vessel (Type IV), developed by Faurecia Hydrogen Solutions, aiming to enhance sustainability and performance through advanced composite solutions. The current carbon fibre composite tanks would be upgraded with GRM-enhanced epoxy matrices to improve tensile strength, impact toughness, and fatigue resistance while enabling a 5–10 % reduction in weight. This reduction not only enhances system efficiency and vehicle range but also decreases material consumption and manufacturing costs. A key innovation lies in balancing improved mechanical performance with circularity, as the new material configuration, while more complex to recycle, reduces the quantity of material needing recovery. EoL practice strategy is aligned with sustainability goals, hence avoiding grinding and landfilling and exploring other recycling techniques, such as solvolysis, pyrolysis, and supercritical fluid solvolysis (SCFS), which enable effective carbon fibre recovery. The tank's modular design promotes easier disassembly and component reuse, contributing to greater lifecycle resource efficiency. Additionally, the improved mechanical robustness and fatigue life of the redesigned composite enable extended service life, particularly valuable in high-pressure applications, with the potential for tank reuse in less demanding applications.

3.3.8. UC8: multiparametric sensors for structural health monitoring

UC8, led by Fundació EURECAT, centres on the development of innovative multiparametric sensors for structural health monitoring (SHM), integrating graphene-related materials (GRMs) and enabling real-time data collection. Designed to be lightweight, compact, and embedded directly into composite structures, these sensors detect a wide range of parameters—such as vibration, strain, temperature, and force—without requiring additional adhesives or external components. While weight saving is inherently achieved due to the minimal mass of the sensors, significant sustainability benefits stem from the use of screen-printing techniques with GRM-based inks, which reduce material waste and lower energy consumption during production. However, recyclability presents challenges due to the sensors' complex, non-disassemblable architecture, necessitating holistic EoL strategies. Potential pathways include mechanical recycling, selective acidic degradation, PET glycolysis, or sensor recalibration for reuse. Assembly efficiency is significantly enhanced by the plug-and-play design; however, this also complicates end-of-life handling.

3.3.9. UC9: self-lubricating functional coating (solid lubricant for linear actuator LD75)

UC9, led by Nanoprom Chemicals S.r.l. in Italy, focuses on replacing traditional grease-based lubrication in linear actuators with an advanced self-lubricating functional coating composed of a silica sol-gel matrix doped with Tungsten Disulfide (WS_2) and Graphene Nanoplatelets (GNPs). This innovation introduces a high-performance, eco-friendly alternative that enhances wear resistance, temperature stability, and corrosion protection while significantly reducing friction and energy losses during operation. The integrated nature of the coating eliminates the need for separate lubricants, simplifying system architecture and resulting in meaningful weight savings and streamlined assembly processes. From a sustainability perspective, the coating supports material reuse by enabling reapplication at end-of-life, avoids contaminating base materials (e.g., steel), and enhances recyclability without requiring complex separation processes. The coating's ability to reduce maintenance frequency and extend the lifespan of actuators aligns with circular design principles by reducing lubricant waste, downtime, and resource consumption. Additionally, its contribution to energy efficiency—through continuous friction minimisation—-translates into lower operational energy requirements and less frequent component remanufacturing.

3.3.10. UC10: H_2 generation catalyst (MEA in PEM electrolysis stacks)

UC10, developed collaboratively by Fundació EURECAT (Spain) and HydroSolid GmbH (Austria), focuses on enhancing the performance and sustainability of hydrogen generation by integrating graphene into membrane electrode assemblies (MEAs) used in proton exchange membrane (PEM) electrolysis stacks. This approach seeks to reduce reliance on platinum-group metals (PGMs), such as platinum, by either enabling lighter catalyst supports or decreasing Pt loading through improved catalytic surface area. These innovations contribute to overall weight reduction, enhanced system handling, and lower carbon emissions throughout the supply chain. Recyclability is addressed through printed catalyst layers, which offer better recovery prospects than physically applied layers. While Nafion®-based membranes pose end-of-life (EoL) challenges, reconditioning of MEA components (e.g., recoating electrodes and reacidifying membranes) enables partial reuse. UC10 also supports modular assembly and disassembly of the PEM stack, enhancing the feasibility of component reuse. The improved mechanical stability and catalytic efficiency of catalysts extend the functional lifespan of the system, reducing maintenance frequency and resource consumption. Furthermore, the enhanced catalytic activity and increased surface area of the new materials enable a higher hydrogen production rate, allowing more hydrogen to be generated in a shorter time. This capability is particularly advantageous for integration with intermittent renewable energy sources, as it enables efficient hydrogen production during periods of limited energy availability.

3.3.11. UC11: hydrogen storage materials

UC11, led by HydroSolid GmbH in Austria, is exploring a novel hydrogen storage approach using graphene-related materials (GRMs) to enhance efficiency, safety, and sustainability. Originally based on functionalized graphene oxide (GO) and reduced GO foams, the updated strategy shifts toward higher-density storage media, including transition metal-doped graphene powders and GRM-enhanced metal hydride pellets. While this revision increases the system mass from 1 kg to 5.5 kg, it enables significantly greater hydrogen storage capacity, enhanced thermal stability, and the potential for low-pressure operation, thereby improving safety and lifecycle efficiency. The cylindrical tank design, built to withstand pressures of up to 120 bar and temperatures of up to 100 °C, is modular, featuring replaceable valves and embedded sensors for monitoring and temperature control. From a circularity standpoint, UC11 offers various end-of-life options, including reusing GRMs in polymer matrices, recycling metal hydrides through re-alloying or hydrogen cycling regeneration, and repurposing the tanks for alternative gas storage applications (e.g., CO_2 or CH_4). Disassembly is feasible due to the modular nature of the non-welded components, while service life is extended thanks to reduced mechanical stress at lower operating pressures. The volumetric hydrogen density is increased by up to four-fold, boosting energy efficiency and reducing refuelling frequency. Moreover, the GRM-based multifunctional's capacity to bind hydrogen at the atomic level and release it under mild heating positions this solution as a cutting-edge alternative to conventional high-pressure storage, offering promising implications for the widespread and sustainable adoption of hydrogen energy.

3.4. Preliminary assessment method for manufacturing challenges and solutions across UCs

A preliminary qualitative assessment was conducted to systematically address the manufacturing complexity associated with each of the 11 UCs, mapping potential manufacturing challenges to process scalability, material integration, and operational safety. This process began by identifying the most probable challenges for each UC, grounded in their respective technological requirements, functional constraints, and targeted industrial applications. The evaluation methodology was designed to reflect general theoretical barriers and those grounded in realistic manufacturing environments. A heatmap-style matrix illustrated in Table 3 was developed to visualise the relevance and impact of each challenge area per UC, serving as a diagnostic tool to prioritise interventions. Proposed solutions to these challenges were subsequently explored and iteratively refined through a lens of feasibility and sustainability. This involved assessing each solution's alignment with circular design principles, its potential for energy and material savings, and its adaptability to existing or emerging production methods. The result is a structured foundation for process optimization that enables smoother scale-up pathways and supports the development of environmentally responsible manufacturing strategies.

4. Results and discussion

4.1. UCs eco-design assessment

The application of Design for X (DfX) methodologies has been crucial in aligning innovation with circularity and sector-specific performance demands across the 11 industrial UCs. Building on Sections 3.1, 3.2 and 3.3, for each UC, the “X” in DfX represents a targeted set of design priorities—such as recyclability, assembly/disassembly, lightweighting, energy efficiency, and cost-effectiveness—identified and tailored to the unique functional and environmental requirements of the product in question. These priorities are systematically defined and allocated in Table 4, which maps the strategic DfX factors adopted per use case. This structured approach enables a consistent and transparent integration of circular design principles from concept through development. Complementing this, the Matrix assessment results presented in Table 5 provide a comparative analysis of each UC's performance against the selected DfX factors, offering a quantitative foundation for evaluating design feasibility, sustainability impact, and cross-sector transferability.

The DfX methodologies in Table 4 operationalise the core metrics and are selected according to the functional and environmental requirements of each use case. Additionally, Table 5 presents weighted scores as a predictive assessment tool rather than as final measured data. The scores reflect expected directional improvements associated with the adoption of circular design strategies using currently available technologies.

Each UC is assessed based on a weighted combination of common and specific factors—such as weight savings, recyclability, assembly and disassembly, lifespan, and energy efficiency—with weightings tailored to the functional priorities of each application. Notably, the automotive UCs (UC1 and UC2) and hydrogen storage UC7 emphasise weight savings, reflecting the critical role of lightweighting in these sectors. In contrast, UC 11 gives greater weight to longevity and energy performance, with weight reduction being a secondary consideration. The modified designs in all UCs exhibit improved overall scores, underscoring enhancements achieved through advanced material integration, process innovation, and design optimisation. For instance, UC7 shows a substantial increase from a score of 3.0 to 4.5, driven by significant material and structural improvements. Similarly, water treatment and catalyst-based UCs (UC3 and UC4) display a notable leap in recyclability and energy efficiency through the adoption of graphene-enhanced membranes and catalytic systems. These results validate the tailored Design for X (DfX) approach employed across the UCs, enabling strategic, use-case-specific decisions that support circularity, sustainability, and performance in next-generation multifunctional materials and components.

By leveraging graphene-based materials and advanced manufacturing processes, the redesigned components aim to achieve measurable improvements in key sustainability metrics. These include significant weight reductions, enhanced recyclability and more viable EoL treatment pathways (Fig. 13), as well as the integration of optimised bonding strategies that facilitate easier assembly and disassembly (Fig. 14). Additionally, the redesigned solutions promote longer component lifespans (Fig. 15) and higher energy efficiency throughout their lifecycle (Fig. 16).

The design studies in this work provide quantitative support for the numerical performance metrics highlighted in the abstract. For example, replacing the conventional composite in the supersonic aircraft's leading edge with a graphene-modified polyimide laminate eliminates the protective film and yields 20–30 % weight savings; similarly, redesigning the automotive underbody shield cuts its weight from 4.15 kg to 3 kg, a 27.7 % reduction. The adoption of thermoplastic matrices and end-of-life treatments such as solvolysis and pyrolysis enables almost complete recovery of fibres and matrices (Chohan et al., 2025; Giorgini et al., 2014); in particular, pyrolysis followed by chemical cleaning recovers fibres and matrices with minimal property loss, and solvolysis allows full material recovery for the underbody shield (Gopalraj and Kärki, 2020; Wu et al., 2022), supporting projected recyclability above 90 %. Process-level improvements also translate into operational gains. Introducing a graphene-enhanced catalyst in water-treatment systems improves purification efficiency by 15–20 %, and removing high-energy lamination steps in composite manufacture reduces energy consumption accordingly. Finally, techno-economic analyses show that lighter components and simplified processes minimise material use and processing steps, yielding about 10 % cost savings across the examined use cases.

Examples of reversible joint designs include thermo-reversible bonding layers that soften upon localised heating, mechanical fasteners combined with heat-release adhesives, and snap-fit or bolted composite interfaces designed to distribute load while allowing non-destructive separation. Such configurations maintain structural integrity during service while enabling efficient disassembly, repair, or material recovery at the end of product life.

The results presented in Figs. 13–16 are purposely qualitative, reflecting early-stage evaluation criteria designed to guide circular design decisions. At this stage, the analysis provides directional insight—whether a proposed redesign is expected to deliver improvement—without substituting for the final quantitative validation that will emerge from the ongoing life cycle and life cost analyses later in the end.

While the primary evaluation of end-of-life (EoL) routes in this study focuses on technical feasibility and material recoverability, economic aspects are qualitatively addressed through factors such as process scalability, operational simplicity, and energy intensity. These criteria collectively determine the likelihood that a given EoL pathway—such as thermomechanical recycling, solvolysis, or direct functional reuse—can be implemented cost-effectively at scale. This approach enables a

Table 3
Challenge–solution qualitative impact heatmap.

0 = No mitigation/irrelevant	1 = Low: Addresses some sub-elements	2 = Moderate: Effective under limited conditions	3 = Strong: Fully addresses challenge robustly

Table 4
Design for X methodologies selected for the 11 UCs.

UCs	Design for				
	Weight saving	Recyclability	Assembly/disassembly	Lifespan	Energy efficiency
UC1	✓	✓	✓	✓	✓
UC2	✓	✓	✓	–	✓
UC3	–	✓	✓	✓	✓
UC4	–	✓	✓	✓	✓
UC5	✓	✓	✓	✓	✓
UC6	✓	✓	✓	✓	✓
UC7	✓	✓	✓	✓	–
UC8	–	✓	✓	**Manufacturability**	–
UC9	✓	✓	✓	✓	✓
UC10	✓	✓	✓	✓	✓
UC11	✓	✓	✓	✓	✓

holistic interpretation of EoL performance, balancing recyclability potential with indicative economic practicality.

4.2. Manufacturing scenarios and challenges with optimised processes for improvement

Building upon the structured methodology described in Sections 2.3 and 3.4, the following presents the expected challenges associated with manufacturing technologies and processes for each of the 11 UCs. A comprehensive preliminary assessment was carried out to evaluate these potential barriers in alignment with the functional and technological constraints specific to each UC. This evaluation aimed to ensure that the identified challenges reflect realistic manufacturing conditions rather than abstract or generalised assumptions. By doing so, the analysis bridges the gap between theoretical projections and operational realities. The manufacturing challenges were assessed, focusing on their practical implications within real-world process settings, considering scalability, process stability, material handling, and occupational safety. The manufacturing challenges and corresponding solutions presented here were identified through a preliminary, qualitative assessment. Each potential barrier was mapped against the functional and technological constraints of the relevant use case and evaluated in terms of scalability, process stability, material handling and occupational safety. To avoid abstract or theoretical biases, we sought input from the technical leads and industrial partners associated with each UC; whom provided suggestions and recommendations that were integrated into the matrix. The resulting challenge–solution pairs were then iteratively refined for feasibility, sustainability and circularity before being tabulated as a heatmap in Table 6. This integrated approach enabled the prioritisation of critical process optimisations and the identification of solution pathways that can be adapted across multiple UCs, thereby enhancing the robustness and replicability of the overall design-for-manufacture strategy.

Established methodologies in sustainable design and manufacturing literature support the assessment criteria presented in Table 6. In particular, Pigosso et al. (2010) outline how multi-criteria frameworks in eco-design and remanufacturing integrate environmental, technical, and safety-related considerations within the product development process. Their work emphasises that effective evaluation of sustainable systems must account for factors such as *material design* (resource efficiency and recyclability), *automated control* (process consistency and precision), and *safety and maintenance protocols* (operational reliability). Similarly, Lausecker et al. (2018) demonstrate how environmentally benign manufacturing, through digital lithography and renewable materials, embodies *advanced deposition* and *modular equipment* principles to minimise waste, energy use, and chemical impact. Together, these studies provide the theoretical and methodological basis for the selection of the Table 6 criteria and confirm their consistency with the integrative approach discussed in related sections.

A synthesis of the results in Table 6 highlights recurring manufacturing patterns across the studied applications. The most prevalent challenges include (a) material compatibility during hybrid composite formation, (b) control of process temperature and pressure windows to prevent voids or delamination, (c) limited scalability of laboratory-based deposition or coating methods, and (d) safety considerations related to particulate emissions and operator exposure. Commonly transferable mitigation strategies comprise modular tooling architectures, inline process monitoring, solvent-free or low-energy consolidation routes, and robust environmental control systems. These measures collectively strengthen manufacturability, safety, and scalability of advanced multifunctional composites, coatings, and membrane systems across sectors (descriptions of the mitigating actions used for each UC based on Table 6 are added in Appendix A).

Several rows in Table 6 indicate that "safety protocols" are used as a response to seemingly disparate manufacturing challenges. This reflects the cross-cutting role that occupational health and environmental protection play, especially when working with graphene and other nanomaterials. Regardless of whether the challenge concerns resin compatibility, curing uniformity, scale-up or coating deposition, operators must mitigate risks associated with inhalation or exposure to nanoparticles. Therefore, stresses are made that nanoparticle handling requires strict safety measures—such as engineering controls, ventilation systems, personal protective equipment and specialised training—to accompany any technical intervention. These protocols do not "solve" the technical challenge but provide a safe operating envelope within which solutions like resin formulation optimisation, process-temperature control or equipment upgrades can be implemented.

4.3. Cost analysis

The cost analysis provides a comprehensive evaluation of the manufacturing feasibility and scalability potential across industrial use cases (UCs) in the automotive, aerospace, water treatment, and hydrogen storage sectors. Key cost drivers are identified as raw materials, energy consumption, and labour costs—each showing substantial variability depending on application-specific requirements. The use of high-performance constituents, such as carbon fibres, glass fibres, graphene oxide, and advanced catalytic materials, notably influences raw material costs. EU sourcing offers quality assurance and regulatory alignment but at a premium. Energy consumption emerges as a critical consideration (Eurostat: Electricity price statistics, 2025), particularly for aerospace and automotive components that rely on energy-intensive thermal curing processes (e.g., autoclaves and hot presses), in contrast to water treatment systems, where energy demands are generally lower. Still, chemical use and waste management have become key economic factors. Labour costs—ranging between €30 and €45 per hour (Eurostat: Hourly labour costs, 2025)—are elevated in complex sectors, such as aerospace, where precision tasks demand specialist expertise, increasing costs by 25–30 %. The integration of automation technologies (e.g., automated fibre placement in UC6 or filament winding in UC7) helps

Table 5
Assessment scores for UCs.

		Common factors			Specific factors		Weighted score
UC1		**Weight saving**	**Recyclability**	**Assembly/ disassembly**	**Lifespan**	**Energy efficiency**	*0.25xweight + 0.15xrecyclability + …*
		25 %	**15 %**	**10 %**	**25 %**	**25 %**	
Reference design score		3	2	5	3	3	**3.05**
Modified design score		3	4	5	5	2	**3.60**
UC2		**Weight saving**	**Recyclability**	**Assembly/ disassembly**	**Lifespan**	**Energy efficiency**	*0.30xweight + 0.25xrecyclability + …*
		30 %	**25 %**	**15 %**	**–**	**30 %**	
Reference design score		3	3	5	–	3	**3.3**
Modified design score		5	3	5	–	2	**3.6**
UC3		**Weight saving**	**Recyclability**	**Assembly/ disassembly**	**Lifespan**	**Energy efficiency**	*0.25xrecyclability + 0.15x assembly/ disassembly + …*
		–	**25 %**	**15 %**	**30 %**	**30 %**	
Reference design score	Membrane	–	1	5	3	3	**2.8**
	Catalyst	–	1	5	3	3	**2.8**
Modified design score	Membrane	–	5	5	4	4	**4.1**
	Catalyst	–	5	5	4	4	**4.4**
UC4		**Weight saving**	**Recyclability**	**Assembly/ disassembly**	**Lifespan**	**Energy efficiency**	*0.25xrecyclability + 0.15x assembly/ disassembly + …*
		–	**25 %**	**15 %**	**30 %**	**30 %**	
Reference design score	Membrane	–	1	5	3	3	**2.8**
	Catalyst	–	1	5	3	3	**2.8**
Modified design score	Membrane	–	5	5	4	3	**4.1**
	Catalyst	–	5	5	4	4	**4.4**
UC5		**Weight saving**	**Recyclability**	**Assembly/ disassembly**	**Lifespan**	**Energy efficiency**	*0.25x weight saving + 0.20x recyclability + …*
		25 %	**20 %**	**15 %**	**25 %**	**15 %**	
Reference design score		2	2	3	3	3	**2.55**
Modified design score		4	2	3	4	2	**3.15**
UC6		**Weight saving**	**Recyclability**	**Assembly/ disassembly**	**Lifespan**	**Energy efficiency**	*0.25x weight saving + 0.20x recyclability + …*
		25 %	**20 %**	**10 %**	**20 %**	**25 %**	
Reference design score		2	2	5	3	3	**2.75**
Modified design score		4	2	5	4	2	**3.2**
UC7		**Weight saving**	**Recyclability**	**Assembly/ disassembly**	**Lifespan**	**Energy efficiency**	*0.50x weight saving + 0.30x recyclability + …*
		50 %	**30 %**	**10 %**	**10 %**	**–**	
Reference design score		3	3	3	3	–	**3**
Modified design score		5	4	3	5	–	**4.5**
UC8		**Weight saving**	**Recyclability**	**Assembly/ disassembly**	**Manufacturability**	**Energy efficiency**	*0.25x recyclability + 0.25x Assembly/ Disassembly …*
		–	**25 %**	**25 %**	**50 %**	**–**	
Reference design score		–	3	3	3	–	**3**
Modified design score		–	3	4	4	–	**3.75**
UC9		**Weight saving**	**Recyclability**	**Assembly/ disassembly**	**Lifespan**	**Energy efficiency**	*0.25x weight saving + 0.15x recyclability + …*
		25 %	**15 %**	**10 %**	**25 %**	**25 %**	
Reference design score		3	3	3	3	3	**3**
Modified design score		4	4	5	4	4	**4.1**
UC10		**Weight saving**	**Recyclability**	**Assembly/ disassembly**	**Lifespan**	**Energy efficiency**	*0.25x weight saving + 0.25x recyclability + …*
		25 %	**25 %**	**25 %**	**10 %**	**15 %**	
Reference design score		3	3	3	3	3	**3**
Modified design score		4	4	3	5	4	**3.85**
UC11		**Weight saving**	**Recyclability**	**Assembly/ disassembly**	**Lifespan**	**Energy efficiency**	*0.1 x weight saving + 0.20x recyclability + …*
		10 %	**20 %**	**10 %**	**35 %**	**25 %**	
Reference design score		3	3	3	3	3	**3**
Modified design score		1	4	3	5	5	**4.2**

reduce labour intensity but necessitates high capital expenditure and sophisticated maintenance infrastructure. Overall, the analysis highlights the importance of strategic trade-offs, including investing in energy and process efficiency, optimising raw material usage, and judiciously adopting automation to achieve long-term cost-effectiveness and environmental sustainability in scaled manufacturing.

This section presents a qualitative assessment of cost drivers, rather than a quantitative cost analysis, the goal at this stage is to establish early insights into economic feasibility and identify the main cost-driving factors—such as material substitution, energy demand, process scalability, and maintenance intervals—that influence the adoption of circular design solutions. This early-stage assessment serves as a guiding tool to embed cost-effectiveness within the conceptual design phase and ensure industrial feasibility prior to the completion of full techno-economic evaluations.

4.3.1. *Specific cost considerations*

The comparative cost analysis, summarised in Table 7, of manufacturing methods across the UCs reveals a diverse landscape of technical pathways, each with distinct implications for raw material sourcing, energy demand, labour intensity, and scalability.

4.3.2. *Cost and scalability analysis*

The current feasibility varies significantly across industries, with the

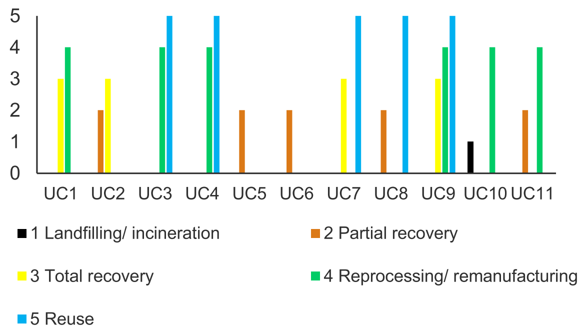

Fig. 13. Potential recyclability and EOL routes.

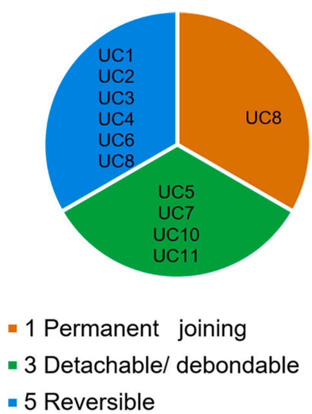

Fig. 14. Initial bonding for assembly/disassembly design.

primary drivers being production methods, material requirements, and operational costs. Production methods at high volume, such as compression moulding and hot press curing, can leverage economies of scale, helping keep costs relatively low in the automotive sector, UC1 and UC2. Applications also involve a relatively small quantity of graphene oxide (GO), which contributes to cost containment. On the other hand, aerospace applications present several specific demands for precision and certification. Although bulk discounts on CF may partly compensate for material costs, the operation of autoclaves increases energy and labour-related costs, contributing to the overall complexity of production. Scalability in water treatment depends partly on progress with catalyst developments and membrane fabrication. Stable chemical supply chains are relevant for consistent production. Hydrogen storage applications are enabled by special materials that include advanced composites based on carbon fibre (CF) and doping agents. Capital-intensive steps, such as chemical vapour deposition (CVD) and catalyst applications, are essential for achieving the high-performance standards required in this sector.

Among these UCs, the prospects for scalability and future cost savings appear fairly promising. Adopting automation and process optimisation techniques, such as automated fibre placement in UC6 or automated wet filament winding in UC7, drastically lower per-unit labour costs over time. Raw material costs should also be reduced through innovations in the manufacturing process; for example, bulk production of GO, GNPs, and doping agents could lower raw material costs by 25–35 % as graphene-enabled applications are developed. Energy use could also be further reduced through energy efficiency improvements, such as switching to lower temperature curing or using quicker chemical synthesis routes, such as hydrothermal approaches in the case of UC4. Other sector-specific implications have different implications for scalability and costs. It would also mean higher production volumes and relatively easy scaling processes, which are pertinent to the automotive and water treatment applications, while in the case of aerospace, these have to face rather slow cost reductions due to their very stringent qualification and certification conditions. For UC7-UC11, which involves hydrogen storage, considerable large-scale doping techniques and membrane productions would provide key steps in achieving economic scalability in the long run.

4.3.3. Sector-specific challenges

Material availability is a big challenge, while high-grade CF and derivatives of graphene are mostly confined to specific regions. This might lead to supply bottlenecks, further complicating the efforts toward consistent production and scalability. Additionally, in industries such as aerospace (UC5, UC6), and hydrogen storage (UC7-UC11), regulatory compliance is rigorous and contributes to the overall cost. Compliance with such high certification and quality assurance standards is necessary, but it requires specialised expertise and resources that can stretch budgets. Additionally, high investments in the latest infrastructure put an extra strain on finances. Capital-intensive equipment, such as autoclaves, automated fibre placement machines, and CVD setups, demands a significant initial investment. Such investments require a stable and predictable market demand to amortise their costs over a period of time. It will require strategic planning, collaboration along the supply chain, and innovative solutions to achieve cost-effectiveness, material accessibility, and process efficiency.

4.4. Aspects of functional lightweight design to reach appropriate lightweight solutions

Functional, lightweight design emerges as a critical lever for achieving sustainable innovation across automotive, aerospace, and hydrogen storage applications (Sandrini et al., 2024; Mallick, 2010). Lightweighting, traditionally viewed as a technical objective, is elevated as a transversal strategy within the broader eco-design methodology, impacting not only raw material extraction and energy efficiency during use but also manufacturability, transportation, and End-of-Life (EoL) outcomes (Koffler and Rohde-Brandenburger, 2010; Suski et al., 2024). Key to this approach is a nuanced balance between material choice, geometry, process feasibility, and lifecycle cost. Automotive use cases UC1 and UC2 employ hybrid resin systems with carbon or glass fibres and hot press compression moulding to achieve substantial mass reductions while adapting the geometrical design to maintain structural compatibility. In aerospace (UC5 and UC6), weight savings are achieved

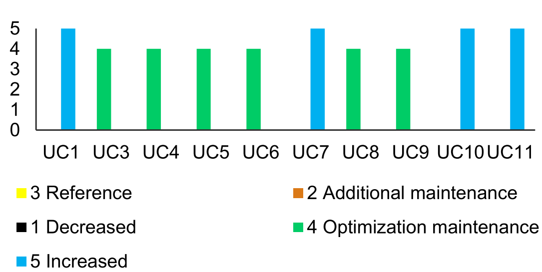

Fig. 15. Expected enhancements related to lifespan.

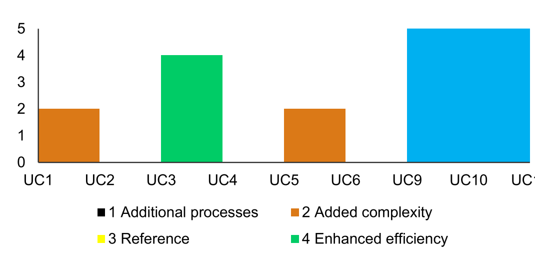

Fig. 16. Expected enhancements related to energy efficiency.

through functional integration—eliminating single-use protective films or metallic meshes by embedding the required performance directly within graphene-modified composite materials, thereby preserving the aerodynamic form. For hydrogen storage (UC7), weight reduction is achieved by substituting traditional high-volume carbon fibre with GRM-enhanced epoxy composites, enabling the creation of thinner,

Table 6
UCs manufacturing scenarios challenge–solution qualitative impact heatmap.

Proposed manufacturing scenarios & Associated challenges ↓/Solutions' categories→	Material design	Automated control	Modular equipment	Advanced deposition	Safety protocols
UC1: Fast warm/hot press curing process using a hybrid thermoplastic/thermoset polyester/epoxy resin system with 50 % recycled PET. Application of GNP-based sol-gel spray coating.					
Material compatibility: Phase separation (Adeniyi et al., 2016); Recycled PET impact inconsistent performances (Santomasi et al., 2024).	3	0	0	0	2
Optimising process: PET recycling curing parameters (Dębska et al., 2024); avoiding defects (*Trans. Indian Inst. Metals*, 2024).	0	3	2	0	2
Scale-up: reproducibility; equipment modification	0	3	3	0	2
Coating application: Thickness Uniformity (Ciriminna and Pagliaro, 2022; Barrino, n.d.); Adhesion	3	2	1	3	2
Safety & health: Nanoparticle handling (Pelin et al., 2018; Devasena et al., 2021; Andrews et al., 2024).	0	0	0	0	3
UC2: One-shot, low-pressure warm compression moulding of GF-based GNP-modified recyclable resin on an rPET foam core.					
Process complexity: One-shot moulding with multiple materials can lead to voids/incomplete bonding (Zhou et al., 2023; Guerra et al., 2023); inaccurate temperature control may degrade rPET foam. (Özel and Soylemez, 2024; Karagöz, 2021; Nathan and Prabhu, 2022).	3	2	2	0	2
Material compatibility: Differential expansion between resin, fibres, and foam can cause delamination; macroscopical adherence between the resin and the rPET foam core (Özel and Soylemez, 2024).	3	0	0	0	2
Quality control: Maintaining uniformity across production batches (Ke et al., 2024; Li et al., 2024a); aesthetic issues from recycled material affecting surface finish.	2	3	1	0	2
Equipment limitations: Moulds may need to be custom-built for materials and geometry; cycle time is constrained by curing and quality demands.	2	3	2	0	2
UC3: Preparation of GO-improved NF membranes on a polymeric substrate coated/impregnated with GO. Integration of GO-Fe_3O_4 nanocomposite catalysts.					
Material compatibility: membrane stability (Jia et al., 2022; Zhang et al., 2020); mechanical and chemical resistance (Sharma et al., 2024; Cairney et al., 2024).	3	0	0	3	2
Scale-up: fabricating large-area defect-free membranes (Pourebrahim and Doroodmand, 2024; Bairapudi et al., 2023); high production rates and requiring efficient and reliable processes.	2	3	3	3	2
Catalyst incorporation: Ensuring uniform catalyst distribution and long-term activity	3	2	2	0	2
System Integration: Compatibility with existing membrane housings, operational flow rate, and pressure.	2	3	3	0	2
Fouling and cleaning: Particles accumulate and reduce permeability. Antifouling characteristics need to be developed accordingly (Shafi et al., 2016; Yi et al., 2019).	3	1	1	2	3
Cost constraints: High-quality GO and catalysts may increase the cost.	2	1	2	1	0
UC4: Fabrication of LIG-enhanced ultrafiltration membranes. Employing TiO_2-coated functionalized GO sheets as photocatalysts.					
Material Compatibility: Membrane mechanical Stability (Kucera, 2023; Echakouri et al., 2022) &chemical stability to resist degradation integrity in oil/water mixtures (Kucera, 2023; Cipollini, 2007).	3	0	1	3	2
Scale-up: LIG requires precise laser control (Karimi et al., 2021; Singh et al., 2022; Liu et al., 2023) and may not scale (Wang et al., 2018; LiMichael et al., 2020); high cost of laser systems (MurrayMicheal et al., 2021) and its maintenance (Le et al., 2022).	3	2	2	2	2
Catalyst performance: TiO_2 coating may degrade (Gao et al., 2024; Wang et al., 2024; Sriram et al., 2020); UV activation is required (Kirk et al., 2024; Ponce-Robles et al., 2023).	2	2	1	3	2
System integration: System compatibility and parameter optimization for flow/pressure.	2	3	3	0	2
Safety & health: Nanomaterial contamination & waste management.	2	0	0	0	3
UC5: preparation of the lay-up, lamination, and curing with GNP-doped thermoset polyimide (PI) resin.					
Material compatibility: PI resins require >300 °C curing, and are not always equipment-compatible (Qian et al., 2021; Matsutani et al., 2005; Wang et al., 2022b); energy-intensive.	2	2	2	0	2
GNP dispersion: GNP agglomeration (Kausar and Ahmad, 2023; Zhang and Zhou, 2010; Zhang et al., 2021; Sobhani et al., 2022) and high viscosity (Zhu et al., 2023) affect	3	2	2	3	2

uniformity and lamination (Ishida et al., 2021).					
Process complexity: Maintaining viscosity for prepregs (Suzumura et al., 2014; Saito et al., 2024) and managing short shelf-life (Vora and Lau, 2022; Somarathna et al., 2024) of high-temp resins.	3	2	2	0	2
Equipment requirements: Limited access to autoclaves (Vita et al., 2019); need for high-temp moulds.	2	0	3	0	2
Health and safety: Emission of harmful volatiles during curing; need for PPE and ventilation.	0	0	0	0	3
UC6: Optimised consolidation processes for carbon fibre-based PEEK composites with high-conductivity GNP-based coatings.					
Process complexity: PEEK composite high-temperature (360 °C) processing (Li et al., 2023; Guo et al., 2023; Bessard et al., 2011; Jin et al., 2024) & viscosity challenge for CF impregnation (Lu et al., 2024; Ma et al., 2023).	3	2	3	0	2
Coating application: Coating adhesion (Gao et al., 2023; Sun et al., 2024; Sin et al., 2020) and surface conductivity (Parten et al., 2024; Leow et al., 2023; Oliveira et al., 2024) must be optimised across thermal cycles.	3	2	2	3	2
Material compatibility: Thermal expansion mismatch may cause delamination (Leow et al., 2021; Ren et al., 2022).	3	0	0	2	2
Equipment limitations: PEEK requires specialised high-temp equipment and is costly.	2	3	3	0	2
Quality assurance: Detecting defects like voids/incomplete consolidation is essential.	3	3	2	0	3
UC7: Automated wet filament winding process with CFs/GRMs-based epoxy composites.					
Material compatibility: GNP aggregation reduces strength (Liu et al., 2021, 2025a); viscosity must support fibre wetting (Kotsilkova et al., 2022; Srivastava et al., 2024).	3	2	2	2	2
Process complexity: Accurate fibre winding (Zhang et al., 2024; 童喆益, 2011) and cure management needed to avoid thermal/exothermic issues.	2	3	2	0	2
Scale-up: Resin dosing and equipment calibration needed; curing cycle optimisation required.	2	3	3	0	2
Structural integrity: High level of voids/dry spots can cause premature pressure failure; composite must be high-impact resistant.	3	2	2	0	3
Regulatory compliance: Full-scale tests (e.g. BURST, cycling) needed for certification due to GRM material in load-bearing shell.	3	2	2	0	3
UC8: rGO-based conductive and dielectric inks were applied onto polymeric substrates using both screen-printing and inkjet printing techniques.					
Material compatibility: rGO particles must not sediment (Loh et al., 2021; Chamelot et al., 2024; Ahmed et al., 2024; Nalepa et al., 2024); viscosity must suit print method without degrading conductivity (Kim et al., 2021; Zitoun et al., 2022; Wang et al., 2017).Ink must adhere to polymers and resist humidity, mechanical stress, and temperature variations.	3	2	2	3	2
Quality assurance: Resolution and repeatability can be affected by ink flow, printhead, and process conditions (Chang et al., 2018; Murayama et al., 2013).	2	3	2	3	2
Installation challenges: Sensor embedding should not alter mechanical properties of structures or degrade signal integrity.	3	2	2	0	2
Scale-up: Precision printing becomes harder with high throughput; cost control is a concern.	2	3	3	3	2
UC9: Low-cost spray coating techniques are used for applying metal-GRM composite coatings.					
Material compatibility: Maintaining thickness (Jacobs et al., 2021; Deng et al., n.d.) and coverage (Noguchi et al., 2023; Ling et al., 2024) uniformity over large or complex surfaces. Preventing Surface contamination (Lytovchenko et al., 2020; Bobzin and Knoch, 2017) and supporting strong bonding mechanisms (Liu et al., 2025b; Liao et al., 2020) for strong adhesion. Wear and durability: Sustaining resistance to abrasion, thermal cycling, and harsh environments.	3	3	3	3	2
Process complexity: Spray parameter consistency, pressure/angle/distance tuning, and post-curing.	2	3	3	3	2
Health and safety: Exposure to nanomaterials and regulatory compliance.	2	2	2	2	3
UC10: The doping of transition metals is introduced by the method of template-assisted CVD for doped rGO.					
Process complexity: CVD requires precise control of temp, pressure, gas (Jia et al., 2020; Konar and Nessim, 2022; Buchkov et al., 2024); deposition uniformity must be maintained	2	3	3	3	2

(Hong et al., 2023; Chen et al., 2020).					
Scale-up: CVD has batch throughput limits (Xin and Li, 2018) and high cost.	2	3	3	3	2
Catalyst stability: Catalysts must remain stable under acidic conditions; avoid deactivation by impurities.	3	2	0	2	2
Cost constraints: Transition metals are cheaper than Pt, but still costly; high-quality rGO synthesis in bulk is a challenge.	3	2	0	2	2
System integration: New catalysts must be MEA-compatible and pass performance validation.	3	3	2	2	2
UC11: Synthesis of transition metal-doped storage materials in GO/rGO-based foams using template-assisted CVD.					
Material compatibility: Uniform pore structure (Le et al., 2024; Paz et al., 2023) and reproducibility of storage materials. Material Stability: Avoiding material degradation under H_2 cycling (Broom, 2011).Impurities in hydrogen gas can affect material integrity.	3	2	2	2	2
Process complexity: Balancing material weight and H_2 storage capacity; requires specific pressure/temperature to operate.	3	2	2	0	2
Scale-up: CVD-based methods are challenging to scale, in addition to high material costs (transition metals and high-purity graphene).	3	2	3	2	2
Health and safety: Hydrogen embrittlement (Li et al., 2024b) and leak prevention.	2	2	2	0	3

Acronyms:

CF	Carbon fibre	**CVD**	Chemical vapour deposition	**GF**	Glass fibre	**GNP**	Graphene nanoplatelet
GO	Graphene oxide	**LIG**	Laser-induced graphene	**NF**	Nanofiltration	**PEEK**	Polyether ether ketone
PET	Polyethylene terephthalate	**rPET**	Recycled polyethylene terephthalate	**rGO**	Reduced graphene oxide	**UF**	Ultrafiltration

structurally equivalent layers. Although water treatment and sensor UCs do not prioritise lightweight design, mass reduction offers system-wide lifecycle benefits.

4.5. Performance-driven material selection for circular material solutions and eco-design optimisation

Following the approach explained in Section 2.5, the assessment shown in Fig. 17 evaluates each UC by aligning functional performance indicators with selected materials, enabling informed decisions that support sustainable and circular design. The analysis reveals how technical viability—whether related to stiffness, conductivity, thermal resistance, or catalytic stability—is intrinsically linked to the feasibility of advanced materials and processes. For instance, UC1 and UC2 emphasise lightweighting and structural efficiency, leading to targeted material combinations and recycling strategies such as mechanical grinding and extrusion-based reuse. UCs like UC3 and UC4 focus on membrane and catalyst efficiency, guiding improvements in nanomaterial stability and promoting strategies to minimise nanoparticle release. High-performance thermosets and thermoplastics in UC5 and UC6 require process optimisation and energy-conscious manufacturing, balanced by recovery routes such as pyrolysis and coating separation. UCs addressing sensor integration (UC8), lubrication (UC9), and hydrogen systems (UC10–UC11) highlight the importance of printability, durability, and safe recovery of critical materials. Across all UCs, the assessment prioritises early-stage integration of recyclability, modularity, and lifecycle performance. This ensures that each solution not only meets functional and economic requirements but is also optimised for environmental resilience and long-term sustainability.

4.6. Assessment of the eco-design with respect to optimisation of advanced GRM-bM

The assessment of the eco-design of the GRM-bM following Section 2.6 took into account the following aspects: (i) material analysis, (ii) manufacturing method analysis, and (iii) waste generation and management. These categories, along with the corresponding list of sub-indicators related to eco-parameter analysis, are listed in Table 8.

The sub-indicators presented in Table 8 are derived from established life-cycle and eco-design methodologies. Material-related indicators (e.g., toxicity, solubility, biodegradability) follow the life-cycle-thinking frameworks found in literature, e.g. described by Pigosso et al. (2010) and Hauschild et al. (2018). Process-related indicators (resource and energy consumption, pollution, waste generation) reflect the eco-efficiency and cleaner-production principles central to life-cycle engineering (Bocken et al., 2016; Allwood et al., 2011). Waste-management indicators correspond to the “5 Rs” hierarchy, linking reduction, reuse, and recycling to circular-economy performance. This classification ensures that both environmental and technical factors are systematically addressed during eco-design evaluation.

Fig. 18 presents a quantitative evaluation of the environmental impact and improvement potential across multiple UCs, highlighting GRM-based multifunctional families, including composites, coatings, membranes, and foams. Notably, GRM-based Crosspreg composites (UC1 and UC2) in Fig. 18(a) exhibit the highest manufacturing impact due to the energy-intensive lamination and moulding process, yet show significant room for improvement, especially in substituting fossil-derived monomers with bio-based alternatives. In contrast, GRM-bM foams fabricated via solvent casting (UC10) in Fig. 18(d) demonstrate a minimal impact across all categories, with the highest material improvement potential, reflecting their sustainable formulation that utilises rGO and bio-based polymers. Meanwhile, coatings (Fig. 18(b)), such as those in UC9, exhibit moderate impacts in the material and manufacturing domains yet present limited potential for waste management improvement, indicating well-optimised end-of-life strategies. Membranes formed via electrospinning (UC3 and UC4) in Fig. 18(c) stand out for their low environmental impact and high potential for circularity, driven by innovations in polymer and solvent design. These findings validate that while composite and screen-printing-based foam systems demand targeted improvements in manufacturing

Table 7
UCs cost considerations.

UC	Manufacturing method	Key raw materials	Notable cost factors
1	Isothermal hot press	PET foam + CF/ hybrid resin (GO as primary graphene-based material)	Medium material cost (CF), moderate labour; energy usage for hot press
2	One-shot, low-pressure warm compression	PET foam + GF/ hybrid resin (Al reflective film optional)	Lower fibre cost (GF), multi-layer foam integration; energy savings from low curing temperature
3	Chemical decoration	Graphene membrane (PVDF-HFP), GO/ Fe_3O_4 catalyst	Catalyst synthesis adds chemical processing cost; moderate energy demand
4	Chemical decoration	Graphene membrane (PVDF-HFP), rGO/ TiO_2 catalyst	Similar to UC3 but with rGO/TiO_2; hydrothermal step can be energy-intensive
5	Hand layup + autoclave curing	CF-reinforced GO/ GNP-modified polyimide resin	High labour input for layup; autoclave operation is a significant energy driver
6	Automated fibre placement + autoclave	CF-PAEK + sol/gel GNP-based coating	High automation capital cost; higher labour rate in aerospace
7	Automated wet filament winding	CF/GRM-based epoxy composites	Automation lowers labour cost over time; setup cost for winding equipment
8	Screen printing of sensors + sensor integration in composite materials through resin transfer moulding or press mold reactive curing	Thermoplastic substrates, rGO inks, glass/natural fibre reinforcement	Screen printing equipment cost moderate; multi-step integration can raise labor cost
9	Scalable coating systems	Sol-gel silica matrix doped with WS_2, MoS_2, and GNPs	Specialty additives raise raw material costs; relatively low energy demand
10	Screen printing on PEM	rGO/Pt catalytic layer, microporous layer (rGO, LrGO, LIG, C_3N_4, etc.)	Precious metals (Pt) drive up material cost; moderate screen printing energy/ labour
11	Template-assisted CVD/milling and high-shear mixing	Doped rGO, GO, or metal hydrides	Capital-intensive CVD process; milling/high-shear mixing requires moderate energy

sustainability, membrane and coating systems already benefit from effective design-for-environment strategies, albeit with further scope for material innovation.

4.7. Feasibility-driven evaluation of manufacturing approaches and recycling routes

Fig. 19 illustrates the assessment of UCs based on Section 2.7. The analysis of the 11 UCs demonstrates that the selected graphene-based material concepts are technically grounded in terms of feasibility, aligned with functional performance requirements, and supported by scalable manufacturing technologies. UC1 and UC2 utilise well-established thermoplastic and thermoset moulding techniques, integrated with graphene-enhanced laminates to enable lightweight structures while maintaining mechanical strength and thermal stability. UC3 and UC4 employ chemical decoration and membrane integration processes that enable consistent catalyst performance and membrane durability in harsh filtration environments. In high-performance aerospace applications (UC5, UC6), advanced prepreg layups and automated consolidation techniques (e.g., autoclave and spray coating) are employed to meet demanding structural and electrical requirements. Hydrogen-related UCs (UC7–UC11) utilise filament winding, screen printing, cold compaction, and powder metallurgy to realise efficient energy storage and catalytic activity under controlled conditions. Recyclability is addressed through tailored strategies based on material type and EOL scenarios. For thermoplastic composites (UC1–UC2), solvolysis and mechanical grinding enable closed-loop recycling, including the recovery of monomers and fibre reinforcements. UC3–UC4 incorporate catalyst recovery and membrane upcycling techniques to extend material lifecycles. High-temperature materials in UC5 consider pyrolysis and solvolysis to separate fibres and matrix components. Sensor-integrated systems (UC8) focus on chemical layer recovery and recalibration protocols. Nanostructured coatings and catalysts (UC9–UC11) adopt lixiviation, electrochemical regeneration, and thermal reprocessing to recover active nanomaterials and maintain circularity. This assessment confirms the feasibility of the proposed solutions by coupling advanced material functions with viable process routes and embedding end-of-life strategies early in the design phase. These insights contribute to a structured pathway for integrating graphene-related materials in circular and sustainable manufacturing ecosystems across automotive, aerospace, water, and energy domains.

5. Integrated discussion and decision support

The preceding sections presented detailed analyses of eleven graphene-enabled use cases (UCs), each applying the Circular Design for X (CDfX) framework to optimise weight saving, recyclability, assembly/ disassembly, lifespan and energy efficiency. To help readers understand how these individual analyses fit within a unified methodology and to extract generalisable insights, we synthesise the findings across the UCs and clarify the decision-support role of the CDfX framework.

5.1. Key findings across use cases

Across all eleven UCs, the modified designs consistently achieved higher sustainability scores than the reference designs. Common trends include:

- Recyclability improvements: Adoption of reversible joints, modular sub-assemblies, and recyclable polymer matrices increased recyclability scores for most UCs. For example, use cases based on thermoplastic hybrid resins (UC1 and UC2) benefited from solvolysis-friendly chemistries, while aerospace components (UC6) leveraged reversible mechanical joints.
- Weight saving: Graphene reinforcement and optimised geometries are highly expected to deliver sizable mass reductions per UC. The most significant reductions were observed in automotive and aerospace, followed by hydrogen-storage tank components, where high-strength graphene-enhanced composites allowed for thinner walls without compromising safety.
- Energy efficiency and lifespan: Energy-efficiency gains were sector-dependent. Automotive and hydrogen-storage UCs should experience improved energy performance due to mass reductions and lower rolling/drag resistance. Water-treatment membranes (UC3) also demonstrated extended lifespan thanks to fouling-resistant graphene coatings.
- Trade-offs and cost: In some cases, slightly enhancing recyclability reduced weight savings, underscoring the need for a weighted scoring scheme. For example, introducing additional detachable fasteners, adding modular interfaces, or using thicker thermoplastic components to facilitate reprocessing can slightly increase the component's mass. Consequently, the relative weight savings compared with the baseline design may be smaller than they would have been if mass reduction were the sole objective. Manufacturing cost drivers—such as material cost, energy consumption and

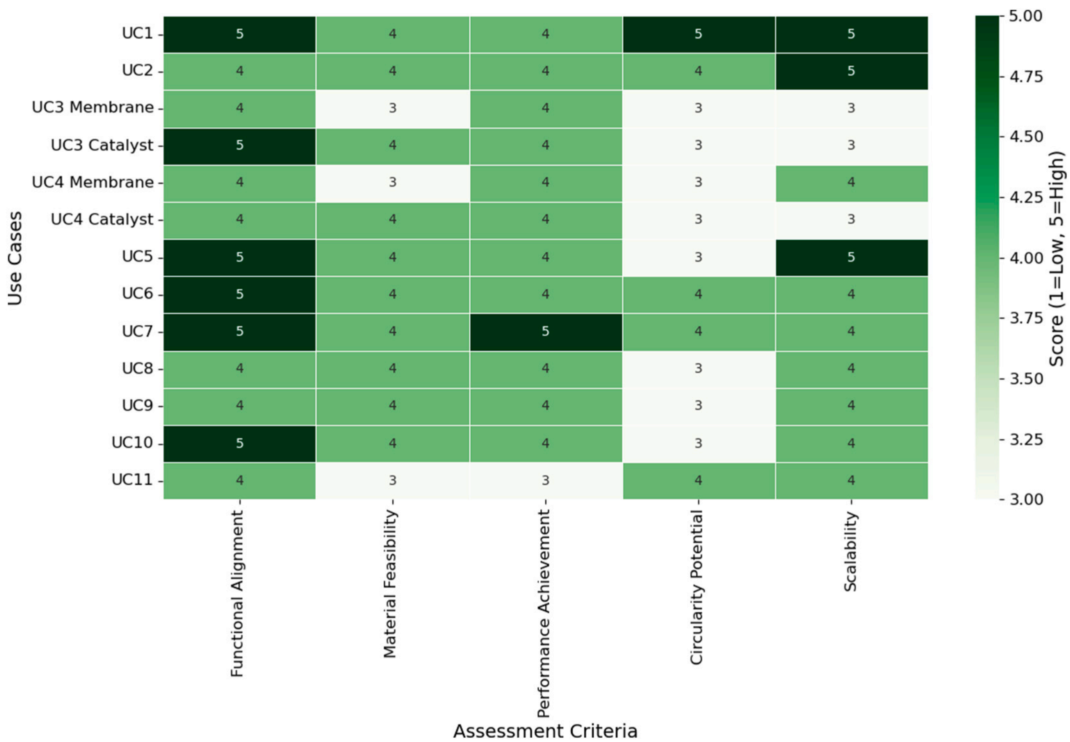

Fig. 17. Assessment for material selection and Eco-design optimisation.

Table 8
Eco-parameter analysis for the GRM-bM.

Indicators	Material analysis	Manufacturing analysis	GRM-bM waste management
Sub-indicators	• Material list • State (solid, liquid) • Size particle • Shape (pellets, powder) • Toxic (yes/not) • Solubility • Biodegradability	• Resource consumption • Energy consumption • Pollution emission • Generated waste	• Refuse (unnecessary, wasteful, critical, or non-recyclable resources) • Reduce (unnecessary, wasteful, critical, or non-recyclable resources) • Reuse • Repurpose • Recycle

labour—varied by sector and were analysed in conjunction with the multi-criteria scores to ensure economic feasibility. Potential manufacturing challenges were identified and integrated into an overarching analytical framework; these insights inform the design choices discussed below.

5.2. Links between framework elements and trade-offs

The DfX heuristics employed are intrinsically interrelated. For example, choosing modularity and reversible joints facilitates disassembly, which in turn enhances recyclability. However, increasing modularity may introduce additional interfaces, potentially affecting weight saving or energy efficiency. By explicitly quantifying each metric and applying customised weightings, the CDfX framework enables designers to balance these competing objectives. The manufacturing challenge assessment (Table 6) and cost analysis (Section 4.3) serve as reality checks: they ensure that the highest-scoring design variant can be produced at scale and does not introduce prohibitive costs or safety issues.

5.3. Illustrative example – UC1 aerodynamic shield

To demonstrate how the framework operates as a unified process, an example is provided using UC1, an aerodynamic shield for automotive applications:

1. Baseline characterisation: The reference shield was a conventional epoxy carbon fibre sheet moulding compound. Permanent metal fasteners and non-recyclable adhesives hindered disassembly and recyclability.
2. DfX and performance objectives selection: Applying design-for-assembly, design-for-disassembly and design-for-recycling heuristics together with targeted interventions for weight saving, lifespan and energy efficiency. The existing bolted joints were retained and complemented with reversible fasteners to replace any permanent adhesives, ensuring that the aerodynamic shield can be removed for maintenance or end-of-life processing without damaging the component. Weight saving was addressed by adopting a graphene-reinforced structure that reduces mass; lifespan was extended through durable graphene-based coatings and enhanced properties; and energy efficiency was indirectly improved due to the resulting mass reduction.
3. Circular interventions: Graphene nanoplatelets (GNPs) were incorporated into the resin, and an additional GNP-based sol–gel coating was applied to enhance mechanical strength and thermal stability. Adding graphene to the composite material will enable the achievement of the same properties of the current product with a reduced content of costly carbon fibres. The composite was reformulated to include 50 % recycled PET content. These changes improved stiffness and allowed thinner walls, leading to weight reduction.

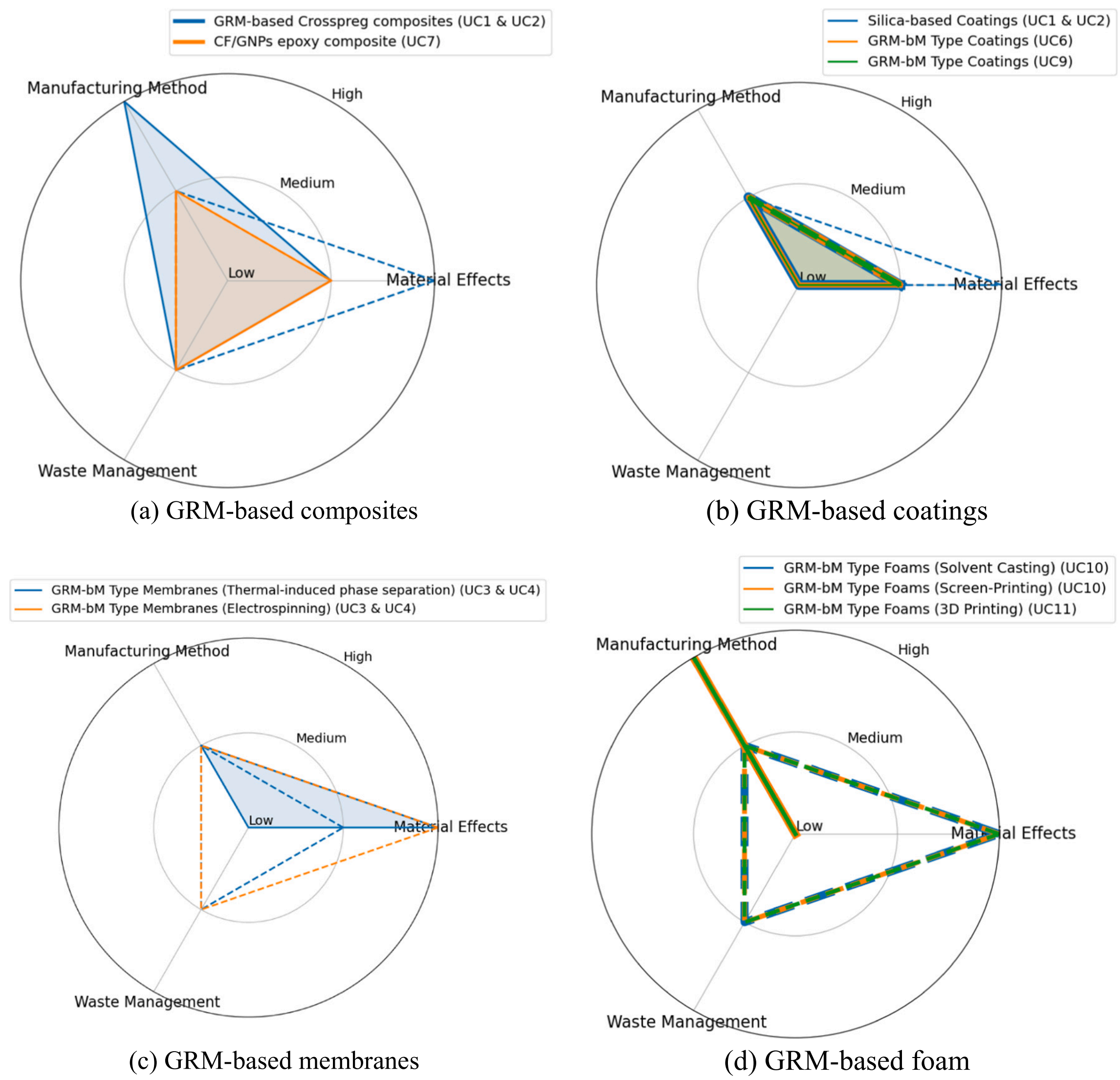

Fig. 18. GRM-based assessment considering environmental impact (solid polygons) and improvement potential (dashed outlines) for material effects, manufacturing analysis and waste management across UCs. Each UC is plotted with both a solid line (present environmental impact) and a dashed line (expected improvement from the proposed circular design).

4. Multi-criteria evaluation:
   - o Weight saving: Expected 27.7 % reduction relative to the baseline.
   - o Recyclability: Score improved due to reversible joints and solvolysis-friendly resin.
   - o Assembly/disassembly: Simplified installation and removal.
   - o Lifespan: Increased due to enhanced thermal stability and mechanical strength.
   - o Energy efficiency: Improved because the lighter shield reduced fuel consumption.

   Weighted scoring (using Table 5 weights) identified the modified design as superior to the baseline.
5. Manufacturing and cost analysis: Potential challenges related to material compatibility and scale-up when introducing recycled PET and GNPs. These could be addressed by optimising curing parameters, ensuring uniform heat distribution during moulding, and validating that the sol-gel coating adhered well. Cost analysis showed that material cost increased slightly but was offset by weight-related operational savings.

Thus, based on this brief explanation, the example illustrates how the CDfX framework guides designers from baseline assessment to decision-making, integrating technical, environmental, and economic factors.

5.4. *Decision support and general guidance*

By comparing weighted scores and identifying common interventions, the CDfX framework supports designers and decision-makers in prioritising circular design strategies. The integrative analysis highlights that (i) reversible joints and modularity consistently improve recyclability and disassembly; (ii) graphene reinforcement (and similar 2D and advanced materials) facilitates weight reduction and lifespan extension; and (iii) manufacturing challenges must be addressed early. These insights inform future development of components across multiple sectors and demonstrate the applicability of the CDfX framework beyond the specific UCs examined.

6. Conclusions

The Circular design framework employed in this work has served as both a conceptual foundation and a practical roadmap for integrating sustainability into the design and development of next-generation graphene-enhanced components. Unlike traditional product development

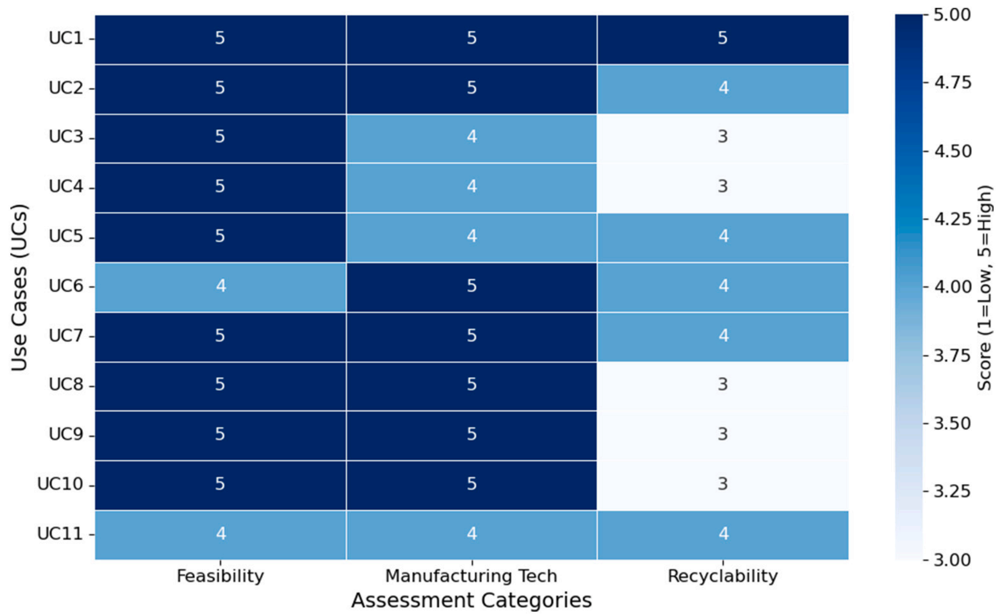

Fig. 19. Feasibility, manufacturing technologies, and recyclability concepts assessment.

approaches that often treat environmental impact as a downstream consideration, the current framework proactively positions circularity at the core of innovation. By leveraging the principles of eco-design, Design for X (DfX) methodologies, and lifecycle thinking, this framework has ensured that each of the 11 industrial UCs transitions from a linear product lifecycle to a more regenerative, resource-efficient paradigm. At its core, the circularity framework served as a scaffolding that connected material innovation with environmental regulations. It enabled each UC to be assessed not only on technical feasibility and performance but also on recyclability, assembly and disassembly potential, material criticality, and EoL strategies. Through tailored DfX prioritisation matrices and cross-sector evaluations, the framework encouraged a dynamic balancing of priorities—such as lightweighting for fuel efficiency (UC1, UC2, UC5, UC6), functional integration to reduce part counts and maintenance needs (UC8, UC9), or the substitution of critical raw materials (UC10, UC11)—all within the context of real-world manufacturability and economic feasibility. A distinctive feature of this framework was its ability to account for the interconnectedness of lifecycle stages. It recognised that a material choice in the design phase could influence energy consumption during processing, repairability during use, and recyclability at EoL. For instance, in UC6, the replacement of metallic mesh with a graphene-based conductive coating not only reduced weight but also eliminated a barrier to thermoplastic recycling—showcasing how circular thinking can unlock multiple benefits simultaneously. Similarly, in UC10 and UC11, the shift toward 2D graphene-based materials and advanced hydrogen storage powders required rethinking disassembly and recycling methods, which the framework addressed through systemic design mapping and recovery strategy development.

Moreover, the framework's strength lies in its sector-specific flexibility and cross-sectoral transferability. While the automotive and aerospace UCs focused heavily on mass savings and structural integrity, water treatment and hydrogen storage UCs leveraged the framework to explore chemical circularity and material reusability. This adaptability ensured that the framework could accommodate high-regulation sectors (e.g., aerospace certification), rapidly scaling technologies (e.g., additive manufacturing and printing in UC8), and emerging circular business models (e.g., product-as-a-service or extended producer responsibility). From a strategic standpoint, the circularity framework also guided trade-offs between cost efficiency and sustainability. By integrating energy and labour metrics into the design analysis (e.g., autoclave curing versus isothermal hot pressing), the work demonstrated how sustainability does not inherently conflict with economic viability—instead when embedded early, it becomes a driver for innovation, risk reduction, and market readiness.

While the circular design framework demonstrated promising qualitative improvements across eleven graphene-enhanced use cases, it is important to recognise the limitations of this early-stage study. The present evaluation relies on conceptual manufacturing scenarios and expert-driven weightings; detailed life-cycle and techno-economic analyses are ongoing and will be needed to validate the projected benefits. Some of the studied applications involve low-TRL technologies whose scalability hinges on advances in catalyst, membrane and other components fabrication. Moreover, sector-specific constraints, such as supply-chain bottlenecks, stringent aerospace certification and the high capital cost of specialised equipment, may temper the practical deployment of certain solutions. Finally, the eleven use cases, though diverse, do not exhaust the spectrum of industrial applications; hence, the generalisability of the framework should be explored in future work.

CRediT authorship contribution statement

Ahmed Refaat Elmasry: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Miguel Moldes:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Gyu-Eun Cho:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Conceptualization. **Carmen R.Tubio:** Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Methodology, Investigation, Conceptualization. **Pablo Acuña:** Writing – review & editing, Visualization, Validation, Investigation, Formal analysis. **Gianluigi Creonti:** Writing – review & editing, Validation, Resources, Investigation. **Ali Rezaei:** Writing – review & editing, Validation, Resources, Investigation. **Diogo Garcia:** Writing – review & editing, Validation, Resources, Investigation. **Ilaria Bolliri:** Writing – review & editing, Validation, Resources, Investigation. **Daniele Pullini:** Writing – review & editing, Validation, Resources, Investigation. **Simone Barletta:** Writing – review & editing, Validation, Resources, Investigation. **Giulia Molinari:** Writing – review & editing, Validation, Resources, Investigation. **Dustin Holohan:** Writing – review

& editing, Validation, Resources, Investigation. **Ozlem Turkarslan:** Writing – review & editing, Validation, Resources, Investigation. **Feride Nur Sasal:** Writing – review & editing, Validation, Resources, Investigation. **Mathieu Chirat:** Writing – review & editing, Validation, Resources, Investigation. **Théo Remy-Lorit:** Investigation, Resources, Validation, Writing – review & editing. **Luciano Macera:** Writing – review & editing, Validation, Resources, Investigation. **Merkur Smajlaj:** Writing – review & editing, Validation, Resources, Investigation. **Engy Ghoniem:** Writing – review & editing, Visualization, Investigation. **Ahmed Elmarakbi:** Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: GIANCE reports financial support was provided by European Union Horizon Europe - Research and Innovation Framework Programme under project GIANCE. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Detailed challenge–solution descriptions for Table 6

This appendix elaborates on the manufacturing challenges and associated solution categories presented in Table 6 of the manuscript. For each use case (UC), the principal challenges identified in the qualitative heat-map are summarised together with the kinds of actions taken to mitigate them.

Table A1
Solution descriptions for Table 6.

Proposed manufacturing scenarios & Associated challenges ↓/Solutions' categories→	Material design	Automated control	Modular equipment	Advanced deposition	Safety protocols
UC1: Fast warm/hot press curing process using a hybrid thermoplastic/thermoset polyester/epoxy resin system with 50 % recycled PET. Application of GNP-based sol-gel spray coating					
Material compatibility: Hybrid resin systems are prone to phase separation (Adeniyi et al., 2016) and inconsistent performance (Santomasi et al., 2024).	Adjust resin formulation (add compatibilisers and tune oligomer content) to reduce phase separation and ensure strong bonding and mechanical performance.	–	–	–	Follow safe handling of resin and coating components.
Optimising process: Achieving a uniform cure while preventing degradation of recycled PET demands (Dębska et al., 2024) tight control of curing parameters and avoiding defects (*Trans. Indian Inst. Metals*, 2024).	–	Implement precise temperature and pressure control with real-time monitoring to ensure uniform curing.	Employ sensors to maintain uniform heat distribution across the mold.	–	Train operators and provide PPE for high-temperature processing.
Scale-up: Transitioning from lab-scale to industrial scale requires reproducibility and equipment adaptation.	–	Standardise temperature/ pressure control and automation to ensure reproducibility at an industrial scale.	Modify moulds and presses to handle larger volumes (e.g., modular equipment with interchangeable tools).	–	Update safety protocols for new equipment.
Coating application: Achieving uniform thickness and strong adhesion in the sol-gel spray coating (Ciriminna and Pagliaro, 2022; Barrino, 2024).	Design self-levelling sol-gel coatings with suitable viscosity to achieve uniform thickness and strong adhesion.	Use sensors to control spray rate and coating thickness.	Use adjustable spray rigs/ nozzles to suit component geometry.	Optimise spray parameters (droplet size, distance) to deposit uniform layers.	Implement personal protective equipment (PPE) and ventilation for nanoparticle-containing coatings.
Safety & health: Handling nanoparticle-rich coatings requires stringent health and safety measures (Pelin et al., 2018; Devasena et al., 2021; Andrews et al., 2024).	–	–	–	–	Enforce strict PPE, fume extraction and training when handling graphene nanoplatelets or sol-gel aerosols.
UC2: One-shot, low-pressure warm compression moulding of GF-based GNP-modified recyclable resin on an rPET foam core					
Process complexity: One-shot moulding with multiple materials can lead to voids/incomplete bonding (Zhou et al., 2023; Guerra et al., 2023); inaccurate	Implement cross-preg layering and tailored resin/foam formulations to improve bonding and reduce voids.	Use automated control of temperature and pressure during the cure process.	Employ heated moulds with integrated controls to accommodate multi-material moulding.	–	Provide safe handling for high-temperature and multi-material processing.

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Table A1 (*continued*)

Proposed manufacturing scenarios & Associated challenges ↓/Solutions' categories→	Material design	Automated control	Modular equipment	Advanced deposition	Safety protocols
temperature control may degrade rPET foam. (Özel and Soylemez, 2024; Karagöz, 2021; Nathan and Prabhu, 2022).					
Material compatibility: Differential expansion between resin, fibres, and foam can cause delamination; macroscopical adherence between the resin and the rPET foam core (Özel and Soylemez, 2024).	Robust chemical interactions between the resin and fibres create a cohesive macroscopic bond, which significantly reduces mismatches in thermal expansion and helps maintain structural coherence across temperature fluctuations.	–	–	–	Ensure safe handling of adhesives and chemicals.
Quality control: Maintaining uniformity across production batches. (Ke et al., 2024; Li et al., 2024a); aesthetic issues from recycled material affecting surface finish.	Standardise material formulations to ensure consistent properties.	Integrate sensors and automated inspection to monitor uniform distribution and surface finish.	Incorporate quality-monitoring modules within moulds.	–	Ensure safe working conditions during inspection.
Equipment limitations: Moulds may need to be custom-built for materials and geometry; cycle time is constrained by curing and quality demands.	Adapt resin formulations to reduce cycle time and ease processing.	Optimise heating/cooling cycles via automated control to minimise cycle time.	Utilise bespoke or modular moulds (aluminium or steel) with integrated heating/cooling.	–	Follow safe operation guidelines for specialised equipment.
UC3: Preparation of GO-improved NF membranes on a polymeric substrate coated/impregnated with GO. Integration of GO-Fe_3O_4 nanocomposite catalysts					
Material compatibility: membrane stability (Jia et al., 2022; Zhang et al., 2020); mechanical and chemical resistance (Sharma et al., 2024; Cairney et al., 2024).	Once incorporated into a composite or membrane, graphene oxide exhibits high stability; published studies consistently show that GO membranes are chemically resistant.	–	–	Layer-by-layer or vacuum-filtration deposition to create uniform GO layers.	Use PPE and safe handling for GO and catalysts.
Scale-up: fabricating large-area defect-free membranes (Pourebrahim and Doroodmand, 2024; Bairapudi et al., 2023); high production rates and requiring efficient and reliable processes.	Adjust formulations to maintain performance at scale.	Use roll-to-roll or slot-die coating with feedback control to ensure uniform thickness.	Deploy modular casting or coating lines for scalability.	Employ scalable deposition methods (slot-die, electrophoretic deposition).	Manage safe handling and waste at larger production volumes.
Catalyst incorporation: Ensuring uniform catalyst distribution and long-term activity	Rather than embedding catalysts directly into the membrane, incorporate them via a separate process. This preserves membrane mechanical and chemical integrity while allowing the catalysts to function in an environment optimised for their activity and uniform dispersion.	Apply automated control systems to ensure the catalysts are uniformly distributed and remain active throughout the process (e.g., by monitoring and adjusting process parameters).	Use dedicated integration equipment (such as a catalyst module or an external reactor) to incorporate catalysts outside the membrane structure. This allows for consistent distribution, easy catalyst replacement, and compatibility with existing membrane systems.	–	Implement standard safety measures (PPE, ventilation, safe handling of catalysts) to protect operators and the environment during catalyst integration and operation.
System integration: Compatibility with existing membrane housings, operational flow rate, and pressure.	Tailor membrane thickness and mechanical properties to fit existing housings and operate at required flows/ pressures.	Use sensors and control systems to monitor flow rate and pressure during operation.	Adopt modular housings or retrofit kits for integration into existing systems.	–	Ensure safe operation under pressure and mitigate leak risks.
Fouling and cleaning: Particles accumulate and reduce permeability. Antifouling characteristics need to be developed accordingly (Shafi et al., 2016; Yi et al., 2019).	Leverage GO's inherent oxidant resistance and high pH tolerance by designing membranes that can endure repeated cleaning cycles without degrading. This might include adjusting the polymer matrix or membrane surface	Implement automated monitoring and control systems that track fouling indicators (e.g., pressure drop, flow rate) and adjust cleaning schedules accordingly. pH and oxidant levels in cleaning solutions should be controlled based on the	Employ modular cleaning modules that can be attached to the membrane system, allowing for controlled cleaning sequences (e.g., flushes with oxidants or alkaline solutions) without dismantling the system. Equipment should be	Ensure that GO layers are deposited uniformly and robustly during membrane fabrication to maximise their chemical resilience. Coating techniques should achieve consistent coverage, enabling the membrane to maintain its antifouling	Ensure safe handling of cleaning chemicals and disposal.

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Table A1 (*continued*)

Proposed manufacturing scenarios & Associated challenges ↓/Solutions' categories→	Material design	Automated control	Modular equipment	Advanced deposition	Safety protocols
	properties so that fouling particles adhere less, and cleaning agents (oxidants, alkaline solutions) do not damage the membrane.	membrane's tolerance to optimise cleaning effectiveness and prevent damage.	adaptable to handle different cleaning chemistries and flow conditions safely and consistently.	properties and resist aggressive cleaning cycles. Post-deposition surface modifications (e.g., hydrophilic coatings) can further reduce fouling.	
Cost constraints: High-quality GO and catalysts may increase the cost.	Optimise membrane design to use minimal high-cost GO or catalysts; explore lower-cost additives.	Improve process efficiency to reduce energy and waste.	Select cost-effective modular equipment to reduce capital expenditure.	Use deposition methods that minimise material waste.	–
UC4: Fabrication of LIG-enhanced ultrafiltration membranes. Employing TiO_2-coated functionalized GO sheets as photocatalysts					
Material compatibility: Membrane mechanical Stability (Kucera, 2023; Echakouri et al., 2022) & chemical stability to resist degradation integrity in oil/water mixtures (Kucera, 2023; Cipollini, 2007).	Design the UF membrane using a PVDF substrate with GO powder, employing the thermally induced phase separation (TIPS) technique. Control polymer concentration, solvent exchange, and cooling rate to achieve 5 cm^3 membrane volume, pore structure, and mechanical strength. GO acts as a lipophobic additive, reducing oil fouling and extending service life.	–	Use equipment sized for the 5 cm^3 membrane; ensure compatibility with 1812 spiral-wound housing and easy replacement.	Apply TiO_2 via uniform deposition (e.g., atomic layer deposition) for consistent coverage.	Provide safe handling of nanomaterials.
Scale-up: LIG requires precise laser control (Karimi et al., 2021; Singh et al., 2022; Liu et al., 2023) and may not scale (Wang et al., 2018; LiMichael et al., 2020); high cost of laser systems (MurrayMicheal et al., 2021) and its maintenance (Le et al., 2022).	Optimise substrate composition and processing conditions; LIG is replaced by the TIPs, which are upscalable.	Use automated control and feedback loops to maintain accuracy.	Utilise modular systems that can be replicated for higher throughput.	Employ scanning strategies to ensure uniformity.	Expand ventilation, PPE, and solvent recovery.
Catalyst performance: TiO_2 coating may degrade (Gao et al., 2024; Wang et al., 2024; Sriram et al., 2020); UV activation is required (Kirk et al., 2024; Ponce-Robles et al., 2023).	Use stabilised TiO_2 or dopants to reduce degradation; optimise coating thickness.	Monitor coating integrity and activate catalysts with controlled UV exposure.	Integrate UV activation modules.	Apply TiO_2 coatings using controlled deposition to ensure uniformity.	Provide UV shielding and safe handling of chemicals.
System integration: System compatibility and parameter optimization for flow/pressure.	Match membrane dimensions and mechanical properties to existing housings.	Use sensors to monitor pressure/flow and adjust operation.	Use 1812 modules; plug-and-play fittings.	–	Leak detection; pressure-relief & safety procedures.
Safety & health: Nanomaterial contamination & waste management.	Encapsulate nanomaterials to minimise release	–	–	–	Comprehensive PPE, ventilation & waste management.
UC5: Preparation of the lay-up, lamination, and curing with GNP-doped thermoset polyimide (PI) resin					
Material compatibility: PI resins require >300 °C curing, and are not always equipment-compatible (Qian et al., 2021; Matsutani et al., 2005; Wang et al., 2022b); energy-intensive.	Select PI resins that cure at lower temperatures or incorporate modifiers to reduce cure temperature and viscosity; improve compatibility with GNPs.	Use precise temperature control during cure.	Employ high-temperature ovens or modular autoclaves to meet curing requirements.	–	Provide PPE and ventilation for high-temperature processes.
GNP dispersion: GNP agglomeration (Kausar and Ahmad, 2023; Zhang and Zhou, 2010; Zhang et al., 2021; Sobhani et al., 2022) and high viscosity (Zhu	Use dispersants and high-shear mixing; prepare pre-dispersed masterbatches to avoid agglomeration.	Monitor viscosity and mixing with automated systems.	Employ mixing/lamination equipment capable of handling high-viscosity resins uniformly.	Apply GNP via wet impregnation or spray coating for homogeneous distribution.	Provide dust control and PPE for nanomaterials.

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Table A1 (*continued*)

Proposed manufacturing scenarios & Associated challenges ↓/Solutions' categories→	Material design	Automated control	Modular equipment	Advanced deposition	Safety protocols
et al., 2023) affect uniformity and lamination (Ishida et al., 2021).					
Process complexity: Maintaining viscosity for prepregs (Suzumura et al., 2014; Saito et al., 2024) and managing short shelf-life (Vora and Lau, 2022; Somarathna et al., 2024) of high-temp resins.	Adjust formulations and include stabilisers to prolong shelf-life; tailor viscosity for prepregging.	Use automated mixing systems with real-time viscosity monitoring.	Adopt modular prepreg machines with controlled temperature/humidity.	–	Manage exothermic reactions safely.
Equipment requirements: Limited access to autoclaves (Vita et al., 2019); need for high-temp moulds.	Explore out-of-autoclave processing (e.g., vacuum bagging).	–	Use modular high-temperature ovens, out-of-autoclave systems, and high-temperature moulds.	–	Provide safe operation and training.
Health and Safety: Emission of harmful volatiles during curing; need for PPE and ventilation.	–	–	–	–	Use fume extraction, ventilation and PPE; monitor air quality during curing.
UC6: Optimised consolidation processes for carbon fibre-based PEEK composites with high-conductivity GNP-based coatings.					
Process Complexity: PEEK composite high-temperature (360 °C) processing (Li et al., 2023; Guo et al., 2023; Bessard et al., 2011; Jin et al., 2024) & viscosity challenge for CF impregnation (Lu et al., 2024; Ma et al., 2023).	LM-PAEK has been chosen as the resin matrix due to its low melting point, which allows for strong layer bonding while retaining key mechanical and thermal properties. Its processing temperature is 40–50 °C lower than PEEK, improving production efficiency. Pre-impregnated carbon fibres and available materials will be utilised.	Employ presses with precise temperature/ pressure control.	Use modular high-temperature equipment designed for PAEK processing.	–	Train operators and provide PPE.
Coating application: Coating adhesion (Gao et al., 2023; Sun et al., 2024; Sin et al., 2020) and surface conductivity (Parten et al., 2024; Leow et al., 2023; Oliveira et al., 2024) must be optimised across thermal cycles.	Optimise coating formulation (binders, thickness) to maintain adhesion and conductivity across thermal cycles.	Monitor coating thickness via sensors and adjust deposition parameters.	Use modular coating equipment integrated into consolidation lines.	Apply coatings through spray, sputtering or other methods to ensure uniform GNP distribution.	Provide safety measures for nanoparticle handling.
Material compatibility: Thermal expansion mismatch may cause delamination (Leow et al., 2021; Ren et al., 2022).	The difference in thermal expansion between graphene-doped coatings and carbon fibre-reinforced thermoplastic composites is unlikely to pose a significant issue.	–	–	The coating layer is sufficiently thin, which should mitigate the risk of delamination, assuming the conditions apply	Provide safe handling of adhesives/coatings.
Equipment limitations: PEEK requires specialised high-temp equipment and is costly.	Explore materials or processes that allow lower processing temperatures (LM-PAEK is selected).	Optimise equipment utilisation through automated scheduling and precise control.	Use modular high-temperature presses/ovens with integrated heating/cooling.	–	Ensure safe operation.
Quality assurance: Detecting defects like voids/ incomplete consolidation is essential.	Select resin systems and GNP content that minimise voids; incorporate robust interleaves.	Use in-situ monitoring (ultrasonic, dielectric) to detect defects during consolidation.	Integrate non-destructive testing modules.	–	Provide training and handle high-energy sensors safely.
UC7: Automated wet filament winding process with CFs/GRMs-based epoxy composites.					
Material compatibility: GNP aggregation reduces strength (Liu et al., 2021, 2025a); viscosity must support fibre wetting (Kotsilkova et al., 2022; Srivastava et al., 2024).	Use dispersants and high-shear mixing to prevent graphene agglomeration; adjust resin viscosity for fibre wetting.	Monitor viscosity and mixing via automated systems.	Use modular winding machines with adjustable dosing/tension control.	Apply pre-treatments or coatings to improve wetting.	Provide safe handling for resins and graphene.
Process complexity: Accurate fibre winding (Zhang et al., 2024; 童喆益, 2011) and	Adjust resin cure kinetics and add toughening agents to limit exothermic spikes.	Use CNC-controlled winding machines with	Use modular mandrels and winding heads for different geometries.	–	Train operators for precise winding and safe exothermic handling.

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Table A1 (*continued*)

Proposed manufacturing scenarios & Associated challenges ↓/Solutions' categories→	Material design	Automated control	Modular equipment	Advanced deposition	Safety protocols
cure management needed to avoid thermal/ exothermic issues.		feedback for tension and temperature control.			
Scale-up: Resin dosing and equipment calibration needed; curing cycle optimisation required.	Stabilise resin viscosity for consistent dosing.	Use automated resin dosing and calibration systems.	Deploy modular resin delivery and curing systems that can be replicated.	–	Provide safe handling for higher volumes.
Structural integrity: High level of voids/dry spots can cause premature pressure failure; composite must be high-impact resistant.	Optimise fibre architecture and resin content; incorporate interleaves or tougheners to reduce voids.	Monitor tension and resin flow in real time.	Use modular inspection tools for void detection.	–	Ensure safe handling of pressurised composite cylinders.
Regulatory compliance: Full-scale tests (e.g. BURST, cycling) needed for certification due to GRM material in load-bearing shell.	Design tank structures and materials to meet certification and include durability features.	Use sensors and control systems to monitor performance during tests.	Employ test fixtures and equipment for burst/ cycling tests.	–	Provide safe testing procedures and PPE.
UC8: rGO-based conductive and dielectric inks were applied onto polymeric substrates using both screen-printing and inkjet printing techniques.					
Material compatibility: rGO particles must not sediment (Loh et al., 2021; Chamelot et al., 2024; Ahmed et al., 2024; Nalepa et al., 2024); viscosity must suit print method without degrading conductivity (Kim et al., 2021; Zitoun et al., 2022; Wang et al., 2017).Ink must adhere to polymers and resist humidity, mechanical stress, and temperature variations.	Formulate inks with stabilisers and dispersants to prevent sedimentation; include adhesion promoters and tune viscosity for each printing method.	Use automated printing systems to control drop formation and flow.	Use modular printing platforms with interchangeable heads.	Apply advanced printing techniques (inkjet, aerosol jet) to deposit uniform films.	Manage safe handling of solvents and nanomaterials.
Quality assurance: Resolution and repeatability can be affected by ink flow, printhead, and process conditions (Chang et al., 2018; Murayama et al., 2013).	Standardise ink formulation to maintain consistent viscosity and dispersion.	Use inline inspection and sensors to monitor print resolution and repeatability.	Use modular maintenance and cleaning units for printheads.	Use multi-pass or layered printing to improve resolution.	Ensure operator safety when handling inks and cleaners.
Installation challenges: Sensor embedding should not alter mechanical properties of structures or degrade signal integrity.	Design inks and sensor packages to be flexible and mechanically compatible; use adhesives or encapsulants that do not compromise performance.	Control deposition and curing to avoid altering structural integrity.	Use modular embedding tools tailored to component geometry.	–	Provide safe handling during embedding and curing.
Scale-up: Precision printing becomes harder with high throughput; cost control is a concern.	Maintain ink consistency across larger batches.	Use high-speed printing systems with feedback control to maintain precision.	Scale production by adding multiple printing modules.	Use continuous or multi-nozzle printing to maintain accuracy at high speeds.	Manage worker safety during high-throughput operations.
UC9: Low-cost spray coating techniques are used for applying metal-GRM composite coatings					
Material compatibility: Maintaining thickness (Jacobs et al., 2021; Deng et al., 2019) and coverage (Noguchi et al., 2023; Ling et al., 2024) uniformity over large or complex surfaces. Preventing surface contamination (Lytovchenko et al., 2020; Bobzin and Knoch, 2017) and supporting strong bonding mechanisms (Liu et al., 2025b; Liao et al., 2020) for strong adhesion. Wear and durability: Sustaining resistance to	Optimise coating formulations (viscosity and solids) and surface preparation to ensure uniform thickness and strong adhesion.	Use automated spray equipment with sensors to monitor thickness and adjust parameters dynamically.	Employ modular spray booths and robotic arms capable of controlling spray angle, pressure and distance.	Utilise advanced spray techniques (cold spray, plasma spray) to improve uniformity.	Provide ventilation, respiratory protection and containment.

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Table A1 (*continued*)

Proposed manufacturing scenarios & Associated challenges ↓/Solutions' categories→	Material design	Automated control	Modular equipment	Advanced deposition	Safety protocols
abrasion, thermal cycling, and harsh environments.					
Process complexity: Spray parameter consistency, pressure/angle/distance tuning, and post-curing.	Select coating systems tolerant of slight parameter variations.	Implement closed-loop control of spray pressure, angle and distance, and integrate post-curing cycles.	Equip spray facilities with adjustable nozzles, multi-axis robots and modular booths.	Use controlled deposition followed by appropriate curing.	Manage safety during spraying and curing.
Health and safety: Exposure to nanomaterials and regulatory compliance.	Select low-toxicity formulations and encapsulate nanomaterials.	Use automation to reduce worker exposure.	Design enclosed spray booths with extraction and filtration.	Use deposition methods that minimise overspray.	Provide PPE, ventilation and waste management to meet regulatory compliance.
UC10: The doping of transition metals is introduced by the method of template-assisted CVD for doped rGO.					
Process complexity: CVD requires precise control of temp, pressure, gas (Jia et al., 2020; Konar and Nessim, 2022; Buchkov et al., 2024); deposition uniformity must be maintained (Hong et al., 2023; Chen et al., 2020).	Optimise doping materials and substrates to broaden process tolerances.	Use automated CVD systems with precise temperature/pressure/gas-composition control and in-situ sensors. Other processes, e.g., screen-printing, could be prioritised for the deposition of material, e.g., a catalytic layer.	Employ modular CVD reactors with integrated gas-handling modules, or widely available screen-printing equipment and modular tooling.	Use template-assisted deposition with adjusted parameters for uniform layers.	Safely manage toxic gases and high-temperature processes.
Scale-up: CVD has batch throughput limits (Xin and Li, 2018) and high cost.	Select catalysts and substrates enabling shorter cycles or continuous processing.	Optimise process control to reduce deposition time and energy consumption. Prioritise screen-printing methods to mitigate the challenges associated with CVD.	Replicate modular designs to expand throughput.	Explore continuous or semi-continuous CVD methods for higher productivity.	Ensure safe operation at increased scale.
Catalyst stability: Catalysts must remain stable under acidic conditions; avoid deactivation by impurities.	Choose catalyst compositions and dopants that resist deactivation under acidic or electrochemical conditions; apply protective coatings.	Monitor catalyst performance and adjust deposition accordingly.	–	Use deposition methods that protect and stabilise catalysts.	Handle catalysts safely and manage waste.
Cost constraints: Transition metals are cheaper than Pt, but still costly; high-quality rGO synthesis in bulk is a challenge.	Use cost-effective dopants and reduce rGO consumption through optimised doping levels.	Improve process efficiency to reduce energy and material consumption.	–	Use deposition methods that minimise waste and enable precursor recycling.	Maintain safe handling while balancing cost.
System integration: New catalysts must be MEA-compatible and pass performance validation.	Tailor catalyst morphology to match membrane-electrode assemblies (MEAs) and ensure mechanical and electrochemical compatibility.	Use sensors to monitor performance and adjust integration parameters.	Utilise test rigs and modules to evaluate and validate integration.	Apply catalysts via deposition techniques, ensuring adhesion to MEAs.	Provide safe procedures for integration and testing.
UC11: Synthesis of transition metal-doped storage materials in GO/rGO-based foams using template-assisted CVD					
Material compatibility: Uniform pore structure (Le et al., 2024; Paz et al., 2023) and reproducibility of storage materials. Material Stability: Avoiding material degradation under H_2 cycling (Broom, 2011). Impurities in hydrogen gas can affect material integrity.	Use templating methods to create uniform pore structures; adjust dopant distribution for reproducibility.	Monitor pore formation using sensors during synthesis.	Use modular CVD reactors designed for uniform foam formation.	Apply multi-stage deposition and templating to achieve uniform doping.	Provide safe handling of templates and foaming agents.
Process complexity: Balancing material weight and H_2 storage capacity; requires specific pressure/temperature to operate.	Design foams to maximise storage capacity without excessive weight; optimise pore size and doping level.	Control temperature and pressure precisely during synthesis and operation.	Use modular synthesis and testing equipment.	–	Manage pressure/temperature safely.
Scale-up: CVD-based methods are challenging to scale, in addition to high material costs (Transition	Identify cost-effective dopants and reduce graphene consumption.	Optimise process parameters to shorten cycle time.	Use modular CVD reactors and replicate them to increase throughput.	Explore continuous or semi-continuous CVD processes.	Ensure safe operation of larger CVD systems.

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Table A1 (*continued*)

Proposed manufacturing scenarios & Associated challenges ↓/Solutions' categories→	Material design	Automated control	Modular equipment	Advanced deposition	Safety protocols
metals and high-purity graphene).					
Health and Safety: Hydrogen embrittlement (Li et al., 2024b) and leak prevention.	Apply coatings or select dopants to mitigate hydrogen embrittlement.	Use sensors to detect leaks and monitor structural integrity.	Use storage modules with integrated leak-detection and pressure-relief systems.	–	Provide comprehensive safety protocols for hydrogen handling and storage.

Acronyms

CF	Carbon fibre	**CVD**	Chemical vapour deposition	**GF**	Glass fibre	**GNP**	Graphene nanoplatelet
GO	Graphene oxide	**LIG**	Laser-induced graphene	**NF**	Nanofiltration	**PEEK**	Polyether ether ketone
PET	Polyethylene terephthalate	**rPET**	Recycled polyethylene terephthalate	**rGO**	Reduced graphene oxide	**UF**	Ultrafiltration

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